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Optimal Bank Transparency

Increasing transparency is recurrently offered as a centerpiece of bank regulation. We study a competitive banking sector whose illiquid assets are funded by short-term debt that must be refinanced. We show that welfare is a nonmonotonic function of the level of transparency: Increasing transparency fosters efficient liquidation but has an adverse effect on rollover risk given the level of risk. Banks may compensate this adverse effect by taking more risk. These offsetting effects render an intermediate level of transparency optimal. Moreover, the existence of negative social externalities of bank failures calls for making banks more opaque rather than more transparent.

SINCE LOUIS D. BRANDEIS FAMOUSLY CLAIMED that "...sunlight is the best of disinfectants" (*Harper's Weekly,* December 20, 1913), enhanced transparency is recurrently offered as a remedy for the problems of banking. Indeed, Basel III, the new international banking regulatory framework developed in response to the recent global financial crisis, has as a key aim to strengthen banks' transparency and assure disclosure. However, the discussions on whether the results of banks' stress tests should be publicized, and on how stringent these tests should be, suggests that

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the case for increasing transparency is not clear-cut—see Goldstein and Sapra (2013) and Landier and Thesmar (2013). In this paper we provide an analysis of the impact of changes of the level of transparency on welfare, banks' risk taking, and rollover risk.

Consider a competitive bank whose illiquid asset portfolio is funded by short-term debt supplied by risk-neutral creditors. The bank selects the level of asset risk. The bank's asset portfolio can be totally or partially liquidated before maturity, though incurring a cost. Creditors decide whether to roll over their credit upon receiving a noisy signal of the probability that the asset will pay its return. We identify the level of transparency with the precision of creditors private signals of the probability that the bank's asset pays its return. We show that under some natural parameter restrictions, given the bank's asset risk choice, the creditor's game has a unique equilibrium, and that this equilibrium is identified by a simple equation. Solving this equation we obtain closed form expressions relating the equilibrium levels of credit refinancing and welfare with the levels of transparency and asset risk.

We show that welfare is a nonmonotonic function of the level of transparency: when the banking system is (not) very transparent, that is, when creditors' signals are (not) very precise, increasing the level of transparency decreases (increases) total welfare. Thus, the socially optimal level of transparency is interior, and hence maximal transparency is not socially optimal. Moreover, because in our competitive setting the interests of a bank and its creditors are perfectly aligned, regulating the level of transparency is unnecessary unless the failure of a bank involves social costs beyond those imposed on the bank's creditors. We show that if bank failures have negative social externalities, then the optimal level of transparency is below the optimal level when externalities are absent; that is, the existence of negative social externalities of bank failures calls for making banks *more opaque* rather than more transparent.

Our comparative static analysis shows that rollover risk, that is, the probability of refinancing short-term debt, increases with the level of transparency for a given level of asset risk. However, we uncover complex indirect effects of transparency on rollover risk via risk taking. In particular, a bank compensates the adverse direct effect of transparency on rollover risk by *increasing risk taking* at least when the level of transparency is above and around its socially optimal level. A sufficient condition for the total effect of transparency on rollover risk to be positive is that creditors' rollover decisions not be too sensitive to asset risk.

A key element explaining our results is the existence of a negative externality that arises when creditors withdraw their credit: the liquidation costs that must be assumed to pay back a creditor who withdraws has a negative impact on the expected payoff of the creditors who roll over. The magnitude of this negative impact is larger, the larger is the fraction of creditors who withdraw.

Increasing transparency decreases the fraction of creditors' who mistakenly roll over as well as the fraction of creditors who mistakenly withdraw. When the realized probability that the asset pays its return is sufficiently low that it is optimal to withdraw, the fraction of creditors who actually withdraw is large. For such realizations,

increasing transparency, which reduces the fraction of creditors who mistakenly roll over, has a large negative impact on the payoff to rolling over. When the realized probability that the asset pays its return is sufficiently high that it is optimal to roll over, then the fraction of creditors who withdraw is small. For these realizations, increasing transparency, which reduces further the fraction of creditors who mistakenly withdraw, has a small positive impact on the payoff to rolling over.

For a given level of risk, these asymmetries imply that increasing transparency has a negative net effect on the payoff to rolling over, which leads creditors to optimally raise their threshold to roll over, and consequently increases rollover risk. Banks may compensate this effect by increasing risk taking, thus offering higher returns to those creditors who roll over. (We assume that return of the asset upon success increases with the level of risk, but we make no assumption about the effect of the level of risk on the mean asset return; e.g., the effect of a change in the level of risk may be a mean preserving spread).

In sum, increasing transparency has a negative effect on welfare via its positive effect on rollover risk. This negative effect, however, is counterbalanced by its positive effect in discouraging (fostering) inefficient (efficient) liquidation. This counterbalancing effect is dominant when the level of transparency is low.

Our model shares some features with the classical bank-run model of Diamond and Dybvig (1983) and is hence related to the work in this tradition. Chari and Jagannathan (1988), Calomiris and Kahn (1991), Chen (1999), and Chen and Hasan (2006), for example, study the role of creditors' information at an interim stage in generating information and panic-based bank runs and observe its disciplining effect on banks behavior. In this literature, as in our model, creditors observe an interim signal on the asset's return before they decide whether to roll over their credit, and withdrawals cause negative payoff externalities. We, too, find that enhanced transparency may decrease creditors' willingness to roll over, but in our setting a bank may counter this effect by increasing risk taking. In this literature the closest paper to ours is Chen and Hasan (2008) who, akin to our results, show that increasing the precision of creditors' signal of the asset's return fosters efficient liquidation and increases the likelihood of a bank run when the prospects of the asset paying its return are bleak. Also He and Manela (2014) show that providing information that slightly differentiates competing solvent-but-illiquid banks may result in inefficient runs.

Although we study the effects of *interim* transparency on banks' risk taking incentives, there is a closely related literature initiated by Cordella and Yeyati (1998) and Matutes and Vives (2000) studying the effects of *ex ante* transparency on banks' risk taking. This literature has shown that if the creditors of a bank do not observe the bank's asset risk choice prior to their lending decisions, then debt finance may make the bank's payoff convex in asset riskiness and hence lead to excessive risk taking. Providing creditors with information of the bank's asset risk choice, by allowing creditors to condition their lending decisions, has a disciplining effect on banks' risk taking. In some settings, this effect of enhanced *ex ante* transparency is strong enough to eliminate excessive risk taking. (However, there are settings in which risk taking actually increases with the level of *ex ante* transparency, see, e.g., Blum 2002,

Hyytinen and Takalo 2002.) In our set-up, following Diamond and Dybvig (1983) we assume that the creditors who roll over become residual claimants, and therefore a creditor's payoff may not be monotonically decreasing in the level of asset risk. Thus, the effects of increasing *ex ante* transparency on banks' risk choice and welfare, which is an issue we do not study, are less obvious.

Our paper also has a connection to the literature studying transparency regulation and financial market liquidity—see, for example, Dang, Gorton, and Holmström (Forthcoming) and Pagano and Volpin (2012). Although we do not model liquidity provision explicitly, we show that enhanced transparency has an adverse direct effect on banks' ability to roll over short-term funding.

Because transparency hinges on incomplete information, and because banks are inherently vulnerable to self-fulfilling runs, models of bank transparency easily generate multiple equilibria and often render comparative statics and welfare analyses inconclusive. Although the literature on bank runs has been influential in pointing out the importance of creditors confidence and its dependence on creditors' expectations, it does not allow an assessment of how confidence relates to the level of creditors' information. Our result on uniqueness of equilibrium builds on the theory of global games and is related to Morris and Shin (1998). Our simple characterization of the unique equilibrium allows us to explicitly compute the volume of credit refinancing, facilitating comparative statics and welfare analyses. In this respect, our paper relates to other papers that use global game methodology to study the problems of banking and lending such as Rochet and Vives (2004), Goldstein and Pauzner (2005), and, more closely, to Morris and Shin (2006) who study the refinancing of government debt. Although most of the papers in this literature deal with a binary action game, in our setting, similarly to Morris and Shin (2006), there is an additional agent (the bank) whose decisions (the level of risk) determine the support of creditors' signals.

In the global game literature, the impact of the level of information on equilibrium has been extensively studied. We follow part of this literature identifying transparency with the precision of creditors private signals. Bannier and Heinemann (2005), for example, study the effect of transparency on the probability of a speculative attack to a currency peg (see also Heinemann and Illig 2002). We show, as they do, that the effect of changes in the level of transparency depends crucially on the way agents' payoffs vary with the underlying state, and that the optimal level of transparency is interior. Even though our model is quite different from that Bannier and Heinemann's (2005) model of currency crises, and somewhat more complex (e.g., transparency affects the creditors' payoffs to roll over and the banks' *ex ante* incentives for risk taking, which are determined endogenously), the economic mechanisms underlying the effects of transparency in both settings are analogous.

