

**LIQUIDITY, DEFAULT, AND CRASHES**

**BY**

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**COWLES FOUNDATION PAPER NO. 1074**



**COWLES FOUNDATION FOR RESEARCH IN ECONOMICS  
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2003

## **Liquidity, Default, and Crashes**

### *Endogenous Contracts in General Equilibrium*

**John Geanakoplos**

#### **1. LIQUIDITY CRISES**

In 1994 and again in 1998, fixed income markets, especially derivatives and mortgage derivatives, suffered terrible liquidity crises, which at the time seemed to threaten the stability of the whole financial system. Though we shall see that economists have had trouble precisely defining liquidity, the general features of the liquidity crises can be succinctly described. In both episodes one saw the following:

1. There was a price crash in defaultable assets, especially for the riskiest assets, but *without* a commensurate increase in subsequent defaults.
2. These effects spilled over many markets, such as high-risk corporate bonds and mortgages, even though the risks of default are probably not correlated between the markets.
3. There was a huge income loss for the most adventurous buyers (e.g., hedge funds purchasing derivatives).
4. There was an increase in the spread between more “liquid” and less “liquid” securities (like off-the-run Treasuries and on-the-run Treasuries), even though the assets had the same probability of default. Thus default spreads and liquidity spreads both increased.
5. The margin requirements on borrowing were raised.
6. Borrowing decreased.

Another crucial observation is that the crises did not seem to be driven by changes in the riskless interest rate. In 1994, Treasury interest rates were rising before the crisis, whereas in 1998 they were falling. Moreover, when the margin requirements on borrowing were raised, the interest rate charged remained virtually the same.

The thesis of this paper is that a liquidity crisis begins when bad news about assets raises their probability of default, which then redistributes wealth away from their natural buyers. But the crisis reaches its climax only when the margin requirements of borrowers using the assets as collateral are tightened.

The major part of my argument shows how the equilibrium forces of supply and demand can endogenously determine margin requirements. Next I show that most kinds of bad shocks loosen margin requirements. But shocks that indicate default are not only more likely, but also quicker, to lead to tighter margin requirements.

In Section 2, I explain how the possibility of default paradoxically makes the asset structure of an economy endogenous. In Sections 3 and 4, I describe the general equilibrium model of collateral equilibrium, including a precise description of endogenous margins. In Section 5, I explain how wealth redistributions and changes in margin requirements exacerbate asset price volatility. In Section 6, I present a concrete two-period example of a liquidity crisis. The result is not satisfactory because the margin requirements move in the wrong directions after a bad shock. However, the example is an important building block to the more elaborate and more satisfying three-period example presented in Section 7, in which volatility is increased by margin feedbacks and wealth redistributions. Sections 8 and 9 extend the analysis to many assets, permitting a rigorous explanation of liquidity spreads and spillovers. Section 10 reviews other possible explanations of liquidity crises. Finally, Section 11 suggests a formal definition of liquidity.

## 2. DEFAULT AND ENDOGENOUS CONTRACTS

Standard general equilibrium theory is unable to answer the question: Which contracts are traded in equilibrium? I argue that introducing default into general equilibrium makes room for a competitive theory of endogenous contracts, and that in such a model, liquidity and liquidity crises can be explained.

Let  $\mathcal{C}$  be the set of marketed contracts, and let  $\mathcal{C}^*$  be the set of contracts that are actively traded by at least one agent in equilibrium. A contract in  $\mathcal{C} \setminus \mathcal{C}^*$  is priced by the market, but untraded. If there are far fewer promises in  $\mathcal{C}^*$ , then we can say that the forces of supply and demand select the set of actively traded promises.

When there is the possibility of default, promises must be augmented by contract provisions that give the seller the incentive to deliver what he or she promised. These generally take one of two forms – punishment or collateral. It would seem to be far more daunting a task for competitive equilibrium theory to explain the terms of the loan contracts, as well as their promises and prices. Given a fixed promise, there are many attendant terms, such as how much collateral has to be put up, what the penalty for default should be, what the maximum allowable sales is, and so on. It would seem that instead of one equation matching supply and demand and one endogenous price, as in conventional general equilibrium theory, there is now a whole host of new endogenous variables representing contract terms, but the same single market-clearing equation for each promise. Equilibrium looks to be underdetermined.

The answer to the puzzle is to let each specification of contract terms  $c \in \mathcal{C}$  define another market, and therefore another market-clearing price. The

contract terms themselves are not endogenous variables like prices, which get set by equilibrium at one determinate value. Instead, they are parameters that help to define the different markets; but equilibrium can set their values just as well. Equilibrium will choose determinate levels of trade  $q_c$  in each market  $c \in C$ . And if, for example,  $q_c = 0$  for all  $c \neq c^*$ , then we can say that the forces of supply and demand have determined the contract terms  $c^*$ . This possibility is often obscured by the economist's preoccupation with price.

The public, and unfortunately the Federal Reserve, also share the economists' preoccupation with price. Every day the newspapers print the interest rates, and the Federal Reserve monitors them closely and systematically. But it might happen that the contract terms  $c^*$  attending most new loans dramatically change, while interest rates stay put. (This would imply that the prices for loans at the old terms had also dramatically shifted, but the newspapers do not print the prices of loans that are hardly transacted.) A change in  $c^*$  may be a more important harbinger of a liquidity crisis than a change in interest rates.

Scarce collateral provides a straightforward and compelling explanation for endogenous limits on contract trade. Simply put, the quantity of desired promises exceeds the value of the available collateral, and so the forces of supply and demand (operating through margin requirements) will ration the volume of trade. The rationing does not reduce the volume of trade in each contract proportionately, but instead it chokes off all trade in most contracts. As real conditions and expectations change, the margin requirements will need to change in order to maintain equilibrium. These margin changes will in turn have real effects, necessitating further adjustments in margins, and occasionally creating an *equilibrium cascade* into crisis.

The mechanisms by which scarce collateral and punishment ration contracts are similar. Both make the marginal utility of buying less than the marginal disutility of selling. With a positive probability of actual default, the buyer of a promise receives less than the seller delivers. For example, if a seller partially defaults and serves time in jail as punishment, she or he delivers both goods and jail time, whereas the buyer of the promise receives only the goods. Similarly, a provision of the contract might be that the seller is forced to put up collateral, that is, to buy and hold some durable good that the seller otherwise might not want, or to hold cash reserves that she or he would otherwise spend. The seller of the promise delivers goods to the buyer of the promise, but the seller also delivers the disutility of making an inconvenient transaction with a third party. The marginal utility of buying a promise may thus be less than the marginal disutility of selling the promise.

When the marginal utility–disutility gap is big for each agent, there is a real possibility that there will be an overlap containing a price greater than every agent's marginal utility of buying the contract, and less than every agent's marginal disutility of selling the contract, at which the contract will not be traded at all. In standard general equilibrium theory, this almost never happens to a nonredundant asset because every agent's marginal utility of buying is equal to his or her marginal disutility of selling. Standard general equilibrium theory

cannot explain which assets are traded because it does not leave room for assets that are *not* traded. General equilibrium with default does.<sup>1</sup>

Together with Dubey and Shubik (Dubey, Geanakoplos, and Shubik, 2001) and with Dubey (Dubey and Geanakoplos, 2001a, 2001b), I built a theory of endogenous punishment and endogenous quantity constraints on sales of promises. In earlier work (Geanakoplos, 1997; Geanakoplos and Zame, 1988). I constructed a model of endogenous collateral levels. In this paper I build on this latter work, reinterpreting collateral levels in terms of liquidity and explaining how shifts in equilibrium collateral levels (margin requirements) can cause equilibrium crises.

### 3. DEFAULT AND COLLATERAL

The difficulty with promises is that they require some mechanism to make sure they are kept. This can take the form of penalties, administered by the courts, or collateral. As I mentioned at the outset, more and more often collateral has displaced penalties. In this paper I deal exclusively with collateral, by supposing that there is no penalty, legal or reputational, to defaulting. Of course, even collateral requires the courts to make sure the collateral changes hands in case of default.

The simplest kind of collateral is pawn-shop collateral – valuable goods such as watches or jewelry left with third parties (warehoused) for safekeeping. Financial markets have advanced as the number of goods that could function as collateral has increased, from watches and jewelry to stocks and bonds. A further advance occurred when lenders (instead of warehouses) held collateral, such as paintings, that afforded them utility. This required a more sophisticated court system, because the lender had to be obliged to return the collateral if the promise was kept. The biggest advance, however, was in allowing borrowers themselves to continue to hold the collateral. This enabled houses, and later cars, to be used as collateral, which again is possible only because of a finely tuned court system that can enforce the confiscation of collateral.

More recently, the complexity of collateral has taken several more giant steps forward. Pyramiding occurs when an agent *A* puts up collateral for his promise to *B*, and then *B* in turn uses *A*'s promise to her, and hence in effect the same collateral, for a promise she makes to *C*, who in turn reuses the same collateral for a promise he makes to *D*. Mortgage passthrough securities offer a classic example of pyramiding. Pyramiding naturally gives rise to chain reactions, as a default by Mr. *A* ripples through, often all the way to *D*.

Still more complex is tranching, which arises when the same collateral backs several promises to different lenders. Needless to say, the various lenders will

<sup>1</sup> Moreover, it is not necessarily the default, nor even the probability of default, but the potential for default that puts the wedge between buying and selling utilities. Even if it is known that the default will not occur, given the contract provisions, these provisions may be so onerous as to choke off trade in the contract.

be concerned about whether their debts are adequately covered. Tranching usually involves a legal trust that is assigned the duty of dividing up the collateral among the different claims according to some contractual formula. Again, collateralized mortgage obligations offer a classic example of tranching.

Every one of these innovations is designed to increase or to stretch the available collateral to cover as many promises as possible. We shall see later that active default is another way of stretching the available collateral.

For the formal analysis in this paper, I avoid pyramiding and tranching. All collateral will, by assumption, be physical commodities. Collateral must be put up at the moment the promise is sold, even if the delivery is not scheduled for much later. Agents are not allowed to pledge their future endowment as collateral, because that would raise questions in the minds of lenders about whether the borrowers actually will have the endowments they pledged, and therefore it would once again destroy the anonymity of markets.

### 3.1. Contracts with Collateral

Let there be two periods,  $S$  states of nature, and  $L$  goods. To each contract  $j$  we must formally associate a promise  $A_j \in \mathbb{R}_+^{SL}$ , and levels of collateral. Any good can potentially serve as collateral, and there is no reason why the single promise  $A_j$  cannot be backed by a collection of goods. The bundle of goods that is required to be warehoused for contract  $j$  is denoted  $C_j^W \in \mathbb{R}_+^L$ , the vector of goods that the lender is allowed to hold is denoted  $C_j^L \in \mathbb{R}_+^L$ , and the vector of goods the borrower is obliged to hold is denoted  $C_j^B \in \mathbb{R}_+^L$ . A contract  $j$  is defined by the promise it makes *and* the collateral backing it,  $(A_j, C_j^W, C_j^L, C_j^B)$ . It is quite possible that there will be contracts that make the same promises  $A_j = A_{j'}$ , but trade at different prices because their collateral levels are different:  $(C_j^W, C_j^L, C_j^B) \neq (C_{j'}^W, C_{j'}^L, C_{j'}^B)$ . Similarly, the two contracts might require exactly the same collaterals, but trade at different prices because their promises are different.

The price of contract  $j$  is denoted by  $\pi_j$ . A borrower sells contract  $j$ , in effect borrowing  $\pi_j$ , in return for which he or she promises to make deliveries according to  $A_j$ .

### 3.2. Production

Collateral is useful only to the extent that it is still worth something when the default occurs. Durability is a special case of production, so we introduce production into our model, and allow all goods to be durable, to varying degrees.

