

Illiquidity Component of Credit Risk*

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Abstract

We describe and contrast three different measures of an institution's credit risk. "Insolvency risk" is the conditional probability of default due to deterioration of asset quality if there is no run by short term creditors. "Total credit risk" is the unconditional probability of default, either because of a (short term) creditor run or (long run) asset insolvency. "Illiquidity risk" is the difference between the two, i.e., the probability of a default due to a run when the institution would otherwise have been solvent. We discuss how the three kinds of risk vary with balance sheet composition. We provide a formula for illiquidity risk and show that it is (i) decreasing in the "liquidity ratio" – the ratio of realizable cash on the balance sheet to short term liabilities; (ii) increasing in the "outside option ratio" – a measure of the opportunity cost of the funds used to roll over short term liabilities; and (iii) increasing in the "fundamental risk ratio" – a measure of ex post variance of the asset portfolio.

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1 Introduction

Credit risk refers to the risk of default by borrowers. In the simplest case, where the term of the loan is identical to the term of the borrower's cash flow, credit risk arises from the uncertainty over the cash flow from the borrower's project. However the turmoil in credit markets in the financial crisis that erupted in 2007 has highlighted the limitations of focusing just on the value of the asset side of banks' balance sheets. The problem can be posed most starkly for institutions such as Bear Stearns or Lehman Brothers that financed themselves through a combination of short-term and long-term debt, but where the heavy use of short-term debt made the institution vulnerable to a run by the short term creditors.¹

The issue is highlighted in an open letter written by Christopher Cox, the (then) chairman of the U.S. Securities and Exchange Commission (SEC) explaining the background and circumstances of the run on Bear Stearns in March 2008.²

“[T]he fate of Bear Stearns was the result of a lack of confidence, not a lack of capital. When the tumult began last week, and at all times until its agreement to be acquired by JP Morgan Chase during the weekend, the firm had a capital cushion well above what is required to meet supervisory standards calculated using the Basel II standard.

Specifically, even at the time of its sale on Sunday, Bear Stearns' capital, and its broker-dealers' capital, exceeded supervisory standards. Counterparty withdrawals and credit denials, resulting in a loss of liquidity – not inadequate capital – caused Bear's demise.”

Thus, in spite of Bear Stearns meeting the letter of its regulatory capital requirements, it got into trouble because its lenders stopped lending. The implication is that the run was liquidity-based rather than solvency-based. However, even on this score, the issues are more complex than meet the eye.

¹See Morris and Shin (2008) and Brunnermeier et al. (2009) for a reappraisal of financial regulation in a system context.

²Letter to the Chairman of the Basel Committee on Banking Supervision, dated March 20th 2008, posted on the SEC website on: <http://www.sec.gov/news/press/2008/2008-48.htm>

Bear Stearns was regulated by the SEC under its Consolidated Supervised Entity (CSE) Program which stipulated a liquidity requirement as well as a Basel II-style capital requirement. The fact that Bear Stearns suffered its crippling run suggests that the liquidity requirement in place was inadequate. We will return to examine this issue in more detail below, and interpret our theoretical framework in the light of the events surrounding Bear Stearns' collapse.

The idea that self-fulfilling bank runs are possible is well established in the banking literature (see Bryant (1980) and Diamond and Dybvig (1983)).³ But the sharp distinction between solvency and liquidity in the SEC Chairman's letter may not be so easy to draw in practice, even *ex post*. Our current understanding of the relation between insolvency risk and illiquidity risk is not well developed. Existing models tend to focus on one or the other and not on the interaction between the two. We regard this division of attention as untenable. Runs don't happen out of the blue; they tend to occur when there are also concerns about the quality of the assets, as in the case of Bear Stearns in 2008 and as documented by Gorton (1988) for U.S. bank runs during the 1863-1914 National Banking Era. It is sometimes difficult to tell (even *ex post*) whether the run merely hastened the failure of a fundamentally insolvent bank, or whether the run scuppered an otherwise sound institution. Nevertheless, the distinction between insolvency and illiquidity is meaningful as a counterfactual proposition asking what *would* have happened in unrealized states of the world. The distinction is also important for the policy choices, since the policy response will depend on whether the bank is fundamentally solvent or not. A solvent but illiquid bank could be given emergency funding to tide it over the crisis, but an insolvent bank is best dealt through least cost resolution. In order to address counterfactual "what if" questions we need a theoretical framework.

For the *ex ante* pricing of total credit risk, it is important to take account of the probability of a run. This is both because the occurrence of a run will undermine the debt value, and because a run will tend to destroy recovery values through disorderly liquidation under distressed circumstances. Merely focusing on the credit risk associated with the fundamentals of the assets will underestimate the total credit risk faced by a long term creditor.

In what follows, we provide a framework that can be used to address these

³See Gorton (2008) for a modern variation on the classic bank run scenario with an account of the crisis of 2007 as a banking panic with a run on repos rather than deposits.

questions. A leveraged financial institution funds its assets using short- and long-term debt, as well as its own equity. Short-term debt earns a lower return, but short-term creditors have the choice not to renew funding at an interim date. We use global game methods (introduced by Carlsson and van Damme (1993) and used in Morris and Shin (1998, 2003)) to solve for the unique equilibrium in the roll-over game among short-term creditors. In particular, we provide an accounting framework to decompose total credit risk into two components. First, the eventual asset value realization may be too low to pay off all debt. We dub this “insolvency risk”. Second, a run by the short-term creditors may precipitate the failure of the institution even though, in the absence of the run, the asset realization would have been high enough to pay all creditors. We refer to this second part as “illiquidity risk”. We demonstrate how total credit risk can be decomposed into insolvency risk and illiquidity risk, and how the two are jointly determined as a function of the underlying parameters of the problem.

Earlier papers such as Morris and Shin (2000, 2004), Rochet and Vives (2004) and Goldstein and Puzner (2005) used global game methods to address coordination failure in roll-over games. However, the earlier literature has focused on how coordination failure depends on current fundamentals rather than on how *future* fundamental uncertainty interacts with strategic uncertainty today. For this reason, the insights from the earlier literature are not well-suited to answer the main question we pose in this paper – namely, how illiquidity risk depends on future insolvency risk. In order to pose the question in the most stark way, our framework has the feature that illiquidity risk would disappear if there were no future insolvency risk.

Two elements determine the size of the illiquidity risk. The “outside option ratio” measures the opportunity cost to short-term creditors of not using their funds elsewhere. The “liquidity ratio” is the ratio of the cash that can be realized relative to the maturing short-term obligations. The cash that can be realized includes liquid assets on the balance sheet but also considers the cash that can be raised by selling risky assets at a fire sale discount or borrowing against the risky assets with a haircut. Since we also have a (standard) expression for the insolvency risk that the bank faces, we can calculate the impact on total credit risk of shifting assets to safe, liquid, low expected return assets from risky, illiquid, higher expected return assets. We show that a switch to cash will reduce total credit risk most when there is greater fundamental uncertainty, and when fire sale discounts or repo haircuts are large.

In contrast to the basic philosophy underpinning the Basel approach to capital regulation which emphasizes the size of the capital cushion relative to risk-weighted assets, our analysis points to the importance of examining the composition of the liability side of the balance sheet, and the ratio of cash to short-term debt. We have argued elsewhere (Morris and Shin (2008)) that for regulatory purposes, the single-minded focus on capital requirements needs to give way to a broader range of balance sheet indicators, including the ratio of liquid assets to total assets and short-term liabilities to total liabilities.⁴ Our results in this paper provide theoretical backing to our earlier arguments.

In this paper, we analyze credit risk, and its decomposition, for an exogenous balance sheet. For policy analysis, we examine the impact on credit risk of an exogenous change in the balance sheet. But the composition of the balance sheet is the outcome of management decisions and its endogeneity will in general be important for assessing credit risk. However, the direction of the impact of endogeneity is unclear. If short run debt is playing an efficient role in disciplining management, as in Calomiris and Kahn (1991), ex post illiquidity risk may be ex ante efficient. On the other hand, if all creditors have an incentive to liquidate too early from an ex ante efficiency (as well as ex post) perspective, because of conflicting interests between debt and equity, as in Acharya, Sundaram and John (2008), then there will be early liquidation risk not driven by coordination problems, and thus with very different comparative statics from this paper. We abstract from the endogeneity of the balance sheet in this paper and in order to focus on channels by which the composition of the balance sheet determines illiquidity risk.⁵

The outline of our paper is as follows. We begin in Section 2 with a framework where a bank holds cash and illiquid risky assets financed through three sources – equity, short-term debt and long-term debt. Short-term debt holders face the choice of rolling over their claims at an intermediate date. We solve a global game model where the outcome of the coordination problem faced by the short-term creditors determines the threshold value of the asset realization below which the run outcome takes place. In Section 3, we use the model to define our decomposition of total credit risk into insolvency risk and illiquidity risk. The core of our paper is the comparative statics analysis of Section 4 showing how the balance sheet composition impacts total credit

⁴The Basel committee has been investigating this viewpoint in the light of the financial crisis, Basel Committee (2009).

⁵Eisenbach (2010) develops a global game model of banking with endogenous balance sheets. See also Kurlat (2009).

risk and its two components.

Our benchmark model makes a number of stark modeling assumptions in order to bring out what we believe to be the key mechanisms in decomposing and analyzing credit risk, assuming, for example, that innovations are uniformly distributed. These assumptions enable us to obtain closed form solutions and, through them, a clean understanding of the channels by which balance sheet composition impacts illiquidity risk. In Section 5, we show how our results can be generalized to incorporate general distributions over haircuts, arbitrary collections of assets, fire sale discounts and haircuts that reflect current market conditions, “partial” liquidation of the bank, alternative assumptions about the resolution of the coordination problem, small ex ante uncertainty about conditions when the short-run creditors make their withdrawal decisions and “partial” payouts to creditors. These extensions demonstrate the robustness of the analysis of the benchmark model, identify extra channels from the balance sheet to illiquidity risk not contained in the benchmark model, allow a detailed discussion of the relation to the literature and illustrate the flexibility of the framework

2 Benchmark Model

2.1 The Balance Sheet and the Funding Game

We will analyze the balance sheet of a leveraged financial institution, called a “bank” for convenience.

There are three dates, ex ante (0), interim (1) and ex post (2). The bank holds a risky asset, such as loans or risky securities. Each unit of the risky asset pays a gross amount θ_2 in the final period (period 2). We write θ_0 and θ_1 for the expected value of θ_2 in periods 0 and 1 respectively. We assume that $\theta_1 = \theta_0 + \sigma_1 \varepsilon_1$ and $\theta_2 = \theta_1 + \sigma_2 \varepsilon_2$, where ε_1 and ε_2 are independently distributed with means 0. We also start by assuming that both ε_1 and ε_2 are uniformly distributed on the interval $[-\frac{1}{2}, \frac{1}{2}]$. We will relax this assumption in Section 5.1. The parameters σ_1 and σ_2 measure the size of interim and final period uncertainty respectively. We will refer to the ratio

$$\rho = \frac{\sigma_2}{\sigma_1}$$

as the “fundamental risk ratio.” It measures the size of the standard deviation

of the final period innovation, normalized by the standard deviation of the interim innovation.

