Rollover Risk and Market Freezes*

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Abstract

We consider the debt capacity of a risky asset when debt is being rolled over and there is a liquidation cost in case of default. We show that debt capacity depends on how information about the asset is revealed. When the information structure is based on "optimistic" expectations, the arrival of no news about the asset is good news; under this structure, debt capacity does not depend upon rollovers and liquidation cost, and is simply equal to expected cash flows from the asset. In contrast, when the information structure is based on "pessimistic" expectations, no news about the asset is bad news; under this structure, debt capacity of the asset is decreasing in the liquidation cost and frequency of rollovers. In the limit, as the number of rollovers becomes unbounded, the debt capacity goes to zero even for an arbitrarily small default risk. Our model explains why markets for rollover debt, such as asset-backed commercial paper, may experience sudden freezes. The model also provides an explicit formula for the haircut in secured borrowing or repo transactions.

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1 Introduction

One of the many striking revelations from the sub-prime crisis of 2007 and 2008 has been the sudden freeze in the market for the rollover of short-term debt. While the rationing of firms in the unsecured borrowing market is not uncommon and has a long-standing theoretical underpinning (see, for example, the seminal work of Stiglitz and Weiss, 1981), what has been somewhat puzzling is the almost complete inability of financial institutions to issue (or roll over) short-term debt backed by assets with relatively low credit risk. From a theoretical standpoint, this is puzzling since the ability to pledge assets and provide collateral has been considered one of the most important tools available to firms in order to get around credit rationing (Bester, 1985). From an institutional perspective, the inability to borrow overnight against high-quality assets has been the most salient market failure that effectively led to the demise of a substantial part of investment banking in the United States. More broadly, this has led to the collapse, in the United States as well as in countries such as the United Kingdom, of banks and financial institutions that had relied on the rollover of short-term wholesale debt in the asset-backed commercial paper (ABCP) and overnight secured repo markets. The failure of Bear Stearns in mid-March 2008 is a classic example of this market freeze.[1]

As an intrinsic part of its business, Bear Stearns relied day-to-day on its ability to obtain short-term financing through secured borrowing. Beginning late Monday, March 10, 2008 and increasingly through that week, rumors spread about liquidity problems at Bear Stearns and eroded investor confidence in the firm. Even though Bear Stearns continued to have high quality collateral to provide as security for borrowing,[2] counterparties became less willing to enter into collateralized funding arrangements with the firm. This resulted in a crisis of

[1] The discussion that follows is based on the Security and Exchange Commission's Chairman Christopher Cox's Letter to the Basel Committee in Support of New Guidance on Liquidity Management, available at: http://www.sec.gov/news/press/2008/2008-48.htm

[2] This high quality collateral mainly consisted of highly rated mortgage-backed assets which had low but not inconsequential credit risk by this time in the sub-prime crisis.

confidence late in the week, where counterparties to Bear Stearns were unwilling to make even secured funding available to the firm on customary terms. This unwillingness to fund on a secured basis placed enormous stress on the liquidity of Bear Stearns. On Tuesday, March 11, the holding company liquidity pool declined from $18.1 billion to $11.5 billion (see Figure 1). On Thursday, March 13, Bear Stearns' liquidity pool fell sharply and continued to fall on Friday. In the end, the market rumors about Bear Stearns' liquidity problems became self-fulfilling and led to the near failure of the firm. Bear Stearns was adequately capitalized at all times during the period from March 10 to March 17, up to and including the time of its agreement to be acquired by J.P. Morgan Chase. Even at the time of its sale, Bear Stearns' capital and its broker dealers' capital exceeded supervisory standards. In particular, the capital ratio of Bear Stearns was well in excess of the 10% level used by the Federal Reserve Board in its well-capitalized standard.

— Figure 1 about here —

In his analysis of the failure of Bear Stearns, the Federal Reserve Chairman Ben Bernanke observed:[3]

> "[U]ntil recently, short-term repos had always been regarded as virtually risk-free instruments and thus largely immune to the type of rollover or withdrawal risks associated with short-term unsecured obligations. In March, rapidly unfolding events demonstrated that even repo markets could be severely disrupted when investors believe they might need to sell the underlying collateral in illiquid markets. Such forced asset sales can set up a particularly adverse dynamic, in which further substantial price declines fan investor concerns about counterparty credit risk, which then feed back in the form of intensifying funding pressures. . . In light of the recent experience, and following the recommendations of the President's Working Group on Financial Markets (2008), the Federal Reserve and

[3]The quotes are based on Ben Bernanke's remarks to the Risk Transfer Mechanisms and Financial Stability Workshop at the Bank for International Settlements, May 29, 2008.

> other supervisors are reviewing their policies and guidance regarding liquidity risk management to determine what improvements can be made. In particular, future liquidity planning will have to take into account the possibility of a sudden loss of substantial amounts of secured financing."

Our paper is an attempt to provide a simple theoretical model of the debt capacity of an asset when (i) the debt is short-term in nature and, hence, needs to be rolled over; (ii) there is the risk of a fire sale in the event the borrower defaults and the current lender needs to seize and liquidate the underlying assets; and (iii) the arrival of information about quality of the assets is "pessimistic" (in a sense that we explain below). These are essentially the features alluded to in the preceding discussion of the conditions surrounding the collapse of Bear Stearns.

A novel feature of our model is the crucial role played by the information structure. When debt is short-term in nature, it is natural to assume that uncertainty about credit risk of the underlying asset will not be fully resolved by the date of next rollover. In fact, debt may have to be rolled over several times before information about the asset is completely revealed. In these circumstances, a lender that is unwilling or unable to extend credit until the assets mature has to take into account the risk that the borrower will not be able to find another lender, that is, to rollover his debt. Does such rollover risk diminish the debt capacity of an asset? The answer to this question depends crucially on the type of information structure.

Consider an information structure in which, at each rollover date, either bad news is released and asset pays zero, or there is no news. In this case, no news is good news. This information structure is "optimistic" (see Figure 2) in the sense that there is a constant small hazard of bad news so that the probability of receiving bad news between the present and the maturity date declines as the maturity date is approached. We show that under such an information structure, rollover risk and liquidation costs are irrelevant to the debt capacity of an asset, which is simply equal to the expected present value of asset's cash flows at maturity.

— Figures 2 and 3 about here —

This conventional result on the debt capacity of an asset breaks down, however, if the information structure is "pessimistic" (Figure 3) in the sense that there is a constant hazard of good news at each rollover date, so that no news is bad news. The likelihood of receiving bad news (no good news) between the present and the maturity date *increases* as the maturity date is approached. We show that, under the pessimistic information structure, the rollover debt capacity of an asset is *always* smaller than its buy-to-hold debt capacity, and is declining in the liquidation cost and credit risk. In fact, we can show that the debt capacity of an asset tends to zero as the number of debt rollovers grows without bound. What is remarkable is that this second result holds for *arbitrarily small credit risks*, capturing the scenario that Bear Stearns experienced during its failure in March 2008. A corollary of this result is that, as the credit risk increases, fewer debt rollovers are needed to make the debt capacity of an asset fall below some arbitrary threshold. Hence, a sudden switch in the market's expectations from optimistic scenario to the pessimistic one can cause a sudden "market freeze" in the rollover of short-term asset-backed debt.[4]

Something like this switch from optimistic to pessimistic expectations may have happened in the first quarter of 2007. The cause was growing awareness of the poor performance of securities backed by sub-prime mortgages and more importantly, the failure of the existing valuation models to predict their market prices. Normal risks are familiar and can be discounted with confidence. The realization that no one knew how to value these complex securities caused a fundamental change in attitudes. The future looked bleak, absent the arrival of some new information that would persuade investors that they could return to business as usual. In the event, such information did not arrive in time to persuade investors that they could carry on business as usual. In fact, many institutions, expecially money market mutual funds, were persuaded that they should not be in the business of accepting

[4]An imperfect analogy is to think about the economy whose state is characterized by a regime-switching model. When it is more likely to be in the healthy state, the more it stays in that state, the less likely it is to switch to the recession state. Conversely, when it is more likely in a recession, the more it stays in that state, the less likely it is to switch to the healthy state. No news in healthy is good news, whereas no news in recession is bad news.

commercial paper backed by these assets. The "freeze" was on. What occurred was an "adverse dynamic," to borrow Bernanke's phrase, whereby a fundamental change in information structures had reduced debt capacity through backward induction, in the limiting case diminishing the debt capacity of the assets to zero.