For ease of notation we shall suppose that production is of the fixed coefficient, constant returns to scale variety. One unit of commodity  $\ell$  becomes a vector of commodities next period. A house may become a house that is one year older, wine may become a wine that is one year older, grapes may

become wine one year later, and so on. In these examples, one good became a different good the next period, but there is no reason not to permit one good to become several goods. By linearity, we can talk more succinctly about the transformation of a vector of goods  $x \in \mathbb{R}_+^L$  into goods  $f_s(x) \in \mathbb{R}_+^L$  for each  $s \in S$ .

The transformation of a commodity depends, of course, on how it is used. We suppose a bundle of goods  $x \in \mathbb{R}_+^L$  is transformed into a vector  $f_s^0(x) \in \mathbb{R}_+^L$  in each state  $s$  if it is used for consumption (e.g., living in a house, or using a light bulb). If it is warehoused, then we assume that it becomes a vector  $f_s^W(x) \in \mathbb{R}_+^L$  in each state  $s$ . Likewise, if it is held as collateral by the lender, it becomes a vector  $f_s^L(x) \in \mathbb{R}_+^L$  in each state  $s$ , whereas if it is held by the borrower it becomes the vector  $f_s^B(x) \in \mathbb{R}_+^L$  in each state  $s$ . The linear functions  $f^0$ ,  $f^W$ ,  $f^L$ , and  $f^B$  summarize these different durabilities.

Observe that we have allowed for differential durability depending on the use to which the commodity is put. However, we have not allowed the durability to be affected by the identity of the user. In this way the anonymity of markets is maintained, and our modeling problem becomes easier.

Given the collateral requirements  $(C_j^W, C_j^L, C_j^B)$  for each contract  $j$ , the security they provide in each state  $s$  is

$$p_s \cdot [f_s^W(C_j^W) + f_s^L(C_j^L) + f_s^B(C_j^B)].$$

The collateral is owned by the borrower but may be confiscated by the lender (actually by the courts on behalf of the lender) if the borrower does not make his or her promised deliveries. Because we have assumed that the borrower has nothing to lose but his or her collateral from walking away from his or her promise, it follows that the actual delivery by every agent  $h$  on asset  $j$  in state  $s$  will be

$$D_{sj}^h = \min \{ p_s \cdot A_s^j, p_s \cdot [f_s^W(C_j^W) + f_s^L(C_j^L) + f_s^B(C_j^B)] \}.$$

#### 4. COLLATERAL EQUILIBRIUM

We are now ready to put together the various elements of our model. An economy  $E$  is defined by a vector

$$E = \left( (u^h, e^h)_{h \in H}, (A^j, C_j^W, C_j^L, C_j^B)_{j \in J}, (f^0, f^W, f^L, f^B) \right)$$

of agent utilities  $u^h : \mathbb{R}_+^{(1+S)L} \rightarrow \mathbb{R}$ , and endowments  $e^h \in \mathbb{R}_+^{(1+S)L}$ , asset promises and collateral levels, and the durability of goods kept by consumers, warehouses, lenders, and borrowers, respectively. We assume that the utilities  $u^h$  are continuous, concave, and weakly monotonic.

In keeping with the standard methodological approach of general equilibrium and perfect competition, we suppose that *in equilibrium* agents take the prices  $(p, \pi)$  of commodities and assets as given.

Our price-taking hypothesis has the implication that agents have perfect conditional foresight, in that they anticipate at time 0 what the prices  $p_s$  will be, depending on which state  $s$  prevails at time 1. Because they know the collateral that has been put up, and they know the production technology, they also understand in each state how much each asset will actually pay.

It might seem therefore that we could simply replace each asset promise  $A_j$  with an actual delivery vector, and thereby bypass the complications of collateral. However, this is not possible, because whether an asset defaults or not in state  $s$  depends on whether the promise or the collateral is worth more. Because both are vectors, this cannot be known in advance until the prices  $p_s \in R_+^L$  have been determined in equilibrium.

#### 4.1. The Budget Set

Given the prices  $(p, \pi)$ , each agent  $h$  decides what commodities to consume,  $x_0^h$ , and what commodities,  $x_W^h$ , to save in a warehouse. The agent also decides what contract purchases  $\theta$  and what contract sales  $\varphi$  he or she will make at time 0. Note that for every promise  $\varphi_j$  that the agent makes, he or she must put up the corresponding collateral  $(C_j^W, C_j^L, C_j^B)\varphi_j$ . The value of all his or her net trades at time 0 must be less than or equal to zero; that is, the agent cannot purchase anything without raising the money by selling something else (initial endowments of money are taken to be zero).

After the state of nature is realized in period 1, the agent must again decide on his or her net purchases of goods  $(x_s - c_s^h - f_s^0(x_0) - f_s^W(x_W))$ . Recall that the goods  $x_0$  whose services the agent consumed at time 0 may be durable, and still available, in the form  $f^0(x_0)$ , for consumption at time 1 in each state  $s$ . These net expenditures on goods can be financed out of sales of the collateral that the agent put up in period 0, and from the receipts from contracts  $j$  that he or she purchased at time 0, less the deliveries the agent makes on the contracts he or she sold at time 0. Putting all these transactions together, and noting again that the agent cannot buy anything without also selling something else of at least equal value, we derive the budget set for agent  $h$ :

$$B^h(p, \pi) = \{(x_0, x_W, (x_s)_{s \in S}, \theta, \varphi) \in R_+^L \times \mathbb{R}_+^L \times R_+^{SL} \times R_+^J \times R_+^J :$$

$$p_0(x_0 + x_W - e_0^h) + \pi(\theta - \varphi) + p_0 \sum_{j \in J} (C_j^W + C_j^L + C_j^B)\varphi_j \leq 0$$

and, for all  $s \in S$ ,

$$\begin{aligned} & p_s(x_s - e_s^h - f_s^0(x_0) - f_s^W(x_W)) \\ & \leq \sum_{j \in J} \varphi_j p_s \cdot [f_s^W(C_j^W) + f_s^L(C_j^L) + f_s^B(C_j^B)] \\ & \quad + \sum_{j \in J} (\theta_j - \varphi_j) \min \{ p_s \cdot A_s^j, p_s \cdot [f_s^W(C_j^W) + f_s^L(C_j^L) + f_s^B(C_j^B)] \}. \end{aligned}$$



## 4.2. Equilibrium

The economy  $E = ((u^h, e^h)_{h \in H}, (A_j, C_j^W, C_j^L, C_j^B)_{j \in J}, (f^0, f^W, f^L, f^B))$  is in equilibrium at macro prices and individual choices  $((p, \pi), (x^h, \theta^h, \varphi^h)_{h \in H})$  if supply equals demand in all the goods markets and asset markets, and if, given the prices, the designated individual choices are optimal, that is, if

$$\sum_{h \in H} (x_0^h + x_W^h - e_0^h + \sum_{j \in J} (C_j^W + C_j^L + C_j^B) \varphi_j^h) = 0, \quad \text{and, for all } s \geq 1, \quad (4.1)$$

$$\sum_{h \in H} (x_s^h - e_s^h - f_s^0(x_0^h) - f_s^W(x_W^h)) - \sum_{j \in J} \sum_{h \in H} \varphi_j^h [f_s^W(C_j^W) + f_s^L(C_j^L) + f_s^B(C_j^B)] = 0, \quad (4.1')$$

$$\sum_{h \in H} (\theta^h - \varphi^h) = 0, \quad (4.2)$$

$$(x^h, \theta^h, \varphi^h) \in B^h(p, \pi), \quad (4.3)$$

$$(x, \theta, \varphi) \in B^h(p, \pi) \Rightarrow u^h \left( x_0 + \sum_{j \in J} [C_j^B \varphi_j + C_j^L \theta_j], \bar{x} \right) \leq u^h \left( x_0^h + \sum_{j \in J} [C_j^B \varphi_j^h + C_j^L \theta_j^h], \bar{x}^h \right). \quad (4.4)$$

We write  $x^h = (x_0^h, \bar{x}^h)$ , so consumption at time 0 is  $x_0^h + \sum_{j \in J} [C_j^B \varphi_j^h + C_j^L \theta_j^h]$ , and consumption at time 1 is  $\bar{x}^h = (x_1^h, \dots, x_S^h)$ .

## 4.3. The Orderly Function of Markets

The agents we have described must anticipate not only what the prices will be in each state of nature, and not only what the contracts promise in each state of nature, but also what they will actually deliver in each state of nature. The hypothesis of agent rationality is therefore slightly more stringent in this model than in the conventional models of intertemporal perfect competition. Nevertheless, equilibrium always exists in this model (under the assumptions made so far), yet in the standard model of general equilibrium with incomplete asset markets, equilibrium may not exist. The following theorem is taken from Geanakoplos and Zame (1998).

**Theorem 4.1.** *Under the assumptions on endowments and utilities already specified, equilibrium must exist, no matter what the structure of contracts and collateral.*

In standard general equilibrium theory, everybody keeps every promise, so agents are allowed to sell as much of a promise as they like, provided they

are sure to get the funds somewhere to deliver on their promise. For example, an agent could sell a huge amount of one promise and use the proceeds to buy another promise that would deliver enough for him or her to cover the promise the agent sold. It is this potential for unbounded trades that sometimes compromises the existence of equilibrium.

When promises are kept only insofar as they are collateralized, this unboundedness problem disappears. If a contract contains no provision for collateral whatsoever, then of course everybody will rightly anticipate that it will deliver nothing, and its equilibrium price will be zero. Indeed, the economy would function exactly the same way if it were not available at all. For assets with some nonzero collateral, agents will not be able to sell arbitrarily large quantities, because the required collateral is a physical good in finite supply. As agents try to sell more of the promise, their demand for the physical collateral will eventually drive its price up above the sales price of the promise, so that on net the asset sellers will have to pay for the privilege of selling. Their sales will be limited by their budget, guaranteeing the existence of equilibrium.

#### 4.4. Endogenous Contracts

One of the major shortcomings of the standard general equilibrium model is that it leaves unexplained which contracts are traded. Generically, all the contracts exogenously allowed into the model will be traded. When default can be avoided only by collateral, the situation is different and much more interesting.

The crucial idea is that without the need for collateral, the marginal utility  $\mu_j^h(B)$  to an agent  $h$  of buying the first unit of a contract  $j$  is almost exactly the same as the marginal utility loss  $\mu_j^h(S)$  in selling the first unit of the contract; we can call both  $\mu_j^h$ . Only by an incredible stroke of luck will it turn out that  $\mu_j^h = \mu_j^{h'}$  for different agents  $h$  and  $h'$ , and hence contract  $j$  will almost surely be traded in a GEI equilibrium. When collateral must be provided by the seller, the disutility of making a promise goes up, sometimes by as much as the consumption forgone by buying the collateral. If the required collateral is borrower held, and if it is something that agent  $h$  planned to hold anyway, then there is no extra utility loss from selling the first unit of contract  $j$ . But if agent  $h$  did not plan to hold the collateral for consumption, or if all that this agent intended to hold as consumption has already been allocated as collateral for other promises, then the loss in utility from selling even the first unit of contract  $j$  would be larger than the marginal utility from buying the first unit of contract  $j$ ,  $\mu_j^h(S) > \mu_j^h(B)$ . It might well transpire that

$$\min_{h \in H} \mu_j^h(S) > \pi_j > \max_{h \in H} \mu_j^h(B),$$

and hence that contract  $j$  does not trade at all in equilibrium.

This situation can be most clearly seen when the value of the Arrow–Debreu promises in some state exceeds the salvage value of all the durable goods

carried over into that state. It is then physically impossible to collateralize every socially useful promise up to the point that every delivery is guaranteed without exception. The market system, through its equilibrating mechanism, must find a way to ration the quantity of promises. This rationing is achieved by a scarcity of collateral. The resulting wedge between the buying marginal utility of each contract and the selling marginal utility of the contract not only serves to limit the quantity of each promise, but more dramatically, it chokes off most promises altogether, so that the subset of contracts that are actually traded is endogenous and potentially much smaller than the set of available contracts.