The bank’s balance sheet in the benchmark model takes a simple form.⁶ On the asset side, the bank holds two assets: cash M and Y units of the risky asset. The bank finances these assets with three sources of funding – short term debt, long term debt and equity. We denote by S_2 the face value of short term debt (the amount promised to short-term debt holders) at date 2, and denote by L_2 the face value of long term debt at date 2. Thus, the (ex post) balance sheet of the bank at date 2 can be written as follows.

| Assets | Liabilities |
|--------------------------|------------------|
| Cash M | Equity E_2 |
| Risky Asset $\theta_2 Y$ | Short Debt S_2 |
| | Long Debt L_2 |

In this paper, we do not address the ex ante portfolio choice of the bank. The rapid growth in very short-term liabilities such as overnight repos in the run-up to the recent crisis is related to the lengthening intermediation chains where intermediaries borrow from other intermediaries.⁷ As such, a proper examination of the portfolio decisions rests on system-wide factors. Our focus is on the events surrounding a single bank and its creditors, and to this extent it is best to view our model as addressing the cross-section of banks at a point in time, rather than addressing the time-series properties of the trends in short and long-term debt.

The residual payoff of the bank’s owners is given by the ex post equity E_2 . The bank is solvent if the ex post equity is positive, i.e.,

$$M + \theta_2 Y \geq S_2 + L_2$$

or, equivalently,

$$\theta_2 \geq \frac{S_2 + L_2 - M}{Y} \equiv \theta^{**}.$$

This “solvency point” θ^{**} will play a crucial role in our analysis. We assume that if the bank is insolvent in period 2 – i.e., $\theta_2 < \theta^{**}$ – then the bank

⁶We later (in Section 5.2) extend the analysis to a more general asset portfolio.

⁷The lengthening of intermediation chains is in part due to rapid growth of intermediary balance sheets. If all banks’ balance sheets double in size, but outside funding sources (such as deposits) do not keep pace, then banks end up with greater liabilities to each other. See Shin (2009) for inferences that can be drawn from the aggregate balance sheet identity.

goes into liquidation. In the benchmark model, we assume that if the bank goes into liquidation then neither short nor long term creditors receive any payoff. Allowing positive recovery rates at this stage would not qualitatively change our analysis, although it could have a quantitative impact. In Section 5.7, we relax this assumption to see how our analysis is affected by positive recovery rates.

At the intermediate date 1, the short-term creditors face a decision on whether to roll over their lending. If the positions of short run creditors are not rolled over, then additional assets must be pledged to raise new funding, or sold into the market to raise cash. A key quantity in our model is how much cash can be raised from the risky asset portfolio. We assume that the cash that can be raised from a unit of the risky asset is ψ , where ψ represents the amount that can be borrowed by pledging one unit of the risky asset as collateral. The total cash that is available to the bank at the interim date is

$$A^* = M + \psi Y.$$

The parameter ψ plays an important role in our analysis. The larger is ψ , the larger is the cash pool that the bank can draw on in the interim period. Our interpretation of ψ is in terms of the cash that can be borrowed when one unit of the risky asset is pledged to the lender as collateral. A low value of parameter ψ reflects a large “haircut” demanded by the lender in the collateralized transaction. However, ψ should not be seen as the haircut that prevails under normal circumstances, but rather in distress states. In those states of the world where the borrower needs to pledge collateral to raise emergency funding, we must recognize that the secondary market value of such assets will also suffer extreme distress. In the case of Bear Stearns, the money market funds involved in the so-called tri-party repos with Bear Stearns were likely sellers of such collateral assets following default, and weighed heavily on the Fed’s thinking at the time.

The runs on Bear Stearns and Lehman Brothers in 2008 have highlighted the crucial role played by haircuts in the financial crisis. Gorton and Metrick (2009) provide striking evidence of fluctuations in haircuts and the way in which haircuts on collateralized borrowing transactions soared in the financial crisis. For lower rated asset-backed securities (ABSs), the haircut rose to 100% in the aftermath of the run on Lehman Brothers, effectively precluding such securities being used as collateral for secured borrowing. For these reasons, we should think of ψ being a small number.

Our ambition in this paper does not go so far as to endogenize ψ within our model. Doing justice to the determination of ψ must make reference to market-wide factors that deserve separate attention. Geanakoplos (2009) and Brunnermeier and Pedersen (2009) are recent theoretical discussions on the determination of haircuts. In Section 5.3, we will examine a version of our model where ψ is a function of the underlying fundamental value of the bank (θ_1), but we believe that market-wide factors are the most important determinant of ψ . We see our contribution as addressing the cross-section of individual banks and their vulnerability to shifts in ψ . For policy discussions of liquidity and their spillover effects, such comparative statics questions are key. Elsewhere⁸, we have discussed modelling these phenomena and other implications for regulatory reform taking account of such short-term liquidity issues.

We mentioned at the outset that Bear Stearns and other security broker dealers were regulated by the SEC and that they were subject to a liquidity requirement, as well as a Basel-style capital requirement. In September 2008, the SEC's Office of Inspector General published the results of an audit into the run on Bear Stearns (SEC (2008)).⁹ The first of its ten official findings states that "Bear Stearns was compliant with the CSE program's capital ratio and liquidity requirements, but the collapse of Bear Stearns raises questions about the adequacy of these requirements."¹⁰ The liquidity requirement in place at the time governed the amount of cash set aside to meet the non-renewal of unsecured funding such as commercial paper, but did not require a liquidity buffer against the ballooning of haircuts on secured borrowing. In the event, it was the inability of Bear Stearns to roll over its secured funding that drove it to failure.

In the benchmark model, we assume that if the run is unsuccessful (i.e. the run does not drive the bank into failure), then the fundamentals of the risky asset remain unaffected and the eventual payoff of the risky asset is unaffected by the extent of the run in the interim period. This assumption is in contrast to the usual assumption in models of bank runs where the bank has to liquidate long-term assets ("dig up potatoes planted in the field") to pay the early withdrawers. The possibility of such "partial liquidations" complicates the analysis of bank run models, but we will side-step this com-

⁸Morris and Shin (2008)

⁹We thank Pete Kyle for pointing us to this reference and for helping us to understand some of the implications.

¹⁰SEC (2008, p.10)

plication in the benchmark version of the model, and examine it separately as an extension in a later section. We address partial liquidations in Section 5.4.

Let us denote by S (without any subscript) the face value of the short-term debt at date 1, the interim date. Thus the bank fails from a run if the proportion of short term debt holders not rolling over is more than

$$\lambda = \frac{A^*}{S},$$

which we dub the *liquidity ratio*. It is the value of the cash that can be realized in the short run relative to short run liabilities. We will focus on the case where

$$\lambda < 1.$$

If the liquidity ratio were to exceed 1, runs would be impossible and there would be no illiquidity risk. Note that in the benchmark model, the amount of cash available to the bank is assumed to not depend on current market conditions.

Finally, we assume that short run debt holders have an alternative investment opportunity in which they can earn gross return r^* . Let r_S be the notional return to short-term debt from date 1 to date 2. In other words, r_S is the amount promised at the ex post date for each dollar that the short-term debt holder claims at the interim date:

$$r_S = \frac{S_2}{S}$$

A crucial parameter will be

$$\mu = \frac{r^*}{r_S},$$

which we will refer to as the *outside option ratio*. It measures the outside option value to short run creditors of their funds at the roll-over date, relative to the amount promised by the bank.

We make the assumption that if a run leads to failure, then short-term creditors who rolled over receive a payoff of zero. Although this is a stark assumption, our assumption is motivated by the funding strains that face even the *creditors* at the time of crises. In any case, it would be simple to introduce some recovery value without affecting the spirit of the analysis. However, the stark assumption also serves to highlight how the threat of

bankruptcy of the debtor elevates the risks associated even with collateralized lending. The failures of Bear Stearns in March 2008 and Lehman Brothers in September 2008 illustrate well how creditors react to impending bankruptcy and the legal uncertainties associated with the stay on creditors. The legal underpinnings surrounding the bankruptcy of securities firms is crucial. US bankruptcy rules (as well as some other jurisdictions) exempt the collateral assets in a repurchase agreement from the automatic stay on creditors.¹¹ But even when repo lenders' claims are well defined, in the state of the world where the borrower declares bankruptcy, the secondary market value of such assets will also suffer extreme distress. Thus, if the lender also faces demands from its own creditors, the relevant payoff is not the long-term value of the collateral asset but the immediate sale value in a distressed market. For the purpose of writing the payoffs of the game, it seems reasonable to treat this value as being a very small number.

The liquidity ratio λ , the outside option ratio μ and the fundamental risk ratio ρ will be key parameters in our analysis. We will eventually be interested in analyzing how ex ante credit risk depends on these parameters. But we must solve by backward induction by first analyzing what happens at the intermediate stage.

2.2 The Rollover Decision of Short Term Creditors and Interim Credit Risk

We now turn to the solution of our model. We first describe how we will deal with the coordination problem among short run debt holders in the interim period. The interim insolvency risk – the probability that the bank will fail *if there is no run* – is given by

$$\begin{aligned} \mathcal{N}_1(\theta_1) &= \Pr(\theta_2 \leq \theta^{**} | \theta_1) & (1) \\ &= \begin{cases} 1, & \text{if } \theta_1 \leq \theta^{**} - \frac{1}{2}\sigma_2 \\ \frac{1}{2} + \frac{\theta^{**} - \theta_1}{\sigma_2}, & \text{if } \theta^{**} - \frac{1}{2}\sigma_2 \leq \theta_1 \leq \theta^{**} + \frac{1}{2}\sigma_2 \\ 0, & \text{if } \theta^{**} + \frac{1}{2}\sigma_2 \leq \theta_1 \end{cases} \quad , & (2) \end{aligned}$$

and is depicted in Figure 1. The notation $\mathcal{N}_1(\theta_1)$ indicates the insolvency risk at date 1, which is a function of θ_1 , and hence can be dubbed the “interim insolvency risk”. Thus the total expected return to rolling over, conditional

¹¹See, for instance, Morrison and Riegel (2005).