Our results can alternatively be stated in terms of the so-called "haircut" of an asset when it is pledged for secured borrowing or used in a repo transaction. Measuring the haircut as one minus the ratio of the debt capacity of an asset to its expected value (or its debt capacity for buy-to-hold debt), our model shows that the haircut can be calculated simply, based on three inputs, the credit risk of the asset (the hazard rate of default), the number of debt rollovers, and the fire-sale discount incurred in the event of liquidation of the assets by the lender. Under the optimistic information structure, the haircut is zero whereas, under the pessimistic structure, the haircut is positive and reaches 100% in the limit as the rollover frequency becomes unbounded.[5]

There are several institutional settings where our model of rollover risk and market freezes is applicable. The most natural candidate is the commercial paper market accessed primarily by financial institutions, but also by highly-rated industrial corporations, where rollover at short maturities is a standard feature. Another recent candidate is the practice of taking assets off-balance-sheet, putting enough capital with them to make them "bankruptcy-remote" and AAA-rated, and then borrowing short-term against these assets. Such structures, characterized by a maturity mismatch between assets and liabilities, were prevalent in many forms ("structured investment vehicles" or SIVs, "conduits," and others) in the period leading up to the sub-prime crisis.[6] And yet another candidate is the entire balance-sheet of a financial institution (such as that of Northern Rock or of the investment banks Bear Sterns

[5]Shin (2008), for example, documents based on data from Bloomberg, that the typical haircuts on treasuries, corporate bonds, AAA asset-backed securities, AAA residential mortgage-backed securities and AAA jumbo prime mortgages are respectively, less than 0.5%, 5%, 3%, 2% and 5%, whereas, in March 2008, these haircuts respectively rose to between 0.25% and 3%, 10%, 15%, 20% and 30%. See also the discussion in Brunnermeier and Pedersen (2005) on widening of haircuts in stress times.

[6]See Crouhy, Jarrow and Turnbull (2007) for an excellent description of such off-balance-sheet vehicles.

and Lehman Brothers) where the funding model inherently resembles that of a SIV, that is, long-term risky assets such as mortgages are funded by short-term, asset-backed commercial paper. All of these markets experienced severe stress during the sub-prime crisis and froze – 100% haircut – for many days at a stretch once the expectations about the quality of mortgage assets became pessimistic, even though, prior to this period, they appeared to be the cheapest form of financing – zero haircut – available in the market.[7]

Before we proceed, it is important to acknowledge that we take the short-term nature of debt and fire sales as given. That investment banks are (or used to be!) funded with rollover debt and that debt capacity can be higher with short-term debt under some circumstances for many underlying assets, are interesting facts in their own right. Indeed, there exist agency-based explanations in the literature (for example, Diamond, 1989, 1991, 2004, Calomiris and Kahn, 1991, and Diamond and Rajan, 2001a, 2001b) for the existence of short-term debt as optimal financing in such settings. Our model presents a counter-example to the claim that short-term debt maximizes debt capacity: when expectations are pessimistic, debt capacity through short-term borrowing may in fact be arbitrarily small, suggesting that institutions ought to arrange for this funding through alternative, long-term financing. Providing a micro-foundation for debt maturity in a model where there is a switch between optimistic and pessimistic regimes is a fruitful goal for future research, but one that is beyond the scope of this paper.

Similarly, there is a large body of literature in finance and economics justifying, verifying or employing fire sales of assets during periods of industry- or economy-wide shocks. On the theoretical front, Williamson (1988) and Shleifer and Vishny (1992) link this to the notion of specificity of assets, that is, the non-transferability of assets across industries. On the empirical front, Pulvino (1998), Krugman (1998), Aguiar and Gopinath (2005), Coval and Stafford (2006), Acharya, Bharath and Srinivasan (2007), and Acharya, Shin and Yorulmazer

[7]In fact, in the case of Northern Rock, other financial institutions such as HBOS, Bradford and Bingley, and Alliance and Leicester, that were heavily reliant on wholesale, short-term paper, also experienced a spillover (Yorulmazer, 2008) and have since the nationalization of Northern Rock in September 2008 been acquired, merged or nationalized.

(2007) have provided evidence of fire sales in real and financial markets in a variety of settings. And, on an applied front, a large literature on financial crises (starting with Allen and Gale 1994, 1998) has employed fire sales as a key modeling device.

From the standpoint of our paper, these two features – short-term borrowing and fire sales – imply that market freezes due to changes in expectations about credit risk of an asset are most likely when borrowing and/or lending horizon becomes short-term and underlying assets are "crowded" in the sense that most financial institutions are on one side of the market for the underlying assets. The first feature generates rollover risk and the second feature generates fire sales in asset liquidations.[8]

The rest of the paper proceeds as follows. Section 2 presents a discrete-time binomial example that illustrates our main result on rollover risk and market freezes. Section 3 discusses the role of the each of the main assumptions in generating our market freeze result. Section 4 extends the binomial example to continuous time with random rollovers and random arrival of information. Section 5 relates the model and results to existing literature. Section 6 discusses merits of some potential interventions to help unfreeze rollover markets. Section 7 concludes with some ideas for further work. Appendix I contains proofs. Appendix II extends the discrete-time model to allow for more general information structures.

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[8]Indeed, the sub-prime crisis of 2007 and 2008 features both. Inter-bank borrowing has in fact switched from three-month unsecured to overnight secured and unsecured as a number of borrowers have been rationed in the longer maturity buckets. There has also been evidence of substantial discounts in sale of assets in SIVs and conduits. See, for instance, and "SIV restructuring: A ray of light for shadow banking," *Financial Times, June 18 2008*; and "Creditors find little comfort in auction of SIV Portfolio assets," *Financial Times, July 18 2008*, which both report that net asset values due to asset fire sales have fallen below 50% of paid-in capital. As the first article reports: "[W]hen defaults on US subprime mortgages rose last summer, ABCP investors stopped buying [short-term ABCP] notes – creating a funding crisis at SIVs. . . . This situation prompted deep concern about the risk of a looming firesale of assets. The prospect was deemed so alarming that the US Treasury attempted to organize a so-called "super-SIV" last autumn, which was supposed to purchase SIV assets."

2 Binomial example

2.1 The basic idea

For sake of illustration, we consider a SIV attempting to raise asset-backed finance. The SIV is set up at date $t = 0$ with a collection of assets as collateral. The SIV issues commercial paper and we normalize units of time so that commercial paper matures in exactly one period. The assets mature at date $t = T + 1$, which implies that the SIV must rollover its debt exactly T times, at dates $t = 1, ..., T$.

At each date $t = 1, ..., T+1$, information about the quality of the assets becomes available. In the case of dates $t = 1, ..., T$, the information is released before the debt is rolled over. For simplicity, we assume that at each date $t = 1, ..., T + 1$, there is a public signal takes two values, H and L, with probabilities p and $1 - p$ respectively. The signals are independent across time. We can think of the signal H as "good news" and the signal L as "no news." If good news arrives in any period, it means that the value of the assets will be V. On the other hand, if there is "no news" in every period $t = 1, ..., T + 1$, an event that occurs with probability $(1 - p)^{T+1}$, the value of the assets is 0. This information structure, which we referred to in the introduction as the "pessimistic" information structure, is illustrated in Figure 2.

If the SIV is forced to default and liquidate the assets, we assume that the assets fetch a fraction $\lambda \in [0, 1]$ of the *maximum amount of finance that could be raised by the SIV as a going concern*. Note that the recovery rate λ is applied to the maximum debt capacity rather than to the fundamental value of the assets. If the buyer of the assets were a wealthy investor who could hold the assets until maturity, the fundamental value would be the relevant benchmark and the investor might well be willing to pay some fraction of the fundamental value, only demanding a discount to make sure that he does mistakenly overpay for the assets. What we are assuming here is that the buyer of the assets is another financial institution that must also issue short term debt in order to finance the purchase. Hence, the buyer is constrained by the same forces that determined the debt capacity in the first place. While the debt capacity provides an upper bound on the purchase price, there is no reason to think that the assets will reach this value. In fact, we assume $\lambda < 1$ in what follows.

For simplicity, we assume that current yield of the assets is zero and the terminal value is either $V > 0$ or 0. We also assume for simplicity that the current risk-free interest rate is zero and that the market is risk neutral.

Our problem is to determine the maximum amount that can be borrowed by the SIV using only the assets as collateral. We can do this by backward induction, beginning with the period before the asset matures.

There are two possible situations that must be considered. Either (i) good news has arrived, in which case the value of the asset is V for certain, or (ii) good news has not yet arrived, in which case the value of the asset remains uncertain.

Suppose that goods news has not yet arrived. In the penultimate period, the SIV issues debt with a face value of D. If $D > V$, the SIV defaults in both states regardless of the value of the asset and the expected value of the debt is

$$p\lambda V + (1-p) \times 0 = p\lambda V.$$

On the other hand, if $D \leq V$, then the expected value of the debt is

$$pD + (1-p) \times 0 = pD.$$

Then the value of debt is

$$\max \{p\lambda V, pD\},$$

which is maximized by setting $D = V$. Let $D_0 = pV$ denote the maximum value of debt.

Now let's move back one period and assume again that good news has not arrived. If the face value of the debt issued is D, the value of the debt in the ante-penultimate period is

$$\begin{cases} p\lambda V + (1-p)\lambda D_0 & \text{if } D > V \\ pD + (1-p)\lambda D_0 & \text{if } D_0 < D \leq V \\ D & \text{if } D \leq D_0. \end{cases}$$

Noting that $V > D_0$, it is clear that the value of the debt issued is maximized by setting $D = V$ and the maximum value of the debt is $D_1 = pV + (1-p)\lambda pV$.

Continuing in this way, we can calculate the maximum value of the debt that can be raised against the SIVs collateral for any number of future roll overs.