The endogeneity of contracts applies to promises as well as to collateral levels (see Geanakoplos, 1997). However, in this paper, we shall be interested only in the latter. Let  $\mathcal{C} = \{(C^W, C^L, C^B) \in Z_+^L \times Z_+^L \times Z_+^L : C_\ell^i \leq 10^{100}\}$  be a finite set of (virtually) all potential collateral levels. Fix a promise  $a \in \mathbb{R}_+^{SL}$ . Consider the set  $J(a) = \mathcal{C}$  of all possible contracts with promise  $a$  and collateral levels  $c \in \mathcal{C}$ . In equilibrium, all of these many contracts will be priced, but only a very few of them will actually be traded. The rest will not be observable in the marketplace, and therefore the appearance will be given of many missing markets. The untraded contracts will lie dormant not because their promises are irrelevant to spreading risk efficiently, but because the scarce collateral does not permit more trade.

For each  $\ell \in L$ , consider the set  $\mathcal{C}_\ell = \{(C^W, C^L, C^B) \in \mathcal{C} : C_k^W = C_k^L = C_k^B = 0 \text{ if } k \neq \ell\}$  of potential collaterals that use only the commodity  $\ell$ . Consider the set  $J_\ell(a) = \mathcal{C}_\ell$  of all possible contracts with promise  $a$  and collateral levels  $c \in \mathcal{C}_\ell$ . In equilibrium, all of these many contracts will be priced, but often only one of them will be *actively* traded. Thus houses are always used as borrower held collateral, and the present value of the promises is usually 80 percent of the value of the house. Mortgage derivatives are always lender held collateral, and the present value of the promises is a number that varies from time to time (90 percent of the value of the collateral in 1997, and 50 percent in 1998).

#### 4.5. Margins and Liquidity

Let contract  $j$  be given by the vector  $(A_j, C_j^W, C_j^B, C_j^L)$ . Define  $p(C_j) = p_0 \cdot [C_j^W + C_j^B + C_j^L]$ . In equilibrium, we will always have  $\pi_j \leq p(C_j)$ , because by assumption the payoff from the contract will never exceed the value of the collateral.

The margin on a contract  $j$  in equilibrium is defined as

$$m_j = \frac{p(C_j) - \pi_j}{p(C_j)}.$$

The margin  $m_j$  will be positive for essentially three reasons. First, the collateral may provide utility before the promises come due, boosting the price of the collateral above the price of the promise. Second, there may be a mismatch between future collateral values and the promises, so that in some states, the

collateral is worth more than the promises. Third, to the extent the mismatch is variable, risk-averse lenders might prefer higher margins  $m_j$  to higher interest rates (i.e., to bigger  $A_j$ ).

We shall see that sometimes we can associate with each collateral a single promise that is actively traded. In that case, we can think of the active margin requirement as pertaining to the collateral. Each durable good  $\ell$  might then have an active margin requirement  $m_\ell$ . As we said, houses generally are bought with 20 percent cash and the rest is borrowed. We shall see in later sections how this active margin requirement is determined endogenously in equilibrium.

Provisionally we shall think of the active equilibrium margin requirements as the liquidity of the system (the higher the margin, the lower the liquidity). Section 11 gives a more careful definition of liquidity.

#### 4.5.1. *Assets and Contracts*

Each actively traded contract defines a margin requirement. We can think of this margin symmetrically as the margin pertaining to the promise of the contract, or as the margin pertaining to the collateral. Our focus so far has been on the promise, but gradually we shall shift our attention to the collateral. When the collateral is a single durable good, we shall often call it an *asset*. The active margin requirement has a big effect on asset prices, as we shall see.

### 4.6. Collateral and Default

It would be interesting to catalog the rules by which the market implicitly chooses one promise over another, or one level of collateral over another. This issue is more fully developed in Geanakoplos (1997) and in Geanakoplos and Zame (1998), but let us note some things here. The active margin requirement determines how much default there is in the economy. Collateral is scarce. The easiest way of economizing on collateral is by allowing default in some states of nature. If one vector of collaterals guarantees full delivery in every state of nature, there is no point in trading the same promise collateralized by greater levels of collateral. Finally, if a vector of promises is very different from the vector of its collateral values across the states of nature, then the contract is not well drawn. In some states there will be too much collateral, and in others not enough. One might suspect that such a contract would also not be traded. The general principle is that the market chooses contracts that are as efficient as possible, given the prices. This is made precise in the next section.

### 4.7. Constrained Efficiency

It is to be expected that an increase in available collateral, either through an improvement in the legal system (e.g., borrower held collateral), or through the increased durability of goods, will be welfare improving. But could it lower welfare in a pathological case? More subtly, we might wonder whether government

intervention could improve the functioning of financial markets given a fixed level of available collateral. After all, the unavailability of collateral might create a wedge that prevents agents from trading the promises in  $J$  that would lead to a Pareto-improving sharing of future risks. If the government transferred wealth to those agents unable to afford collateral, or subsidized some market to make it easier to get collateral, could the general welfare be improved? What if the government prohibited trade in contracts with low collateral levels? The answer, surprisingly, is no, government intervention cannot be Pareto improving, at least under some important restrictions. See the theorem from Geanakoplos and Zame (1998) that follows.

**Constrained Efficiency Theorem.** *Each collateral equilibrium is Pareto efficient among the allocations that (1) are feasible and (2) given whatever period 0 decisions are assigned, respect each agent's budget set at every state  $s$  at time 1 at the old equilibrium prices, and (3) entail that agents will deliver no more on their contract promises than they have to, namely the minimum of the promise and the value of the collateral put up at time 0, given the original prices.*

In particular, no matter how the government redistributes income in period 0, and taxes and subsidizes various markets at time 0, if it allows markets to clear on their own at time 1, then we can be sure that if the time 1 market-clearing relative prices are the same as they were at the old equilibrium, then the new allocation cannot Pareto dominate the old equilibrium allocation. This will be illustrated in our examples.

In contrast, this theorem does *not* hold if relative prices do change. By intervening to prohibit high leverage (selling contracts with low levels of collateral), the government can reduce the volatility of future prices. If the volatility is sufficiently disruptive, leveraging limits can actually be Pareto improving (see Geanakoplos and Kubler, 1999, for an example).

## 5. VOLATILITY

### 5.1. Natural Buyers, the Marginal Buyer, and the Distribution of Wealth

In any general economic equilibrium, the price of a good depends on the utilities of the agents and the distribution of wealth. If the agents who are fondest of the good are also relatively wealthy, the good's price will be particularly high. Any redistribution of wealth away from these "natural buyers" toward agents who like the good less will tend to lower the price of the good.

To a large extent, the value of durable goods depends on the expectations, and, when markets are incomplete, on the risk aversion of potential investors, as well as on the intrinsic utility of the good. These multiple determinants of value make it quite likely that there will be wide divergences in the valuations different agents put on durable goods.

For example, farms in 1929 could be thought of as an investment, available to farmers and bankers, but to farmers there is a superior intrinsic value that made it sensible for them to own them and use them at the same time. Because the farmers did not have enough money to buy farms outright, they typically borrowed money and used their farms as collateral. Similarly, mortgage derivatives in the 1990s were worth much more to investors who had the technology and understanding to hedge them than they were to the average investor.

Since the 1929 stock market crash, it has been widely argued that low margin requirements can increase the volatility of stock prices. The argument is usually of the following kind: When there is bad news about the stocks, margins are called and the agents who borrowed using the stocks as collateral are forced to put them on the market, which lowers their prices still further.

The trouble with this argument is that it does not quite go far enough. In general equilibrium theory, every commodity (and thus every asset) is for sale at every moment. Hence the crucial step in which the borrowers are forced to put the collateral up for sale has by itself no bite. Nevertheless, the argument is exactly on the right track.

We argue that indeed using houses or stocks, or mortgage derivatives, as collateral for loans (i.e., allowing them to be bought on margin) makes their prices more volatile. The reason is that those agents with the most optimistic view of the assets' future values, or simply the highest marginal utility for their services, will be enabled by buying on margin to hold a larger fraction of them than they could have afforded otherwise.

The initial price of those assets will be much higher than if they could not be used as collateral for two reasons: Every agent can afford to pay more for them by promising future wealth, and second, the marginal buyer will tend to be somebody with a higher marginal utility for the asset than would otherwise be the case.

As a result of the margin purchases, the investment by the optimistic agents is greatly leveraged. When the asset rises in value, these agents do exceedingly well, and when the asset falls in price, these agents do exceedingly badly. Thus on bad news the stock price falls for two reasons: The news itself causes everyone to value it less, and this lower valuation causes a redistribution of wealth away from the optimists and toward the pessimists who did not buy on margin. The marginal buyer of the stock is therefore likely to be someone less optimistic than would have been the case had the stock not been purchased on margin, and the income redistribution not been so severe. Thus the fall in price is likely to be more severe than if the stock could not have been purchased on margin.<sup>2</sup>

<sup>2</sup> Instead of imagining that the shock and income redistribution causes the assets to become partly owned by less enthusiastic buyers, which we called the marginal buyer effect, we could imagine instead that the original buyers themselves became less enthusiastic as their diminished wealth (and inevitable diminished consumption) lowered the asset's marginal utility relative to the marginal utility of consumption.

## 5.2. Volatility and Incomplete Markets

The analysis here depends on the (endogenous) incompleteness of risk markets. When risk markets are incomplete, trade in assets and contracts might make the distribution of wealth *more* volatile, especially across low-probability events. If asset prices are very sensitive to the distribution of wealth, this can lead to occasional, large changes in asset prices.

When risk markets are complete, trade in contracts will tend to make the distribution of wealth fairly constant across states, eliminating the wild swings possible with incomplete markets.

Scarce collateral endogenously limits the contract trade, forcing incomplete risk markets even when any contract could be written (but delivery not enforced).

## 5.3. Volatility II: Asset Values and Margin Requirements

Even without any change in the distribution of income, changes in margin requirements can dramatically affect asset values. Durable assets can provide dividends for years into the future, vastly exceeding the quantity of consumption goods in the present. However, if the buyers of the assets cannot spend by borrowing against their future wealth, the price of the assets might remain quite low simply because the “liquidity constrained” buyers cannot call on enough financial resources. A toughening of margin requirements can thus cause asset prices to tumble.

## 5.4. Why Margin Requirements Get Tougher

The thesis of this paper is that liquidity crises reach their climax with a stiffening of margin requirements following bad news. But many kinds of bad news should have the effect of loosening margin requirements. Of course, regulators can suddenly enforce higher margins. If returns become more volatile, or lenders become more risk averse, margin requirements will likely stiffen. Furthermore, if worries about adverse selection or moral hazard increase, margin requirements will toughen. All these factors probably contributed to the crises of 1994 and 1998. But here we are seeking reasons stemming purely from the logic of collateral equilibrium that could explain why adverse news might lead to tighter margins, and thus a multiplier effect on prices.

One possibility is that when lenders lose money to some defaulting borrowers, their decreased wealth makes them more risk averse. They might then demand higher margins, and this may lead to a fall in asset prices. However, in the mortgage derivative crisis of 1998, none of the lenders lost any money, including the creditors of Long-Term Capital.

One important question is whether a fall in asset prices themselves will lead to higher margins. The answer depends on what caused the fall in price. Very often, bad news for asset prices will lead to a reduction in margin requirements.

For example, if asset prices decline because of an income shock to the natural buyers, lenders may demand less onerous margins because they feel asset prices have less far to fall.

