The Design of Credit Information Systems*

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Abstract

We examine large credit markets with borrower moral hazard and bounded records. Defaulters should be temporarily excluded in order to incentivize repayment, but lending to defaulters who are the verge of rehabilitation is profitable. With perfect bounded information, defaulter exclusion unravels and lending cannot be sustained. By pooling recent defaulters with those nearing rehabilitation, coarse information disciplines lenders, since they cannot target loans towards the latter. Equilibria where defaulters get a loan with positive probability also improve efficiency, by raising the proportion of likely re-offenders in the pool of defaulters. Thus, endogenously generated borrower adverse selection mitigates moral hazard.

JEL codes: C73, D82, G20, L14, L15.

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1 Introduction

We examine the design of information and rating systems in large markets where transactions are bilateral and moral hazard is one-sided. Many examples fit: when the buyer of a product places an order, the seller must decide how diligently to execute it; when a house-owner engages a builder to refurbish his house, the builder knows that shoddy work may temporarily go undetected. Our leading example is unsecured debt — the borrower takes a loan and must subsequently decide whether to repay or wilfully default.[1] The market is large and each pair of agents transacts infrequently. Thus, opportunistic behavior (by the seller, builder or borrower) can be deterred only by a "reputational mechanism", whereby opportunism results in future exclusion. We assume that information on past transgressions is subject to *bounded social memory* and is retained only for a finite length of time. While this is plausible in any context, it is legally mandated in many credit markets. In the United States, if an individual files for bankruptcy under Chapter 7, her bankruptcy "flag" remains on the record for 10 years, and must then be removed; if she files under Chapter 13, it remains on her record for 7 years.[2] Elul and Gottardi (2015) find that among the 113 countries with credit bureaus, 90 percent had time-limits on the reporting of adverse information on borrowers. Bounded memory also arises under policies used by internet platforms to compute the scores summarizing their participants' reputations. For example, Amazon lists a summary statistic of seller performance over the past 12 months — given that buyers have limited attention, this may serve as to effectively limit memory. In the United States, 24 states and many municipalities[3] have introduced "ban the box" legislation, prohibiting employers from asking job applicants about prior convictions unless those relate directly to the job.[4]

[1]Our analysis also applies to no-recourse loans. If the borrower defaults, the lender can seize the collateral but the borrower is not liable for any further compensation in case the value of the collateral does not cover the full value of the defaulted amount. Default on non-recourse loans became particularly attractive during the sub-prime crisis, with the fall in property values. A large fraction of commercial mortgages are non-recourse, and are frequently re-negotiated if the value of the asset plummets, the threat of strategic default giving the lender some bargaining-power vis-à-vis the lender.

[2]Under Chapter 7, a debtor forfeits all non-exempt assets, and his/her eligible debts (which include almost all unsecured debt) are discharged and future wages are protected. The average debt repayment rate under Chapter 7 is 1 percent, and about 80 percent of debtors avail of this option (see Dobbie and Song (2015)). Under Chapter 13, the 2005 law defines a procedure that determines, over a five-year period, how much of the debt must be repaid, while the remainder is discharged, and the debtor's assets are protected. See White (2007), who provides a summary of the changes in bankruptcy law in 2005, and discusses its implications for credit card debt. Individuals may also default on unsecured loans without declaring bankruptcy, relying on the reluctance of the lender to incur the costs of pursuing them.

[3]See "Pandora's box" in *The Economist*, August 13th 2016.

[4]One should note the broader philosophical appeal of bounded memory, that an individual's transgressions in the distant past should not be permanently held against them. This is embodied in the European Court of

How do markets function when moral hazard is important and information systems are constrained by bounded memory? For concreteness, consider the credit market example.Since borrowers have a variety of sources of finance in a modern economy, we study a model with a large number of long-lived borrowers and lenders, where each borrower-lender pair interacts only once. Lending is efficient and profitable for the lender, provided that the borrower intends to repay the loan. However, the borrower is subject to moral hazard, and has short-term incentives to wilfully default. Additionally, there is a small chance of involuntary default. Thus lending can only be supported via long-term repayment incentives whereby default results in the borrower's future exclusion from credit markets.