2.2 The general formula

The general formula can be derived by backward induction. Let n denote the number of rollovers required in the future and let D_n be the maximum amount that can be raised assuming that no news has been received in period n and the SIV is solvent. As an induction hypothesis, we assume that

$$D_n = \left(\sum_{i=0}^{n} (1-p)^i \lambda^i \right) pV. \tag{1}$$

This formula agrees with the results obtained above, namely, $D_0 = pV$ and $D_1 = pV + (1-p)\lambda pV$, so we have already proved that the induction hypothesis holds for $n = 0, 1$.

Now suppose that the induction hypothesis holds when the number of rollovers remaining is n and consider what happens in the preceding period. Note first, that the maximum amount D_{n+1} must satisfy

$$D_{n+1} = \max\left\{ pV + (1-p)\lambda D_n, D_n \right\},$$

depending on whether the face value of the debt is set equal to V or to D_n, and that

$$D_{n+1} = pV + (1-p)\lambda D_n \tag{2}$$

if and only if

$$pV + (1-p)\lambda D_n \geq D_n$$

which is equivalent to

$$\begin{aligned} D_n &\leq \frac{pV}{1-(1-p)\lambda} \\ &= \left(1 + (1-p)\lambda + (1-p)^2 \lambda^2 + \cdots \right) pV \\ &= \left(\sum_{i=0}^{\infty} (1-p)^i \lambda^i \right) pV. \end{aligned}$$

Our induction hypothesis guarantees that this inequality is satisfied and hence that (2) is satisfied. Then using (2) and the induction hypothesis (1), we calculate

$$
\begin{aligned}
D_{n+1} &= pV + (1-p)\,\lambda D_n \\
&= pV + (1-p)\,\lambda \left(\sum_{i=0}^{n} (1-p)^i \lambda^i \right) pV \\
&= \left(\sum_{i=0}^{n+1} (1-p)^i \lambda^i \right) pV,
\end{aligned}
$$

as required.

Thus, we have proved by induction that,

Lemma 1 *Regardless of how many roll overs are required before the assets mature, the maximum amount of finance that can be raised is given by the formula (1).*

A straightforward consequence is that

Corollary 2 *The maximum amount of finance that can be raised against the assets is declining in the fire-sale discount* $(1-\lambda)$ *and credit risk* $(1-p)$.

Proof. See Appendix I. ■

2.3 Market freezes

We define the market for short-term borrowing by the SIV to be experiencing a "freeze" if the maximum debt capacity of the SIV goes to zero. To characterize a market freeze, we examine the effect of the number of rollovers n on the maximum finance D_n that can be raised. There are various ways of interpreting the changes in the model that lead to an increase in the number of rollovers. We could think of this as involving a shortening of the maturity of the commercial paper (reducing the length of the time period). Alternatively, we could think of this as involving an increase in the the horizon T. Either way, it is convenient simply to track the number of rollovers to maturity and treat n as the exogenous variable in our comparative static analysis. There should, of course, be a ceteris paribus assumption that the fundamental value of the asset remains constant as we vary n. That is, $(1-p)^{n+1}$ should remain equal to a constant $(1-p')$, say, so that the fundamental value of the assets $p'V$ is constant.

The Figures 4a and 4b plot the behavior of debt capacity D_n as a function of n as credit risk $(1-p')$ and liquidation cost $(1-\lambda)$ vary. The plots reveal that in all cases, D_n is declining in n and goes to zero as n becomes very large.

— Figures 4a, 4b about here (D_n for different n as p' and λ vary) —

To confirm that this is a general property, we establish analytically that $D_n \to 0$ as we let $n \to \infty$, holding the fundamental value of the assets unchanged. First, note that

$$\sum_{k=0}^{n} (1-p)^k \lambda^k \leq \sum_{k=0}^{\infty} (1-p)^k \lambda^k = \frac{1}{1-(1-p)\lambda} \leq \frac{1}{1-\lambda}.$$

Then, substituting this inequality in the expression for D_n, we find that

$$D_n = \left(\sum_{k=0}^{n} (1-p)^k \lambda^k \right) pV \leq \frac{1}{1-\lambda} pV.$$

Now, holding the fundamental value $(1-p') = (1-p)^{n+1}$ constant implies that p, the probability of good news arriving in any period, goes to zero as $n \to \infty$. So $\frac{1}{1-\lambda}pV \to 0$ as $n \to \infty$ and the value of the debt becomes vanishingly small too. This yields our main result:

Proposition 3 *As long as there is credit risk on the asset ($p' < 1$) and there is the risk of fire sale at rollover stage ($\lambda < 1$), the maximum rollover debt capacity of the asset ($n > 1$) is strictly smaller than its buy-to-hold debt capacity ($p'V$) and goes to zero as n becomes unbounded.*

Proof. See Appendix I. ■

In other words, there is a "market freeze" when the debt to be raised by the SIV has to be rolled over sufficiently frequently, *for arbitrarily small levels of credit risk of the underlying assets.*

2.4 A formula for haircuts

Our results can alternatively be stated in terms of the so-called "haircut" of an asset. In secured borrowing or repo transactions, the haircut on an asset is the proportion of (some notion) of its fundamental value that the investor cannot borrow against. We define the fundament value as debt capacity of the asset for buy-to-hold debt. In other words, we can measure the haircut H_n in the model as one minus the ratio of D_n to $p'V$. The haircut then is given by the formula:

$$H_n = 1 - \frac{p}{p'}\left(\sum_{i=0}^{n}(1-p)^i\,\lambda^i\right),$$

where $p' = 1 - (1-p)^{n+1}$, as before.

Thus, the haircut can be calculated simply based on three inputs:

1. $(1 - p')$, the credit risk of the asset;
2. n, the number of debt rollovers, or its rollover risk; and,
3. λ, the recovery rate, or $(1-\lambda)$, the fire-sale discount to be incurred in case of liquidation of the asset by a lender.

Then, it can be shown that

Proposition 4 *The haircut of an asset is increasing in its liquidation risk* $(1-\lambda)$. *In particular, as long as* $p' < 1$ *and* $\lambda < 1$, *the haircut of an asset is strictly positive and approaches* 100% *as its rollover risk* n *becomes unbounded.*

Proof. See Appendix I. ■

Brunnermeier and Pedersen (2005) and Shin (2008) discuss in detail the sharp widening of haircuts in stress times, even for relatively high quality assets such as AAA-rated asset pools. Our model provides an explanation for why stress times – when credit risk, rollover risk and liquidation risk rise – are associated with such large swings in haircuts. Figures 5a and 5b provide some illustrative calibrations to generate haircuts of the magnitude described by Shin (2008) and summarized in footnote 5.

— Figures 5a, 5b about here (H_n for different n as p' and λ vary) —

Equally importantly, the second part of the corollary provides a potential explanation for why Bear Stearns experienced a complete inability in March 2008 to obtain *any* overnight rollover financing against its even high quality assets.

3 Factors driving market freezes

Before we proceed to generalize the model, it is useful to stress what are the key drivers of market freezes in our setup. As we explain below, it is the combination of pessimistic investor expectations, liquidation risk and the need to rollover debt which lead to the freeze. While some credit risk is necessary for the freeze, it is not the primary driver. An arbitrarily small credit risk is sufficient. In any case, the assumption of at least some credit risk is natural when one thinks of asset-backed commercial paper and non-government bond repo transactions.

3.1 The information structure

A pessimistic information structure is crucial for the market freeze result. To see this, we consider the alternative, optimistic information structure of Figure 3 and ask "Do rollover and liquidation risk lead to a market freeze?" The answer is no. Recall that in the optimistic information structure, there is a probability $1 - q$ in each period that bad news will arrive, signaling that the value of the underlying assets is 0. If no news has arrived by the time the asset matures, its value is V. Now consider the debt capacity of the asset one period before maturity. If the face value of the debt is $D \leq V$ then the expected value of the debt is qD, which is maximized by putting $D = V$. So the maximum debt capacity is clearly qV. (If the face value of the debt is $D > V$ then the expected value of the debt is $q\lambda V < qV$). Now, in the period before, suppose the face value of debt is D. With likelihood $(1 - q)$, there is default next period and the payoff is zero; with likelihood q, there is full payment if $D \leq qV$, the maximum debt capacity in that state; or if $D > qV$ there is liquidation and the payoff is λqV. Clearly, debt capacity is maximized by setting $D = qV$ and its expected value is q^2V. Proceeding backwards, the debt capacity of the asset at date 0 is simply q^nV. Holding constant the credit risk of the asset, that is, setting $(1 - q^n)$ equal to $(1 - q')$, the debt capacity equals $q'V$, the fundamental value of the asset. In particular, this is true *regardless of the rollover frequency and the liquidation cost.*

What this calculation shows is that under an optimistic information structure, there is indeed no haircut in borrowing against the credit-risky asset even at extremely high rollover frequencies. In other words, our result on market freeze relies critically on the information structure being pessimistic as in Figure 2. As we explained in the introduction, a switch from optimistic to pessimistic expectations may arise upon arrival of news such as sub-prime losses with which investors have little prior experience, causing them to switch to pessimistic beliefs where they expect the worst unless good news arrives.

3.2 Liquidation risk

Given a pessimistic information structure and some (arbitrarily small) credit risk, there is a haircut in borrowing against the underlying asset as long as at least one rollover is required and there is some liquidation cost faced by the lender in case of default. Put another way, if there is zero liquidation cost, for example, because the underlying asset is fully liquid and requires no asset-specific skills on the part of the borrower, then regardless of credit risk, rollover risk and information structure, the debt capacity of the asset is equal to the fundamental value of the asset (set $\lambda = 1$ in formula 1).