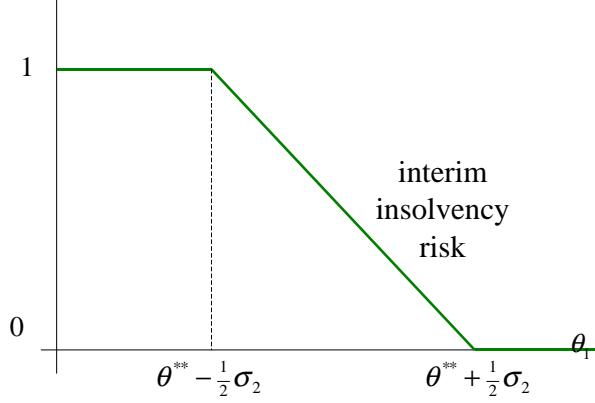


Figure 1: Interim solvency risk

on there not being a run, is

$$r_S (1 - \mathcal{N}_1(\theta_1)) = \begin{cases} 0, & \text{if } \theta_1 \leq \theta^{**} - \frac{1}{2}\sigma_2 \\ \left(\frac{1}{2} + \frac{\theta_1 - \theta^{**}}{\sigma_2}\right) r_S, & \text{if } \theta^{**} - \frac{1}{2}\sigma_2 \leq \theta_1 \leq \theta^{**} + \frac{1}{2}\sigma_2 \\ r_S, & \text{if } \theta^{**} + \frac{1}{2}\sigma_2 \leq \theta_1 \end{cases} ,$$

while the return to not rolling over is r^* (whether there is a run or not).

A key variable in an individual short-term creditor's decision will be his beliefs about the proportion of other short-term creditors that will roll over their debt. We first describe a simple and natural assumption about these beliefs that pins down short-term creditor behavior in this situation and analyze its implications for the occurrence of fatal runs. We then sketch how results from the global games literature can provide a foundation for the assumption about short-term creditors' beliefs.

Assume each short-term creditor believes that the proportion of short-term creditors not rolling over their debt is uniformly distributed on the interval $[0, 1]$. A successful run will not occur if the proportion not rolling over their debt is less than $\lambda = \frac{A^*}{S}$. Each short-term creditor will expect this to occur with probability $\lambda = \frac{A^*}{S}$. Thus the expected return to rolling over becomes

$$r_S (1 - \mathcal{N}_1(\theta_1)) \lambda = \begin{cases} 0, & \text{if } \theta_1 \leq \theta^{**} - \frac{1}{2}\sigma_2 \\ \lambda \left(\frac{1}{2} + \frac{\theta_1 - \theta^{**}}{\sigma_2}\right) r_S, & \text{if } \theta^{**} - \frac{1}{2}\sigma_2 \leq \theta_1 \leq \theta^{**} + \frac{1}{2}\sigma_2 \\ \lambda r_S, & \text{if } \theta^{**} + \frac{1}{2}\sigma_2 \leq \theta_1 \end{cases} \quad (3)$$

A run will occur if this expression is less than r^* . Recalling the definition of the outside option ratio $\mu = \frac{r^*}{r_S}$, we have that a run will occur if and only if $\theta_1 < \theta^*$, where we define the "run point" θ^* as the value of θ_1 setting (3) equal to r^* , so

$$\theta^* = \theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right).$$

A fully rational foundation for the assumption about short-term creditor beliefs is provided by global games theory (see Morris and Shin (2003)). Suppose that each short term creditor i , instead of observing θ_1 exactly observed instead a noisy signal $x_i = \theta_1 + \tau\eta_i$, where η_i is a noise term distributed in the population according to some density and $\tau > 0$ is a parameter measuring the size of the noise. With this noisy information, we have a game of incomplete information that has a unique equilibrium. In this equilibrium, there will be a critical signal value x^* such that creditors will roll over if and only if their signals exceed x^* . Now consider a marginal creditor whose signal happens to be exactly equal to x^* . What are his beliefs about the proportion of creditors not rolling over? In the unique equilibrium, this will equal his beliefs about the proportion of creditors who have observed signals above x^* . Because θ_1 is uniformly distributed, he will have the uniform belief hypothesized above. Now if τ is small, the behavior of the marginal creditor will be close to that of a creditor who knows θ_1 and has the uniform belief. Thus as τ tends to zero, this model predicts uniquely exactly the behavior assumed above. We describe these arguments – standard in the global games literature – in more detail in the appendix. Later in the text (in Section 5.5) we describe how the results would change under different models pinning down equilibrium strategic uncertainty.

Now the interim *illiquidity risk* is the probability that the bank will fail because of a run, when it would not have been insolvent in the absence of a run. It is given by

$$\mathcal{L}_1(\theta_1) = \begin{cases} 0, & \text{if } \theta_1 \leq \theta^{**} - \frac{1}{2}\sigma_2 \\ \frac{1}{2} - \frac{1}{\sigma_2}(\theta^{**} - \theta_1), & \text{if } \theta^{**} - \frac{1}{2}\sigma_2 \leq \theta_1 \leq \theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) \\ 0, & \text{if } \theta_1 > \theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) \end{cases} .$$

The notation $\mathcal{L}_1(\theta_1)$ indicates the illiquidity risk at date 1, which is a function of θ_1 . Summing the insolvency risk and illiquidity risk gives the interim

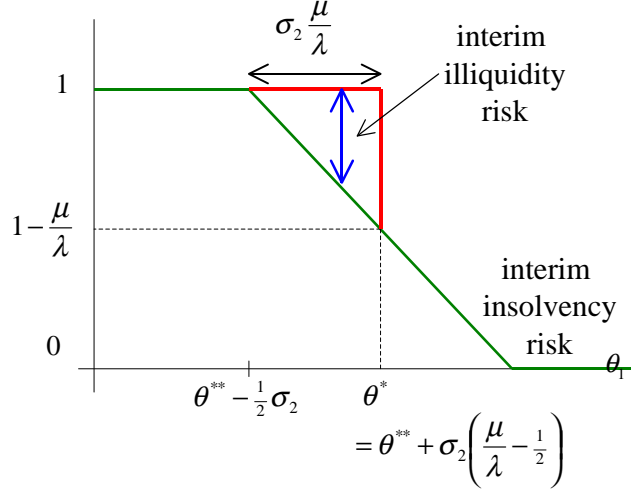


Figure 2: Total interim credit risk

(total) credit risk, which is

$$C_1(\theta_1) = \begin{cases} 1, & \text{if } \theta_1 \leq \theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) \\ \frac{1}{2} + \frac{1}{\sigma_2} (\theta^{**} - \theta_1), & \text{if } \theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) \leq \theta_1 \leq \theta^{**} + \frac{1}{2} \sigma_2 \\ 0, & \text{if } \theta^{**} + \frac{1}{2} \sigma_2 \leq \theta_1 \end{cases} .$$

Figure 2 illustrates the interim total credit risk $C_1(\theta_1)$ consisting of the insolvency risk and the illiquidity risk.

3 Ex Ante Credit Risk

We now characterize ex ante credit risk, i.e., probability of default, for a holder of long run debt in the initial period 0. In particular, we obtain an additively separable decomposition of illiquidity and insolvency risk and thus an elementary formula showing how illiquidity depends on a property of the balance sheet (the liquidity ratio, λ), a property of credit market conditions (the outside option ratio, μ) and the amount of uncertainty about the bank's solvency (the fundamental risk ratio, ρ).

We will do this analysis under the assumption that the fundamental risk ratio is sufficiently small, i.e.,

$$\rho = \frac{\sigma_2}{\sigma_1} < 1.$$

Without this assumption, additive decompositions are no longer possible, but we will describe in Section 5.6 the case where σ_1 is small relative to σ_2 . In the benchmark model, we will also make the assumption that the prior mean of returns is not so far from the solvency point that the analysis becomes trivial. In particular, we assume:

$$\theta_0 \in \left[\theta^{**} - \frac{1}{2}(\sigma_1 - \sigma_2), \theta^{**} + \frac{1}{2}(\sigma_1 - \sigma_2) \right].$$

Now

$$\begin{aligned} \text{Ex Ante Insolvency Risk} &= \mathcal{N}_0(\theta_0) \\ &= \text{Prob. (return below solvency point)} \\ &= \text{Prob. } (\theta_2 \leq \theta^{**}) \\ &= \int_{\varepsilon=-\frac{1}{2}}^{\frac{1}{2}} \mathcal{N}_1(\theta_0 + \sigma_1 \varepsilon) d\varepsilon \\ &= \frac{1}{\sigma_1} \left[\theta^{**} - \left(\theta_0 - \frac{1}{2}\sigma_1 \right) \right] \\ &= \frac{1}{2} + \frac{\theta^{**} - \theta_0}{\sigma_1}. \end{aligned} \tag{z}$$

This expression is independent of σ_2 . This follows from the uniform distribution assumptions and the fact that σ_2 is small. The ex ante illiquidity risk is

$$\text{Ex Ante Illiquidity Risk} = \mathcal{L}_0(\theta_0) \tag{4}$$

$$\int_{\varepsilon=-\frac{1}{2}}^{\frac{1}{2}} \mathcal{L}_1(\theta_0 + \sigma_1 \varepsilon) d\varepsilon \tag{5}$$

$$\begin{aligned} &= \frac{1}{2\sigma_1} \left[\left[\theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) \right] - \left[\theta^{**} - \frac{1}{2}\sigma_2 \right] \right] \frac{\mu}{\lambda} \\ &= \frac{\rho}{2} \left(\frac{\mu}{\lambda} \right)^2. \end{aligned} \tag{6}$$

Recall that ρ is the fundamental risk ratio, μ is the outside option ratio and λ is the liquidity ratio.

Our benchmark case allows the additive separability of insolvency risk and illiquidity risk. The reason for this additive separability comes from our assumption that the initial shock is uniformly distributed and that σ_1 is large. The illiquidity risk is given by the expectation of the triangle indicated in Figure 2, where the expectation is taken with respect to the realization of the initial shock $\sigma_1 \varepsilon_1$. Since ε_1 is uniform and σ_1 is large, the expectation of the illiquidity triangle does not depend on the solvency point θ^{**} or the run point θ^* .

Let us highlight some qualitative properties of these closed form expressions. In Section 5.1, we will show that these qualitative properties continue to hold with general distributions on noise when it is not possible to obtain closed form solutions.

1. Insolvency risk is independent of μ and λ once the solvency point θ^{**} is given. Market conditions and balance sheet composition have no impact on solvency over and above their effect on the solvency point.
2. Changes in the solvency point have a constant impact on insolvency risk, i.e.,

$$\sigma_1 \frac{d\mathcal{N}_0}{d\theta^{**}} = 1.$$

3. The liquidity ratio λ is a sufficient statistic for the impact of the balance sheet on illiquidity risk. In particular, illiquidity risk does not depend on the solvency point θ^{**} . Illiquidity risk is increasing in the outside option ratio μ , so thus increases when credit conditions are tight; decreasing in the liquidity ratio λ ; and it disappears when $\sigma_2 = 0$; thus there is no illiquidity risk disappears when there is no uncertainty about future fundamentals.
4. A more subtle finding concerns the marginal impact of the liquidity ratio on illiquidity risk,

$$\frac{d\mathcal{L}_0}{d\lambda} = -\frac{\sigma_2 \mu^2}{\lambda^3}.$$

Increasing the liquidity ratio has larger impact on reducing illiquidity risk the higher is fundamental uncertainty σ_2 , the higher is the outside option ratio μ and the lower is the liquidity ratio λ . The intuition for

this result comes from figure 2: changes in the critical solvency probability where runs occur will have their biggest impact when illiquidity risk is highest.