Following Morris and Shin (2002), another branch of the literature has debated the social value of public information and the role of social conformity—see, for example, Angeletos and Pavan (2004) and Svensson (2006). In our setting, in which conformity plays no role, introducing public information (e.g., an announcement by a central bank disclosing information about banks' assets) poses no problem. Of course, introducing an additional independent public signal may render multiple equilibria if

its precision is sufficiently high (see Hellwig 2002) and may make it more difficult to assess the impact of changes in the level of transparency interpreted as changes in the precision of either the private or the public signal. Even if the public signal is sufficiently imprecise that uniqueness of equilibrium is preserved, the impact of changes in the level of precision of the public signal is ambiguous and depends on whether the realization of the signal reveals that the fundamentals are weak or strong. (We provide a discussion of this issue in Section 4; see also Prati and Sbracia 2010, for a discussion of this subject in a model of currency crises.) In contrast, we are able to provide a simple and conclusive analysis of the effects of changes on the precision of creditors' private signals on rollover risk, banks' risk taking and welfare.

In our model, increasing transparency amounts to shrinking the support of creditors' posterior beliefs of the probability of success. Alternative levels of transparency may result from regulating the precision, frequency, etc., with which banks must disclose information about their asset portfolio to their creditors. Our interpretation is that information is privately communicated to creditors. Banks' private communication with their creditors is a common practice, especially of privately held banks, which is likely to affect creditors' rollover decisions. (Although there are stringent rules against insider trading of publicly listed banks' shares, the effects of banks' private communication with creditors and its regulation are much less well understood.)

The paper is organized as follows. In Section 1 we layout the basic setting. In Section 2 we describe the creditors' game. In Section 3 we prove that creditors' game has a unique equilibrium, which we show is the solution to a simple equation. In Section 4 we study the impact of changes transparency on rollover risk and welfare given the asset risk. In Section 5 we endogenize the banks' risk choice. In Section 6 we provide a welfare analysis and discuss the impact of negative social externalities that bank failures may have. In Section 7 we provide a numerical example verifying the compatibility of our parameter assumptions and showing how to use the model to calculate the socially optimal level of transparency. In Section 8 we present our main conclusions. Appendices A and B contain calculations used to derive our results.

1. THE MODEL

We consider a competitive bank whose illiquid asset portfolio is funded by short-term credit that needs to be refinanced. At maturity, the bank's asset pays a positive return if it is successful, and zero if it is not. The *probability of success p* is drawn from a uniform distribution $P(\mu)$ on $[1 - \mu, 1]$. The parameter $\mu \in (0, 1)$ is a proxy for the asset's riskiness: the larger μ the more likely it is that the asset pays no return. The return paid by the asset upon success is $1 + R(\mu)$. Thus, the return of the asset is distributed uniformly on $[(1 - \mu)(1 + R(\mu)), 1 + R(\mu)]$. The mean return is

$$Q(\mu) := E\left([1 + R(\mu)]P(\mu)\right) = [1 + R(\mu)]E(P(\mu)),$$

where

$$E(P(\mu)) = 1 - \frac{\mu}{2}$$

is the mean probability of success. In Sections 2 to 4 we take μ as given and simplify notation by suppressing μ as an argument of P, R, and Q. Our results in these sections (Propositions 1–5) hold regardless of the relationship between asset risk and returns. We endogenize the bank's choice of risk μ in Section 5.

The bank's asset portfolio is divisible and can be liquidated before maturity: one unit of the asset liquidated before maturity yields λ monetary units. We assume that

$$Q > 1 > \lambda > 0, \tag{1}$$

which implies that liquidating the asset before maturity is costly and *ex ante* inefficient.

The bank has a continuum of creditors, whose measure is normalized to one, each of whom has one unit of uninsured credit. Creditors maximize expected returns (i.e., they are risk neutral). Hence, in contrast to many bank run models, in our setting risk sharing is not an issue. Some creditors, a fraction $h > 0$, are *active* and may withdraw their credit before the asset matures. The remaining creditors, a fraction $1 - h$, maintain their unit of credit until the asset matures and therefore play a passive role. Henceforth we refer to the active creditors simply as creditors when no confusion may arise. The assumption that only a fraction of creditors are active captures the fact that some of the bank's loans (e.g., long-term retail deposits) are stickier than others (e.g., wholesale funding from the overnight interbank market). We assume that

$$h < \lambda, \tag{2}$$

which implies that the bank is always liquid, that is, the bank does not fail even if all active creditors withdraw their credit. (The bank only fails when the realized return of the asset is zero). Although the bank is always liquid, condition (1) implies that *ex ante* it is in a creditor's (and society's) interest to roll over. These simplifying assumptions allow for an analysis focused on the impact of transparency on risk taking, rollover risk, and welfare.

Each creditor observes a noisy signal of the realized probability of success,

$$S_i = P + T_i,$$

where the noise terms T_i are conditionally independently and uniformly distributed on $[-\varepsilon, \varepsilon]$, for some $\varepsilon > 0$. Then all creditors simultaneously decide whether to *withdraw* or to *roll over* their credit. Note that though creditors information about the state differs, no creditor has superior information.

The timing of the game that active creditors face is as follows: (i) The bank selects the level of risk μ, which becomes common knowledge among creditors; (ii) nature draws the success probability p; (iii) each creditor observes a signal s, and then

decides whether to withdraw or to roll over her credit; (iv) the returns are realized and the creditors are compensated accordingly.

2. THE CREDITORS GAME

We normalize the nominal value of the bank's short-term debt to unity. This feature of the credit contract, which is consistent with usual practices in financial markets, redeeming at par (at least) credit withdrawable on demand, is common in the literature. Our results hold insofar as the fixed payment to the creditors who withdraw is some value $l \in (\lambda, 1 + R)$. (The assumption $l > \lambda$ is required to preserve strategic complementarities.) The effects of changing l on the creditors' payoff are complex. An optimal value of l must induce efficient liquidation. Although the issue of which is the optimal credit contract is beyond the scope of this study, it can be shown that setting $l = \lambda$, though intuitively appealing, is not generally optimal. The design of the optimal contract needs to take into account the presence of inactive creditors, who never withdraw. For example, when the creditors' private signals are sufficiently precise, it may be socially desirable to pay active creditors who withdraw more than the liquidation value of the asset, because this will ensure that a larger share of the asset is liquidated if the prospects of the asset paying return are bad.

We also assume that competition leads the bank to promise to pay the entire asset's return to creditors who roll over. This second feature of the credit contract differs from the typical deposit contract but is in line with the tradition of Diamond and Dybvig (1983). Indeed, if creditors who withdraw get a fixed payment, it is optimal for a competitive bank to render the remaining creditors residual claimants. We may interpret our setting as if all the credit is initially at the banks with predetermined nominal value in case of withdrawal, and the banks compete in rates of return for credit renewal.

In the creditors game, a strategy for a creditor is a mapping from the set of signals $[1 - \mu - \varepsilon, 1 + \varepsilon]$ into the set of actions {roll over, withdraw}. The payoff to a creditor depends on her action, the state p, and the fraction of *all* creditors who withdraw, which we denote by $x \in [0, h]$. Given the debt contract, our assumption that $h < \lambda$ implies that the payoff to a creditor who withdraws is 1, whatever may be the state and the fraction of creditors who withdraw. (Note that a creditor who withdraws gets more than the liquidation value of her asset.) The payoff to a creditor who rolls over depends on p and x, and is given by

$$u(p, x) = \frac{1 - x/\lambda}{1 - x} (1 + R) \, p. \tag{3}$$

Because $\lambda < 1$, then $\partial u(p, x)/\partial x < 0$. Hence withdrawing becomes more attractive relative to rolling over the more creditors withdraw. (This *strategic complementarity* is key to obtaining uniqueness of equilibrium.) Also $\lambda < 1$ implies that $\partial^2 u(p, x)/\partial x^2 < 0$, and therefore that the negative externality of withdrawals on the creditors who roll over is increasing in the fraction of creditors who withdraw.

Obviously, the payoff to rolling over increases with the probability of success, that is, $\partial u(p, x)/\partial p > 0$. These properties play an important role in establishing our results.

A Lebesgue measurable profile of creditors' strategies may be described by a *strategy distribution* τ that for each signal $s \in [1 - \mu - \varepsilon, 1 + \varepsilon]$ provides the fraction of active creditors that withdraw their credit upon receiving the signal s, $\tau(s) \in [0, 1]$. Given a strategy distribution τ the fraction of all creditors who withdraw if the state is p is

$$x(p, \tau) = hE(\tau(S)|P = p), \tag{4}$$

and the *expected payoff* to a creditor who rolls over when her signal is s is

$$U(s, \tau) = E(u(P, x(P, \tau))|S = s),$$

where $P|S = s$ is distributed uniformly on $[1 - \mu, 1] \cap [s - \varepsilon, s + \varepsilon] = [\max\{1 - \mu, s - \varepsilon\}, \min\{1, s + \varepsilon\}]$—see Appendix B. Because the upper and lower bounds of this interval are increasing in s, then $P|S = s'$ first order stochastically dominates $P|S = s$ whenever $s' > s$. And because $u(p, x)$ is continuous, then $U(s, \tau)$ is continuous. Moreover, if $\tau, \hat{\tau}$ satisfy $\hat{\tau}(s) \geq \tau(s)$ for all s, then

$$x(p, \hat{\tau}) = hE(\hat{\tau}(S)|P = p) \geq hE(\tau(S)|P = p) = x(p, \tau)$$

for all $p \in [1 - \mu, 1]$, and therefore, because u is decreasing in x, we have

$$U(s, \hat{\tau}) \leq U(s, \tau).$$

A strategy distribution τ is an *equilibrium* of the creditors' game if for all $s \in [1 - \mu - \varepsilon, 1 + \varepsilon]$, $U(s, \tau) < 1$ implies $\tau(s) = 1$, and $U(s, \tau) > 1$ implies $\tau(s) = 0$; that is, the strategy profile defining the strategy distribution τ is such that (almost) all active creditors follow an optimal strategy.