What does this imply about the markets in which a freeze is most likely to occur? Since $\lambda < 1$ is really a metaphor for illiquidity of the asset, one interpretation is that a market freeze is most likely in rollover debt backed by assets where the likely acquirers are all on one side of the market. That is, when potential acquirers are likely to be hit by a common shock or the underlying trade is “crowded”, then its liquidation will lead to fire sales. An alternate interpretation is that a market freeze is likely in assets that are complex and where owners of assets have expertise or management skills which are not transferable when lenders try to seize and liquidate the asset (Williamson, 1988, Shleifer and Vishny, 1992). A fitting example here might be mortgage-backed securities since prepayment and default risk of households on home loans are borne by the financial sector as a whole, but the risk gets repackaged also within the financial sector through these securities. Hence, a common shock to the financial sector would render this asset class relatively illiquid, as witnessed briefly during the Long Term Capital Management crisis of 1998 and more extensively during the sub-prime crisis of 2007-08.

3.3 Rollover frequency

As argued above, under both optimistic and pessimistic structures, regardless of credit risk and liquidation risk, debt capacity of buy-to-hold debt is equal to the fundamental value of the asset. Hence, rollover risk is critical to obtaining haircuts in secured borrowing. As our main result showed, when rollover frequency is very high, debt capacity in fact goes to zero. It seems, based on market reactions as well as Federal Reserve Chairman Ben Bernanke's remarks following the collapse of Bear Stearns in March 2008 (see the introduction), that it was never anticipated that short-term rollover financing against relatively high-quality collateral could experience a complete freeze. The reliance on short-term debt financing has been argued by some to have caused the demise of the investment banking structure during the sub-prime crisis. As this discussion has argued, when expectations are optimistic, short-term rollover financing has little, if any, cost. But if expectations become (unexpectedly) pessimistic and rollover frequency and liquidation cost are high, then the rollover debt market can experience a sudden freeze.

3.4 Credit risk

Though credit risk is qualitatively only required to be non-trivial to obtain the market freeze result, quantitatively it is clearly material. As our formula for haircuts (equation **??**) shows, the higher the credit risk, the higher the haircut, all else equal. Hence, the rollover debt capacity for assets that have greater risk is more likely to experience sharper reductions, holding rollover frequency and liquidation costs equal. It is a common feature of markets that haircuts in borrowing are generally increasing in the default risk of the asset, consistent with our haircut formula.

4 A continuous-time model

In the binomial example discussed in the text of the paper, it is assumed that the debt must be re-financed at regular intervals and that information arrives at the same time as the debt is rolled over. It is interesting to consider also the case where re-financing is not precisely synchronized with the arrival of new information. In fact, there may be uncertainty about the frequency of re-financing as well as uncertainty about the arrival rate of new information. This allows us to consider not only variations in the relative rates of information arrival and re-financing, but also uncertainty about the number of re-financings that may be necessary before the underlying asset matures. First we sketch a model in which information arrives according to a continuous-time Poisson process. Then we introduce uncertainty about the dates at which the debt must be rolled over.

4.1 A Poisson model of information arrival

We assume as before that there is a binary signal that reveals "good news" and arrives according to a Poisson process with parameter α. Suppose that time is continuous and represented by the interval $[0,1]$. The probability that some "good news" will have arrived by time t is $1-e^{-\alpha t}$ and the probability that some "good news" arrives between times t and t', given that it has not arrived by time t, is $1-e^{-\alpha(t'-t)}$. More generally, we can work with a stochastic process where the probability of delivering "good news" between t and t' that is denoted by $P(t,t')$. Suppose that the rollover dates are evenly spaced at times

$$t_n = \frac{N+1-n}{N+1}$$

for $n = 1, ..., N$. The probability that "good news" arrives between successive rollover dates is a constant

$$\begin{aligned} p &= P\left(\frac{n}{N+1}, \frac{n+1}{N+1}\right) \\ &= 1 - \exp\left\{\frac{-\alpha}{N+1}\right\}. \end{aligned}$$

The derivation of the debt capacity as a function of the rollover date goes through the same as in the case of discrete time:

$$D(t_n) = \left(\sum_{i=0}^{n} [(1-p)\lambda]^i\right) pV.$$

By induction, this shows that the maximum that can be raised at time 0 is

$$D(0) = \left(\sum_{i=0}^{N} [(1-p)\lambda]^i\right) pV.$$

This expression is essentially identical to formula (1) in the binomial case and, as in that case, we can establish analytically here too that $D(0) \to 0$ as we let $n \to \infty$, holding the fundamental value of the assets unchanged.

4.2 Random re-financing

Now we extend the Poisson model by assuming that, instead of being evenly spaced, the re-financing dates arrive randomly according to a Poisson process with parameter ρ. We assume that the information arrival process is independent of the rollover process. Then the probability that a rollover and information occur in the same period of length Δt is simply the product of the two probabilities $\lambda \Delta t$ and $\rho \Delta t$, i.e.,

$$(\lambda \Delta t)(\rho \Delta t) = \lambda \rho (\Delta t)^2 = o(\Delta t).$$

Let $D(t)$ denote the maximum amount of money that can be raised at time t assuming that good news has not yet arrived and that the SIV is solvent. Then $D(t)$ must satisfy the difference equation

$$D(t) = (1 - \alpha \Delta t - \rho \Delta t) D(t + \Delta t) + \alpha \Delta t V + \rho \Delta t \lambda D(t + \Delta t) + o(\Delta t). \tag{3}$$

With probability $(1 - \alpha\Delta t - \rho\Delta t)$, no information arrives and the debt is not re-financed in the period $(t, t + \Delta t)$ and the pledgeable value of the asset is $D(t + \Delta t)$. With probability $\alpha\Delta t$, good news arrives and the pledgeable value is V. And with probability $\rho\Delta t$ it is necessary to re-finance the debt and, assuming the face value of the debt is $V > D(t + \Delta t)$, the asset has to be sold at a fire sale and realizes a sale price of $\lambda D(t + \Delta t)$.

To see that it is optimal to set the face value of the debt equal to V, consider the effect of choosing $D < V$ as the face value. Clearly, there is no point choosing $D > D(t + \Delta t)$ or $D < D(t + \Delta t)$ so consider $D = D(t + \Delta t)$ for some period Δt. Then the value of the debt with face value D is

$$\begin{aligned}(1 - \alpha\Delta t - \rho\Delta t) D(t + \Delta t) + \alpha\Delta t D(t + \Delta t) + \rho\Delta t D(t + \Delta t) + o(\Delta t) = \\ D(t) + \alpha\Delta t (D(t + \Delta t) - V) + (1 - \lambda)\Delta t D(t + \Delta t) + o(\Delta t).\end{aligned}$$

Now

$$\alpha (D(t + \Delta t) - V) + (\lambda - 1) D(t + \Delta t) + \frac{o(\Delta t)}{\Delta t} < 0$$

for Δt sufficiently small if

$$\alpha \left(1 - \frac{V}{D(t + \Delta t)}\right) + (1 - \lambda) < 0. \tag{4}$$

We assume this condition is satisfied for the time being and check it later.

Re-arranging the terms of (3), we obtain

$$\frac{D(t + \Delta t) - D(t)}{\Delta t} = -\alpha V + (\alpha + \rho(1 - \lambda)) D(t + \Delta t) + \frac{o(\Delta t)}{\Delta t}.$$

Taking limits as $\Delta t \to 0$, we obtain the differential equation

$$\dot{D}(t) = -\alpha V + (\alpha + \rho(1 - \lambda)) D(t).$$

This can be solved to yield a general solution of the form

$$D(t) = \frac{\alpha V}{\alpha + \rho(1 - \lambda)} + Ce^{(\alpha + \rho(1 - \lambda))t}$$

where C is an undetermined coefficient. Setting $t = 1$ and using the boundary condition $D(1) = 0$, we get

$$0 = \frac{\alpha V}{(\alpha + \rho(1-\lambda))} + Ce^{(\alpha+\rho(1-\lambda))}$$

or

$$C = -\frac{\alpha V}{(\alpha + \rho(1-\lambda))} e^{-(\alpha+\rho(1-\lambda))}.$$

Then the solution is

$$D(t) = \frac{\alpha V}{\alpha + \rho(1-\lambda)} \left(1 - e^{(\alpha+\rho(1-\lambda))(t-1)}\right).$$

The maximum finance that can be raised at the initial date is obtained by setting $t = 0$ in the above formula. It is clear that $D(0) > D(t)$ for any $t > 0$, so in order to confirm condition (4) it is sufficient to show that it holds for $t = 0$. Then

$$\begin{aligned}
\alpha\left(1 - \frac{V}{D(0)}\right) + (1-\lambda) &= \alpha\left(1 - \frac{\alpha + \rho(1-\lambda)}{\alpha}\left(1 - e^{-(\alpha+\rho(1-\lambda))}\right)\right) + (1-\lambda) \\
&= -\rho(1-\lambda)\left(1 - e^{-(\alpha+\rho(1-\lambda))}\right) + (1-\lambda) < 0,
\end{aligned}$$

as required.