In Section 5.1, we note how all these qualitative properties of the decomposition and comparative statics of credit risk continue to hold with more general densities governing the fundamental uncertainty.

4 Balance Sheet Impact on Credit Risk

At the outset, we stated one of our goals as investigating the effect of changed asset composition, where risky assets are replaced by cash. We will pose the question by asking what is the impact on total credit risk of converting risky assets into cash at the ex ante stage. To do this, we will normalize the expected return of the risky asset θ_0 to 1 and ask what is the effect of simultaneously increasing cash holdings and decreasing holdings of the risky asset. We will first analyze the impact on insolvency risk and then the impact on illiquidity risk. This decomposition provides a natural decomposition of the comparative statics.

Recall that the solvency point, θ^{**} , is a sufficient statistic for the impact of the balance sheet on insolvency risk and that

$$\theta^{**} = \frac{S_2 + L_2 - M}{Y}.$$

where S_2 is the notional value of short term debt at date 2 and L_2 is the notional value of long-term debt at date 2. Thus the impact of cash on the solvency point is

$$\frac{d\theta^{**}}{dM} = -\frac{1}{Y},$$

while the impact of the risky asset is

$$\frac{d\theta^{**}}{dY} = -\frac{S_2 + L_2 - M}{Y^2}.$$

To interpret this expression, define ex ante expected equity E by

$$E = M + Y - S_2 - L_2,$$

The equity E is the ex ante expectation of equity at the final date. Using this notation, observe that

$$\frac{d\theta^{**}}{dY} = \frac{1}{Y} \left(\frac{E}{Y} - 1 \right).$$

Now from (??)

$$\frac{d\mathcal{N}_0}{d\theta^{**}} = \frac{1}{\sigma_1},$$

so

$$\frac{d\mathcal{N}_0}{dM} = \frac{d\mathcal{N}_0}{d\theta^{**}} \frac{d\theta^{**}}{dM} = -\frac{1}{\sigma_1 Y},$$

while

$$\frac{d\mathcal{N}_0}{dY} = \frac{d\mathcal{N}_0}{d\theta^{**}} \frac{d\theta^{**}}{dY} = \frac{1}{\sigma_1 Y} \left(\frac{E}{Y} - 1 \right).$$

Shifting one unit of risky asset into cash leaves the expected equity unchanged but reduces variance. Thus as long as equity is positive, insolvency is reduced:

$$-\frac{d\mathcal{N}_0}{dY} + \frac{d\mathcal{N}_0}{dM} = -\frac{E}{\sigma_1 Y^2}.$$

This effect is most pronounced when equity is high.

Recall that

$$\lambda = \frac{A^*}{S} = \frac{M + \psi Y}{S}.$$

Thus the impact of cash on the liquidity ratio is

$$\frac{d\lambda}{dM} = \frac{1}{S},$$

while the impact of the risky asset is

$$\frac{d\lambda}{dY} = \frac{\psi}{S}.$$

Now from (6)

$$\frac{d\mathcal{L}_0}{d\lambda} = -\frac{\sigma_2 \mu^2}{\sigma_1 \lambda^3},$$

so

$$\frac{d\mathcal{L}_0}{dM} = \frac{d\mathcal{L}_0}{d\lambda} \frac{d\lambda}{dM} = -\frac{\sigma_2 \mu^2}{\sigma_1 \lambda^3 S}$$

while

$$\frac{d\mathcal{L}_0}{dY} = \frac{d\mathcal{L}_0}{d\lambda} \frac{d\lambda}{dY} = -\frac{\sigma_2\mu^2\psi}{\sigma_1\lambda^3 S}.$$

Thus the net effect of shifting from risky assets to cash is to decrease illiquidity risk as long as the fire sale discount of the risky asset is less than one (i.e., the rate of exchange between the risky asset and cash in the first period), so $\psi < 1$:

$$-\frac{d\mathcal{L}_0}{dY} + \frac{d\mathcal{L}_0}{dM} = -\frac{\sigma_2\mu^2(1-\psi)}{\sigma_1\lambda^3 S}.$$

The assumption that $\psi < 1$ says that the return to holding cash to period 1 is higher than the return to holding the risky asset and selling it in the intermediate period at its fire sale discount price.

Shifting to cash reduces illiquidity risk more when

- ex post uncertainty (σ_2) is high
- the fire sale discount / haircut is large (i.e., ψ is close to 0)
- outside option ratio (μ) is high
- the liquidity ratio (λ) is low

Arguably, all these features figured prominently for the case of highly leveraged financial intermediaries such as Bear Stearn and Lehman Brothers.

5 Extensions

We made a number of modeling choices in our earlier analysis to highlight the importance of key variables in determining illiquidity risk. In this section, we analyze what happens under a sequence of alternative formulations. This analysis serves four purposes. First, it demonstrates the robustness of the qualitative conclusions from our earlier analysis. Second, it identifies novel channels from balance sheet to illiquidity and insolvency risk abstracted from in our benchmark model. Third, it assists in comparisons with the related literature (in Section 5.7). Fourth, it illustrates the flexibility of our approach to incorporate many alternative institutional scenarios.

5.1 General Distributions

We now relax the assumption of uniform densities, and examine the case where the ex ante shocks ε_1 and ε_2 are distributed with smooth densities f_1 and f_2 with corresponding c.d.f.s F_1 and F_2 . We will assume that the densities have full support on the real line. We will retrace the argument used above for this more general case, while leaving the other assumptions of the benchmark case unchanged. The interim insolvency risk becomes

$$\mathcal{N}_1(\theta_1) = F_2\left(\frac{\theta^{**} - \theta_1}{\sigma_2}\right).$$

The total expected return to rolling over, conditional on there not being a run, is

$$r_S \left(1 - F_2\left(\frac{\theta^{**} - \theta_1}{\sigma_2}\right)\right);$$

while the return to not rolling over is r^* .

Appealing to the strategic uncertainty in the limiting case of the global game where noise becomes small, the probability that the run is successful conditional on being at the switching point is A^*/S . Hence, the indifference condition characterizing the run point is

$$\frac{A^*}{S} \left(1 - F_2\left(\frac{\theta^{**} - \theta^*}{\sigma_2}\right)\right) r_S = r^*;$$

or

$$\theta^* = \theta^{**} - \sigma_2 F_2^{-1}\left(1 - \frac{\mu}{\lambda}\right).$$

Now the interim illiquidity risk is

$$\mathcal{L}_1(\theta_1) = \begin{cases} 1 - F_2\left(\frac{\theta^{**} - \theta_1}{\sigma_2}\right), & \text{if } \theta_1 \leq \theta^* \\ 0, & \text{if } \theta_1 > \theta^* \end{cases}.$$

Total interim credit risk is $\mathcal{C}_1(\theta_1) = \mathcal{N}_1(\theta_1) + \mathcal{L}_1(\theta_1)$, so that

$$\mathcal{C}_1(\theta_1) = \begin{cases} 1, & \text{if } \theta_1 \leq \theta^* \\ F_2\left(\frac{\theta^{**} - \theta_1}{\sigma_2}\right), & \text{if } \theta_1 > \theta^* \end{cases}.$$

Ex ante insolvency risk is

$$\mathcal{N}_0(\theta_0) = \int_{\theta_1=-\infty}^{\infty} F_2\left(\frac{\theta^{**} - \theta_1}{\sigma_2}\right) \frac{1}{\sigma_1} f_1\left(\frac{\theta_1 - \theta_0}{\sigma_1}\right) d\theta_1. \quad (7)$$

Ex ante illiquidity risk is

$$\mathcal{L}_0(\theta_0) = \int_{\theta_1=-\infty}^{\theta^{**}-\sigma_2 F_2^{-1}\left(1-\frac{\mu}{\lambda}\right)} \left(1 - F_2\left(\frac{\theta^{**}-\theta_1}{\sigma_2}\right)\right) \frac{1}{\sigma_1} f_1\left(\frac{\theta_1-\theta_0}{\sigma_1}\right) d\theta_1. \quad (8)$$

Total ex ante credit risk is the sum of the two

$$\begin{aligned} \mathcal{C}_0(\theta_0) &= \mathcal{N}_0(\theta_0) + \mathcal{L}_0(\theta_0) \\ &= F_1\left(\frac{\theta^{**}-\theta_0-\sigma_2 F_2^{-1}\left(1-\frac{\mu}{\lambda}\right)}{\sigma_1}\right) \\ &\quad + \int_{\theta_1=\theta^{**}-\sigma_2 F_2^{-1}\left(1-\frac{\mu}{\lambda}\right)}^{\infty} F_2\left(\frac{\theta^{**}-\theta_1}{\sigma_2}\right) \frac{1}{\sigma_1} f_1\left(\frac{\theta_1-\theta_0}{\sigma_1}\right) d\theta_1. \end{aligned}$$

Recall that in the benchmark case with uniform distributions and sufficiently large σ_1 , we had:

1. $\mathcal{N}_0(\theta_0) = \frac{1}{2} + \frac{\theta^{**}-\theta_0}{\sigma_1}$, and thus independent of μ and λ .
2. $\sigma_1 \frac{d\mathcal{N}_0}{d\theta^{**}} = 1$.
3. $\mathcal{L}_0(\theta_0) = \frac{\sigma_2}{2\sigma_1} \left(\frac{\mu}{\lambda}\right)^2$, and thus independent of θ^{**} .
4. $\sigma_1 \frac{d\mathcal{L}_0}{d\lambda} = -\frac{\sigma_2 \mu^2}{\lambda^3}$.

Here, we claim that qualitatively similar results hold with general distributions. In particular, we have:

1. $\mathcal{N}_0(\theta_0)$ is independent of μ and λ .
2. as $\sigma_1 \rightarrow \infty$, $\sigma_1 \frac{d\mathcal{N}_0}{d\theta^{**}}$ is constant (i.e., independent of θ^{**}).
3. as $\sigma_1 \rightarrow \infty$, $\sigma_1 \mathcal{L}_0(\theta_0)$ is independent of θ^{**} .
4. as $\sigma_1 \rightarrow \infty$, $\sigma_1 \frac{d\mathcal{L}_0}{d\lambda}$
 - (a) is negative;
 - (b) is linear in σ_2 ;

(c) has absolute value decreasing in λ , if the hazard ratio, $\frac{f_2(z)}{1-F_2(z)}$, is non-decreasing.