In our large-population random matching environment, each lender is only concerned with the profitability of his current loan. As long as he expects that loan to be repaid, he has no interest in punishing a borrower for past transgressions. Thus a borrower can only be deterred from wilful default if this record indicates that she is likely to default on a subsequent loan.[5] With bounded memory, *disciplining lenders* to not lend to borrowers who have defaulted recently turns out to be a non-trivial problem. What are the information structures and strategies that support efficient lending in such an environment?

A natural conjecture is that providing maximal information is best, so that the lender has complete information on the past K outcomes of the borrower, where K is the bound on memory. This turns out to be false. Perfect information on the recent past behavior of the borrower, in conjunction with bounded memory, precludes any lending, as it allows lenders to cherry-pick those borrowers with the strongest long-term incentives to repay. In *any* equilibrium that satisfies a mild and realistic requirement of being robust to small payoff shocks, borrower exclusion unravels.

In particular, a borrower whose most recent default is on the verge of disappearing from her record has the same incentives as a borrower with a clean record. Thus she will repay a loan if long-term incentives are such that a borrower with a clean record does so. Lenders, who can distinguish her from more recent defaulters, find it profitable to extend her a loan, reducing the length of her punishment. Repeating this argument, by induction, no length of punishment can be sustained. As a result, no lending can be supported. The problem is that, under perfect information, lenders cannot be disciplined to not make loans to borrowers with

Justice's determination that individuals have the "right to be forgotten", i.e. they may compel online search engines to delete past records pertaining to them.

[5]The reader may ask why the lender cannot be disciplined by allowing future borrowers to condition their behavior on the lender's current decision. This mechanism, which is standard in many repeated games, turns out to be unviable given the informational constraints of our context. This is discussed in see Section 7.4.

a bad record.[6] In our context, rogue lending undermines borrowers' long-term incentives, as lenders seeking profit opportunities impose negative externalities on other lenders.

The negative result leads us to explore information structures that provide the lender with simple coarse information about these histories.[7] Specifically, the lender is told only whether the borrower has ever defaulted in the past K periods (labelled a *bad credit history*) or not (labelled a *good credit history*). A borrower's long-term incentives to repay a new loan differs according to the most recent instance of default in her history. More recent defaulters, with most of their exclusion phase ahead of them, have a stronger incentive to recidivate. Since lenders do not have precise information on the timing of defaults, they are unable to target their loans to defaulters who are more likely to repay. Coarse information therefore generates adverse selection among the pool of borrowers with a bad credit history, thereby mitigating lender moral hazard. Our question is, how can a coarse information structure be tailored to sustain efficient outcomes?

The simple information partition prevents a total breakdown of lending. If the punishment phase is sufficiently long, the pool of lenders with a bad credit history is sufficiently likely to re-offend, on average, as to dissuade rogue loans by the lender. Depending on the (exogenous) profitability of loans, the length of exclusion may be longer than is needed to discipline a defaulting borrower. Indeed, disciplining the lender to not lend to borrowers with a bad credit history may require longer punishments than those that suffice to deter a borrower with a good credit history from defaulting.

Nonetheless, we show that under the simple information structure, there always exists an equilibrium where the borrower exclusion is minimal, and thus borrower payoffs are constrained optimal, subject to integer constraints. If loans are not very profitable, then this achieved via a pure strategy equilibrium and lender profits are also constrained optimal. If loans are very profitable, then the equilibrium requires that borrowers with bad credit histories are provided loans with positive probability. Some of them will default, altering the constitution of the pool of borrowers with bad credit histories, as borrowers with stronger incentives to re-offend will be over-represented. This serves to discipline lenders. Paradoxically, if individual loans are very profitable, an equilibrium with random exclusion may result

[6] Reckless sub-prime mortgage lending has been at the heart of the recent financial crisis. The expectation that house prices and incomes would rise, together with the emergence of collateralized debt obligations inflating the demand for mortgage-based financial products, meant even loans to borrowers with low ("sub-prime") FICO scores were considered worthwhile by lenders.

[7] Coarse information is widely used in many markets. Amazon provides summary statistics on sellers via a five-star rating system. The finer FICO scores are often bundled into "sub-prime" (620 FICO and below), "near prime" (621 - 679), and "prime" (680 or greater) ratings (see Silvia (2008)).

in low overall profits for lenders, by inducing a large pool of borrowers with bad records, even though borrower payoffs are high.