If asset values follow a geometric random walk, then after an adverse shock, prices may be lower, but the standard deviation of outcomes is also scaled down, so the margin requirement (which is a ratio) may very well hold constant.

A productivity shock that raises the probability of (the same) bad outcome will tend to lower asset prices, but also to *ease* margins. For example, suppose that some asset  $Y$  could produce 1 with probability  $b$  or  $R < 1$  with probability  $1 - b$ . Suppose the contracts that are backed by  $Y$  involve promises that are multiples of the payoffs (1, 1) across the two states. If the natural buyers were risk neutral and believed in  $b$ , the asset would sell for  $p_Y = b1 + (1 - b)R$ , provided that these buyers had access to enough cash. If the lenders were infinitely risk averse, it is not unreasonable to guess that they would lend at most  $R$  against one unit of  $Y$  as collateral. The margin requirement would then be

$$m = \frac{p_Y - R}{p_Y} = \frac{b1 + (1 - b)R - R}{b1 + (1 - b)R} = \frac{b(1 - R)}{b(1 - R) + R}$$

$$= \frac{1}{1 + \{R/[b(1 - R)]\}}.$$

It is clear that if the probability of a bad event increases,  $b$  goes down, and  $m$  decreases, if  $0 < R < 1$ . The reason is that the drop  $\Delta$  in  $p_Y$  causes a percentage drop  $\Delta/p_Y$  in the price of  $Y$ , but a bigger percentage drop,  $\Delta/(p_Y - R)$ , in the required down payment.

In contrast, in the same situation, a productivity shock that lowers  $R$ , keeping  $b$  fixed, dramatically *raises* the margin requirement, as can be seen in the formula just given.

Bad news about assets typically does not take the form that, if default occurs, the recovery will be less. Typically the bad news suggests that default is more likely, but not worse. So how can bad news create tighter margins? By indicating that the default, if it comes, will come sooner! We shall see that the combination of *more likely* and *sooner* can lead to higher margins (even though *more likely* by itself often leads to lower margins).

We must rigorously investigate how the margin is set. In the last paragraph, we described utilities for which it seemed plausible that the margin would be set high enough to eliminate default. Suppose instead that the natural buyers of  $Y$  are risk neutral as before, but that they also get a utility boost simply from holding  $Y$ . Suppose the lenders are also risk neutral, and agree with the buyers that the probability of the good state is  $b$ . Then it can easily be shown that the relevant loan will promise 1 in both states, but because of default it will deliver what  $Y$  delivers, namely 1 or  $R$  (thereby defaulting by  $1 - R$  in the bad state).

The next sections present a more elaborate example, worked out in detail, to see how equilibrium determines a unique collateral level.



## 6. ENDOGENOUS COLLATERAL WITH HETEROGENOUS BELIEFS: A SIMPLE EXAMPLE

Let us begin with the same example in which there are two goods ( $L = 2$ ),  $X$  and  $Y$ , in each state  $s = 0, 1, 2$ .  $X$  is a storable consumption good, like tobacco, and  $Y$  is an investment good (say a tobacco plant) that delivers 1 unit of  $X$  when things go well in state  $s = 1$ , and a smaller amount  $R < 1$  in state  $s = 2$ .  $Y$  is reminiscent of a defaultable bond or a securitized mortgage, for which there are normal payments in state  $s = 1$  and default with recovery  $R$  in state  $s = 2$ .

In Section 5 we assumed infinitely risk-averse lenders and trivially deduced that active margin requirements would rule out default. Next we assumed completely risk-neutral borrowing and lending and trivially deduced that there would be active default. We turn now to a more subtle situation in which there are optimists who think that state 1 is very likely and pessimists who do not. The price of  $Y$  (in terms of  $X$ ) at time 0 will naturally be somewhere between 1 and  $R$ , reflecting the average opinion about the probability of the good state. At that price, the optimists would like to buy  $Y$  from the pessimists, but they do not have the cash. They would gladly borrow the money, but they must put up  $Y$  as collateral for their loans. There will be a menu of loans, some with low required collateral (low margin), but high interest rates, and other contracts with low interest rates but high margin requirements. Will only one contract be traded in equilibrium, thus determining both the interest rate and the margin requirement? If so, will it be the socially efficient contract? Let us be precise.

Let each agent  $h \in H \subset [0, 1]$  assign probability  $h$  to  $s = 1$  and probability  $1 - h$  to  $s = 2$  (see Figure 5.1). Agents with  $h$  near 1 are optimists; agents with  $h$  near 0 are pessimists. (The heterogeneity in beliefs may be regarded as a reduced-form version of a more complicated model in which low- $h$  agents are more risk averse, or have relatively bigger endowments in state 1.) Suppose that each unit of  $X$  gives 1 unit of consumption utility in each state and that  $Y$  gives no utility of consumption:

$$u^h(x_0, y_0, x_1, y_1, x_2, y_2) = x_0 + hx_1 + (1 - h)x_2.$$

Suppose that each agent  $h$  has an endowment of  $e$  units of good  $X$  and 1 unit

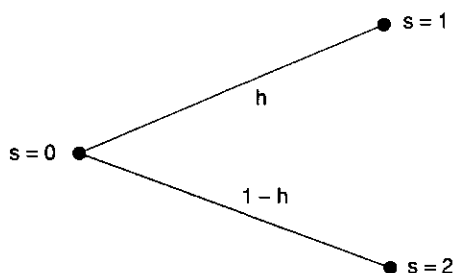


Figure 5.1.

of good  $Y$  in state  $s = 0$  and nothing otherwise:

$$e^h = (e_{0x}^h, e_{0y}^h, e_{1x}^h, e_{1y}^h, e_{2x}^h, e_{2y}^h) = (e, 1, 0, 0, 0, 0).$$

Suppose that  $X$  is perfectly durable if warehoused and extinguished if consumed (like tobacco). Suppose that 1 unit of  $Y$  gives 1 unit of  $X$  in state  $s = 1$  and  $R < 1$  units of  $X$  in  $s = 2$ .

We can write this formally as

$$\begin{aligned} f_s^0((x, y)) &= f_s^L((x, y)) = f_s^B((x, y)) = (0, 0), \quad s = 1, 2, \\ f_s^W((x, y)) &= (x + y, 0), \quad s = 1, \\ f_s^W((x, y)) &= (x + Ry, 0), \quad s = 2. \end{aligned}$$

We suppose that every contract  $j$  promises 1 unit of  $X$  in each state  $s = 1, 2$ :

$$A_s^j = (1, 0), \quad s = 1, 2, \quad j \in J.$$

The collateral required by contract  $j$  is  $j$  units of good  $Y$  in a warehouse:

$$\begin{aligned} C_j^L &= C_j^B = (0, 0), \quad j \in J, \\ C_j^W &= (0, j), \quad j \in J. \end{aligned}$$

Buying 1 unit of  $Y$  on margin via contract  $j$  in state 0 means selling  $1/j$  units of contract  $j$  for  $\pi_j/j$ , then paying  $p_{0Y} - \pi_j/j$  cash margin plus the borrowed  $\pi_j/j$  for the 1 unit of  $Y$ .

For convenience, we take a continuum of agents  $H = [0, a]$  and assets  $J = [0, 10^{100}]$ . (The definition of equilibrium must then be modified in the obvious way, replacing the sum  $\sum_h$  by the integral  $\int dh$  and restricting each agent to trade a finite number of contracts.) The parameter  $a$  will control the number of optimists. We proceed to compute equilibrium.

The first (and perhaps most important) property of equilibrium is indeed that only one contract will be traded. In fact, it is the contract with  $j^* = 1/R$ , guaranteeing that full delivery is just barely made in state  $s = 2$  (and made with ease in  $s = 1$ ). Let us temporarily take this claim on faith and construct the equilibrium, verifying the claim at the end.

We choose  $X$  as numeraire, fixing  $p_{sX} = 1 \forall s = 0, 1, 2$ . Clearly,  $p_{1Y} = p_{2Y} = 0$ .

Some agent  $b \in (0, a)$  will be indifferent to buying or selling  $Y$  at time 0. Because of the linear utilities, we guess that agents  $h > b$  will buy all they can afford of  $Y$  (after selling all their  $X$  and borrowing to the max), and agents  $h < b$  will sell all they have of  $Y$ , lend (buy contract  $j^*$ ), and consume  $X$ . Because there is no default, and no impatience (discounting), the price  $\pi_{j^*} = 1$ , and the interest rate is zero. The total money spent on purchases of  $Y$  will be the  $X$  endowments of agents  $h \in (b, a]$ , totalling  $e(a - b)$ , plus the money they can borrow, which is  $R$  on each unit of  $Y$  they own, plus  $R$  on each unit of  $Y$  they buy. Total net sales of  $Y$  are the  $b$  units of agents  $h \in [0, b)$ , giving a price in

equilibrium of

$$p_{0Y} = \frac{e(a-b) + (a-0)R}{b}. \quad (6.1)$$

A buyer on margin of  $Y$  must put down  $p_{0Y} - R = [e(a-b) + aR]/b - R = [(a-b)(e+R)]/b$  of his or her own money, getting a payoff of  $1 - R$  in state 1 and zero in state 2. Because  $h = b$  is indifferent to buying on margin,  $[(a-b)/b](e+R) = b(1-R)$ , or  $b^2(1-R) + b(e+R) - a(e+R) = 0$ , or

$$b = \frac{-(e+R) + \sqrt{(e+R)^2 + 4a(e+R)(1-R)}}{2(1-R)}. \quad (6.2)$$

Notice that agent  $b$  must also be indifferent to buying  $Y$  directly from cash, without borrowing, so

$$p_{0Y} = b1 + (1-b)R. \quad (6.3)$$

The price of  $Y$  is given by the marginal utilities of the *marginal buyer*  $b$ .

It follows that buying  $Y$  on margin via contract  $j^*$  costs on net  $p_{0Y} - R = b(1-R)$ , and pays  $1 - R$  in state 1 and zero in state 2.

Thus for  $h > b$ ,  $x_0^h = 0$ ,  $y_0^h = 0$ ,  $C_Y^W \varphi_{j^*}^h = 1 + b/(a-b) = a/(a-b)$ ,  $\varphi_{j^*}^h = R[a/(a-b)]$ ,  $x_1^h = (1-R)[a/(a-b)]$ ,  $x_2^h = 0$ , and all other choice variables equal zero. For  $h < b$ ,  $x_0^h = e + [(a-b)/b]e$ ,  $y_0^h = 0$ ,  $\theta_{j^*}^h = R(a/b)$ ,  $x_1^h = R(a/b) = x_2^h$ , and all other choice variables equal zero. One can easily check that supply equals demand, and that each agent is balancing his or her budget, using the definition of  $p_{0Y}$ .

To finish the description of the equilibrium, we must describe all the other prices, and show that the agent actions are optimal. In particular, we must check that no agent wants to buy or sell (lend or borrow) any contract  $j$  with collateral level  $C_j \neq C_{j^*}$ . This is surprising, because optimists are very eager to buy  $Y$ , and one might imagine that they would be willing to pay a high interest rate (i.e., get a low  $\pi_j$ ) to borrow via contract  $j$  with a lower collateral level. However, we shall see that the equilibrium interest rate  $(1/\pi_j - 1)$  will be so high that the optimists will choose not to borrow at collateral levels  $j \neq j^*$ . We must also check that, at such a high interest rate, nobody wants to lend.

We already said that for collateral level  $C_{j^*} = (0, j^*) = (0, 1/R)$ ,  $\pi_{j^*} = 1$ . In general, we set

$$\pi_j = b \min\{1, j\} + (1-b) \min\{1, jR\} \quad (6.4)$$

equal to the marginal utility of agent  $b$ . For  $j > j^*$ , collateral levels are wasteful, because then the collateral more than covers the loan. Thus  $\pi_j = 1$  for all  $j > j^*$ . Nobody has any reason to lend (buy) via contract  $j > j^*$ , because he or she gets the same price and return as with contract  $j^*$ . Similarly, nobody would sell (borrow via)  $j > j^*$ , because the price is the same on  $j$  as  $j^*$ , and the collateral terms are more onerous.