Assume momentarily that creditors have complete information, that is, that $\varepsilon = 0$ so that creditors observe the probability of success with no error, and recall that u is continuous, increasing in p and decreasing in x. If $u(1, h) > 1$ then for $p \in (\bar{p}, 1)$, where $u(\bar{p}, h) = 1$, we have

$$u(p, x) > u(\bar{p}, h) = 1,$$

that is, rolling over is a strictly dominant strategy. Likewise, if $u(1 - \mu, 0) < 1$, then for $p \in (1 - \mu, \underline{p})$, where $u(\underline{p}, 0) = 1$, we have

$$u(p, x) < u(\underline{p}, 0) = 1,$$

that is, withdrawing is strictly dominant strategy. However, for intermediate values $p \in (\bar{p}, \underline{p})$, we have $u(p, h) < 1 < u(p, 0)$, and therefore a creditor's optimal action depends on the fraction of creditors who roll over. Hence depending on which action creditors *coordinate on* different equilibria arise—for example, there is an equilibrium

in which all creditors coordinate on withdrawing whenever $p \leq \bar{p}$, and roll over otherwise; and there is another equilibrium in which all creditors coordinate on rolling over whenever $p \geq \underline{p}$ and withdraw otherwise. Indeed this game of complete information has a continuum of equilibria. This multiplicity of equilibria is common in models of banking.

Under incomplete information (i.e., when $\varepsilon > 0$), the existence of *dominance* or *contagious regions* as those described above, in which a creditor's optimal behavior does not depend on the actions of the other creditors, implies uniqueness of equilibrium. We derive some natural parameter restrictions that guarantee the existence of these dominance regions.

The existence of an *upper dominance* region requires that there be an interval of sufficiently high signals of the probability of success that a creditor's optimal action is to roll over her credit even if all the other active creditors withdraw (i.e., $x = h$). Specifically, if the inequality

$$\frac{(\lambda - h)}{\lambda(1-h)}(1+R)(1-\varepsilon) > 1 \tag{5}$$

holds, then the expected payoff to a creditor who rolls over when her signal is $s > 1 - \varepsilon$ is

$$E(u(P,x)|S=s) \geq E(u(P,h)|S=s) = \frac{\lambda - h}{\lambda(1-h)}(1+R)\,E(P|S=s)$$
$$\geq \frac{\lambda - h}{\lambda(1-h)}(1+R)(1-\varepsilon) > 1; \tag{6}$$

that is, the expected payoff to rolling over is greater than the expected payoff to withdrawing regardless of what the other active creditors do. Hence a creditor getting a signal $s > 1 - \varepsilon$ rolls over. Because $Q > 1$ implies that $1 + R > 1$, the inequality (5) holds when ε is small and λh is sufficiently close h. The difference $\lambda h - h$ is the maximum (negative) externality of withdrawals on the payoff of the creditors who roll over, which is smaller the closer is λ to one and the closer is h to zero.

The existence of a *lower dominance* region requires that there be an interval of sufficiently low signals of the probability of success that a creditor's optimal action is to withdraw even if everyone else rolls over (i.e., $x = 0$). Specifically, if the inequality

$$(1+R)(1-\mu+\varepsilon) < 1 \tag{7}$$

holds, then the expected payoff to a creditor who rolls over when her signal is $s < 1 - \mu + \varepsilon$ is

$$E(u(P,x)|S=s) \leq E(u(P,0)|S=s) = (1+R)\,E(P|S=s)$$
$$\leq (1+R)(1-\mu+\varepsilon) < 1; \tag{8}$$

that is, the expected payoff to withdrawing is greater than the expected payoff to rolling over regardless of what the other active creditors do. Hence a creditor getting

a signal $s < 1 - \mu + \varepsilon$ withdraws. In essence, (7) implies that the return distribution must have a sufficiently wide support to allow for net-present values below 1 even though the *ex ante* expected return of the asset is above 1.

The inequality

$$0 < \varepsilon < \bar{\varepsilon} := \min \left\{ \frac{1}{1+R} - (1-\mu), \, 1 - \frac{\lambda(1-h)}{(1+R)(\lambda-h)} \right\} \tag{9}$$

warrants the existence of the upper and the lower dominance regions, that is, that the inequalities (5) and (7) hold. Note that the existence of the upper dominance region requires the inequality (2) to hold. (In Goldstein and Pauzner 2005, the existence of this region is implied by their assumption that premature liquidations do not reduce asset returns.) It is easy to see that the inequalities $u(1 - \mu, 0) < 1 < u(1, h)$ are implied by conditions (5) and (7), and therefore that the creditors' game has multiple equilibria when $\varepsilon = 0$.

Henceforth we assume that (9), as well as (1) and (2), hold. We show that under these conditions the creditors' game has a unique equilibrium.

3. EQUILIBRIUM OF THE CREDITORS GAME

A simple class of strategies is that of *switching* strategies, whereby a creditor withdraws if her signal is below a *threshold* $t \in [1 - \mu - \varepsilon, 1 + \varepsilon]$ and rolls over otherwise. When all creditors follow the same switching strategy identified by a threshold t, then we denote by τ_t the resulting strategy distribution, which is given by $\tau_t(s) = 1$ if $s < t$, and $\tau_t(s) = 0$ otherwise. Also we write $V(s, t) := U(s, \tau_t)$. Because $\tau_{\hat{t}}(s) \geq \tau_t(s)$ whenever $\hat{t} \geq t$, then $V(s, t)$ is decreasing in t. Moreover, because τ_t is decreasing in s, $P \, | \, S = s'$ first order stochastically dominates $P \, | \, S = s$ whenever $s' > s$, and u is increasing in p and decreasing in x, then $V(s, t)$ is increasing in s. We establish below that $V(t, t)$ (i.e., the restriction of V to the diagonal) is strictly increasing on the interval $[1 - \mu + \varepsilon, 1 - \varepsilon]$. Note that the inequalities (1) and (7) jointly imply that

$$(1 + R)(1 - \mu + \varepsilon) < 1 < Q = (1 + R)(1 - \mu/2),$$

that is,

$$2\varepsilon < \mu.$$

Hence $1 - \mu + \varepsilon < 1 - \varepsilon$, so that the interval $[1 - \mu + \varepsilon, 1 - \varepsilon]$ is nonempty.

For $t \geq 1 - \varepsilon$ the inequality (6) implies

$$V(t, t) = E(u(P, x(P, \tau_t)) | S = t) > 1.$$

Likewise, for $t \le 1 - \mu + \varepsilon$ the inequality (8) implies

$$V(t, t) = E(u(P, x(P, \tau_t))| \, S = t) < 1.$$

Hence there is a unique $t^* \in (1 - \mu + \varepsilon, 1 - \varepsilon)$ such that $V(t^*, t^*) = 1$. Moreover, the strategy distribution τ_{t^*} is an equilibrium: Because V is increasing in s, if

$$V(s, t^*) = U(s, \tau_{t^*}) < 1 = V(t^*, t^*),$$

then $s < t^*$, and therefore $\tau_{t^*}(s) = 1$; and if

$$V(s, t^*) = U(s, \tau_{t^*}) > 1 = V(t^*, t^*),$$

then $s > t^*$ and $\tau_{t^*}(s) = 0$. We establish that in fact τ_{t^*} is the unique equilibrium of the creditors' game.

PROPOSITION 1. *The creditors' game has a unique equilibrium. In equilibrium all creditors follow the same switching strategy. This strategy is identified by the threshold $t^* \in (1 - \mu + \varepsilon, 1 - \varepsilon)$, which uniquely solves the equation $V(t, t) = 1$.*

PROOF. The proof follows the lines of Morris and Shin (1998)'s Lemma 3. Assume that τ is an equilibrium strategy distribution, and define

$$\underline{s} := \inf\{s \mid \tau(s) < 1\},$$

and

$$\bar{s} := \sup\{s \mid \tau(s) > 0\}.$$

Then

$$\bar{s} \ge \sup\{s \mid 0 < \tau(s) < 1\} \ge \inf\{s \mid 0 < \tau(s) < 1\} \ge \underline{s}.$$

Because τ is an equilibrium and U is continuous, then

$$U(\underline{s}, \tau) \ge 1 \ge U(\bar{s}, \tau).$$

Consider the strategy distribution $\tau_{\underline{s}}$. We have $\tau(s) \ge \tau_{\underline{s}}(s)$ for all s, and therefore

$$V(\underline{s}, \underline{s}) = U(\underline{s}, \tau_{\underline{s}}) \ge U(\underline{s}, \tau) \ge 1 = V(t^*, t^*).$$

Because $V(t, t)$ is increasing, then $t^* \le \underline{s}$.