We then show that both borrower and lender payoffs can achieve the constrained optimal level by a using a non-monotonic information partition, where borrowers with multiple defaults are treated favorably and pooled with non-defaulters. This provides strong incentives for defaulters to re-offend, and thus disciplines lenders. We also show that mandates preventing lenders from "chasing borrowers", by requiring an initial loan application by the borrower, can also increase efficiency. In conjunction with coarse information, such a rule transforms the interaction between borrowers and lenders into a signaling game. Among the borrowers with a bad credit history, those who intend to default have stronger incentives to apply than those who intend to repay. This causes lenders to be suspicious of applicants with a bad record, and dissuades them from lending, and the resulting equilibrium ensures that both lender and borrower payoffs are at the constrained optimal level.

The remainder of this section discusses the related literature. Section 2 sets out the model. Section 3 derives the constrained efficiency benchmarks, which can be attained with infinite memory. It also shows that with bounded perfect memory, no lending can be supported. Section 4 shows that a simple coarse information structure prevents the breakdown of lending, and Section 5 shows that such an information structure ensures constrained efficient payoffs for the borrower, either via pure strategies or mixed strategies. Section 6.1 examines the role of non-monotone information structures in disciplining lenders, while Section 6.2 shows that preventing lenders from chasing borrowers also prevents excessive lending; in both cases, the effect is raise payoffs of both parties to the constrained efficient level. Section 7 presents several extensions and we show that our main results apply to a large class of two-player (stage) games, and Section 8 concludes.

1.1 Related Literature

The model we study contributes to the literature on repeated games with community enforcement, which includes Kandori (1992), Ellison (1994) and Deb (2008). Players belonging to a small (finite) population are randomly matched in each period to play the prisoner's dilemma.[8] Contagion strategies, where a single defection results in the breakdown of cooperation across the population, are typically used in order to support cooperation. Since we assume a large (continuum) population, contagion strategies are ineffective in our context. We therefore assume that lenders have some information on the current borrower's

[8]Deb and González-Díaz (2010) extend the analysis to more general games.

past actions. Thus our paper is more closely related to Takahashi (2010) and Heller and Mohlin (2015), who analyze the prisoner's dilemma played in a large population. Takahashi shows that if each player observes the entire sequence of past actions taken by her opponent, or observes the action profile played in the previous period by her opponent and her opponent's partner, then cooperation can be supported by using "belief-free" type strategies, where a player is always indifferent between cooperating and defecting. [9] He also shows that grim-trigger strategy equilibria sustain cooperation if only the partner's action is in the previous period is observed, if the prisoner's dilemma game is supermodular, but not if it is submodular. Heller and Mohlin (2015) assume that players observe a random sample of the past actions of their opponent, and assume that a small fraction of players are commitment types, an assumption that enables them to rule out belief-free strategies. Thus they show that cooperation can be supported if the prisoner's dilemma payoffs are supermodular but not if they are submodular.

Our main departure from the existing literature on community enforcement is that our modelling of lender-borrower interaction involves a sequential structure, with a natural delay between the initiation of the loan and the repayment decision. The sequential structure makes a considerable difference to the analysis. In our lender-borrower example, only the borrower has an incentive to deviate if both players expect the efficient outcome to be played. But this feature arises from a sequential structure and is not specific to the lender-borrower example, as we show in Section 7.3. Indeed, the prisoner's dilemma with sequential moves,[10] or *any game where each player moves at most once*, inherits this feature. Second, since players move sequentially, one has to ask the question, what is the borrower's optimal response when a lender makes a loan that should not have been made? In other words, sequential rationality has considerable power, and this makes a significant difference to the analysis. We also assume imperfect monitoring, with some defaults being unavoidable, so that efficient equilibria require that borrower exclusion be temporary. Finally, we require that equilibria be robust to small payoff shocks, and therefore be purifiable, as in Harsanyi (1973) — we view purifiability as a mild requirement, showing that our equilibria are robust. Our substantive results differ markedly from the negative results in Bhaskar (1998) and Bhaskar, Mailath, and Morris (2013), which demonstrate that purifiability, in conjunction with bounded memory, results in a total breakdown of cooperative behavior. In contrast,

[9] Observe that finite memory precludes a player observing the entire history of actions taken by his opponent. Finite memory belief-free strategies in our setting are not purifiable.