We now turn to contracts  $j < j^*$ . These contracts involve default, but they demand higher interest (lower price for the same promise). In effect, they pay less in state 2 but more in state 1 than asset  $j^*$ . This is bad for optimistic borrowers  $h > b$  and also bad for pessimistic lenders  $h < b$ , because these contracts deliver more in the event borrowers think will happen and lenders think will not happen. If anything, cautious optimists with  $h$  barely bigger than  $b$  might want to lend via contract  $j$ . But lending requires money, and they would rather spend all their free liquidity on  $Y_0$ . We now show rigorously that there will be no trade in contracts  $j < j^*$ .

A buyer of contract  $j$  receives  $D_1^j = \min\{1, j\}$  in state 1 and  $D_2^j = \min\{1, jR\} = jR < D_1^j$  in state 2. A seller of contract  $j$  must also buy the collateral consisting of  $j$  units of  $Y$ . On net in state  $s$ , he or she receives  $-D_s^j + jf_{s1}(0, 1)$ . In state 1 this is  $-\min\{1, j\} + j \geq 0$ , and in state 2 this is  $-\min\{1, jR\} + jR = 0$ . Notice that both the buyer and seller of contract  $j$  get a payoff at least as high in state 1 as in state 2. All prices are determined linearly by taking expectations with respect to  $(b, 1 - b)$ . Agents  $h < b$  will therefore regard each payoff as too expensive, or at best, as break even. To see that agents  $h > b$  do not wish to trade either side of contracts  $j \neq j^*$ , observe that their budget set is included in  $B \equiv \{(x_0, x_1, x_2) : x_0 + bx_1 + (1 - b)x_2 = e + b1 + (1 - b)R\}$ . Every asset and contract trades at a price equal to its contingent  $X$  payoffs, valued at price  $(1, b, 1 - b)$ . The collateral requirements make trades more difficult, reducing the real budget set strictly inside  $B$ . In  $B$ , agents  $h > b$  clearly would take  $x_1 = [e + b + (1 - b)R]/b, x_0 = x_2 = 0$ ; that is, they would spend all their wealth in state 1. But, as we saw, that is exactly what they are able to do via margin borrowing on contract  $j^*$ . Therefore, they have no incentive to trade any other contract  $j \neq j^*$ .

Table 5.1 gives equilibria for various values of the exogenous parameters  $(R, a, e)$ .

Consider the case where  $a = e = 1$  and  $R = 0.2$ . The marginal buyer is  $b \approx 0.69$ , and the price of the asset  $p_{0Y} \approx 0.69(1) + 0.31(0.02) = 0.75$ .

Table 5.1.

$R$	0	0.1	0.2	0	0.2	0	0.2
$a$	1	1	1	0.75	0.75	1	1
$e$	1	1	1	1	1	0.75	0.75
$b$	0.618034	0.652091	0.686141	0.5	0.549038	0.568729	0.647233
$p_{0Y}$	0.618034	0.686882	0.748913	0.5	0.63923	0.568729	0.717786
$m$	1	0.854415	0.732946	1	0.687124	1	0.721366
$x_{0H}$	0	0	0	0	0	0	0
$x_{1H}$	2.618034	2.586882	2.548913	3	2.985641	2.318729	2.267786
$x_{2H}$	0	0	0	0	0	0	0
$x_{0L}$	1.618034	1.533529	1.457427	1.5	1.366025	1.318729	1.158779
$x_{1L}$	0	0.153353	0.291485	0	0.273205	0	0.309008
$x_{2L}$	0	0.153353	0.291485	0	0.273205	0	0.309008

### 6.1. The Marginal Buyer

A striking property of the example is that the prices of the asset  $Y$  and all the contracts  $j \in J$  are set by the marginal utilities of a particular marginal buyer  $b \in H$ .

### 6.2. Endogenous Margin Requirement

We saw that equilibrium endogenously sets the maximum loan backed by 1 unit of  $Y$  at  $R$ , thus ruling out default. The margin requirement is then

$$m \equiv \frac{p_{0Y} - (1/j^*)\pi_{j^*}}{p_{0Y}} = 1 - \frac{R}{p_{0Y}}; \quad (1 - m) = \frac{R}{p_{0Y}}, \quad (6.5)$$

where  $p_{0Y} = b1 + (1 - b)R$ . For  $(R, a, e) = (0.2, 1, 1)$ , the margin requirement is  $m \approx (0.75 - 0.2)/0.75 \approx 0.73$ .

### 6.3. Margin Feedback Effects

In Table 5.1 we see that a decrease in  $R$  leads to a decline in  $p_{0Y}$ . This is natural, because with lower  $R$ ,  $Y$  has lower expected payoff. The interesting point is that  $p_{0Y}$  falls by *more* than the expected output of  $Y$ , calculated with respect to the probabilities of the marginal buyer  $b$  in the old equilibrium. For example, when  $(R, a, e) = (0.2, 1, 1)$ ,  $p_{0Y} = b1 + (1 - b)0.2 \approx 0.69(1) + 0.31(0.2) \approx 0.75$ . When  $R$  falls to 0.1, expected output at the old  $b$  falls to  $0.69(1) + (0.31)(0.1) \approx 0.72$ . But actual  $p_{0Y}$  falls to 0.69, as can be seen in Table 5.1. Thus  $p_{0Y}$  falls by twice as much as would be expected from its drop in expected output.

Of course, the reason for this large fall in  $p_{0Y}$  is that  $b$  falls. As  $R$  falls, formula (6.2) shows that  $b$  must fall.<sup>3</sup> By (6.3),  $p_{0Y}$  falls for two reasons. It falls because with lower  $R$ , the expected payoff from  $Y$  falls, computed with respect to the old probability  $b$ . But  $p_{0Y}$  falls again because the new marginal buyer is less optimistic,  $\bar{b} < b$ , and with  $\bar{b}$  replacing  $b$ ,  $p_{0Y}$  would fall even with the old  $R$ .

The reason for the drop in  $b$  is the sharp increase in margin requirements. With  $Y$  much less expensive, one would expect  $b$  to rise, because presumably a smaller crowd of optimists could now afford to buy up all the  $Y$ . The only possible explanation is that the equilibrium margin requirements have gone way up, which we can confirm analytically. Using the margin requirement  $m$  in (6.5), we can write  $R = (1 - m)p_{0Y}$ . Plugging that into the right-hand side of (6.1), we get

$$p_{0Y} = \frac{e(a - b)}{b - a(1 - m)} = \frac{1}{-1 + [am/(a - b)]}. \quad (6.6)$$

<sup>3</sup> To see this analytically, consider the equation  $f(b, R) = b^2(1 - R) + b(e + R) - a(e + R)$ , and recall that  $b(R)$  is defined so that  $f(b(R), R) = 0$ . Clearly  $\partial f/\partial b > 0$ , and  $\partial f/\partial R = -b^2 + b - a < 0$ . If  $R$  falls,  $b$  must fall to restore  $f(b(R), R) = 0$ .

Because  $b$  and  $p_{0Y}$  fall when  $R$  falls, it follows from (6.6) that  $m$  must rise as  $R$  falls. Indeed, at  $(R, a, e) = (0.1, 1, 1)$ , the margin requirement rises to  $m \approx 0.85$ .

Thus a fall in  $R$  has a direct effect on  $p_{0Y}$ , because it lowers expected output, but it also has an indirect effect on  $p_{0Y}$  by raising margin requirements. And the indirect effect can be as large as the direct effect.

To put the matter in different words, an asymmetrically perceived decrease in the productivity and safety of the asset  $Y$  leads to an even greater fall in its price, because it also makes it harder to borrow, and markets become less liquid.

By contrast, consider the effect of a decrease in liquid wealth  $e$ . This also reduces the value of  $Y$ . A drop in  $(R, a, e) = (0.2, 1, 1)$  to  $(0.2, 1, 0.75)$  causes  $p_{0Y}$  to drop from 0.75 to 0.72, and  $b$  to drop from 0.69 to 0.65. However, the drop in liquidity is partly ameliorated by a decrease in margin requirements, from  $m = 0.73$  to  $m = 0.72$ .

Similarly, a fall in the number of optimistic buyers  $a$  naturally leads to a drop in  $p_{0Y}$  and in  $b$ . As  $(R, a, e)$  falls from  $(0.2, 1, 1)$  to  $(0.2, 0.75, 1)$ ,  $p_{0Y}$  falls from 0.75 to 0.64. However,  $m$  also falls from 0.73 to 0.69, partly damping what would have been a worse fall in  $p_{0Y}$ .

Thus we see that, on one hand, certain kinds of shocks tend to reduce asset prices, but in a damped way because they also lower margin requirements. On the other hand, we shall see that shocks that reduce value less for buyers than for sellers lower price by more than they lower expected value to the original marginal buyer, because they also tend to raise the margin requirement, making a less optimistic buyer the marginal buyer, giving a second reason for prices to fall.

#### 6.4. Endogenous Default

We saw in the example that the equilibrium margin requirements were set so that there would be no default, but that is not necessarily the case. Consider a variant of the last example in which there are three states, with payoffs of  $Y$  and agent-dependent probabilities given as shown in Figure 5.2. Note that all agents agree on the probability of  $s = 3$ . It is easy to check that for any  $\tilde{R} < R$ , in equilibrium, *only* asset  $j^* = 1/R$  will be traded, exactly as before. If  $\tilde{R} < R$ , then there will be defaults in state 3. Rather than adjusting the collateral level to maintain zero default, equilibrium will adjust the price of all the loans to compensate lenders for the higher expected loss from default. In the new equilibrium, the price of  $Y$  and every contract  $j$  again is calculated according to the probabilities of the new marginal trader  $\tilde{b}$ :

$$\begin{aligned}\tilde{p}_{0Y} &= \frac{\tilde{b}}{1+\varepsilon} 1 + \frac{1-\tilde{b}}{1+\varepsilon} R + \frac{\varepsilon}{1+\varepsilon} \tilde{R}, \\ \tilde{\pi}_j &= \frac{\tilde{b}}{1+\varepsilon} \min\{1, j\} + \frac{1-\tilde{b}}{1+\varepsilon} \min\{1, jR\} + \frac{\varepsilon}{1+\varepsilon} \min\{1, j\tilde{R}\}.\end{aligned}$$

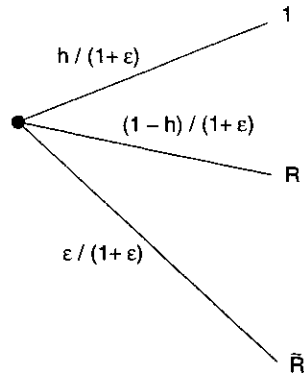


Figure 5.2.

If the new equilibrium with  $\varepsilon > 0$  had the same marginal buyer as before, when  $\varepsilon = 0$ , then the new price  $\tilde{p}_{0Y}$  would be less than the old  $p_{0Y}$  by the expected loss in output  $[\varepsilon/(1 + \varepsilon)](p_{0Y} - \bar{R})$ . The fall in  $R\pi_j$ , would, however, only be  $[1/(1 + \varepsilon)](R - \bar{R})$ , which is smaller. Hence agents would need less cash after borrowing to buy  $Y_0$ . This drives the price of  $Y_0$  up, or equivalently it drives the marginal buyer  $\tilde{b} > b$ . (A countervailing force is that agents  $h > b$  can borrow less on the  $Y$  they begin by owning. For  $\bar{R}$  near  $R$ , this is a less important effect.) Thus the equilibrium price  $\tilde{p}_{Y_0}$  falls *less* than the expected drop in output at the old  $b$ . Far from a feedback, news of a potential default, if universally agreed upon in probability, lowers asset prices by less than the direct effect.