We illustrate the dependence of $D(0)$ on the parameters α and λ in the figures below.

— Figures 6a, 6b, 6c about here —

To analyze the effect of changes in the relative speed of information arrival and re-financing, we can re-write the expression for $D(0)$ as follows:

$$\frac{D(0)}{V} = \frac{\alpha\left(1 - e^{-(\alpha+\rho(1-\lambda))}\right)}{\alpha + \rho(1-\lambda)}.$$

Recall that the probability that good news does not arrive in the interval $[0, 1]$ is $e^{-\alpha}$. This is also the probability that the underlying asset has no value. In the figure below, we vary ρ to get a sense of the importance of the relative speeds of information arrival and re-financing. We choose α so that $e^{-\alpha} = 0.001$ (magenta), 0.01 (red) and 0.1 (green) and set $\lambda = 0.7$.

— Figure 6d about here —

Note that as ρ approaches 0 the financing ratio $D(0)/V$ approaches the fundamental value of the asset $V(1-e^{-\alpha t})$. The smaller the risk of the asset becoming valueless, the higher the value of ρ needed to reduce the ratio $D(0)/V$ to any particular level. With a probability of zero value equal to 0.1, it takes $\rho = 7.5142$ to reduce the ratio to 0.5, with a probability of zero value equal to 0.01, it takes $\rho = 15.348$, and with a probability of 0.001 it takes $\rho = 23.026$. Since ρ is equal to the expected number of roll overs in the unit interval, we can see that there is a substantial haircut after a reasonably small number of roll overs, even if the probability of the asset losing value is extremely small.

5 Related literature

Rosenthal and Wang (1993)

Huang and Ratnovski (2008)

6 Policy implications

[TO BE COMPLETED.]

Can a regulator do something to unfreeze the market?

- Reduce reliance on short-term debt and get more capital into SIV/banks. Will that help? If debt capacity is zero, capital required will be large as asset has no liquidation value! If injecting capital somehow lowers liquidation cost, then yes, it can help somewhat.

- Directly attempt to improve lambda by lending against the asset based on its full buy-and-hold value. But it seems important that EACH rollover lender anticipate this. Perhaps this explains why Fed policy of lending against weak collateral failed? There was no clarity on until when such lending would be done by the Fed.

- Any light to be shed on the FED buying CP directly?

7 Conclusion

[TO BE COMPLETED.]

Discuss other stories here?

- Knightian uncertainty.

- Risk of not getting assets back in bankruptcy/liquidation.

Open questions for future work:

Short-term debt (incentives) + Market freeze.

Strategic disclosure and our information structure.

Appendix I: Proofs

Proof of Corollary 2: It is clear from expression (1) that debt capacity D_n is increasing in λ and thus decreasing in the liquidation risk $(1-\lambda)$.

For the effect of credit risk $(1-p)$, consider the recursive expression in equation (2). Differentiating with respect to p, we obtain that

$$\begin{aligned}\frac{dD_{n+1}}{dp} &= V - \lambda D_n + (1-p)\lambda\frac{dD_n}{dp} \\ &> (1-\lambda)V + (1-p)\lambda\frac{dD_n}{dp},\end{aligned}$$

since $D_n < V$. Now note that $D_0 = pV$, so that $\frac{dD_0}{dp} = V > 0$. Then making the induction hypothesis that $\frac{dD_n}{dp} > 0$, we obtain that $\frac{dD_{n+1}}{dp} > 0$, or in other words, that debt capacity is declining in credit risk $(1-p)$ for any n. $\diamondsuit$

Proof of Proposition 3: The second part of the proposition is proved in the main text.

For the first part, note that using equation (1) and that $p < 1$ and $\lambda < 1$,

$$\begin{aligned} D_n &= \left(\sum_0^n (1-p)^i \lambda^i \right) pV \\ &< \left(\sum_0^n (1-p)^i \right) pV \\ &= \left(\frac{1-(1-p)^{n+1}}{1-(1-p)} \right) pV \\ &= (1-(1-p')) V \ = \ p'V, \end{aligned}$$

where we have also employed $(1-p)^{n+1} = 1-p'$. Thus, $D_n < D_0$ for all n as long as $\lambda < 1$ and $p' < 1$. $\diamondsuit$

Proof of Proposition 4: Since $H_n = 1 - \frac{D_n}{p'V}$, D_n is declining $(1-\lambda)$, and $p'V$ is invariant to $(1-\lambda)$, it follows that H_n is increasing in $(1-\lambda)$. Also from Proposition 3, when $p' < 1$ and $\lambda < 1$, $D_n < p'V$ for $n > 1$, and $D_n \to 0$ as $n \to \infty$. In turn, the haircut H_n is always positive under these conditions and goes to 100% as number of rollovers become unbounded. $\diamondsuit$

Appendix II: General information structures

The binomial example that has been used extensively in this paper is insightful, but it is also a rather special case. To establish the robustness of these results, we consider a more general class of information structures in this appendix. We assume for simplicity that re-financing occurs at a fixed sequence of regular intervals.

Suppose there are $N+1$ periods, where the period length corresponds to the maturity of the commercial paper issued. The information revealed in each period is represented by a random variable with a finite number of values. Without loss of generality we assume there are S different outcomes in period n and denote them by $\omega_n = 1, ..., S$. The information set in period n can be identified with the vector $\omega^n = (\omega_1, ..., \omega_n)$ and the states of nature can be identified with the vector $\omega = (\omega_1, ..., \omega_{N+1}) \in \Omega = \{1, ..., S\}^{N+1}$. The probability of state ω is denoted by $P[\omega]$.

Again, we assume the assets have a terminal value $V_{N+1}(\omega)$ in period $N+1$ but no yield in periods $n = 1, ..., N$ and for simplicity we assume that the short-term interest rate is 0.

Our task is to calculate the maximum amount of finance that can be raised in the initial period, before any information has been released. We compute this amount by backward induction, starting with the last period before the assets' value is realized. The assets are worth $V(\omega)$ at in state ω in period $N+1$ so, assuming the face value of the debt is D, the SIV is solvent if and only if

$$D \leq V(\omega).$$

The *payoff function* of the SIV is denoted by $B_{N+1}(\omega; D)$ and defined by

$$B_{N+1}(\omega; D) = \begin{cases} D & \text{if } D \leq V(\omega) \\ \lambda V(\omega) & \text{if } D > V(\omega) \end{cases},$$

for any state ω and face value D. Then the expected value of the debt in period N, conditional on the face value D and the information set ω^N, is

$$\mathbf{E}\left[B_{N+1}(\omega; D) \mid \omega^N\right].$$

The maximum pledgeable value of the asset is denoted by $V_N\left(\omega^N\right)$ and defined by

$$V_N\left(\omega^N\right) = \max_{D \geq 0} \mathbf{E}\left[B_{N+1}(\omega; D) \mid \omega^N\right].$$

Now suppose that we have defined $B_n(\omega^n; D)$ and $V_n(\omega^n)$ for $n = N-k, ..., N$. For $n = N-k-1$ we define $V_n(\omega^n)$ by putting

$$V_n(\omega^n) = \max_{D \geq 0} \mathbf{E}\left[B_{n+1}\left(\omega^{n+1}; D\right) \mid \omega^n\right].$$

Then we can define $B_n(\omega^n; D)$ in the obvious way, putting

$$B_n(\omega^n; D) = \begin{cases} D & \text{if } D \leq V_{n+1}(\omega^{n+1}) \\ \lambda V_{n+1}(\omega^{n+1}) & \text{if } D > V_{n+1}(\omega^{n+1}) \end{cases}.$$

By induction, we have defined $V_n(\omega^n)$ for every period $n = 1, ..., N$ and every information set ω^n. V_0 is the maximum amount of finance that can be raised at the first date.

We make two assumptions that are counterparts to the parametric assumptions in the text.

A.1 The terminal value of the asset $V(\omega)$ is bounded by $\bar{V} < \infty$ for every terminal state $\omega \in \Omega$.

A.2 There exists a terminal state $\bar{\omega} = (\bar{\omega}_1, ..., \bar{\omega}_{N+1})$ such that $V(\bar{\omega}) = 0$ and, for every period n, $P[\bar{\omega}_{n+1}|\bar{\omega}^n] \geq 1 - p > 0$.

Under the maintained assumptions we can show that

$$V_0 \leq p\bar{V}.$$

To prove this, we begin by considering the information set $\bar{\omega}^N$ and note that, under the maintained assumptions $A.1$ and $A.2$, the maximum finance that can be raised must be bounded by

$$\mathbf{E}\left[V\left(\omega^{N+1}\right) \mid \bar{\omega}^N\right] \leq (1-p) \times 0 + p\bar{V} = p\bar{V}.$$

Thus, $V_N\left(\bar{\omega}^N\right) \leq p\bar{V}$. Now suppose that

$$\begin{aligned} V_n(\bar{\omega}^n) &\leq \left[1 + (1-p)\lambda + \cdots + (1-p)^{N-n}\lambda^{N-n}\right] p\bar{V} \\ &= \left[\sum_{k=0}^{N} (1-p)^k \lambda^k\right] p\bar{V} \end{aligned}$$

and use the maintained assumptions to conclude that the inequality holds for $n-1$.