To show these claims, recall that insolvency risk is given by (7). Thus it does not depend on μ and λ (claim 1). As $\sigma_1 \rightarrow \infty$

$$\begin{aligned} \sigma_1 \frac{d\mathcal{N}_0}{d\theta^{**}} &\rightarrow \int_{\theta_1=-\infty}^{\infty} \frac{1}{\sigma_2} f_2\left(\frac{\theta^{**} - \theta_1}{\sigma_2}\right) f_1(0) d\theta_1 \\ &= f_1(0), \end{aligned}$$

which is constant (claim 2). Illiquidity risk is given by (8) which can be re-written, with the change of variables

$$r = 1 - F_2\left(\frac{\theta^{**} - \theta_1}{\sigma_2}\right),$$

as

$$\sigma_1 \mathcal{L}_0(\theta_0) = \int_{r=0}^{\frac{\mu}{\lambda}} r f_1\left(\frac{\theta^{**} - \theta_0 - F_2^{-1}(1-r)}{\sigma_1}\right) \frac{\sigma_2}{f_2(F_2^{-1}(1-r))} dr.$$

As $\sigma_1 \rightarrow \infty$,

$$\sigma_1 \mathcal{L}_0(\theta_0) \rightarrow \int_{r=0}^{\frac{\mu}{\lambda}} f_1(0) \frac{\sigma_2 r}{f_2(F_2^{-1}(1-r))} dr.$$

This is independent of θ^{**} (claim 3). Now as $\sigma_1 \rightarrow \infty$,

$$\sigma_1 \frac{d\mathcal{L}_0(\theta_0)}{d\lambda} \rightarrow -\frac{\mu^2 \sigma_2 f_1(0)}{\lambda^3 f_2(F_2^{-1}(1 - \frac{\mu}{\lambda}))}.$$

This expression is negative (claim 4a) and linear in σ_2 (claim 4b). It depends on λ through $\frac{1}{\lambda^3 f_2(F_2^{-1}(1 - \frac{\mu}{\lambda}))}$. Setting $x = F_2^{-1}(1 - \frac{\mu}{\lambda})$, this equals

$$\frac{(1 - F_2(x))^3}{\mu^3 f_2(x)} = \left(\frac{(1 - F_2(x))^2}{\mu^3}\right) \left(\frac{1 - F_2(x)}{f_2(x)}\right).$$

If f_2 further satisfies the non-decreasing monotone hazard ratio condition that $\frac{f_2(z)}{1-F_2(z)}$ is non-decreasing in z , then we can conclude that that $\frac{1-F_2(x)}{f_2(x)}$ is

non-increasing in x ; the full support assumption implies that $\frac{(1-F_2(x))^2}{\mu^3}$ is decreasing in x , and so $\frac{(1-F_2(x))^3}{\mu^3 f_2(x)}$ is decreasing in x . Now since $x = F_2^{-1}\left(1 - \frac{\mu}{\lambda}\right)$ is increasing in λ , we have that $\frac{\mu^2 \sigma_2 f_1(0)}{\lambda^3 f_2(F_2^{-1}(1 - \frac{\mu}{\lambda}))}$ is decreasing in λ (claim 4c).

We can conclude as follows. Many of the features of the uniform density benchmark case results survive in a more general framework with general densities. For the result that illiquidity risk is decreasing in the liquidity ratio λ (claim 4c), we have used the non-decreasing monotone hazard ratio condition that $\frac{f_2(z)}{1-F_2(z)}$ is non-decreasing in z . Otherwise, the spirit of our earlier results go through with very few modifications, giving some confidence that the results of the benchmark case have more general applicability.

5.2 General Balance Sheet

We first establish that our results extend straightforwardly to more general asset portfolios. There were only two assets in our benchmark model: a riskless, liquid, zero return asset called “money” and a risky, illiquid and positive expected return asset. But “riskiness” is not the same as “illiquidity,” and so it is desirable to have a framework that allows the two concepts to be analyzed separately.

Let the bank hold assets in $N + 1$ categories indexed by $k \in \{0, 1, \dots, N\}$. We denote by A_k the face value of assets in asset class k . Assume that the per unit return of asset k at final date 2 is $\alpha_k + \beta_k \theta_2$. Thus we assume – for simplicity – that the returns to all asset categories are perfectly correlated. Let ψ_k be the pledgeable value of one unit of asset k .

The model analyzed in the previous sections corresponds to the case with two assets, where asset 0 is money, so $A_0 = M$, $\alpha_0 = 1$, $\beta_0 = 0$ and $\psi_0 = 1$; and asset 1 is the risky asset, so $A_1 = Y$, $\alpha_0 = 0$, $\beta_0 = 1$ and $\psi_0 = \psi$. Now the relevant solvency point is

$$\theta^{**} = \frac{S_2 + L_2 - \sum_{k=0}^N \alpha_k A_k}{\sum_{k=0}^N \beta_k A_k},$$

while the cash that can be raised from the bank's assets becomes

$$A^* = \sum_{k=0}^N \psi_k (\alpha_k + \beta_k \theta_0) A_k.$$

With these alternative formulas for A^* and θ^{**} , the expressions for ex ante credit risk and its decomposition are unchanged.

5.3 Firesale Prices and Current Market Conditions

We made the simplifying assumption that the cash that can be raised by pledging the risky asset portfolio depends on the face value. A more realistic assumption would be that the cash that can be raised depends on the realization of θ_1 . In this more realistic formulation, the cash that is available to meet withdrawals by short-term creditors is a function of θ_1 , and given by

$$A^*(\theta_1) = M + (\psi + \delta(\theta_1 - \theta_0))Y.$$

We show (in Appendix 7.1.1) that a first order approximation (for small δ) for illiquidity risk is then

$$\frac{\sigma_2}{2\sigma_1} \left(\frac{\mu}{\lambda}\right)^2 \left(1 - \frac{\delta Y}{\lambda S} (\theta^* - \theta_0)\right)^2$$

where $\lambda = \frac{M + \psi Y}{S} = \frac{A^*(\theta_1)}{S} \Big|_{\delta=0}$. We see that illiquidity risk now depends on the ex ante expected of returns of the risky asset, θ_0 , and the liquidity ratio is no longer a sufficient statistic for how the balance sheet impacts illiquidity risk. This interaction occurs in an intuitive way. If the ex ante expectation of returns was above the run point, then the effect of current market conditions is to reduce available cash and thus increase illiquidity risk.

Normally, we expect the ex ante expected value θ_0 to be above the run point θ^* , so that the illiquidity risk is increasing in θ_0 . For a fixed value of the haircut value parameter ψ (the realizable cash from risky assets if $\theta_1 = \theta_0$), a higher value of θ_0 will imply that being at the run point reflects a worse innovation and thus that $A^*(\theta^*)$ and the liquidity ratio are lower.

5.4 Long Run Implications of Partial Liquidation

Our benchmark model assumed that if the bank was able to meet period 1 withdrawals, there was no long run impact on the bank's solvency. We argued that such an assumption makes sense in the context of collateralized borrowing arrangements where the bank covers claims by borrowing against its illiquid assets. This assumption allowed us to conduct the analysis without worrying about the effect of partial liquidations of the assets, where the incidence of the run impacts on the solvency point θ^{**} .

If we wish to introduce partial liquidations, we need to modify our analysis by explicitly modeling the dependence of θ^{**} on the incidence of the run. In our benchmark model, if the bank survived until the last period, it was solvent if

$$\theta_2 \geq \theta^{**} \equiv \frac{S_2 + L_2 - M}{Y}.$$

Now suppose the bank was forced to meet non-renewal of funding by liquidating illiquid assets at fire sale prices and that proportion π of short term creditors withdrew their money. If the claims of the short run creditors could be met with cash, so that

$$\pi S \leq M,$$

then there will be notional claims $(1 - \pi)S_2 + L_2$ outstanding in the last period and cash $M - \pi S$, so the bank will be solvent if

$$\theta_2 \geq \theta^{**}(\pi) \equiv \frac{(1 - \pi)S_2 + L_2 - M + \pi S}{Y}.$$

But if

$$M \leq \pi S \leq A^*,$$

the bank can pay claims, but must sell $\frac{\pi S - M}{\psi}$ units of the risky asset to meet its claims. In this case, the bank will be solvent if

$$\theta_2 \geq \theta^{**}(\pi) \equiv \frac{(1 - \pi)S_2 + L_2}{Y - \frac{\pi S - M}{\psi}}.$$

Because of this dependence of the solvency point on the proportion of withdrawals, we can show (in Appendix 7.1.2) that the run point can differ from the solvency point even as ex post uncertainty disappears. Specifically, assume that

$$\psi < \theta^{**} \equiv \frac{S_2 + L_2 - M}{Y}$$

and simplify algebra by setting $S_2 = S$. Now if write $\theta^*(\sigma_2)$ for the critical value of θ_1 below which there is a run, we have

$$\theta^*(\sigma_2) \rightarrow \begin{cases} \theta^{**} \equiv \frac{S+L_2-M}{Y}, & \text{if } \mu \leq \frac{M}{S} \\ \frac{(1-\mu)S+L_2}{Y-\frac{\mu S-M}{\psi}}, & \text{if } \frac{M}{S} \leq \mu \leq \frac{A^*}{S} \end{cases}$$

as $\sigma_2 \rightarrow 0$. This in turn implies that the insolvency risk is as before as $\sigma_2 \rightarrow 0$ but the illiquidity risk (as $\sigma_2 \rightarrow 0$) is

$$\frac{(\mu S - M)(S + L_2 - M - \psi Y)}{\sigma_1 Y (\psi Y - \mu S + M)}$$

and thus, in particular, strictly positive, if

$$M < \mu S \leq A^*.$$

As we discuss in Section 5.7, this illiquidity risk, that arises even with no ex post uncertainty from partial liquidation, is the focus of Rochet and Vives (2004).

5.5 Public Signals, Optimism and Strategic Uncertainty

In the benchmark model, we assumed that the marginal short term creditor deciding whether to roll over his debt faced the standard global game "Laplacian" uncertainty about how other short run creditors would behave and noted how assumptions from the global games literature would endogenously lead to this conclusion in a rational model without common knowledge.

However, one might believe that short term creditors are more optimistic (or pessimistic) about other short term creditors' withdrawal decisions; this will occur in a rational common prior model if the realized return is low (high) relative to ex ante public information (e.g., as in Morris and Shin (2004)). It can also occur because "behavioral" agents anticipate that others will be more optimistic than them (Izmalkov and Yildiz (2009), Morris and Shin (2007)). There is experimental evidence that subjects choose an action closer to the efficient outcome than the Laplacian prediction (Heinemann, Nagel and Ockenfels (2004)).