[10] If the player moving first defects, he can be disciplined by the second mover in the stage game itself, and so inter-temporal incentives are needed only to deter defections by the second mover.

the present paper shows that by providing partial information on past histories, one can robustly support efficient outcomes.

We assume that the relationship between any pair of individuals is necessarily short-lived, so that long-term incentives can only be provided if subsequent partners have information on past behavior. This distinguishes our setting from efficiency wage type models, where the relationship is potentially long-lived, but where a deviating party has the option of starting a new relationship.[11] Dutta (1992) and Kranton (1996) analyze the prisoner's dilemma played in such an environment, and show that new relationships must include an initial non-cooperative phase of "starting small". Ghosh and Ray (1996) point out that the initial phase of starting small is not renegotiation-proof, but that adverse selection alleviates the problem, by making the initial phase renegotiation-proof.[12] In our context, punishments unravel due to considerations of sequential rationality alone, and also, coarse information *endogenously* generates adverse selection, without any exogenous difference in types.

While the credit market is our leading motivating application, an alternative application of our model is the interaction between a buyer and a seller, where the buyer makes a purchase decision, and the seller must decide what quality to supply. This problem has been studied in the large literature on seller reputation. Most closely related is Liu and Skrzypacz (2014), who assume that buyers are short-lived and have bounded information on the seller's past decisions, but do not observe the magnitude of past sales, and are therefore not able to infer the information observed by past buyers. Buyers also assign a small probability to the seller being committed to high quality. Since the normal type of seller has a greater incentive to cheat when sales are larger, equilibria display a cyclical pattern, whereby the seller builds up his reputation before milking it.[13] Ekmekci (2011) studies the interaction between a long-run player and a sequence of short run players, where the long run player's action is imperfectly observed, and there is initial uncertainty about the long run player (as in reputation models). He shows that bounded memory allows reputations to persist in the long run, even though they necessarily dissipate when memory is unbounded.

Our work also relates to the burgeoning literature on information design, initiated by Kamenica and Gentzkow (2011), and pursued by Kremer, Mansour, and Perry (2014), Che and Hörner (2015), Marinovic, Skrzypacz, and Varas (2015), Bergemann and Morris (2016),

[11]Bilateral long-term relationships are plausibly the main way of providing incentives in labor markets, while information and community enforcement seems to play a major role in buyer-seller interactions and modern credit markets, as witnessed by the importance of credit scores and seller reputations.

[12]Ghosh and Ray (2016) use related ideas to examine relationship lending in informal credit markets.

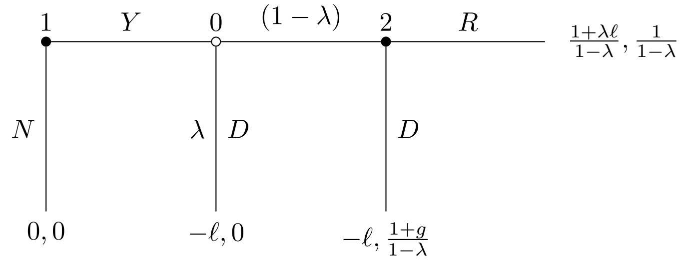
[13]Sperisen (2016) extends this analysis by considering non-stationary equilibria.

Taneva (2016), Mathevet, Perego, and Taneva (2016) and Ely (2017). While this literature has focused on the case of one or few players, our design question relates to a large society. Whereas the distribution of types or states is usually exogenous in the information design context, the induced distributions over types (or private histories) in the present paper arise endogenously, as a result of the information structure itself.

Our work also relates to the influential macro literature on “money and memory”. Kocherlakota (1998) shows that money and unbounded memory play equivalent roles. Wiseman (2015) demonstrates that when memory is bounded, money can sustain greater efficiency than memory can.