Likewise, consider the strategy distribution $\tau_{\bar{s}}$. We have $\tau_{\bar{s}}(s) \ge \tau(s)$ for all s, and therefore

$$V(\bar{s}, \bar{s}) = U(\bar{s}, \tau_{\bar{s}}) \le U(\bar{s}, \tau) \le 1 = V(t^*, t^*).$$

Because $V(t, t)$ is increasing, then $\bar{s} \le t^*$.

Thus, $\bar{s} = \underline{s} = t^*$, and therefore $\tau(s) = \tau_{t^*}(s)$ for all s. □

We calculate the function $V(s, t)$ on $[1 - \mu + \varepsilon, 1 - \varepsilon]^2$. When all active creditors follow the threshold strategy $t \in [1 - \mu + \varepsilon, 1 - \varepsilon]$, then the expected fraction of active creditors who withdraw is

$$
E\left(\tau_t(S)\mid P = p\right) = \begin{cases} 1 & \text{if } p \in [1 - \mu, t - \varepsilon) \\ \frac{1}{2\varepsilon}\left(t - p + \varepsilon\right) & \text{if } p \in [t - \varepsilon, t + \varepsilon) \\ 0 & \text{if } p \in [t + \varepsilon, 1], \end{cases} \tag{10}
$$

where

$$
\frac{1}{2\varepsilon} \int_{p-\varepsilon}^{t} ds = \frac{1}{2\varepsilon}\left(t - p + \varepsilon\right).
$$

The expected fraction of all creditors who withdraw is $x(p, \tau_t) = h E(\tau_t(S)\mid P = p)$.

If a creditor signal is $s \in [1 - \mu + \varepsilon, 1 - \varepsilon]$, then $P\mid S = s$ is distributed uniformly on $[1 - \mu, 1] \cap [s - \varepsilon, s + \varepsilon] = [s - \varepsilon, s + \varepsilon]$. Therefore her expected payoff if she rolls over is

$$
V(s, t) = \frac{1}{2\varepsilon} \int_{s-\varepsilon}^{s+\varepsilon} u(p, x(p, \tau_t)) dp,
$$

which can be rewritten using (3) as

$$
V(s, t) = \frac{1 + R}{\lambda} \left(\frac{1}{2\varepsilon} \int_{s-\varepsilon}^{s+\varepsilon} p\, dp - (1 - \lambda) \int_{s-\varepsilon}^{s+\varepsilon} \frac{p\, dp}{2\varepsilon\left(1 - x(p, \tau_t)\right)} \right). \tag{11}
$$

Evaluating the integrals in this expression, and setting a creditor's signal equal to the threshold t, we obtain the function $V(t, t)$. This is a tedious task that we relegate to Appendix A. There we show that for $t \in (1 - \mu + \varepsilon, 1 - \varepsilon)$ we have

$$
V(t, t) = \frac{1 + R}{\lambda h}\left(\beta t + \alpha \varepsilon\right), \tag{12}
$$

where

$$
\alpha := -\frac{(1 - \lambda)}{h}\left[2h + (2 - h)\ln\left(1 - h\right)\right],
$$

and

$$
\beta := h + (1 - \lambda)\ln\left(1 - h\right).
$$

In Appendix A we also show that $\alpha > 0$ and $h > \beta > 0$. Hence,

$$
\frac{dV(t, t)}{dt} = \frac{1 + R}{\lambda h}\beta > 0,
$$

that is, $V(t, t)$ is strictly increasing in t.

The *equilibrium threshold* t^* solves $V(t, t) = 1$; that is,

$$t^* = \frac{1}{\beta} \left(\frac{\lambda h}{1 + R} - \alpha \varepsilon \right). \tag{13}$$

Because $t^* \in (1 - \mu + \varepsilon, 1 - \varepsilon)$, then the equilibrium *ex ante* expected fraction of creditors who withdraw x^* is

$$x^* = E(x(P, \tau_{t^*})) = \frac{h}{\mu} \int_{1-\mu}^{1} x(p, \tau_{t^*}) dp.$$

Computing this expression by using equations (4) and (10) we get

$$x^* = \frac{h}{\mu} \left(t^* - (1 - \mu) \right). \tag{14}$$

Note that $x^* \in (h\varepsilon/\mu, h(\mu - \varepsilon)/\mu)$. If we interpret the ratio $[t^* - (1 - \mu)]/\mu = 1 - (1 - t^*)/\mu$ as the *ex ante* limiting probability of a bank run (as $\varepsilon \to 0$), then x^* is the fraction of active creditors times the probability that an agent runs on the bank—see Goldstein and Pauzner (2005). Proposition 2 states these results.

PROPOSITION 2. *The equilibrium threshold is* $t^* = (\lambda h/(1 + R) - \alpha \varepsilon)/\beta$ *and the ex ante expected fraction of creditors who withdraw is* $x^* = h(t^* - (1 - \mu))/\mu$, *where* $\alpha = -(1 - \lambda)[2h + (2 - h) \ln(1 - h)]/h > 0$ *and* $\beta = h + (1 - \lambda) \ln(1 - h) > 0$.

4. TRANSPARENCY, ROLLOVER RISK, AND WELFARE

In this section we study the effect of transparency on *rollover risk,* that is, on the *ex ante* expected fraction of creditors who withdraw x^*, and on *welfare.* In this first pass we continue treating the level of asset risk μ as exogenous, focusing on the effect of transparency on banks' liabilities.

We identify the level of transparency with the precision of creditors' private signals of the probability of success, that is, with the value of ε. Smaller values of ε correspond to greater levels of transparency, and vice versa. Specifically, in our setting a creditor's posterior beliefs about the probability of success upon receiving a signal s is a uniform distribution on the interval $[1 - \mu, 1] \cap [s - \varepsilon, s + \varepsilon]$. Thus, when the precision of creditors' signals increases (i.e., ε decreases) the support of a creditor's posterior belief around her signal shrinks. (The literature on currency crisis, for example, Heinemann and Illig 2002, and Bannier and Heinemann 2005, follows this approach. An alternative approach studies the impact changes in the precision of public information—see, for example, Morris and Shin 2002. We discuss the issue of public information at the end of this section.)

Alternative levels of transparency may result from regulating the information about asset portfolio that a bank must disclose to its creditors. Such disclosures may be privately communicated to the creditors. Regulation may take the form of requirements of information that a bank must (or must not) provide to its creditors, as well as restrictions in the use of the information received by creditors. For simplicity, we assume that the level of transparency can be increased at no cost—see Hyytinen and Takalo (2002) for an analysis of compliance costs of transparency regulation. Our approach allows for a simple and conclusive analysis of the impact of changes in transparency via comparative static exercises.

To evaluate the impact of ε on rollover risk (i.e., on x^*), it is first instructive to study the impact of ε on the fraction of creditors who withdraw for a given p. Taking derivatives in equation (10) reveals that the sign of $\partial x(p, \tau_t)/\partial \varepsilon = h \partial E(\tau_t(S)| P = p)/\partial \varepsilon$ is equal to that of $(p - t)$; that is, the fraction of creditors who withdraw decreases with the level of transparency (i.e., as ε becomes smaller) when the probability of success is high relative to the threshold for withdrawal (i.e., $p > t$), and vice versa. This is intuitive: as ε decreases, choosing the optimal action becomes more likely; that is, a creditor is more likely to roll over (withdraw) when the true value of p is above (below) the threshold t. In this sense, increasing transparency has *procyclical* effects, facilitating refinancing when the prospects of the asset paying return are promising, but impeding refinancing when they are bleak.

The effect of transparency on rollover risk *through the cycle* is given by the derivative $\partial x^*/\partial \varepsilon$. Equation (14) shows that x^* depends on ε only indirectly through t^*. Taking derivatives in (13) we get

$$\frac{\partial t^*}{\partial \varepsilon} = -\frac{\alpha}{\beta} < 0,$$

which shows that the equilibrium threshold t^* increases with the level of transparency; that is, the more precise are the creditors' signals (i.e., the smaller is ε), the larger is the creditors' equilibrium threshold. Then, equation (14) immediately implies that

$$\frac{\partial x^*}{\partial \varepsilon} = \frac{h}{\mu} \frac{\partial t^*}{\partial \varepsilon} < 0.$$

Hence the *ex ante* expected fraction of creditors who withdraw increases with the level of transparency; that is, the more precise are the creditors' signals, the larger is rollover risk x^*. We state this result in Proposition 3.