Such optimism (or pessimism) can be factored into the risk decomposition straightforwardly. Suppose that, whatever a creditor's expected value of θ_1 in the interim period, the probability that he attaches to less than proportion

z of his creditors having a lower expectation is $f(z)$, where $f : [0, 1] \rightarrow [0, 1]$. Then the adjusted run point will be

$$\theta^* = \theta^{**} + \sigma_2 \left(\frac{\mu}{f(\lambda)} - \frac{1}{2} \right)$$

and the adjusted ex ante illiquidity risk will be

$$\frac{1}{2} \rho \left(\frac{\mu}{f(\lambda)} \right)^2.$$

The Laplacian assumption implied that f is the identity map, but qualitative comparative statics will remain the same for any increasing f .

5.6 Small Ex Ante Uncertainty

In our benchmark model, we calculated ex ante credit risk and its decomposition into insolvency and illiquidity risk under the assumption that there was a significant amount of ex ante uncertainty (relative to ex post uncertainty). If ex ante uncertainty is small, then the decomposition of credit risk will of course depend on how the ex ante expected return relates to the “run point” for θ_1 and the “solvency point” for θ_2 . In particular, we show in Appendix 7.1.3 how illiquidity risk, and the impact of portfolio changes on illiquidity risk, become small if the ex ante probability of being close to the run point is low, but explode if the ex ante probability of being close to the run point is high.

We will see in the concluding section and in Figure 4 that one feature of the recent period in the run-up to the financial crisis was the rapid increase in overnight funding of U.S. primary dealers. A short horizon for lenders between making a loan and their withdrawal decision means that little information will be realized and thus – in our model – σ_1 is small. The case of small σ_1 is therefore more realistic when viewed from an asset pricing perspective. The analysis in Appendix 7.1.3 reveals how the formulas change from the benchmark case. Further development of the asset pricing consequences of our model would yield additional insights.

5.7 Partial Payouts and Related Literature

We conclude this section by discussing in more detail the relation to other papers using global game methods to address illiquidity risk.

Morris and Shin (2004) analyzed the impact of illiquidity risk on ex ante pricing of long run debt. It emphasized the distinctive impact of *public* information (via its impact on strategic uncertainty) on the pricing of debt. This issue – briefly discussed in Section 5.5 above – is absent from the benchmark model in the current paper. Because there was no ex post uncertainty in the sense of the current paper, the relationship between insolvency risk and illiquidity risk was not captured in the earlier paper.

The stylized portfolio we study is essentially that of Rochet and Vives (2004) [RV]: if we simultaneously allowed general distributions (as discussed above in Section 5.1), firesale prices reflecting current information (as in Section 5.3), and partial liquidation (as in Section 5.4), our model would be close to theirs. For example, our observation in Section 5.4 that the run point will equal the solvency point for small ex post uncertainty if $\mu \leq \frac{M}{S}$, but will be higher if $\mu > \frac{M}{S}$ is a re-statement of their Proposition 2.

The crucial difference between our model and RV is that we allow for ex post uncertainty. In our benchmark model, this is the only source of illiquidity risk (i.e., illiquidity risk goes to zero as ex post uncertainty disappears). We think that ex post uncertainty is key to understanding the link between illiquidity risk and insolvency risk. We believe that focussing only on the partial liquidation effect that underlies the difference between insolvency risk and illiquidity risk in RV may be missing the primary channel.

Both RV and this paper have short term creditors withdraw only if the probability that the bank is both liquid (so creditors can be paid in period 1) and solvent (so creditors can be paid in period 2) is below some critical threshold. RV justify this assumption by a reduced form agency problem: the withdrawal decision is not made by the creditors themselves but by agents whose rewards are sensitive only to the probability of failure. But in this paper, this behavioral rule was rational for the creditors themselves, under our assumption of exogenous returns to rolling over short term debt and (lower) returns for investing the money elsewhere. We were able to use this alternative modelling because we assumed away partial payouts in our benchmark model.

Goldstein and Pauzner (2005) [GP] consider the classic Diamond and Dybvig (1983) model of demand-deposit banking under the assumption that there is uncertainty about whether long term investments will pay out, with creditors observing noisy signals of the true probability. In this setting, some investors have “liquidity needs” in the intermediate period but others may withdraw only because they expect others to withdraw. They solve for the

critical signal where runs occur (analogous to the “run point” in our model). It would be natural to define a “solvency point” corresponding to when the bank would fail if it was possible to constrain creditors without liquidity needs from withdrawing in the interim period. In this way, credit risk could be decomposed into “insolvency risk” and “illiquidity risk” and it is driven by ex post uncertainty. Although they do not carry out this comparative static, one could presumably show that greater ex post uncertainty (in their model, this would be reflected in probabilities of failure a long way from 0 or 1) leads to greater illiquidity risk. Because GP, like Diamond and Dybvig (1983), model the bank as a cooperative acting in the interest of depositors, the bank portfolio and creditor payoffs are different from this paper, although we would expect analogous comparative static effects to exist in their model.

Creditors’ payoffs in GP are complex, both because they are residual claimants in the final period, and because, in the event all claims cannot be paid in the intermediate period, only a random subset of creditors are paid. In order to solve their model, they had to extend global game arguments to deal with withdrawal decisions that were not strategic complements. In our benchmark model, we make the simplifying – but, we think, plausible assumption – that creditors either end up getting the face value of their claim or do not get paid at all. If we wanted to allow for more complicated partial payments to creditors, we would have to rely on the arguments developed by GP to solve the model. This would require stronger assumptions on the information structure but would not change the qualitative conclusions.

6 Concluding Remarks

Our benchmark model provides a tractable way of decomposing credit risk into insolvency risk and illiquidity risk. As a positive model, it highlights factors that will lead to increased illiquidity risk. In the current financial crisis, commercial banks and some hedge funds may have faced similar negative shocks to their asset portfolios, but hedge fund “gates” reduced early withdrawals and thus exposure of hedge fund creditors to losses. Our framework is highly flexible and – within the two period framework – can incorporate a wide range of assumptions about balance sheets and institutional rules. The extension to a richer timing structure is an important open question, although it could be done appealing to tools for modelling dynamic bank runs developed in Guimaraes (2006) and He and Xiong (2009a,b).

Our analysis is a partial equilibrium treatment of an individual bank, and it thus does not model systemic effects that played a large role in the recent crisis. If our model of one bank was embedded in a model of the banking system, then parameters that we treat as exogenous would naturally become endogenous. In particular, the outside opportunity cost of the funds of short run creditors and the fire sale price of liquid assets would reflect market conditions and would be natural channels for the transmission of problems in the banking system.

Our results have particular significance in the light of two recent trends that played a role in the 2008 credit crisis. The first is the secular decline in the cash holdings by banks over the last thirty or so years, until the outbreak of the recent financial crisis. Figure 3 shows the proportion of cash assets in the total assets of U.S. commercial banks, drawn from the Federal Reserve's H8 series. Even as recently as the early 1980s, cash assets were around 10% of total assets, but that ratio fell below 3% by the eve of the crisis. However, the cash ratio has risen sharply since September 2008 following the failure of Lehman Brothers.

Although there are several special circumstances that surround the events since September 2008 (such as actions of the Federal Reserve to expand its balance sheet), our theory points to the financial stability consequences both of the long, secular decline in cash holdings until 2008, as well as the portfolio choice motives of banks when faced with credit market turmoil. In particular, our theory highlights the vulnerability of leveraged institutions to the combination of low cash ratios and the prevalence of short term debt. To that extent, the secular decline in the cash ratio in recent years suggests vulnerabilities were increasing in the US banking sector.

A second trend in recent years has been the shortening maturity of bank liabilities, especially for the broker-dealer sector of the financial system. The broker-dealer sector is the sector that included the major Wall Street investment banks.

Figure 4 plots the trend on the composition of liabilities of the banking system comparing the total amount of overnight repurchase agreements with the amount of longer maturity term repo agreements. We can see that the period preceding the current financial crisis saw a dramatic increase in the use of overnight repos, compared to longer maturity term repo agreements (see also Adrian and Shin (2007) and Brunnermeier (2009)).

Our analysis reveals the importance of the maturity of debt through the tradeoffs faced by the short-term creditors. We discuss in Section 5.6 how

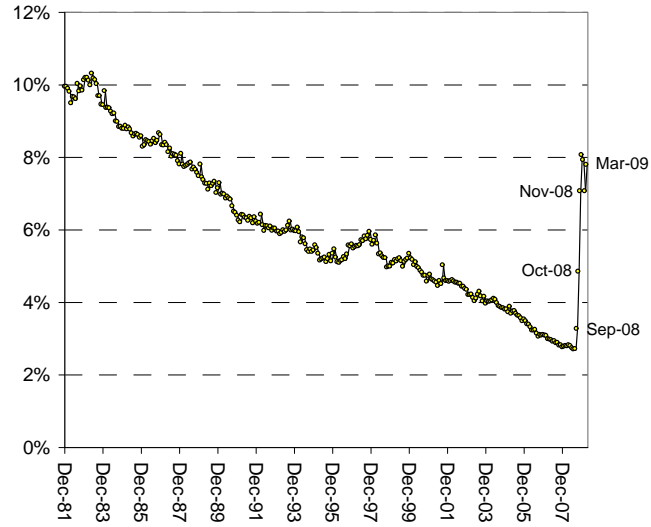


Figure 3: US Commercial Bank Cash Ratio (Source: Federal Reserve H8)

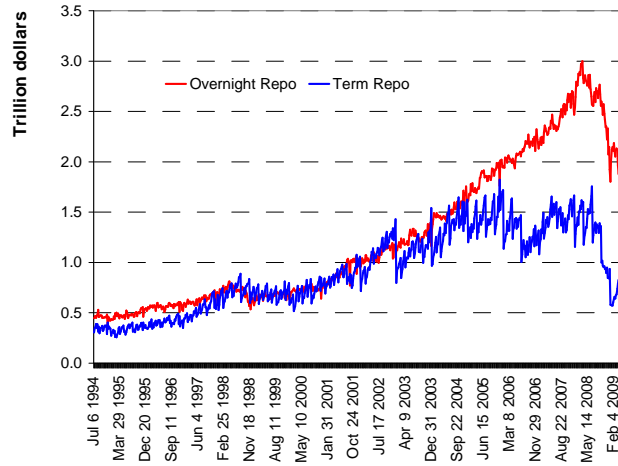


Figure 4: Outstanding Repurchase Agreements of US Primary Dealers (\$ Billion): Source, Adrian and Shin (2008)

when the short-term debt becomes very short term, the illiquidity component of credit risk increases due (paradoxically) to the reduced uncertainty over the short-term as compared to long-term outcomes. The very feature of short-term debt that makes it safe for the creditors (its safety over the short-term) makes the bank vulnerable to a run. Thus the fact that short-term debt becomes *ultra*-short term can be seen as an important consideration when thinking of the fragility of the financial system.