We now briefly summarize the relevant empirical work on credit markets. Fay, Hurst, and White (2002) estimate a panel data model of household bankruptcy decisions and find that strategic considerations — the financial incentives to default — are more important than adverse shocks as the major determinants of defaults. Dobbie and Song (2015) cite evidence showing that in the United States bankruptcy system is extremely generous, providing more social insurance than all state unemployment insurance programs combined. The moral hazard implications of such extensive social insurance has been pointed out by White (2007), but has received less attention, as compared to the analysis of the incentive effects of unemployment benefits. Musto (2004) empirically documents the effects of removing bankruptcy flags, and finds that credit scores and lending increase in consequence. He argues that the loss of information has adverse consequences for resource allocation. More recent work (Jagtiani and Li (2015), Gross, Notowidigdo, and Wang (2016), Dobbie, Goldsmith-Pinkham, Mahoney, and Song (2016)) also finds that the removal of bankruptcy flags raise credit scores and lending. We discuss this empirical evidence in more detail after analyzing our model, in Section 7.2. Chatterjee, Corbae, Nakajima, and Ríos-Rull (2007) set out a quantitative model of default, where default records are stochastically expunged, that replicates the main empirical features of the market for unsecured debt in the US.

Elul and Gottardi (2015) argue that limited records may be welfare-improving in the presence of adverse selection. They analyze a market with two types of borrower, who are also subject to moral hazard. Utilitarian efficiency dictates lending to both types, but lending to the high risk borrower is unprofitable. Bounded memory can increase efficiency by allowing high risk borrowers to pool with low risk ones. Kovbasyuk and Spagnolo (2016) consider a lemons market with Markovian types where the invariant distribution is adverse enough to result in market breakdown, but initial information may permit trade with some borrowers. They find that bounding memory can improve outcomes in this context. Padilla



(a) *Extensive form.*

	R	D
Y	$1, 1$	$-\ell, 1+g$
N	$0, 0$	$0, 0$

(b) *Strategic form.*

Figure 1: *Extensive and strategic form representations of the stage-game*

and Pagano (1997) also argue that information provision may be excessive. Our paper differs from this literature on two dimensions, both because of our focus on moral hazard rather than adverse selection, and because we model the expunging of records as deterministic rather than stochastic, consistent with the legal requirement.

2 The model

Time is discrete and the horizon infinite. In each period, individuals from a continuum population (the lenders) are randomly matched with individuals from a distinct continuum population (the borrowers), to play the sequential-move game illustrated in Figure 1a. First, the lender (player 1, "he") chooses between $\{Y, N\}$, i.e. whether or not to extend a loan. If he chooses N, the game end, and both parties get a payoff of zero. If he chooses Y, then the borrower (player 2, "she") invests this loan in a project with uncertain returns. With a small probability λ, the borrower is unable to repay the loan, i.e. she is constrained to default, D. With the complementary probability she is able to repay the loan, and must choose whether or not do so, i.e. she must choose in the set $\{R, D\}$, where R denotes repayment and D denotes default. We assume that lending is profitable if the borrower intends to repay, and unprofitable if she intends to default, and that wilful default is profitable for the borrower. To understand the incentives of the players, the reader may find the strategic form of the game, given in Figure 1b, more illuminating, where Y and N are the lender's strategies, corresponding to extending or not extending the loan. For the borrower, R denotes "repay when possible", and D denotes "always default". Since $g > 0$ and $\ell > 0$, the strategic form is a one-sided prisoner's dilemma, where it is optimal for the lender to extend the loan if he expects that the borrower will not wilfully default, and where the borrower prefers to wilfully default if extended a loan. [14] [15]

We assume that only the borrower can observe whether or not she is able to repay, i.e. the lender or any outside observer can only observe the outcomes in the set $O = \{N, R, D\}$.

Borrowers have discount factor $\delta \in (0, 1)$. The discount factor of the lenders is irrelevant for positive analysis.[16] Since the borrower has a short-term incentive to default, she will do so in every period unless future lenders have information about her behavior. We henceforth assume that they do, and the details of the information structure will vary.

We focus on stationary Perfect Bayesian Equilibria, where agents are sequentially rational at each information set, with beliefs given by Bayes' rule wherever possible. The stationarity assumption implies that players do not condition on calendar time. We shall focus on equilibria where all lenders follow the same strategy, and all borrowers follow the same strategy. We also require that our equilibria be purifiable, as we now explain.