PROPOSITION 3. *Given the level of asset risk μ, increasing the level of transparency (i.e., decreasing ε) increases rollover risk (i.e., increases x^*).*

Proposition 3 is a direct implication of the fact that $V(t, t)$ is increasing in ε—see equation (12). The intuition of this property is as follows: because increasing transparency shrinks the support of creditors' private signals around the true value of p, it reduces the probability that a creditor mistakenly withdraws as well as the probability that a creditor mistakenly rolls over. Hence increasing transparency

decreases (increases) the fraction of creditors who withdraw $x(p, \tau_t)$ when the prospects of the asset paying its return are good (bad) and therefore has a pro-cyclical effect on the payoff to rolling over, that is, $u(p, x)$ decreases (increases) with ε when p is large (small). Because the fraction of creditors who withdraw $x(p, \tau_t)$ is smaller when the prospects of the asset paying its return are good than when they are bad, and because the negative externality of withdrawals is larger the larger is x (recall that $\partial^2 u(p, x)/\partial x^2 < 0$), then the negative effect of transparency on the payoff to rolling over is more pronounced than the positive effect. Thus, over the cycle, an increase in transparency causes a decrease of the payoff to rolling over, and hence leads creditors to optimally raise their threshold to roll over.

Although our results on the effect of transparency are seemingly at odds with those of Heinemann and Illig (2002), who show that increasing transparency unambiguously reduces the probability of a currency crisis, the economic mechanism operating in both settings is analogous: in their setting, speculators' expected payoff to attacking the peg is a decreasing and a convex function of the underlying state. Increasing transparency shrinks the range of possible state of fundamentals and reduces the expected payoff to attacking the peg.

The equilibrium fraction of creditors who roll over, $1 - x^*$, may also be interpreted as a measure of creditors' *confidence* on banks. By Proposition 3, increasing transparency has a negative effect on creditors' confidence. The comparative statics of creditors' confidence with respect to other exogenous parameters, such as λ and h, are complex. However, it is straightforward to show that $\partial^2 x^*/\partial \varepsilon \partial \lambda > 0$; that is, the larger the liquidation value of the asset, the smaller is the negative impact of transparency on creditors' confidence. This again hinges on the absolute value of the derivative $\partial^2 u(p, x)/\partial x^2$, which is proportional to $1 - \lambda$.

Let us now study the impact of transparency on welfare given the asset's risk. Because the bank pays to its creditors the entire asset returns, a measure of social welfare is simply the sum of creditors' *ex ante* expected payoffs and is therefore given by

$$W(\varepsilon, \mu) = E\left[x(P, \tau_{t^*}) + \left(1 - \frac{x(P, \tau_{t^*})}{\lambda} \right) (1 + R)P \right] \tag{15}$$

$$= x^* + (1 + R) \left(E(P) - \frac{E\left(x(P, \tau_{t^*})P \right)}{\lambda} \right).$$

Here $x(p, \tau_{t^*})$ is the total payoff to the creditors who withdraw and get their monetary unit, and $(1 - x(p, \tau_{t^*})/\lambda)(1 + R)p$ is the return of the nonliquidated assets, which is also the total payoff of the creditors who roll over.

For $t \in [1 - \mu + \varepsilon, 1 - \varepsilon]$, we have

$$E[x(P, \tau_t)P] = \frac{h}{\mu} \left(\int_{1-\mu}^{t-\varepsilon} p \, dp + \frac{1}{2\varepsilon} \int_{t-\varepsilon}^{t+\varepsilon} (t - p + \varepsilon) \, p \, dp \right)$$

$$= \frac{h}{6\mu} \left(3t^2 + \varepsilon^2 - 3(1 - \mu)^2 \right).$$

Thus, using (14) and $E(P) = 1 - \mu/2$ we may write (15) as

$$
W(\varepsilon, \mu) = \frac{h}{\mu}\left(t^* - (1 - \mu)\right)
$$

$$
+ (1 + R)\left(1 - \frac{\mu}{2} - \frac{h}{6\lambda\mu}\left(3t^{*2} + \varepsilon^2 - 3(1 - \mu)^2\right)\right).
$$

Clearly, for a given t^*, social welfare is increasing in the level of transparency. As we have shown, however, an increase in the level of transparency raises the creditors' threshold to rolling over. Therefore the optimal level of transparency trades off the *direct effect* of ε on W and its *indirect effect* through t^*.

We have

$$
\frac{\partial W}{\partial \varepsilon} = \frac{h}{\mu}\left(1 - \frac{(1 + R)}{\lambda}t^*\right)\frac{\partial t^*}{\partial \varepsilon} - \frac{(1 + R)h\varepsilon}{3\lambda\mu} \tag{16}
$$

$$
= -\frac{h}{\mu}\left(1 - \frac{h}{\beta} + \frac{(1 + R)}{\lambda\beta}\alpha\varepsilon\right)\frac{\alpha}{\beta} - \frac{(1 + R)h\varepsilon}{3\lambda\mu}
$$

$$
= \frac{h}{\mu}(a - b\varepsilon),
$$

where

$$
a = \frac{(h - \beta)\alpha}{\beta^2},
$$

and

$$
b = \frac{(1 + R)}{\lambda}\left(\frac{\alpha^2}{\beta^2} + \frac{1}{3}\right) > 0.
$$

Also we have

$$
\frac{\partial^2 W}{\partial \varepsilon^2} = -\frac{hb}{\mu} < 0,
$$

that is, W is a concave function of ε.

Because $0 < \beta < h$ and $\alpha > 0$, then $a > 0$. Hence $\partial W/\partial \varepsilon > 0$, when ε is smaller than a/b. In particular, $\partial W/\partial \varepsilon > 0$ near $\varepsilon = 0$. And $\partial W/\partial \varepsilon < 0$ for ε larger than a/b. That is, when creditors' signals are very noisy, social welfare increases with the level of transparency. When creditors' signals are sufficiently precise, however, social welfare decreases with the level of transparency. Hence maximal transparency is not socially optimal. We summarize these findings in Proposition 4.

PROPOSITION 4. *Given the level of asset risk μ, the socially optimal level of transparency is $\varepsilon^* = a/b > 0$. Thus, maximal transparency is not socially optimal.*

Even though an increase in the level of transparency increases rollover risk by Proposition 3, it reduces creditors' mistakes, thus fostering efficient liquidation when the realized value of p is low, that is, when $p \leq \lambda/(1 + R)$, and discouraging inefficient liquidation when p is high. These counterbalancing effects favor an intermediate level of transparency $\varepsilon^* = a/b$.

In our setting, it can be shown that $\varepsilon^* < \bar{\varepsilon}$ if, for example, λ is sufficiently close to one. Recall that we have assumed that $0 < \varepsilon < \bar{\varepsilon}$ to guarantee uniqueness of equilibrium—see condition (9) . If $\varepsilon^* > \bar{\varepsilon}$, then multiple equilibria may arise as the banking system becomes vulnerable to self-fulfilling crises. Thus, even though maximum transparency is not socially optimal, a low level of transparency may also be undesirable because self-fulfilling crises may arise. In the literature, this rationale has suggested regulation to warrant a sufficiently high level of transparency to prevent these self-fulfilling crises from arising—see, for example, Rochet and Vives (2004). Thus, this argument may favor a more transparent banking system than that implied by ε^*.

4.1 Transparency and Public Information

An alternative approach followed in the literature studies the impact of changes in the precision of public information—see, for example, Morris and Shin (2002), Angeletos and Pavan (2004), and Svensson (2006). Although we focus on the precision of private information, it is easy to accommodate a public signal into our model. Assume that the creditors observe a conditionally independent public signal $Y = P + W$, where W is distributed uniformly on $[-\delta, \delta]$. Upon observing the realization of this public signal y, in the creditors' game it becomes common knowledge that the probability of success lies in the interval $[\underline{z}(y, \delta), \bar{z}(y, \delta)] = [1 - \mu, 1] \cap [y - \delta, y + \delta]$, where $\bar{z}(y, \delta) = \min\{1, y + \delta\}$ and $\underline{z}(y, \delta) = \max\{1 - \mu, y - \delta\}$.

When the public signal is very precise (i.e., when δ is small), then the creditors game may fail to have one or both dominance regions, and therefore multiple equilibria may reappear. When the public signal is sufficiently imprecise that the support of creditors' beliefs upon receiving the public signal contains an upper and a lower dominance region, as we postulate in Section 3, then uniqueness of equilibrium is preserved—see Hellwig (2002) on this issue.

In either case, in the interior symmetric equilibrium of the creditors' game the equilibrium threshold t^* lies in the interval $[\underline{z}(y, \delta) - \varepsilon, \bar{z}(y, \delta) + \varepsilon]$—see Appendix B— and its value is given by Proposition 2 independently of the realization of the public signal y and its precision δ. However, the expected fraction of creditors who withdraw given the public signal, and the creditors' welfare depend on y and δ. Specifically, increasing the precision of the public signal (i.e., decreasing δ) has opposite (interim) effects when the public signal of the prospects of the asset paying its return are good and when they are bad. See, for example, Prati and Sbracia (2010) for a discussion on this issue in the context of a currency crisis model.

5. ASSET RISK

Let us consider the problem of a bank that chooses the level of risk μ. We assume that the set of feasible values of μ is an interval I with a nonempty interior, and that condition (9) holds on I. This assumption implies existence and uniqueness of equilibrium, and therefore that the creditors equilibrium payoffs are well defined on I. Also we assume that the return conditional on success is strictly increasing with the level of risk:

$$R'(\mu) > 0.$$

That is, lower probabilities of success are associated with higher rates of return conditional on success—recall that $E(P(\mu))$ is decreasing in μ. This assumption is standard and provides scope for the possibility that the mean asset return function,

$$Q(\mu) = [1 + R(\mu)]E(P(\mu)),$$

is increasing, decreasing, or even constant. Cordella and Yeyati (1998) and Matutes and Vives (2000), for example, assume that Q is a mean preserving spread (i.e., that Q is constant, so that $Q'(\mu) = 0$). Our numerical example of Section 7 illustrates our results for a mean return function Q that is increasing for low values of μ and decreasing for high values of μ, and hence is concave as in, for example, Blum (2002).