There are a number of policy interventions that make sense in the setting of this paper. Rochet and Vives (2004) used a model like this one to formalize the desirability of central banks acting as a "lender of last resort" in financial crises. However, in reality (as opposed to the models), it may be hard to identify which institutions have liquidity problems rather than solvency problems.¹² We have focussed on the implications of our results for financial regulation. We discuss these issues in more detail in our Brookings Papers piece on financial regulation (Morris and Shin (2008)). When the spillover effects across financial institutions are taken into account, liquidity requirements take on greater significance as a policy tool. If the debtor bank held more cash in place of illiquid assets, it could meet the withdrawals more easily, thereby lowering the threshold in the coordination game among the creditors to the bank. The cost of miscoordination for the creditor banks could also be reduced if they held more cash, since they would be less vulnerable to a run themselves. A more liquid creditor bank would be less jittery. Our theory suggests that understanding credit risk depends on fully grasping the interactions of illiquidity risk and fundamental insolvency risk. More research beckons in exploring further the themes outlined in this paper.

¹²Naqvi (2007) formalizes this tradeoff.

7 Appendix

7.1 Analysis for the Extensions Section

7.1.1 Firesale prices and current market conditions

We now assume that assets available to short run creditors are

$$A^*(\theta_1) = M + (\psi + \delta(\theta_1 - \theta_0))Y,$$

instead of

$$A^* = M + \psi Y.$$

The run point θ^* is now the value of θ_1 solving the equation

$$\frac{M + (\psi + \delta(\theta_1 - \theta_0))Y}{S} \left(\frac{1}{2} + \frac{\theta_1 - \theta^{**}}{\sigma_2} \right) = \mu. \quad (9)$$

This equation is a quadratic and can thus be solved in closed form but the analysis becomes complicated. To provide some intuition, we here solve for the case where δ is close to zero. Writing

$$\lambda = \frac{M + \psi Y}{S} = \frac{A^*(\theta_1)}{S} \Big|_{\delta=0}, \quad (10)$$

we know that the solution when $\delta = 0$ is

$$\theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right).$$

Let us assume that

$$\theta^* = \theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) + \xi, \quad (11)$$

and solve for ξ as a function of δ , when δ is small. Substituting (10) and (11) into (9), we have

$$\left(\lambda + \frac{\delta Y (\theta^{**} - \theta_0 + \sigma_2 (\frac{\mu}{\lambda} - \frac{1}{2}) + \xi)}{S} \right) \left(\frac{\mu}{\lambda} + \frac{\xi}{\sigma_2} \right) = \mu.$$

Totally differentiating with respect to δ , we have

$$\left\{ \begin{array}{l} \frac{Y(\theta^{**} - \theta_0 + \sigma_2 (\frac{\mu}{\lambda} - \frac{1}{2}) + \xi)}{S} \left(\frac{\mu}{\lambda} + \frac{\xi}{\sigma_2} \right) \\ + \frac{\delta Y}{S} \left(\frac{\mu}{\lambda} + \frac{\xi}{\sigma_2} \right) \frac{d\xi}{d\delta} \\ + \frac{1}{\sigma_2} \left(\lambda + \frac{\delta Y (\theta^{**} - \theta_0 + \sigma_2 (\frac{\mu}{\lambda} - \frac{1}{2}) + \xi)}{S} \right) \frac{d\xi}{d\delta} \end{array} \right\} = 0.$$

Evaluating at $\xi = \delta = 0$, we have

$$\frac{\mu Y (\theta^{**} - \theta_0 + \sigma_2 (\frac{\mu}{\lambda} - \frac{1}{2}))}{\lambda S} + \frac{\lambda}{\sigma_2} \frac{d\xi}{d\delta} \Big|_{\xi=\delta=0} = 0$$

or

$$\frac{d\xi}{d\delta} \Big|_{\xi=\delta=0} = - \frac{\sigma_2 \mu Y (\theta^{**} - \theta_0 + \sigma_2 (\frac{\mu}{\lambda} - \frac{1}{2}))}{\lambda^2 S}.$$

Thus for small δ ,

$$\theta^* \approx \theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) - \frac{\sigma_2 \mu Y}{\lambda^2 S} \left(\theta^{**} - \theta_0 + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) \right) \delta$$

This implies that

$$\begin{aligned} \mathcal{L}_0(\theta_0) &\approx \frac{1}{2\sigma_1\sigma_2} \left[\left(\theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) \right) - \frac{\delta\sigma_2\mu Y}{\lambda^2 S} \left(\theta^{**} - \theta_0 + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) \right) - \left(\theta^{**} - \frac{1}{2}\sigma_2 \right) \right]^2 \\ &= \frac{\sigma_2}{2\sigma_1} \left[\frac{\mu}{\lambda} - \frac{\delta\mu Y}{\lambda^2 S} \left(\theta^{**} - \theta_0 + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) \right) \right]^2 \\ &= \frac{\sigma_2}{2\sigma_1} \left(\frac{\mu}{\lambda} \right)^2 \left[1 - \frac{\delta Y}{\lambda S} \left(\theta^{**} - \theta_0 + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right) \right) \right]^2 \\ &= \frac{\sigma_2}{2\sigma_1} \left(\frac{\mu}{\lambda} \right)^2 \left(1 - \frac{\delta Y}{\lambda S} (\theta^* - \theta_0) \right)^2 \end{aligned}$$

7.1.2 Long Run Implications of Partial Liquidation

We showed in the main body of the paper that with irreversible partial liquidation, the solvency point becomes a function of the proportion of short term creditors, π , who choose not to roll over. In particular, with $S_2 = S$, the solvency point will be

$$\theta^{**}(\pi) = \begin{cases} \frac{S+L_2-M}{Y}, & \text{if } \pi \leq \frac{M}{S} \\ \frac{(1-\pi)S+L_2}{Y-\frac{\pi S-M}{\psi}}, & \text{if } \frac{M}{S} \leq \pi \leq \frac{A^*}{S} \end{cases}$$

The assumption that

$$\psi < \theta^{**} \equiv \frac{S_2 + L_2 - M}{Y}$$

implies that this expression is weakly increasing in π .

Now writing F_2 for the c.d.f. of the uniform distribution on $[-\frac{1}{2}, \frac{1}{2}]$,

$$F_2(z) = \begin{cases} 0, & \text{if } z \leq -\frac{1}{2} \\ z + \frac{1}{2}, & \text{if } -\frac{1}{2} \leq z \leq \frac{1}{2} \\ 1, & \text{if } \frac{1}{2} \leq z \end{cases},$$

the run point $\theta^*(\sigma_2)$ must now solve

$$\int_{\pi=0}^1 \left(1 - F_2 \left(\frac{\theta^{**}(\pi) - \theta_1}{\sigma_2} \right) \right) d\pi = \mu. \quad (12)$$

Now observe that as $\sigma_2 \rightarrow 0$,

$$1 - F_2 \left(\frac{\theta^{**}(\pi) - \theta_1}{\sigma_2} \right) \rightarrow \begin{cases} 0, & \text{if } \theta_1 < \theta^{**}(\pi) \\ \frac{1}{2}, & \text{if } \theta_1 = \theta^{**}(\pi) \\ 1, & \text{if } \theta_1 > \theta^{**}(\pi) \end{cases}$$

Write $[\theta^{**}]^{-1}(\theta_1)$ for the unique value of $\pi \in [\frac{M}{S}, \frac{A^*}{S}]$ solving

$$\theta_1 = \theta^{**}(\pi) = \frac{(1 - \pi)S + L_2}{Y - \frac{\pi S - M}{\psi}},$$

so that

$$\pi = [\theta^{**}]^{-1}(\theta_1) = \frac{1}{S} \left[M + \psi Y - \frac{S + L_2 - M - \psi Y}{\frac{\theta_1}{\psi} - 1} \right].$$

Now as $\sigma_2 \rightarrow 0$

$$\int_{\pi=0}^1 \left(1 - F_2 \left(\frac{\theta^{**}(\pi) - \theta_1}{\sigma_2} \right) \right) d\pi \rightarrow \begin{cases} 0, & \text{if } \theta_1 < \frac{S+L_2-M}{Y} \\ \frac{M}{2S}, & \text{if } \theta_1 = \frac{S+L_2-M}{Y} \\ [\theta^{**}]^{-1}(\theta_1), & \text{if } \theta_1 > \frac{S+L_2-M}{Y} \end{cases} \quad (13)$$

Also observe that $\int_{\pi=0}^1 \left(1 - F_2 \left(\frac{\theta^{**}(\pi) - \theta_1}{\sigma_2} \right) \right) d\pi$ is weakly increasing in θ_1 and continuous in θ_1 and σ_2 for $\sigma_2 > 0$. Now (12) and (13) imply that, as $\sigma_2 \rightarrow 0$, if $\mu < \frac{M}{S}$,

$$\theta^*(\sigma_2) \rightarrow \frac{S + L_2 - M}{Y};$$

and if $\frac{M}{S} < \mu < \frac{A^*}{S}$

$$[\theta^{**}]^{-1}(\theta^*(\sigma_2)) \rightarrow \mu$$

and thus

$$\theta^*(\sigma_2) \rightarrow \theta^{**}(\mu) = \frac{(1-\mu)S + L_2}{Y - \frac{\mu S - M}{\psi}}.$$

Now the ex ante illiquidity risk, as $\sigma_2 \rightarrow 0$, is

$$\begin{aligned} \mathcal{L}_0(\theta_0) &= \Pr\left(\frac{S + L_2 - M}{Y} \leq \theta_1 \leq \frac{(1-\mu)S + L_2}{Y - \frac{\mu S - M}{\psi}} \middle| \theta_0\right) \\ &= \Pr\left(\frac{\frac{S + L_2 - M}{Y} - \theta_0}{\sigma_1} \leq \varepsilon_1 \leq \frac{\frac{(1-\mu)S + L_2}{Y - \frac{\mu S - M}{\psi}} - \theta_0}{\sigma_1}\right) \\ &= \frac{1}{\sigma_1} \left(\frac{(1-\mu)S + L_2}{Y - \frac{\mu S - M}{\psi}} - \frac{S + L_2 - M}{Y} \right) \\ &= \frac{1}{\sigma_1} \left(\frac{(1-\mu)SY + L_2Y - SY - L_2Y + MY + S\frac{\mu S - M}{\psi} + L_2\frac{\mu S - M}{\psi} - M\frac{\mu S - M}{\psi}}{Y\left(Y - \frac{\mu S - M}{\psi}\right)} \right) \\ &= \frac{1}{\sigma_1} \left(\frac{-\mu SY + MY + S\frac{\mu S - M}{\psi} + L_2\frac{\mu S - M}{\psi} - M\frac{\mu S - M}{\psi}}{Y\left(Y - \frac{\mu S - M}{\psi}\right)} \right) \\ &= \frac{(\mu S - M)(S + L_2 - M - \psi Y)}{\sigma_1 Y (\psi Y - \mu S + M)} \end{aligned}$$

7.1.3 Small Ex Ante Uncertainty

In the benchmark model, we calculated ex ante credit risk and its decomposition into insolvency and illiquidity risk under the assumption that there was a significant amount of ex ante uncertainty (relative to interim uncertainty). In this section, we examine how the results would change if there was only a small amount of ex ante uncertainty.