This can be verified by noting that the economy with parameters  $(a, e, R, \varepsilon, \bar{R})$  has the same equilibrium marginal buyer as the old economy with parameters  $(a, \tilde{e}, R)$ , where  $\tilde{e} = e + b^2(1 - R)/(a - b) - (R - \bar{R})$ .

### 6.5. Efficiency Versus Constrained Efficiency

Collateral equilibrium is clearly not Pareto efficient. In our example, agents  $h < b$  end up consuming  $R(a/b)$  units in states  $s = 1$  and  $s = 2$ . In particular, agent  $h = 0$ , who attaches probability zero to  $s = 1$ , consumes  $R(a/b) > 0$  in state 1, if  $R > 0$ . It would be better if this agent could sell some of his or her  $s = 1$  consumption to agent  $h = b - \varepsilon$  in exchange for some  $s = 2$  consumption.

When  $R = 0$ , agents  $h > b$  consume nothing in state 2, and agents  $h < b$  consume nothing in state 1, but still the collateral equilibrium is inefficient, because agents  $h < b$  consume  $1 + [(a - b)/b]$  units at time 0. Again agents  $h = 0$  and  $h = b - \varepsilon$  could *both* be made better off if they could trade some  $x_0$  for some  $x_2$ .

We now compute the Arrow–Debreu prices  $(1, b^*, 1 - b^*)$ . They must induce all agents  $h \in (b^*, a]$  to consume only in state 1, and all agents  $h \in [0, b^*)$  to consume only in state 2, for some  $b^*$ . Because aggregate output in state 1 is  $ea + a$ , and in state 2 it is  $ea + aR$ , we conclude that  $[I(a - b^*)]/b^* = ea + a$

and  $Ib^*/(1 - b^*) = ea + aR$ , where  $I = b^*(e + 1) + (1 - b^*)(e + R)$  is the wealth at prices  $b^*$  of every agent  $h \in [0, a]$ . It follows from some algebra that

$$b^* = \frac{-(1 + a)(e + R) + \sqrt{(1 + a)^2(e + R)^2 + 4a(e + R)(1 - R)}}{2(1 - R)} < b. \tag{6.7}$$

We see, therefore, that in collateral equilibrium it is possible for asset prices to be much higher than in Arrow–Debreu equilibrium. This of course is confirmed by simulation. When  $R = 0$  and  $e = a = 1$ , then  $b^* = p_{0Y}^* = 0.414 < 0.62 = p_{0Y}$ . When  $R = 0.2$  and  $e = a = 1$ ,  $p_{0Y}^* = 0.43 < 0.75 = p_{0Y}$  and so on.

Because collateral equilibrium gives rise to asset prices that are too high ( $p_{0Y} > p_{0Y}^*$ ), one is tempted to think that government intervention to impose high margin requirements would be beneficial. It is particularly tempting when there are defaults, as in the variant of the example considered in Section 6.4. But by the constrained efficiency theorem in Geanakoplos and Zame, no allocation achievable with the collateral enforcement mechanism for delivery could do better, because relative prices  $p_{sY}/p_{sX} = 0$  at every equilibrium, for  $s = 1, 2$ .

### 7. CRASHES

We turn now to a dynamic context in which we can find feedback from wealth redistribution and margin changes at the same time. Imagine a multiperiod model, with the agent-specific probabilities and payoffs from asset  $Y$  indicated in Figure 5.3. It is now convenient to label agent  $h$ 's opinion of the probability of up by  $g(h)$ .

The tree roughly corresponds to the possibility of default getting closer, as well as more probable. An asset  $Y$  can pay off 1 or default and pay off  $R < 1$ . Each period, there is either good news or bad news, independently drawn. The asset  $Y$  defaults only if there are two bad signals. After the first bad signal, the probability of default rises, and the horizon over which there may be a default

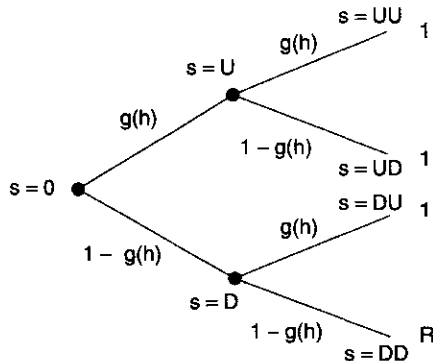


Figure 5.3.



shortens. (The rest of the tree, e.g., where there is one good signal and two bad signals, is compressed for simplicity into the simple three-stage tree shown here.)

Take the case where  $g(h) = 1 - (1 - h)^2$ . At time 0, agent  $h$  attaches probability  $(1 - h)^4$  of eventual default in asset  $Y$ . If this agent gets bad news,  $s = D$ , then his or her probability rises to  $(1 - h)^2$  in the next period. For an optimist with  $h$  near 1, this may be hardly any change at all.

Each node or state  $s$  in the tree is defined by its history of  $U$ s and  $D$ s. The node  $sD$  means the node where the move  $D$  occurred after the history  $s$ . This is similarly true for  $sU$ .

Again let there be two goods  $X$  and  $Y$  in each state, where  $X$  is like cigarettes, and  $Y$  is like a tobacco plant that will produce only in the last period.  $Y$  produces one cigarette, unless two independent events go bad, in which case it produces only  $R < 1$ .

Endowments are 1 unit of  $X$  and  $Y$  at  $s = 0$ , and zero otherwise:

$$e_{0X}^h = e_{0Y}^h = 1, \quad e_{sX}^h = e_{sY}^h = 0 \quad \forall s \neq 0, \quad \forall h \in H.$$

As before,  $X$  is durable but extinguishable by production, and  $Y$  is durable until its final output of  $X$  is produced. Let  $f_s(z_1, z_2)$  denote the output in state  $s$  from the inputs  $(z_1, z_2)$  of  $X$  and  $Y$  in the unique state  $s^*$  preceding  $s$ . Then for  $s \neq 0$ , consumption destroys the good:

$$f_s^0(z_1, z_2) = f_s^B(z_1, z_2) = f_s^L(z_1, z_2) = 0.$$

Warehousing, in contrast, produces

$$\begin{aligned} f_U^W(z_1, z_2) &= f_D^W(z_1, z_2) = (z_1, z_2), \\ f_{UU}^W(z_1, z_2) &= f_{UD}^W(z_1, z_2) = f_{DU}^W(z_1, z_2) = (z_1 + z_2, 0), \\ f_{DD}^W(z_1, z_2) &= (z_1 + Rz_2, 0). \end{aligned}$$

Utility as before is given by the expected consumption of  $x$ :

$$\begin{aligned} U^h(x, x_W, y) &= x_0 + g(h)x_U + (1 - g(h))x_D + g^2(h)x_{UU} \\ &\quad + g(h)(1 - g(h))[x_{UD} + x_{DU}] + (1 - g(h))^2x_{DD}. \end{aligned}$$

We assume now that  $H = [0, \alpha]$ .

In each state  $s^*$  there is a contract  $j \in J$  that promises 1 unit of  $X$  in each successive state  $s$  and requires  $j$  units of  $Y$  as collateral at time  $s^*$ . We write

$$\begin{aligned} A_{sj} &= (1, 0) \quad \forall s \neq 0, \\ C_{s^*j} &= (0, j) \quad \forall s \neq 0. \end{aligned}$$

Prices, as before, are given by  $p_{sX}$ ,  $p_{sY} \quad \forall s$ , and  $\pi_{sj}$  for all states  $s$  and all  $j \in J$ . It is understood that  $e_{0^*}^h = 0$  and that  $\pi_{sj} = 0$  for the terminal states  $s \in \{UU, UD, DU, DD\}$ .

The budget set for each agent  $h$  is given by exactly the same equations as before, but for every state  $s$  separately. It is understood that the output  $f_s(z_1, z_2)$  belongs to the owner of the input  $(z_1, z_2)$  at state  $s^*$ .

Let us now compute equilibrium. It is clear that in state  $U$  we will have  $p_{UY} = 1 = \pi_{Uj^*}$  where  $j^* = 1$ . The price  $p_{DY}$  will depend on what happens at  $s = 0$ , and on the resulting redistribution of wealth at  $s = D$ . Let us guess again that all contract trade at  $s = D$  takes place via the contract  $j_D$ , where  $j_D = 1/R$ , and that all contract trade at  $s = 0$  takes place via the contract  $j_0$ , where  $j_0 = 1/p_{DY}$ .

Following this guess we further suppose that at time 0, all agents  $h \in (a, \alpha]$  borrow to the max and buy up all the  $Y$ . In the likely state  $s = U$ , they get rich. In the (for them) unlikely state  $D$ , they lose everything. The rest of the agents  $h \in [0, a)$  sell  $Y$  and lend at  $s = 0$ . Thus in state  $s = D$ , agents  $h \in [0, a)$  begin with endowments  $\alpha/a$  of both  $X$  and  $Y$ . Of these, agents  $h \in (b, a)$  will borrow to the max to buy  $Y$  in state  $D$ , and agents  $h \in [0, b)$  will sell  $Y$  and lend to them, as in our first example.

If our guess is right, then the price  $p_{DY}$  will crash far below  $p_{0Y}$  for three reasons. First, every agent believes that  $D$  is bad news, and so by each agent's reckoning, the expected output of  $Y$  is lower. Second, the optimistic agents at  $s = 0$  leverage, by borrowing to the hilt, and so they suffer a huge wealth setback at  $s = D$ , creating a feedback on prices  $p_{DY}$ , as we saw in the last section. (The elimination of the top echelon of optimists reduces the price at  $s = D$ .) Third, the margin requirement increases.

Computing equilibrium is similar to the simple example from Section 6, but with one wrinkle.

Agent  $a$  is the marginal buyer at  $s = 0$ , but at state  $s = D$  this agent is much more optimistic than the marginal buyer  $b$ . Therefore he or she anticipates that \$1 is worth much more than \$1 worth of consumption of  $x_D$ . Indeed, it is worth  $g(a)/g(b)$  times as much. The reason is exactly as we saw in Section 6. Agent  $a$  can buy  $y_D$  on the margin, paying  $g(b)\delta$  at time  $D$  to get  $\delta$  in state  $DU$ , which gives expected utility  $g(a)\delta$ . It follows that he or she should not consume  $x_0$ , but rather save it, then consume it if  $s = U$ , but if  $s = D$  use the  $X$  to buy  $Y$  on margin. The marginal utility to  $a$  of  $x_0$  is therefore  $g(a)1 + (1 - g(a))[g(a)/g(b)]$ .

The marginal utility to agent  $h$  from buying  $Y$  at  $s = 0$  and holding it to the end is

$$MU_Y^h \equiv [1 - (1 - g(h))^2]1 + (1 - g(h))^2 R.$$

Thus we must have

$$\frac{[1 - (1 - g(a))^2]1 + (1 - g(a))^2 R}{p_{0Y}} = g(a)1 + (1 - g(a))\frac{g(a)}{g(b)}1. \quad (7.1)$$

Agents  $h \in (a, \alpha]$  will buy  $Y$  on margin, spending in total  $(\alpha - a) + \alpha p_{DY}$ , and agents  $h \in [0, a)$  will sell  $Y$ , giving

$$p_{0Y} = \frac{(\alpha - a) + \alpha p_{DY}}{a}. \quad (7.2)$$

Table 5.2.