Competition forces the bank to choose the level of asset risk μ that maximizes the *ex ante* expected payoff of a creditor, which coincides with the sum of the creditors *ex ante* expected payoffs $W(\varepsilon, \mu)$—see equation (15). Thus, in a perfect Bayesian equilibrium μ^* solves the problem

$$\max_{\mu \in I} W(\varepsilon, \mu).$$

We proceed under the assumption that the solution to this problem is interior, that is, we assume that the banks' asset risk choice $\mu^* \in I$ solves the equation

$$\frac{\partial W}{\partial \mu} = 0,$$

and that W satisfies the second-order sufficient condition for welfare maximization

$$\frac{\partial^2 W}{\partial \mu^2} \leq 0. \tag{17}$$

(If μ^* were a corner solution, then transparency would have no impact on the banks' asset risk choice).

Let us consider the impact of transparency on the level of risk μ^*. Because in an interior equilibrium the level of asset risk μ^* solves $\partial W/\partial \mu = 0$, we have

$$\frac{\partial^2 W}{\partial \mu^2} d\mu + \frac{\partial^2 W}{\partial \mu \partial \varepsilon} d\varepsilon = 0,$$

and therefore

$$\frac{d\mu^*}{d\varepsilon} = \frac{\partial^2 W}{\partial \mu \partial \varepsilon} \left(-\frac{\partial^2 W}{\partial \mu^2} \right)^{-1}.$$

Moreover, because $\partial^2 W/\partial \mu^2 < 0$, then

$$sign\left(\frac{d\mu^*}{d\varepsilon} \right) = sign\left(\frac{\partial^2 W}{\partial \mu \partial \varepsilon} \right).$$

By Young's theorem, we have

$$\frac{\partial^2 W}{\partial \mu \partial \varepsilon} = \frac{\partial^2 W}{\partial \varepsilon \partial \mu}.$$

Differentiating (16) with respect to μ we get

$$\frac{\partial^2 W}{\partial \varepsilon \partial \mu} = -\frac{h}{\mu^2}(a - b\varepsilon) - \frac{h\varepsilon}{\mu}\frac{\partial b}{\partial \mu} = -\frac{h}{\mu^2}(a - b\varepsilon) - \frac{h\varepsilon}{\mu}\frac{R'}{\lambda}\left(\frac{\alpha^2}{\beta^2} + \frac{1}{3} \right).$$

$$(18)$$

Because $R' > 0$, then the second term on the RHS of (18) is negative. As for the first term, it is negative for $\varepsilon < a/b$, and it is positive for $\varepsilon > a/b$. Thus, if $\varepsilon \leq a/b$, then $\partial^2 W/\partial \varepsilon \partial \mu < 0$, whereas if $\varepsilon > a/b$, then the sign $\partial^2 W/\partial \varepsilon \partial \mu$ is ambiguous.

Therefore if the level of transparency decreases toward the socially optimal level, that is, if ε approaches a/b from below, then risk taking increases; that is, $d\mu^*/d\varepsilon < 0$ on $(0, a/b]$. In particular, if ε is around its optimal value of a/b, then risk taking increases with the level of transparency. However, if ε is well above its optimal value, then the impact on risk taking of increasing transparency toward the socially optimal level is ambiguous. We state these results in Proposition 5.

PROPOSITION 5. *Banks' asset risk taking increases with the level of transparency above and around the socially optimal level. For levels of transparency sufficiently low, however, the impact of transparency on risk taking is ambiguous.*

Because a competitive bank chooses the level of asset risk to maximize the welfare of its creditors, the effect of changes in the level of transparency on the bank's asset risk choice are explained by their effects on welfare. An increase in the level of transparency has a direct positive effect on social welfare: Given the threshold to rolling over, a decrease in ε decreases creditors' mistakes, promoting efficient

liquidation of assets when the realized value of p is low and preventing inefficient liquidation when p is high—see equation (16). However, an increase in the level of transparency also has an indirect effect on welfare because it makes creditors less willing to roll over (recall that $\partial t^*/\partial \varepsilon < 0$ by Proposition 3), which increases the level of asset liquidation for any given value of p. Without imposing additional assumptions, we cannot sign this indirect effect on welfare via asset liquidation.

When the level of transparency is high (i.e., $\varepsilon < a/b$), an increase in the level of transparency has a negative total effect on welfare (i.e., $\partial W/\partial \varepsilon < 0$—see equation (16)). Therefore the indirect effect on welfare is negative (and of a magnitude greater than that of the direct effect); that is, increasing transparency leads to too much liquidation. The bank takes *more* risk to compensate this excessive liquidation: Differentiating equation (13), we observe that

$$\frac{\partial t^*}{\partial \mu} = -\frac{\lambda h R'}{\beta (1 + R)^2} < 0, \tag{19}$$

that is, the creditors' threshold to rolling over decreases with asset risk. This effect arises because the asset return at maturity conditional on success increases with the level of risk (i.e., $R' > 0$), and therefore the expected payoff to rolling over increases with asset risk for a given p and x—see equation (3).

When the level of transparency is low (i.e., $\varepsilon > a/b$), however, an increase in the level of transparency has a positive total effect on welfare. Therefore we cannot sign the indirect effect and cannot tell if the change in the level of transparency calls for more or less risk taking. Nevertheless, even for low levels of transparency the bank's asset risk may increase with the level of transparency because the second term on the RHS of (18) is negative. In particular, it can be shown that if the elasticity of asset returns R with respect to the level of risk μ is above certain bound (which is below one), then $d\mu^*/d\varepsilon < 0$ for all feasible levels of ε. Intuitively, the more sensitive is the asset return to the level of risk, the stronger are the bank's incentives to take more risk to reduce the creditors' threshold to rollover, as indicated by equation (19).

The impact of changes in the level of transparency on the level of rollover risk x^* is now twofold: there is a *direct effect* on a bank's rollover risk given its asset risk choice, and an *indirect effect* through its influence on the bank's asset risk choice; that is,

$$\frac{dx^*}{d\varepsilon} = \frac{\partial x^*}{\partial \varepsilon} + \frac{\partial x^*}{\partial \mu} \frac{d\mu^*}{d\varepsilon}.$$

By Proposition 3, the direct effect $\partial x^*/\partial \varepsilon$ is negative. As for the sign of the indirect effect, in view of Proposition 5, let us assume that $d\mu^*/d\varepsilon \leq 0$. Differentiating (14) with respect to μ yields

$$\frac{\partial x^*}{\partial \mu} = \frac{h}{\mu^2} \left(1 - t^* (1 + \eta)\right),$$

where

$$\eta := -\frac{\partial t^*}{\partial \mu} \frac{\mu^*}{t^*}$$

is the elasticity of the equilibrium threshold with respect to the asset risk. Note from (19) that η is positive. Because $t^* \in (1 - \mu + \varepsilon, 1 - \varepsilon)$ by Proposition 1, then $1 - t^* > 0$. However, the sign $1 - t^*(1 + \eta)$ is ambiguous and, by implication, the sign of the indirect effect $\partial x^*/\partial \mu$ is ambiguous too. If η is small, then $\partial x^*/\partial \mu > 0$, and the sign of the indirect effect and total effect are negative. We state these results in Proposition 6.

PROPOSITION 6. *If the elasticity of the equilibrium threshold with respect to asset risk is sufficiently small, then increasing the level of transparency around and above its socially optimal level increases rollover risk. Otherwise, the effect of changes in the level of transparency on rollover risk is ambiguous.*

Transparency has potentially ambiguous effects on rollover risk because the impact of asset risk taking on withdrawals is ambiguous. Increasing transparency may lead banks to increase the level of risk, which has two opposite effects on withdrawals: it makes more likely that creditors get low signals of the probability of success p, but also decreases the equilibrium threshold to roll over—see (19). The net effect on withdrawals of changes in the level of risk (i.e., the sign of $\partial x^*/\partial \mu$) depends on the elasticity of the equilibrium threshold with respect to the level of asset risk.

6. WELFARE ANALYSIS

Let us reconsider the impact of changes in the level of transparency on welfare accounting for the change it induces on the level of asset risk. Given the level of transparency ε social welfare is given by

$$W^*(\varepsilon) = W(\varepsilon, \mu^*(\varepsilon)),$$

where $\mu^*(\varepsilon)$ is the bank's risk choice given ε. Thus,

$$\frac{dW^*}{d\varepsilon} = \frac{\partial W}{\partial \varepsilon} + \frac{\partial W}{\partial \mu} \frac{\partial \mu^*}{\partial \varepsilon}.$$

Because $\mu = \mu^*$ maximizes $W(\varepsilon, \mu)$ given ε, the Envelope Theorem implies that

$$\frac{dW^*}{d\varepsilon} = \frac{\partial W}{\partial \varepsilon}.$$

Thus, the marginal impact of changes of the level of transparency on welfare are the same as in the version of the model where μ is exogenous. Therefore the results

established in Proposition 4 above apply with no change. In particular, maximal transparency is not socially optimal.