In particular, we see the impact of only a small amount of information being released between times 0 and 1. We will use the notation

$$q \equiv \frac{\mu}{\lambda}$$

In order to examine the case of small ex ante uncertainty, we look at the case where

$$\sigma_1 < \sigma_2(1 - q).$$

In this case, we derive simple expressions for ex ante credit risk as follows. Define the following cut-off values of θ_0 .

$$\begin{aligned} a_1 &\equiv \theta^{**} + \sigma_2 q - \frac{1}{2}\sigma_2 - \frac{1}{2}\sigma_1; \\ a_2 &\equiv \theta^{**} + \sigma_2 q - \frac{1}{2}\sigma_2 + \frac{1}{2}\sigma_1; \\ a_3 &\equiv \theta^{**} + \frac{1}{2}\sigma_2 - \frac{1}{2}\sigma_1; \\ a_4 &\equiv \theta^{**} + \frac{1}{2}\sigma_2 + \frac{1}{2}\sigma_1. \end{aligned}$$

Then we have: $\mathcal{C}_0(\theta_0) =$

$$\begin{cases} 1, & \text{if } \theta_0 \leq a_1 \\ \left(\begin{array}{l} 1 - \frac{1}{\sigma_1} (\theta_0 - \theta^{**} - \sigma_2 (q - \frac{1}{2}) + \frac{1}{2}\sigma_1) q \\ - \frac{1}{2\sigma_1\sigma_2} (\theta_0 - \theta^{**} - \sigma_2 (q - \frac{1}{2}) + \frac{1}{2}\sigma_1)^2 \end{array} \right), & \text{if } a_1 \leq \theta_0 \leq a_2 \\ \frac{1}{2} + \frac{1}{\sigma_2} (\theta^{**} - \theta_0), & \text{if } a_2 \leq \theta_0 \leq a_3 \\ \frac{1}{2\sigma_1\sigma_2} (\theta^{**} - \theta_0 + \frac{1}{2}\sigma_2 + \frac{1}{2}\sigma_1)^2, & \text{if } a_3 \leq \theta_0 \leq a_4 \\ 0, & \text{if } a_4 \leq \theta_0 \end{cases}$$

Figure 5 plots $\mathcal{C}_0(\theta_0)$ for the case when there is small interim uncertainty. Thus

$$\sigma_1 \frac{d\mathcal{C}_0}{d\theta^{**}}(\theta_0) = \begin{cases} 0, & \text{if } \theta_0 \leq a_1 \\ q + \frac{1}{\sigma_2} (\theta_0 - \theta^{**} - \sigma_2 (q - \frac{1}{2}) + \frac{1}{2}\sigma_1), & \text{if } a_1 \leq \theta_0 \leq a_2 \\ \frac{\sigma_1}{\sigma_2}, & \text{if } a_2 \leq \theta_0 \leq a_3 \\ \frac{1}{\sigma_2} (\theta^{**} - \theta_0 + \frac{1}{2}\sigma_2 + \frac{1}{2}\sigma_1), & \text{if } a_3 \leq \theta_0 \leq a_4 \\ 0, & \text{if } a_4 \leq \theta_0 \end{cases}$$

and

$$\sigma_1 \frac{d\mathcal{C}_0}{dq}(\theta_0) = \begin{cases} 0, & \text{if } \theta_0 \leq a_1 \\ \sigma_2 q, & \text{if } a_1 \leq \theta_0 \leq a_2 \\ 0, & \text{if } a_2 \leq \theta_0 \end{cases}.$$

These expressions are illustrated in Figure 6. Now the impact of the solvency

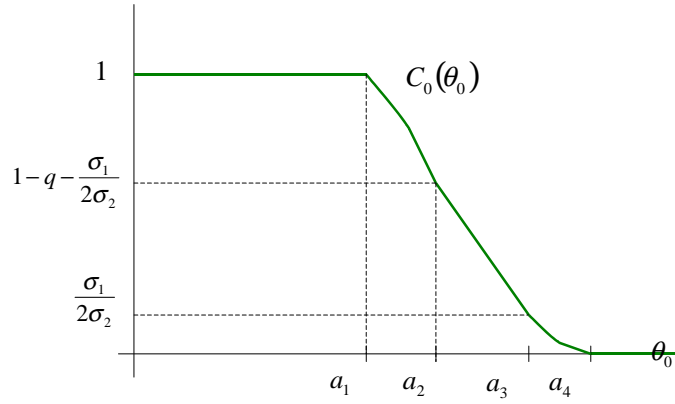


Figure 5: Total credit risk with small interim uncertainty

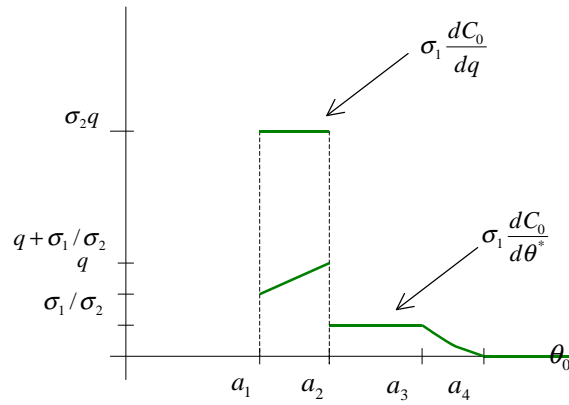


Figure 6: $\sigma_1 \frac{dC_0}{dq}$ and $\sigma_1 \frac{dC_0}{d\theta^*}$

point and $q = \frac{\mu}{\lambda}$ on ex ante credit risk is extremely sensitive to the initial value of θ_0 . In fact, we see that the illiquidity index will have no impact except in the range $\theta_0 \in [a_1, a_2] \cup [a_3, a_4]$ and, in the limit, the solvency will have most of its impact in that range. In that range, it remains the case that the illiquidity index has a relatively large impact if σ_2 is large. In particular, as $\sigma_2 \rightarrow \infty$,

$$\sigma_1 \frac{d\mathcal{C}_0}{d\theta^{**}} \rightarrow \begin{cases} 0, & \text{if } \theta_0 \leq a_1 \\ \frac{1}{2}, & \text{if } a_1 \leq \theta_0 \leq a_2 \\ 0, & \text{if } a_2 \leq \theta_0 \leq a_3 \\ \frac{1}{2}, & \text{if } a_3 \leq \theta_0 \leq a_4 \\ 0, & \text{if } a_4 \leq \theta_0 \end{cases} .$$

7.2 Global Game Foundations

We analyze the global game model in the text. We will consider the variant described in Section 5.3 where

$$A^*(\theta_1) = M + (\psi + \delta(\theta_1 - \theta_0))Y \quad (14)$$

and consider the limit where δ tends to 0.

Suppose that each short term creditor i , instead of observing θ_1 exactly observed instead a noisy signal $x_i = \theta_1 + \tau\eta_i$, where η_i is a zero mean noise term distributed in the population according to some density and $\tau > 0$ is a parameter measuring the size of the noise. Suppose that the noise terms are distributed according to a density g with c.d.f. G and support $[-\frac{1}{2}, \frac{1}{2}]$. Recall that all creditors know that θ_1 is uniformly distributed on the interval $[\theta_0 - \frac{1}{2}\sigma_1, \theta_0 + \frac{1}{2}\sigma_1]$. We will consider the case where τ is small compared to σ_2 .

Consider a creditor observing signal $x \in [\theta_0 - \frac{1}{2}\sigma_1 + \tau, \theta_0 + \frac{1}{2}\sigma_1 - \tau]$. If the true state is $\theta_1 \in [x - \frac{1}{2}\tau, x + \frac{1}{2}\tau]$, the proportion of agents observing a signal higher than x will be $\pi = 1 - G\left(\frac{x - \theta_1}{\tau}\right)$. The creditor observing signal x is unsure of π because he does not know the true value of θ_1 . What probability does he assigns to the proportion of creditors observing x or more being π or less. This will occur only if

$$1 - G\left(\frac{x - \theta_1}{\tau}\right) \leq \pi$$

or

$$\theta_1 \leq x - \tau G^{-1}(1 - \pi). \quad (15)$$

But the creditor observing signal x knows that $\theta_1 = x - \tau\eta$, where η is the noise term in his signal which is distributed according to g . Thus he assigns probability

$$1 - G\left(\frac{x - \hat{\theta}}{\tau}\right) \quad (16)$$

to θ_1 being less than $\hat{\theta}$. Substituting (15) into (16), we have the probability a creditor observing signal x assigns to the proportion of creditors observing x or more being π or less is

$$\begin{aligned} & 1 - G\left(\frac{x - (x - \tau G^{-1}(1 - \pi))}{\tau}\right) \\ &= 1 - G\left(\frac{\tau G^{-1}(1 - \pi)}{\tau}\right) \\ &= 1 - G(G^{-1}(1 - \pi)) \\ &= 1 - (1 - \pi) \\ &= \pi. \end{aligned}$$

Crucially, this is independent of x . It reflects the elementary intuition that with θ_1 uniformly distributed, the level of a creditor's signal gives no information about the ranking of his signal with respect to others, and thus he has a uniform belief over his rank.

Now suppose that creditors followed the strategy of rolling over only if $x_i \geq x^*$. In the limit (as $\delta \rightarrow 0$ in expression (14)), the best response of a creditor observing signal x^* , calculated from the payoffs described in the text, is to roll over only if

$$x^* \geq \theta^* = \theta^{**} + \sigma_2 \left(\frac{\mu}{\lambda} - \frac{1}{2} \right).$$

A creditor observing a lower signal will have less incentive to roll over and a creditor observing a higher signal will have more incentive to roll over. Thus there is an equilibrium where creditors roll over if and only if they observe signals of θ_1 greater than θ^* . As τ tends to zero, this gives exactly the behavior described in the text. Under the assumption that $\delta > 0$ in expression (14), each creditor has a dominant strategy to run if x_i is small

enough and to stay if x_i is large enough. The existence of these "two sided dominance regions" can be used to show that there are no other equilibria.

Morris and Shin (2003) show that the above argument is valid for general densities provided that some mild regularity conditions on the smoothness of densities are preserved. We refer the reader to that discussion for the full argument.

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