Conversely, we can show that there is a lower bound to the amount of finance that can be raised.

A.3 For some constants $\bar{v} > 0$ and $p > 0$, $P\left[V(\omega) \geq \bar{v} \mid \omega^N\right] \geq \pi$, for any information set ω^N.

Then, under Assumption $A.3$, it can be shown that

$$V_n(\omega^n) \geq p\bar{v},$$

for any information set ω^n. The proof is obvious.

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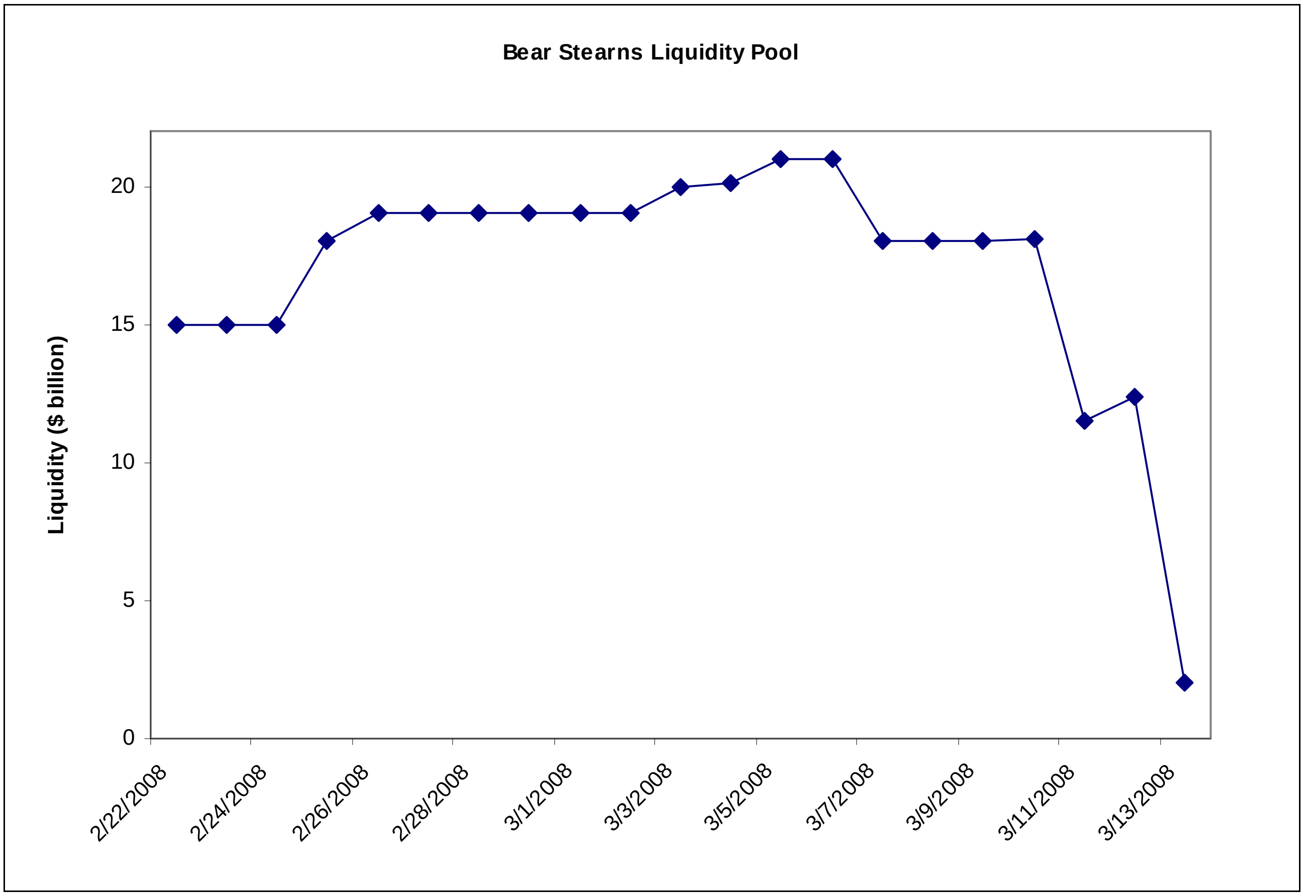

Figure 1: Bear Stearns' liquidity pool just before its near failure (Source: SEC Chairman Christopher Cox's letter to Basel Committee in support of New Guidance on Liquidity Management, available at: http://www.sec.gov/news/press/2008/2008-48.htm).

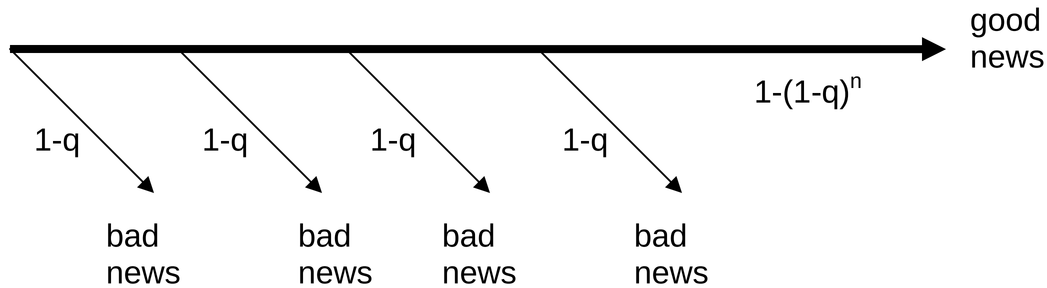

Figure 2: The Optimistic Information Structure
At each date, there is a probability $1 - q$ that bad news arrives and the value of the asset is 0. If bad news has not arrived by the maturity date, an event that occurs with probability $1 - (1 - q)^n$, the value of the asset is $V > 0$.

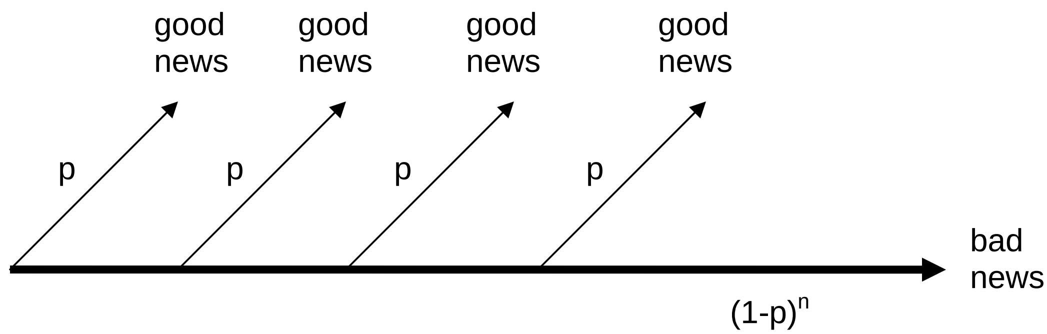

Figure 3: The Pessimistic Information Structure
At each date, there is a probability p that good news arrives and the value of the asset is $V > 0$. If good news has not arrived by the maturity date, an event that occurs with probability $(1-p)^n$, the value of the asset is 0.

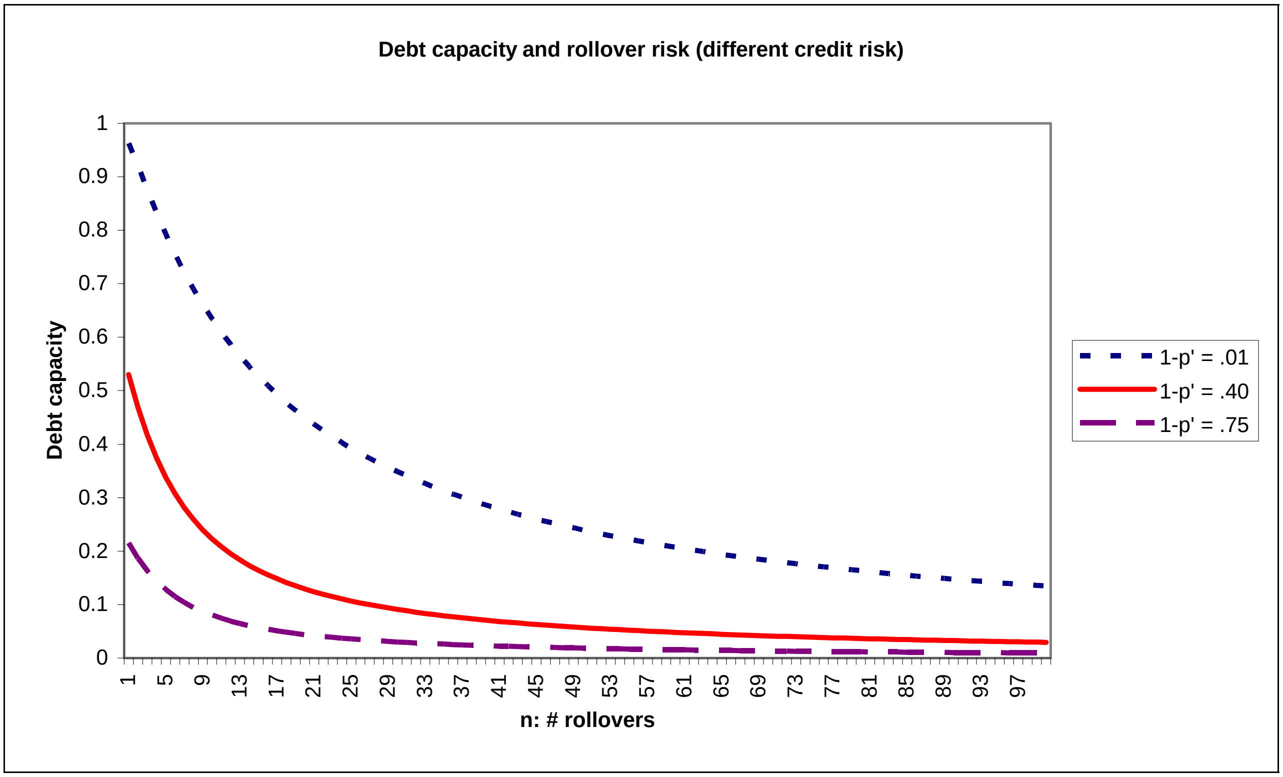

Figure 4a: Debt capacity as a function of *n* for different levels of credit risk (1-*p'*) for λ = 0.7.