Because in our setting there is no conflict of interests between the bank and its creditors, one may argue that competitive pressure may force the bank to choose the socially optimal level of transparency as well as the socially optimal level of asset risk, which suggests that there is no need for regulating the level of transparency. Nonetheless, a bank's decisions may have welfare implications beyond their direct effects on its creditors. In particular, the failure of a bank may have social costs beyond the costs it imposes on its creditors. For example, depriving some agents of banking services may lead to a misallocation of savings and investments or may constrain the credit available to borrowers in the real sector. Moreover, banks' investments may generate social returns in addition to private returns. Also, bank failures may be contagious and lead to a credit crunch. The existence of these externalities may lead to a misalignment of the objectives of banks and those of society.

Consider a social welfare function $\hat{W}^*$ that accounts for these externalities,

$$\hat{W}^*(\varepsilon) = W^*(\varepsilon) - \gamma[1 - E(P(\mu^*))].$$

In this expression, the term $\gamma[1 - E(P(\mu^*))]$, with $\gamma > 0$, captures the external social cost of a bank's failure, as in, for example, Matutes and Vives (2000) and Freixas, Lóránth, and Morrison (2007).

Because $dW^*/d\varepsilon = \partial W/\partial \varepsilon$, as shown above, we have

$$\frac{d\hat{W}^*(\varepsilon)}{d\varepsilon} = \frac{\partial W}{\partial \varepsilon} - \frac{\gamma}{2}\frac{d\mu^*}{d\varepsilon}. \tag{20}$$

Because W^* increases and μ^* decreases with ε on $(0, a/b)$ by Propositions 4 and 5, then the RHS of (20) is strictly increasing at least on $(0, a/b)$. Furthermore, around $\varepsilon = a/b$ the first term on the RHS is zero, but the second term is positive. Hence, when the social cost of bank failures are taken into account, social welfare $\hat{W}^*$ increases with ε beyond a/b. That is, when we account for the social cost of bank failures, the socially optimal level of transparency is smaller than when only the private interests of creditors are taken into account. This result is stated in Proposition 7.

PROPOSITION 7. *If bank failures have negative social externalities, in addition to their direct effect on creditors payoffs, then the socially optimal level of transparency is below the level that is optimal when such externalities are absent.*

The policy implications of Proposition 7 are strong: to the extent that bank failures call for transparency regulation, this regulation should result in a more opaque rather than a more transparent banking system.

7. A NUMERICAL EXAMPLE

We compute a numerical example that verifies the compatibility of our parameter assumptions and show how to use the model to calculate the socially optimal level of transparency.

Despite its apparent complexity, our model is parsimonious in that the primitives are just the liquidation cost, λ, the fraction of active creditors, h, and the return function, $R(\mu)$. It is not obvious which range of values for λ we should postulate because in practice the liquidation value of an asset may depend upon the realized state (it may be low if it is the result of a firesale in a recession, but large if the asset is traded in a booming market) and on its specific nature (e.g., loans to high-tech start-ups may have a low liquidation value, whereas prime mortgage loans may have a high one). As for the fraction of active creditors h, we may identify it with the share of short-term debt relative to the banks' total external debt or total liabilities, which also varies wildly. We therefore postulate values for these parameters that we deem as reasonable, but certainly there are other interesting values to try.

In our numerical example we set up $\lambda = 2h = 3/4$, and postulate a linear return function, $R(\mu) = \mu$. Hence the expected return function,

$$Q(\mu) = (1 + R(\mu)) \left(1 - \frac{\mu}{2}\right) = 1 + \frac{1}{2}\mu(1 - \mu),$$

is increasing on $(0, 1/2)$, decreasing on $(1/2, 1)$, and is maximized at $\mu = 1/2$. (Thus, Q is concave as in Blum 2002). Note that

$$Q(\mu) > 1 > \lambda > h > 0,$$

holds as required.

Using the values of λ and h, we calculate α and β. Then we use these values and the function R to calculate the equilibrium threshold t^* and, ignoring condition (9), the socially optimal level of transparency $\varepsilon^* = a/b$, which is a function of the level of risk μ. Substituting these values in (15) we obtain the welfare function $W(\varepsilon^*, \mu)$ that is maximized at $\mu^* \approx 0.64738$. For this level of asset risk μ^* condition (9) yields the bound $\bar{\varepsilon} \approx 0.24122 > \varepsilon^* \approx 0.022112$. Thus, equilibrium is unique for a broad range of values of $\varepsilon \in (0, \bar{\varepsilon})$ around ε^*.

8. CONCLUSION

Our main conclusion, that an intermediate level of transparency is socially optimal, suggests that calls for maximal transparency are not justified. The optimality of an intermediate level of transparency results from trading off its opposing effects: increasing transparency fosters efficient liquidation, but also increases rollover risk given the level of asset risk. Banks may compensate this adverse effect on rollover

risk by taking more risk. (This is the case at least when the level of transparency is above and around its socially optimal level. When transparency is sufficiently below the socially optimal level the effect of changes in the level transparency on risk taking is ambiguous.) Some of these effects have been considered in the literature to argue in favor and against increasing bank transparency, rendering an inconclusive debate—see Goldstein and Sapra (2013) and Landier and Thesmar (2013). Our analysis shows that effects of transparency on risk taking are complex and suggests that assessing the socially optimal level of transparency requires a quantitative exercise. Moreover, in a competitive banking sector regulating transparency may be necessary only when there are social costs or social externalities associated to bank failures. When this is the case, regulation is required to reduce the level of transparency below the level that is socially optimal in the absence of these externalities.

In our model, the negative externality imposed by the creditors who withdraw their short-term debt on the creditors who roll over plays a key role. Although this externality of short-term debt is a fundamental ingredient in most models of banking, there are other features that may be important in shaping the impact of transparency. Specifically, the literature has shown that limited liability, asset substitution, deposit insurance, fund diversification, or ex-post renegotiation may endogenously generate a conflict of interest between a bank and its creditors. Introducing such features in our model would certainly alter the welfare effects of changes in the level of transparency. Thus, our conclusions about the potential detrimental effect of transparency on social welfare should be taken cautiously.

Other interesting topics of future research include the role of the agency problem posed by the conflict of interests among insiders (management and controlling shareholders) and outside creditors (short-term creditors and small investors), see Vauhkonen (2010), as well as the effects of transparency on contagion, see Chen and Hasan (2006) and Giannetti (2007), and the incentives for private information acquisition, see Hellwig and Veldekamp (2009) and He and Manela (2014).

APPENDIX A: CALCULATING $V(t, t)$

In this appendix, we calculate the function $V(s, t)$ for $s, t \in (1 - \mu + \varepsilon, 1 - \varepsilon)$. As established in (11) in the main text

$$V(s, t) = \frac{1 + R}{\lambda} \left(\frac{1}{2\varepsilon} \int_{s-\varepsilon}^{s+\varepsilon} p\, dp - (1 - \lambda) \int_{s-\varepsilon}^{s+\varepsilon} \frac{p\, dp}{2\varepsilon \left(1 - x(p, \tau_t)\right)} \right).$$

We have

$$\frac{1}{2\varepsilon} \int_{s-\varepsilon}^{s+\varepsilon} p\, dp = s.$$

For p and t satisfying $p - \varepsilon < t < p + \varepsilon$ we have

$$2\varepsilon \left(1 - x(p, \tau_t)\right) = 2\varepsilon \left(1 - \frac{h(t - p + \varepsilon)}{2\varepsilon}\right) = c + hp,$$

where

$$c := 2\varepsilon - h(t + \varepsilon).$$

Also we have

$$\int \frac{p\,dp}{2\varepsilon\left(1 - x(p, \tau_t)\right)} = \frac{p}{h} - \frac{c}{h^2} \ln\left(c + hp\right) + \text{constant}.$$

Assume that $s > t$. For $p \in (t + \varepsilon, s + \varepsilon)$ equation (4) yields $x(p, \tau_t) = 0$. Also, because $p - \varepsilon < t < p + \varepsilon$ for $p \in (s - \varepsilon, t + \varepsilon)$, we may write

$$\frac{1}{2\varepsilon} \int_{s-\varepsilon}^{s+\varepsilon} \frac{p\,dp}{1 - x(p, \tau_t)} = \int_{s-\varepsilon}^{t+\varepsilon} \frac{p\,dp}{2\varepsilon\left(1 - x(p, \tau_t)\right)} + \frac{1}{2\varepsilon} \int_{t+\varepsilon}^{s+\varepsilon} p\,dp$$

$$= -\frac{1}{h^2} \left[c \ln\left(c + hp\right) - hp\right]_{s-\varepsilon}^{t+\varepsilon} + \frac{1}{2\varepsilon} \int_{t+\varepsilon}^{s+\varepsilon} p\,dp$$

$$= -\frac{1}{h^2} \left(c \ln \frac{c + h(t + \varepsilon)}{c + h(s - \varepsilon)} - h(t + \varepsilon) + h(s - \varepsilon)\right)$$

$$+ \frac{1}{4\varepsilon}(s - t)(s + t + 2\varepsilon).$$

Hence

$$V(s, t) = \frac{1 + R}{\lambda} \left(s - \frac{(1 - \lambda)(s - t)(s + t + 2\varepsilon)}{4\varepsilon}\right)$$

$$+ \frac{(1 + R)(1 - \lambda)}{\lambda h^2} \left(c \ln \frac{c + h(t + \varepsilon)}{c + h(s - \varepsilon)} - h(t + \varepsilon) + h(s - \varepsilon)\right).$$