$R$	0	0.1	0.2
$b$	0.5012	0.55055	0.60022
$1 - g(b)$	0.24880144	0.202005	0.159824
$g(b)$	0.75119856	0.797995	0.840176
$p_{DY}$	0.75119856	0.818195	0.872141
$a$	0.877700718	0.910007	0.936414
$1 - a$	0.122299282	0.89993	0.063586
$p_{0Y}$	0.995211492	0.998002	0.999267
$1 - g(a)$	0.014957114	0.008099	0.004043
$g(a)$	0.985042886	0.991901	0.995957
$(1 - g(a))^2$	0.000223715	$6.56 \times 10^{-5}$	$1.63 \times 10^{-5}$
$g(a)/g(b)$	1.31129496	1.242992	1.185415
$E_a Y / p_{0Y}$	1.004656074	1.001968	1.00075
$m_0$	0.245134929	0.180146	0.127194
$mD$	1	0.87778	0.770679

However, as before,

$$p_{DY} = g(b)1 + (1 - g(b))R, \quad (7.3)$$

and

$$p_{DY} = \frac{(a - b) + aR}{b}. \quad (7.4)$$

Combining (7.3) and (7.4) gives

$$a = \frac{b[(1 + g(b)) + (1 - g(b))R]}{1 + R}. \quad (7.5)$$

These five equations can be solved simultaneously by means of a simple algorithm. Choose  $b$  arbitrarily. From the last equation compute  $a$ . Then compute  $p_{DY}$  and then  $p_{0Y}$ . Finally, check that Equation (7.1) holds. If not, iterate.

Table 5.2 describes the equilibrium for three different values of  $R$ , given  $g(h) \equiv 1 - (1 - h)^2$ , and  $\alpha = 1$ .

### 7.1. What Caused the Crash? Feedback

Consider the case  $R = 0.2$ . In state  $D$ , the asset price  $p_{DY}$  crashes, falling from a price of  $p_{0Y} = 0.9993$  to a price  $p_{DY} = 0.8721$ . Three factors explain this change. First, the probability of default increased from  $(1 - h)^4$  to  $(1 - h)^2$  for each agent  $h$ . For the marginal buyer  $a = 0.9364$ , this represents an increase from virtually zero to 0.0040, still a negligible number. The drop in expected output from  $Y$  is thus about 0.003, which itself is negligible, compared to the drop in price of  $(0.9993 - 0.8721) = 0.1272$ .

Second, the drop in value of the price destroyed the wealth of the most optimistic buyers, effectively eliminating the purchasing power of every agent

Table 5.3.

$\alpha$	0.9364136
$R$	0.2
$b$	0.563
$1 - g(b)$	0.190969
$g(b)$	0.809031
$p_{DY}$	0.8472248
$a$	0.866656302
$1 - a$	0.133343698
$p_{OY}$	0.995908206
$1 - g(a)$	0.017780542
$g(a)$	0.982219458
$(1 - g(a))^2$	0.000316148
$g(a)/g(b)$	1.214069001
$E_a Y / p_{OY}$	1.003806263
$m0$	0.149335291
$mD$	0.763935144

$h > a = 0.9364$ . We can see what effect the disappearance of these agents would have *ceteris paribus*, by recomputing equilibrium in the three-period model with  $\alpha = 0.9364$ . The result is listed in Table 5.3.

We see that there is almost no effect on equilibrium prices from eliminating the 7 percent of the most optimistic buyers. *Ceteris paribus*,  $p_{OY}$  drops from 0.9993 to 0.9959.

Third, the time of default gets closer, and the margin requirement jumps from 12.7 percent to 77 percent. We can compute the effect this change would have itself by returning to our two-period model, but with  $g(h) = 1 - (1 - h)^4$ , which is the probability each agent  $h$  attaches to no-default in the three-period model. The result is listed in Table 5.4.

We see again that the effect of changing the margin requirement from 12.7 percent to 79.6 percent (as well as bringing the possibility of default nearer) reduces price  $p_{OY}$  from 0.9993 to 0.9807, again close to negligible.

The conclusion I draw is that the price crash in the example is not due to any one factor, but is due to the reinforcement each brings to the others.

Table 5.4.

$R$	0.2
$a$	1
$e$	1
$b$	0.60585
$1 - g(b)$	0.024134934
$g(b)$	0.975865066
$p_{OY}$	0.980692052
$m$	0.796062383

### 7.2. Why Did the Margin Increase?

The margin requirement on  $Y$  increased because the potential crash grew nearer. An implication of drawing nearer is that the rate of information flow increased, yet agents continued to disagree in their forecasts. The pieces of information  $D$  and  $DD$  are completely symmetric, as the probability of bad news is  $1 - g(h)$  in both cases, and the two events are independent. However, from  $D$ , the significance of the information to be revealed at the next step is huge. It resolves whether  $Y$  is worth 1 or  $R$ , whereas at  $s = 0$ , the next step will resolve whether  $Y$  is worth 1 or  $p_{DY}$ . When put another way, the variance of the price of  $Y$  one period after  $s = D$  is much higher than the variance of  $Y$  one period after  $s = 0$ . Because agents continued to disagree about the probability of future news, the higher volatility must result in higher margins.

### 7.3. Liquidity and Differences of Opinion

The size of the crash depends on how far  $b$  is from  $a$ , and on how fast  $g(h)$  changes as  $h$  changes. With  $b$  near  $a$ ,  $g(b)$  is near  $g(a)$  and  $b$ 's valuation of  $Y$  is not much different from  $a$ 's. However, as  $b$  moves away from  $a$ , this difference accelerates, given the functional form  $g(h) = 1 - (1 - h)^2$ . Had we made  $g(h)$  a constant, so there were no differences of opinion, there would have been no crash.

With  $g(h)$  a constant, there is a deep reservoir of potential buyers of the asset at the same price. With  $1 - g(h)$  very convex, this pool erodes at an accelerating pace, so that twice the bad news does more than twice the damage. Hence the power of multiple factors in the crash, when each alone makes little difference.

This appears to give us a different perspective on liquidity, closer to one of the conventional definitions. In that definition, liquidity is defined as the sensitivity of the reaction function of the price when an agent tries to sell more. It would appear from the foregoing that we might describe a market as illiquid and vulnerable to crashes if changes in the supply of the asset dramatically affect its price.

This definition does not, however, capture what is going on. *Doubling* the supply of the asset  $Y$  (which is equivalent to reducing every agent's endowment of  $X$  by 50 percent) would change equilibrium  $p_{0Y}$  from 0.9993 to 0.9920, a negligible change (see Table 5.5). It is interesting that after the doubling, the economy becomes much more vulnerable to the shock  $D$ , because then the price drops from 0.9920 to 0.7746. We will give a more appropriate definition of liquidity in Section 11.

### 7.4. Profits After the Crash and Cautious Speculators

Before we leave the crash example, it is instructive to reconsider why it is difficult to imagine a crash in a rational expectations world. One would think that if the crash is foreseen, then nobody would want to hold the asset before

Table 5.5.

$\alpha$	1
$R$	0.2
$b$	0.46915
$1 - g(b)$	0.281801723
$g(b)$	0.718198278
$p_{DY}$	0.774558622
$a$	0.854227396
$1 - a$	0.145772604
$p_{0Y}$	0.992060109
$1 - g(a)$	0.021249652
$g(a)$	0.978759348
$(1 - g(a))^2$	0.000451548
$g(a)/g(b)$	1.362785708
$E_a Y / p_{0Y}$	1.00770907
$m_0$	0.219188192
$m_D$	0.741788427

the crash. Or better, that investors would hold their capital, waiting to buy after the crash. After the crash, optimistic investors could make a far greater return than they could before the crash. Investor  $a = 0.9364$  can see that he or she could make an expected return of 18 percent ( $g(a)/g(b)$ ) above the riskless rate starting at  $s = D$ . Why don't investors wait to invest until after the crash (thereby eliminating the crash)?

In fact, a group of investors do wait. At  $s = 0$ , investor  $h = a$  calculates the expected output of  $Y$  per dollar at 1.00075. Unleveraged, this investor anticipates a 0.075 percent return on his or her money, above the riskless rate, from investing in  $Y$ . This investor is risk neutral, yet he or she holds off investing in  $Y$ . Why? Because the investor foresees that if he or she keeps the money in liquid  $X$ , he or she can earn an 18 percent return ( $g(a)/g(b)$ ) on the money above the riskless rate, after leverage, if state  $D$  should occur. There is a whole group of agents  $h \in (a, a)$  who regard  $Y_0$  as a profitable investment, but who choose instead to sell it in order to stay liquid in  $X$  in anticipation of the crash. The probability of the crash is so low, however, that not many investors bother to prepare themselves this way, and so the crash still occurs.

## 8. THE LIQUIDITY SPREAD

Consider two assets that are physically identical, but suppose that only the first can be used as collateral. Will their prices be the same? To some extent this situation prevails with on-the-run and off-the-run Treasuries. The percentage of off-the-run Treasuries that are used as collateral is much smaller than the on-the-run Treasuries, and they sell for a lower price.

We can see in our simple example why this should be so. Suppose a fraction  $f$  of each agent's  $Y$  is painted blue, and can be used as collateral, while the

Table 5.6.

$f$	0.4	0.5	.06
$\alpha$	1	1	1
$e$	1	1	1
$R$	0.2	0.2	0.2
$a$	0.873007	0.841774	0.810657
$b$	0.627968	0.636558	0.645501
$p$	0.702374	0.709246	0.7164
$p^*$	0.746014	0.746839	0.747544

remaining fraction  $(1 - f)$  is painted red and cannot. What will their equilibrium prices be? If the price  $p^*$  of blue is the same as the price  $p$  of red, then all  $h$  above the marginal buyer  $b$  will spend all their money on blue (because they strictly prefer  $Y$  to  $X$ , and leveraging is the way to get as much  $Y$  as possible). All the agents  $h < b$  will sell  $Y$  (since they strictly prefer  $X$  to  $Y$ ). Thus there will be no buyers for red  $Y$ , and markets will fail to clear. It follows that  $p^* > p$ . A moment's thought shows that in equilibrium, households  $h \in [0, \alpha]$  will split into three pieces. The most optimistic  $h \in (a, \alpha]$  will leverage and buy blue  $Y$ . Agent  $a$  will be indifferent to buying blue on margin at the high price, and red at the low price. Agents  $h \in (b, a)$  will buy only the red  $Y$ , selling their blue, and  $X$ . Agents  $h \in [0, b)$  will sell all their  $Y$ . Agent  $b$  is indifferent between buying red  $Y$  and holding  $X$ .

More precisely, we can find equilibrium by solving the following equations:

$$1b + (1 - b)R = p, \quad (8.1)$$

$$\frac{e(a - b) + p^* f(a - b)}{(1 - f)(\alpha - (a - b))} = p, \quad (8.2)$$

$$\frac{e(\alpha - a) + p(1 - f)(\alpha - a) + f\alpha R}{fa} = p^*, \quad (8.3)$$

$$\frac{a(1 - R)}{p^* - R} = \frac{a1 + (1 - a)R}{p}. \quad (8.4)$$

Equation (8.1) asserts that agent  $b$  is indifferent between red  $Y$  and  $X$ . Equation (8.2) says that agents  $h \in (b, a)$  take all their cash, plus the money they get selling off their blue  $Y$ , and spend it all on red  $Y$ . Everyone else sells their red  $Y$ . Equation (8.3) says that agents  $h \in (a, \alpha]$  take all their cash, plus all the money they get selling their red  $Y$  plus all the money they can borrow in the blue  $Y$ , and use it to buy all the blue  $Y$  that is sold by agents  $h \in [0, a)$ . Finally, Equation (8.4) ensures that for agent  $a$ , the marginal utility of \$1 in blue  $Y$  is equal to the marginal utility of \$1 in red  $Y$ .

Table 5.6 gives equilibrium for various values of  $f$ , fixing  $\alpha = 1$ ,  $R = 0.2$ , and  $e = 1$ .