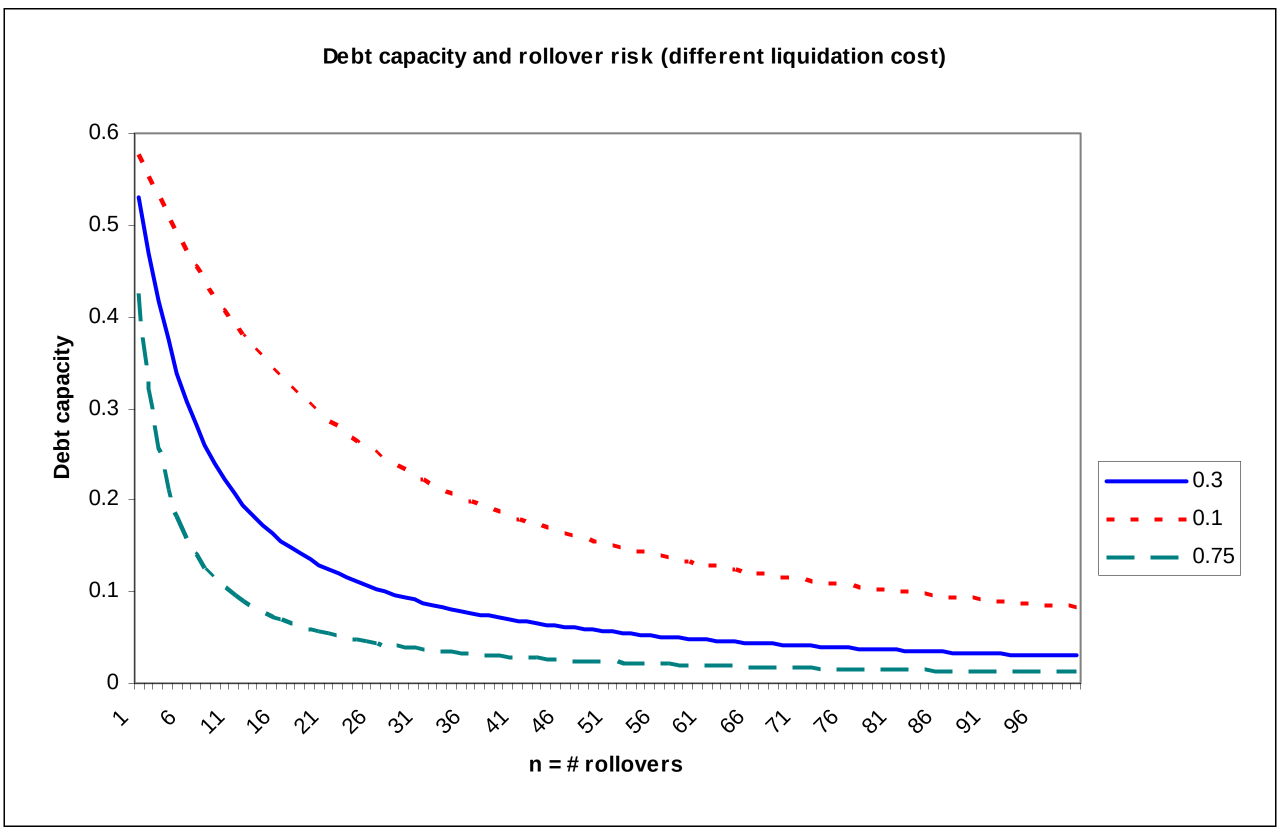

Figure 4b: Debt capacity as a function of *n* for different levels of liquidation risk (1-λ) for *p'*= .60.

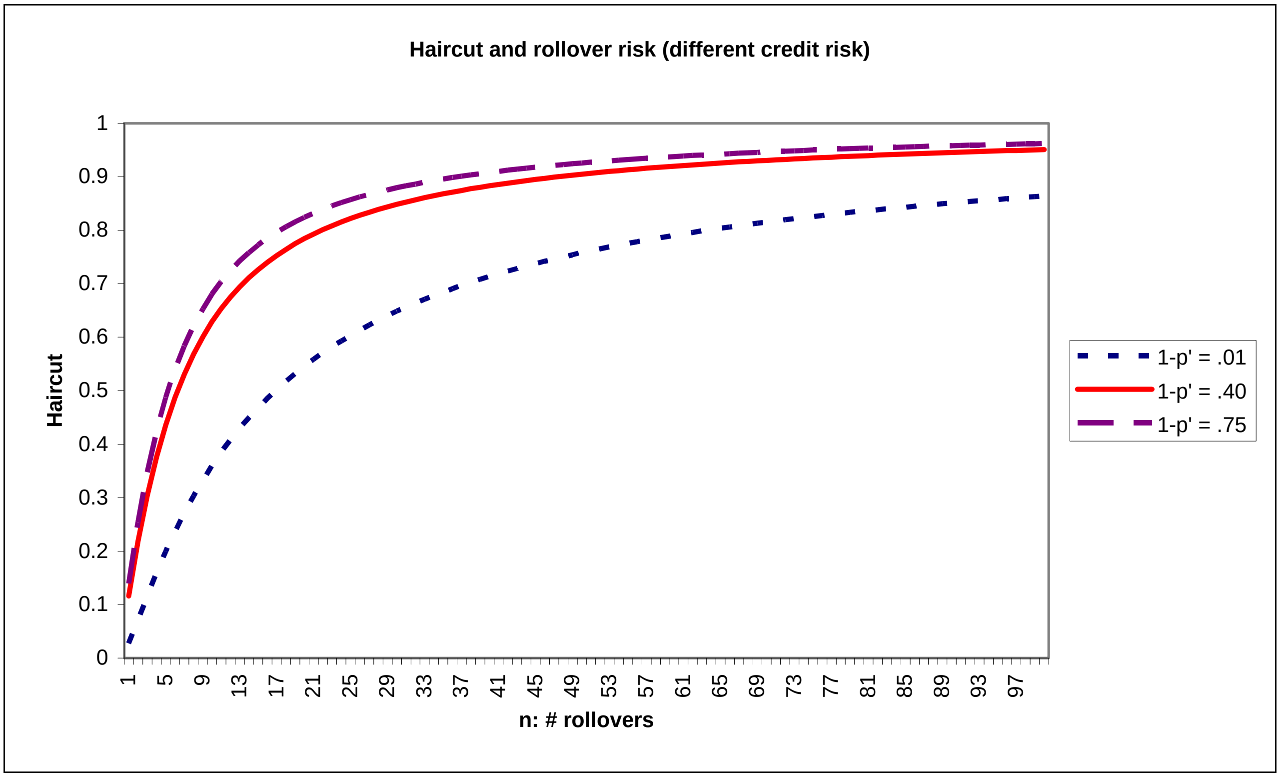

Figure 5a: Haircut as a function of *n* for different levels of credit risk (1-*p'*) for λ = 0.7.