Assume that $s < t$. For $p \in (s - \varepsilon, t - \varepsilon)$ equation (4) yields $x(p, \tau_t) = h$. Also because $p - \varepsilon < t < p + \varepsilon$ for $p \in (t - \varepsilon, s + \varepsilon)$, then we may write

$$\frac{1}{2\varepsilon} \int_{s-\varepsilon}^{s+\varepsilon} \frac{p\,dp}{1 - x(p, \tau_t)} = \frac{1}{2\varepsilon} \int_{s-\varepsilon}^{t-\varepsilon} \frac{p\,dp}{1 - h} + \int_{t-\varepsilon}^{s+\varepsilon} \frac{p\,dp}{2\varepsilon\left(1 - x(p, \tau_t)\right)}$$

$$= -\frac{(s - t)(s + t - 2\varepsilon)}{4\varepsilon(1 - h)} - \frac{1}{h^2} \left[c \ln\left(c + hp\right) - hp\right]_{t-\varepsilon}^{s+\varepsilon}$$

$$= -\frac{(s - t)(s + t - 2\varepsilon)}{4\varepsilon(1 - h)}$$

$$- \frac{1}{h^2} \left(c \ln \frac{c + h(s + \varepsilon)}{c + h(t - \varepsilon)} - h(s + \varepsilon) + h(t - \varepsilon)\right).$$

Hence

$$V(s, t) = \frac{1 + R}{\lambda} \left(s + \frac{(1 - \lambda)(s - t)(s + t - 2\varepsilon)}{4\varepsilon(1 - h)} \right)$$
$$+ \frac{(1 + R)(1 - \lambda)}{\lambda h^2} \left(c \ln \frac{c + h(s + \varepsilon)}{c + h(t - \varepsilon)} - h(s + \varepsilon) + h(t - \varepsilon) \right).$$

When the signal of the creditor coincides with the threshold, that is, $s = t$, then $c + h(s + \varepsilon) = 2\varepsilon$ and $c + h(s - \varepsilon) = 2\varepsilon(1 - h)$, and the expected payoff becomes

$$V(t, t) = \frac{1 + R}{\lambda h} \Big\{ [h + (1 - \lambda) \ln(1 - h)] t$$
$$- \varepsilon(1 - \lambda) \left[2 + \frac{2 - h}{h} \ln(1 - h) \right] \Big\}.$$

Define

$$\alpha := -[2h + (2 - h) \ln(1 - h)](1 - \lambda) / h$$

and

$$\beta := h + (1 - \lambda) \ln(1 - h).$$

We can then rewrite $V(t, t)$ as

$$V(t, t) = \frac{1 + R}{\lambda h} (\beta t + \alpha \varepsilon),$$

which is equation (12) in Section 3.

We show that $0 < \beta < h$. Because $1 > \lambda > h > 0$, then $(1 - \lambda) \ln(1 - h) < 0$ and therefore $\beta < h$. And because

$$\frac{\partial \beta}{\partial h} = \frac{\lambda - h}{1 - h} > 0,$$

and $\beta = 0$ for $h = 0$, then $\beta > 0$.

We show that $\alpha > 0$. Because $1 > \lambda > h > 0$, then $(1 - \lambda) / h > 0$. Moreover, for $h > 0$ we have

$$\frac{\partial}{\partial h} (2h + (2 - h) \ln(1 - h)) = -\frac{h + (1 - h) \ln(1 - h)}{1 - h} < 0.$$

(Showing that the numerator is positive is analogous to proving that $\beta > 0$). Hence

$$2h + (2 - h) \ln(1 - h) < 0,$$

and therefore

$$\alpha = -\left(2h + (2-h)\ln(1-h)\right)\frac{1-\lambda}{h} > 0.$$

APPENDIX B: CREDITORS' POSTERIOR BELIEFS

We calculate a creditor's posterior belief upon receiving a private signal S of the probability of success P. Let P and T be two independent random variables distributed uniformly on $[1-\mu, 1]$ and $[-\varepsilon, \varepsilon]$, respectively, with $\varepsilon \in \mathbb{R}_+$, $\mu \in (0,1)$ and, as implied by our parameter assumptions, $2\varepsilon < \mu$. Then the density of (P, T) is

$$f_{P,T}(p,t) = f_P(p)f_T(t) = \frac{I_{(1-\mu,1)}(p)I_{(-\varepsilon,\varepsilon)}(t)}{2\mu\varepsilon}.$$

Define $S = P + T$. the support of (P, S) is

$$\mathcal{D} := \left\{(p,s) \in \mathbb{R}^2 \mid p \in [1-\mu, 1], s \in [p-\varepsilon, p+\varepsilon]\right\}$$

and its density is

$$f_{P,S}(p,s) = \det(J)\, f_{P,T}(p, s-p)I_{\mathcal{D}}(p,s) = \frac{I_{\mathcal{D}}(p,s)}{2\mu\varepsilon},$$

where J is the Jacobian of the transformation, which is given by

$$J = \begin{pmatrix} \frac{\partial p}{\partial p} & \frac{\partial p}{\partial s} \\ \frac{\partial w}{\partial p} & \frac{\partial w}{\partial s} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1 & 1 \end{pmatrix}.$$

The density of S is

$$f_S(s) = \frac{1}{2\mu\varepsilon}\int_{1-\mu}^{1} I_{\mathcal{D}}(p,s)dp.$$

Finally, the density of $P \mid S$ is $f_{P|S}(p,s) = f_{P,S}(p,s)/f_S(s)$; that is, $P \mid S = s$ is uniformly distributed on $[1-\mu, 1] \cap [s-\varepsilon, s+\varepsilon]$.

We calculate a creditor's posterior belief upon receiving the private signal S and an additional public signal Y. Let W be a random variable distributed uniformly on $(-\delta, \delta)$ and independent of P and T. The density of (P, T, W) is

$$f_{P,T,W}(p,t,w) = f_P(p)f_W(t)f_Z(w) = \frac{I_{(1-\mu,1)}(p)I_{(-\varepsilon,\varepsilon)}(t)I_{(-\delta,\delta)}(w)}{4\mu\varepsilon\delta}.$$

Define $Y = P + W$, and $S = P + T$. Then the support of (P, Y, S) is

$$\mathcal{E} := \left\{(p,y,s) \in \mathbb{R}^3 \mid p \in [1-\mu, 1], y \in [p-\delta, p+\delta], s \in [p-\varepsilon, p+\varepsilon]\right\},$$

and its density is

$$f_{P,Y,S}(p, y, s) = \det(\hat{J}) f_{P,T,W}(p, y - p, s - p) I_{\mathcal{E}}(p, y, s) = \frac{I_{\mathcal{E}}(p, y, s)}{4\mu\varepsilon\delta},$$

where $\hat{J}$ is the Jacobian of the transformation, which is given by

$$\hat{J} = \begin{pmatrix} \frac{\partial p}{\partial p} & \frac{\partial p}{\partial y} & \frac{\partial p}{\partial s} \\ \frac{\partial t}{\partial p} & \frac{\partial t}{\partial y} & \frac{\partial t}{\partial s} \\ \frac{\partial w}{\partial p} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial s} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ -1 & 0 & 1 \\ -1 & 1 & 0 \end{pmatrix}.$$

Hence

$$f_{Y,S}(y, s) = \frac{1}{4\mu\varepsilon\delta} \int_{1-\mu}^{1} I_{\mathcal{E}}(p, y, s) dp = \frac{1}{4\mu\varepsilon\delta} \int_{1-\mu}^{1} I_{(\underline{z},\bar{z})}(p) dp = \frac{\max\{\bar{z} - \underline{z}, 0\}}{4\mu\varepsilon\delta}.$$

where $\underline{z} := \min\{1, y + \delta, s + \varepsilon\} \leq \bar{z} = \max\{1 - \mu, y - \varepsilon, s - \varepsilon\}$, and $[\underline{z}, \bar{z}] = [1 - \mu, 1] \cap [y - \delta, y + \delta] \cap [s - \varepsilon, s + \varepsilon]$ whenever $\bar{z} \leq \underline{z}$. For $p \in [\underline{z}, \bar{z}]$, the density of $P \mid Y, S$ is

$$f_{P|Y,S}(p, y, s) = \frac{f_{P,Y,S}(p, y, s)}{f_{Y,S}(y, s)} = \frac{1}{\bar{z} - \underline{z}},$$

that is, $P \mid Y = y, S = s$ is uniformly distributed on $[\underline{z}, \bar{z}]$.

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