The equilibrium equations sharpen our intuition about why the prices of blue  $Y$  and red  $Y$  differ, despite the fact that they are perfect substitutes. The buyers

of blue  $Y$  and red  $Y$  can be disjoint sets.  $Y$  bought on the margin gives extreme payoffs  $(1 - R, 0)$  that are not collinear with the payoffs  $(1, R)$  from buying  $Y$  with cash.

One can see from the Table 5.6 that, as  $f$  declines, the total value of  $Y$  falls, the spread between red and blue  $Y$  increases, and both blue  $Y$  and red  $Y$  fall in value. The fact that the total value of  $Y$  falls is obvious.  $Y$  is harder to purchase if its liquidity is lower.

The fact that blue  $Y$  is more valuable than its perfect substitute, red  $Y$ , just because it can be used as collateral, is of extreme importance, as is the principle that this spread gets wider as the general liquidity in the economy falls. This liquidity spread widening is one of the hallmarks of a liquidity crisis. In our example, spread widening is inevitable because the supply of blue  $Y$  went down and the supply of red  $Y$  went up. The only curiosity is that the price of blue  $Y$  went down. This is an accidental artifact of our parameters, coming from the fact that as  $p$  declines the liquid wealth of the superoptimists  $h \in (a, \alpha]$ , who are sellers of red  $Y$ , declines, thereby reducing their purchasing power for blue  $Y$ .

A subtler proposition is that when one asset  $Y$  becomes less liquid, say because margin requirements are raised on it, then the spread between liquid and less liquid assets that are unrelated to  $Y$  also tends to increase. We consider such questions in the next section.

## 9. SPILLOVERS

Since the collapse of Long-Term Capital Management in 1998, it has become clear that many assets are much more correlated in times of (liquidity) crisis than they are otherwise. Our simple example of Section 8 can be extended to show some reasons why.

Consider the situation in which there are two assets  $Y$  and  $Z$ , and suppose that the margin requirement on  $Y$  is increased, say because  $R$  falls. Why should we expect the price of  $Z$  to fall?

At least three reasons come to mind. First, the same optimistic buyers might hold  $Y$  and  $Z$ . A negative shock to their wealth, or to their liquidity, will reduce their demand for all normal goods. Second, a decline in their liquidity will give them the incentive to shift into more liquid assets; if  $Z$  has relatively high margin requirements, and there is another comparable asset  $Z'$  with easier margin requirements, they will demand less  $Z$ . Finally, the equilibrium margin requirement may rise on  $Z$ , as a result of decreased recovery  $R$  on  $Y$ .

### 9.1. Correlated Output

At first glance it would seem that, if two assets had very similar returns, then they would be close substitutes. If  $R$  fell for  $Y$ , impairing its value, we might expect investors to switch to  $Z$ , possibly raising its value. However, this substitution



Table 5.7.

$\alpha$	1	1
$f$	0.5	0.5
$e$	1	1
$R$	0.3	0.2
$a$	0.85873	0.841774
$b$	0.646957	0.636558
$p$	0.752871	0.709246
$p^*$	0.802224	0.746839

effect can easily be swamped by an income effect. If  $Y$  and  $Z$  are closely correlated, it is likely that optimists about  $Y$  are also optimistic about  $Z$ . The fall in  $R$  causes an income shock to  $Y$  buyers, which impairs their ability to buy  $Z$ .

When  $R$  falls, we saw that the price of  $Y$  falls for two reasons: First, because the expected output goes down, and second because the new marginal buyer is a more pessimistic fellow. If  $Y$  and  $Z$  are very correlated, then a more pessimistic buyer for  $Y$  will be more pessimistic about  $Z$ , and so the price of  $Z$  should fall as well.

We can see this in the example from the last section. Holding the fraction of blue  $Y$  fixed at 0.5, and lowering  $R$  on both blue  $Y$  and  $Z = \text{red } Y$ , reduces the price of both by more than expected output decreases, as can be seen from Table 5.7.

When  $R$  falls from 0.3 to 0.2, both prices  $p$  and  $p^*$  fall by more than the expected output of  $Y$  and  $Z$ , calculated with respect to either the possibilities  $(a, 1 - a)$  or  $(b, 1 - b)$ . The gap between  $p^*$  and  $p$  narrows from 0.050 to 0.037.

In the example there is no substitution effect. Agents either prefer to buy expensive  $Y$  on the margin, or they prefer to buy cheaper  $Z$ . A change in the margin requirement simply reduces the amount of  $Y$  that can be bought on margin, but it does not by itself induce an agent to switch. If we had three states and a more complicated example, we could have had agents holding both  $Y$  and  $Z$  and then adjusting the proportions of each. Then the gap might have narrowed more.

A similar example in which  $Y$  and  $Z$  are correlated but not identical is the following. Let  $Y$  pay 1 or  $R$ , as usual. Let  $Z$  pay 1 or 0. It is easy to see that the equilibrium is the same as it would be with one asset  $W = Y + Z$ . Lowering  $R$  for  $W$  will reduce  $p_W$  and make the marginal buyer  $b$  more pessimistic, but that lowers the price of both  $Y$  and  $Z$ .

## 9.2. Independent Outputs and Correlated Opinions

It is perfectly possible for each agent  $h$  to think that the returns from  $Y$  and  $Z$  are independent, yet for optimists about  $Y$  to be optimistic about  $Z$ . For

example, we could imagine four states of nature giving payoffs from  $Y$  and  $Z$  as follows:  $(1, 1)$ ,  $(1, R)$ ,  $(R, 1)$ , and  $(R, R)$ . Each household  $h$  might regard his or her probabilities as  $(h^2, h(1-h), (1-h)h, (1-h)^2)$ , respectively. Thus everybody might agree that defaults by the Russian government and American homeowners are independent. Yet many hedge funds might have been optimistic about both, and thus simultaneously invested in Russian debt and mortgages.

In our example, every agent is risk neutral, so equilibrium is exactly the same for the independent case as for the perfectly correlated case just given. As in the example of Subsection 9.1, a decrease in  $R$  for Russian debt will lower American mortgage prices.

### 9.3. Cross-Collateralization and the Margin Requirement

Many lenders cross-collateralize their loans. Thus if the same promise (say of \$1) is taken out by a borrower using  $C_1$  as collateral, and another promise is made by the same borrower using  $C_2$  as collateral, then the lender is paid in each state  $s$

$$\min\{2, f_s^W(C_1) + f_s^W(C_2)\},$$

where  $f_s^W(\cdot)$  is the value of the collateral in state  $s$ .

Consider the situation in the example in Subsection 9.2 in which assets  $Y$  and  $Z$  had independent payoffs. The total value of  $Y + Z$  in the four states would then be  $(2, 1 + R, 1 - R, 2R)$ . If lenders could count on borrowers' taking out an equal amount of  $Y$ -backed loans as  $Z$ -backed loans, then they might loan  $1 + R$  for each collateral of  $Y + Z$  (charging a higher interest rate to compensate for the chance of default). But the margin requirement is then only  $[2p - (1 + R)]/2p = 1 - (1 + R)/2p$ , which is less than the margin requirement for  $Z$  alone,  $(p - R)/p = 1 - R/p$ . Thus cross-collateralization often leads to more generous loan terms.

If  $Y$  disappears, say because Russian debt collapsed, then lenders will be lending against only  $Z$  collateral, and thus margin requirements may rise on mortgages.

### 9.4. Rational Expectations and Liquidity Risk

We have assumed in our examples that agents may differ in their probability assessment of exogenous events ( $U$  or  $D$  or  $UU$ ), but that they all completely understand the endogenous implications of each event. In reality, of course, agents do not have identical opinions about endogenous variables. In particular, there are probably wide disparities in the probability assessments of a liquidity crisis. An optimist about liquidity crises would then be optimistic about all kinds of assets that crash in liquidity crises. He or she might therefore be led to hold all of them. However, if enough liquidity optimists do this, then they create precisely the conditions we have been describing that lead to spillovers in a liquidity crisis.

## 10. TWO MORE CAUSES OF LIQUIDITY CRISES

There are other explanations of liquidity crises that the examples given here suggest but that are not pursued. The first is that when lenders cross-collateralize, but leave it to the borrower to choose the proportions of collateral, there is a moral hazard problem. Desperate hedge funds facing collapse might be tempted to gamble, thus holding a less hedged portfolio, for example, not balancing  $Y$  with  $Z$ . Anticipating this, lenders might raise margin requirements, thus causing the collapse they feared.

Second, I took the possibility of default (the state in which output is  $R < 1$ ) to be exogenous, and I looked for endogenous liquidity crashes. In reality, there is a long chain of interlocking loans and the probability of a cascade of defaults is endogenous, and also an effect of liquidity, rather than just a cause.

## 11. A DEFINITION OF LIQUIDITY AND LIQUID WEALTH

Liquidity is an elusive concept in economics. Sometimes it is used to refer to the volume of trade in a particular market; sometimes it means the average time needed to sell; sometimes it means the bid–ask spread in the market; sometimes it means the price function relating the change in price to the change in quantity orders; and sometimes it refers to the spread between two assets with the same promises (such as the spread between on-the-run and off-the-run Treasuries).

Some of these definitions seem to require a noncompetitive view of the world, as they presume that trades are not instantly transacted at one price. Yet some of the other definitions apply in competitive markets. It is evident that economists do not all have the same notion in mind when they speak of liquidity. However, every one of these standard definitions of liquidity is applied in each market separately.

By contrast, the examples of collateral equilibrium discussed earlier suggest a new definition of the “liquidity of the system” that depends on the interactions of agents between markets.

For simplicity, let us suppose that the production of commodities whose services are being consumed does not depend on whether they are borrower held, or lender held, or owner held:  $f^0 = f^B = f^L$ . Then by a small change in notation, we can more simply write the budget set as

$$\begin{aligned}
 B^h(p, \pi) = & \{(x, \theta, \varphi) \in \mathbb{R}_+^L \times \mathbb{R}_+^L \times \mathbb{R}_+^{SL} \times \mathbb{R}_+^J \times \mathbb{R}_+^J : \\
 & p_0(x_0 + x_w - e_0^h) + \pi(\theta - \varphi) \leq 0, \\
 & \sum_{j \in J} \varphi_j C_j^W \leq x_w, \sum_{j \in J} \varphi_j C_j^B + \sum_{j \in J} \theta_j C_j^L \leq x_0, \\
 & p_s(x_s - e_s^h - f_s^0(x_0) - f_s^W(x_w)) \leq \sum_{j \in J} (\theta_j - \varphi_j) D_{sj}, \\
 & D_{sj} = \min \{ p_s \cdot A_s^j, p_s \cdot f_s^W(C_j^W) + p_s \cdot f_s^0(C_j^B + C_j^L) \}.
 \end{aligned}$$

Now the utilities  $u^h$  depend solely on  $(x_0, x_1, \dots, x_S)$ , because  $x_0$  now includes the goods put up as collateral and held by the borrowers or lenders.

This budget set is identical to the standard general equilibrium budget set with incomplete contracts (GEI), except for two changes. The contract payoffs  $D_{sj}$  are endogenous, instead of exogenous, and contract sales  $\varphi$  are restricted by the collateral requirement, which shows up in the  $2L$  constraints in the third line of the budget set.

I define the liquidity of the system by how closely the collateral budget set comes to attaining the GEI budget set. One crude way of measuring this is by taking the maximum expenditure that can be made on  $x_0, x_W$ , and  $\theta$  in period 0 without violating any of the budget constraints. We might call this the liquid wealth of the agent at time 0.

Liquidity can suddenly deteriorate if the collateral levels increase (i.e., if the contract at which trade is actually taking place shifts to one with the same promise but a higher collateral level).

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