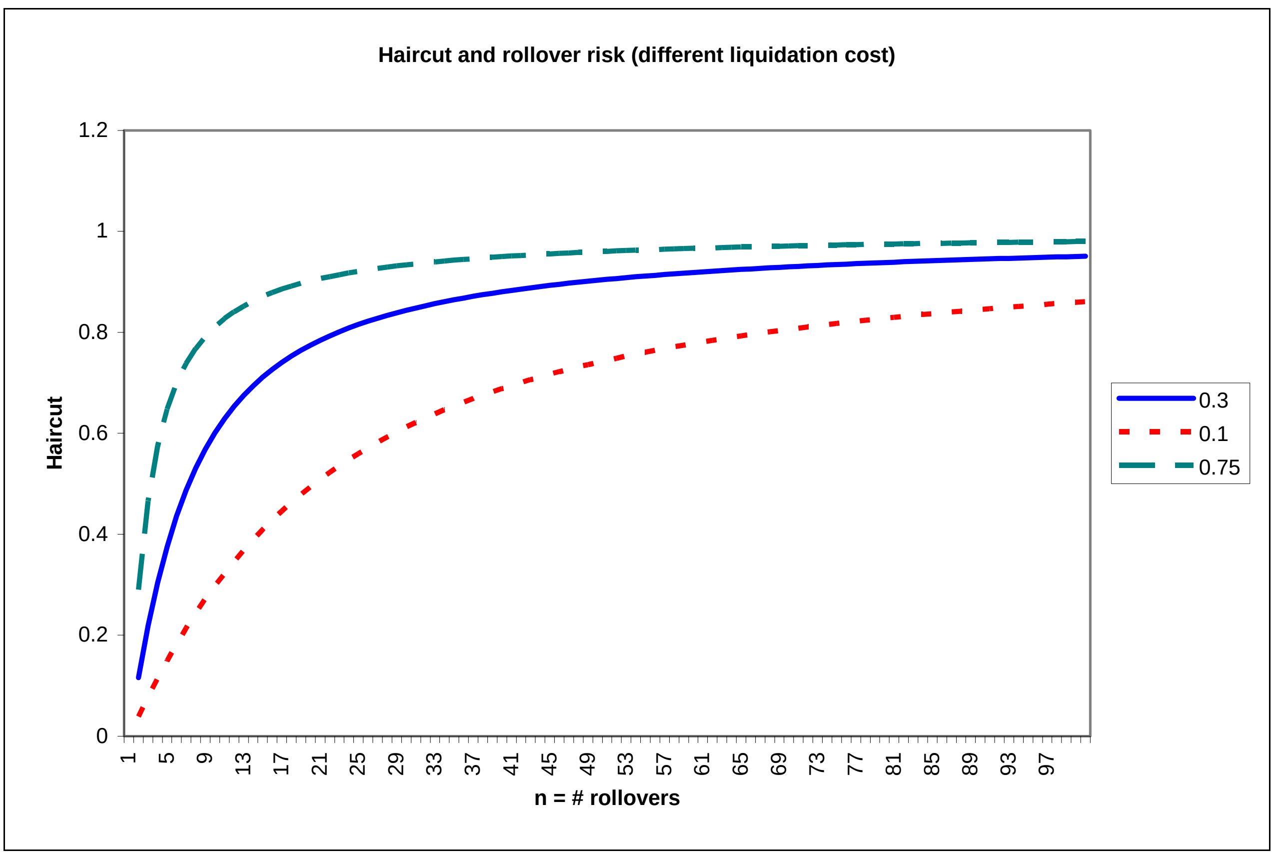

Figure 5b: Haircut as a function of *n* for different levels of liquidation risk (1-λ) for *p'*= .60.

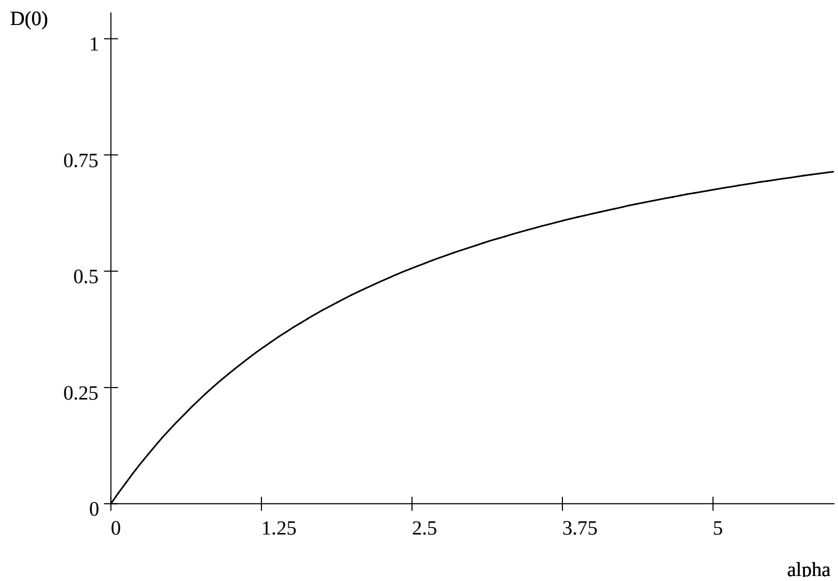

Figure 6a. Relation between $D(0)$ and α, with $V = 1$, $\rho = 8$ and $\lambda = 0.7$.

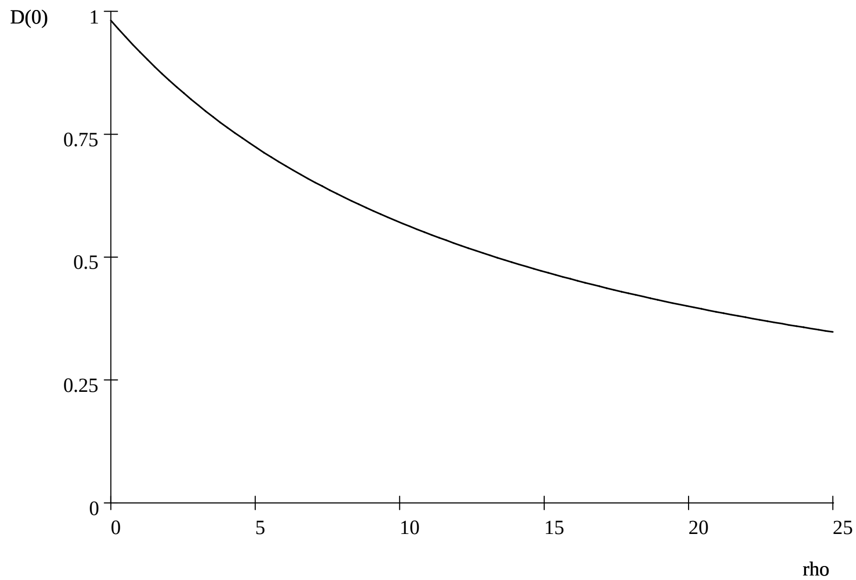

Figure 6b. Relation between $D(0)$ and ρ, with $V = 1$, $\lambda = 0.7$, and $\alpha = 4$.

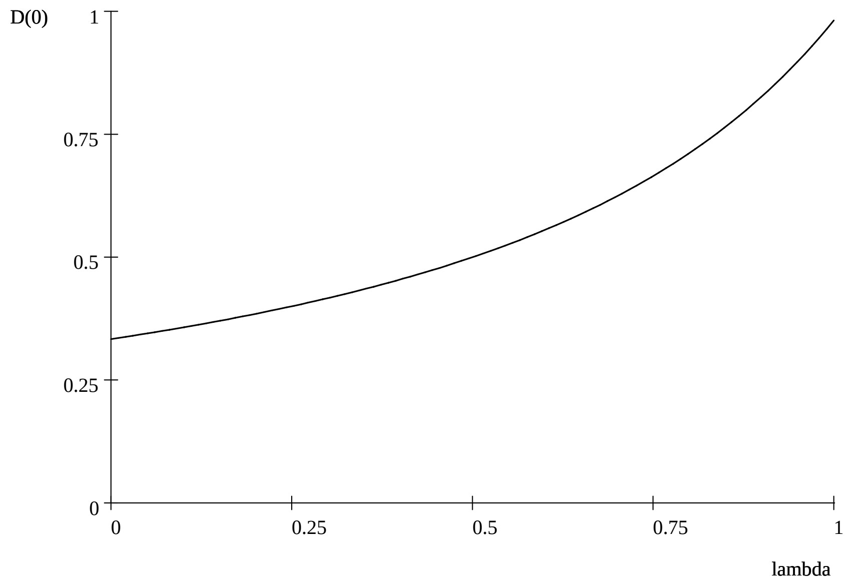

Figure 6c. Relation between $D(0)$ and λ, with $V = 1$, $\rho = 8$ and $\alpha = 4$.

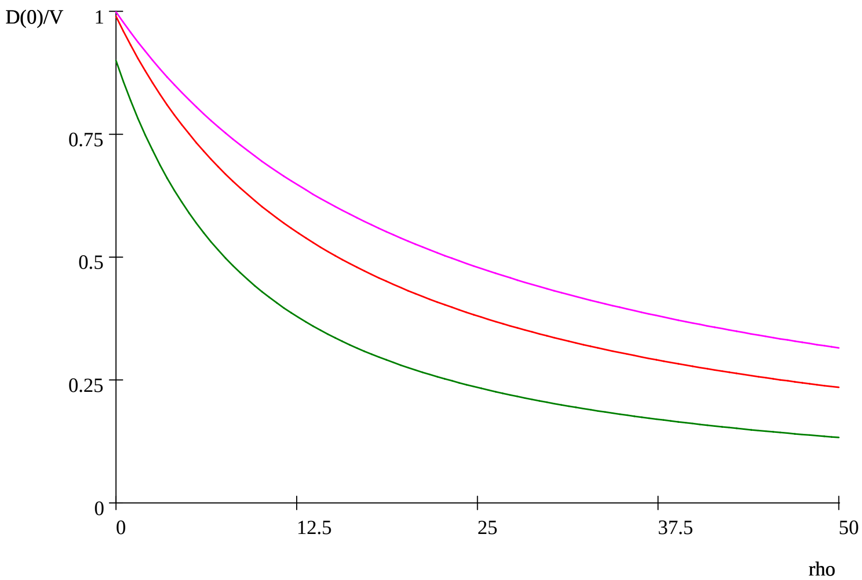

Figure 6d. Relation between $D(0)/V$ and ρ for different values of α.