2.1 Payoff Shocks: The Perturbed Game

We now describe a perturbed version of the underlying game. Let Γ denote the extensive form game that is played in each period, and let Γ^∞ denote the extensive form game played in the random matching environment — this will depend on the information structure, which is at yet unspecified. The perturbed stage game, $\Gamma(\varepsilon)$, is defined as follows. Let X denote the set of decision nodes in Γ, and let $\iota(x)$ denote the player who moves at $x \in X$, making a choice from a non-singleton set, $A(x)$. At each such decision node $x \in X$ where player $\iota(x)$ has to choose an action $a_k \in A(x)$, that player's payoff from action a_k is augmented by εz_x^k, where $\varepsilon > 0$. The scalar z_x^k is the k^{th} component of z_x, where $z_x \in \mathbb{R}^{|A(x)|-1}$ is

[14] The strategic form payoffs are derived as follows. When the borrower is unable to repay so that her default in involuntary, her payoff is 0. If she wilfully defaults even though she is able to repay, her payoff is $\pi_b + \tilde{g}$, where $\tilde{g} > 0$. If the borrower chooses R when she is able to, the borrower has an expected payoff of $(1-\lambda)\pi_b$ and the lender's expected payoff is $(1-\lambda)\pi_l - \lambda\ell$. We normalize these payoffs to $(1, 1)$. The payoffs π_l and π_b are then as in Figure 1a. If the borrower chooses D when she has a choice, the expected payoff is $(1-\lambda)(\pi_b + \tilde{g})$ for the borrower. Define $g := (1-\lambda)\tilde{g}$, so that the expected payoffs when the borrower wilfully defaults are $(-\ell, 1+g)$.

[15] An alternative specification of the model is as follows. The borrower has two choices of project. The safe project results in a medium return M that permits repayment r with a high probability, $1-\lambda$, and a zero return with probability λ. The risky project results in a high return, $H > M$, but with a lower probability, $1-\theta < 1-\lambda$, and a zero return with complementary probability. Let $(1-\lambda)M - r = 1$,$(1-\theta)H - r = 1+g$, $(\theta-\lambda)r = (1+\ell)$. Then the expected payoffs are as before, with the information being slightly different (if the borrower chooses the high return project, she still repays with positive probability). Our analysis can be generalized to this case, but we do not pursue this here.

[16] As we will see in Section 7.4, incentives for the lender have to be provided within the period.Since there is a continuum of borrowers and a continuum of lenders, the behavior of any individual agent has negligible effects on the distribution of continuation strategies in the game.

the realization of a random variable with bounded support. We assume that the random variables $\{Z_x\}_{x \in X}$ are independently distributed, and that their distributions are atomless. Player $\iota(x)$ observes the realization z_x of the shock before being called upon to move. In the repeated version of the perturbed game, $\Gamma^{\infty}(\varepsilon)$, we assume that the shocks for any player are independently distributed across periods.[17] In the specific context of the borrower-lender game, we may assume that the lender gets an idiosyncratic payoff shock from not lending, while the borrower gets an idiosyncratic payoff shock from repaying. Motivated by Harsanyi (1973), we focus on purifiable equilibria, i.e. equilibria of the game without shocks Γ^{∞} that are limits of equilibria of the game $\Gamma^{\infty}(\varepsilon)$ as $\varepsilon \to 0$. Bhaskar, Mailath, and Morris (2013) provide a more complete discussion of purifiability in a large class of stochastic games.

Call an equilibrium of the unperturbed game *sequentially strict* if a player has strict incentives to play her equilibrium action at every information set, whether this information set arises on or off the equilibrium path. The following lemma, proved in Appendix A.4.3, is very useful:

Lemma 1 *Every sequentially strict equilibrium of* Γ^{∞} *is purifiable.*

2.2 Information

We have in mind a designer or social planner who, subject to memory being bounded, designs an information structure for this large society, and recommends a non-cooperative equilibrium to the players.[18] The designer's goal is to achieve a high borrower payoffs, and high lender payoffs – our focus is mainly on the former.[19] This requires supporting equilibria where lending is sustained, and where a borrower who defaults is not permanently excluded from credit markets, i.e. denial of credit is only temporary. Permanent exclusion is clearly inefficient because of the possibility of involuntary default — even if a borrower intends to repay, with probability λ she will be unable to do so.

Let K denote the chosen bound on memory – we allow K to be arbitrarily large but finite. An information system provides information to the lender based on the past K outcomes of the borrower. We assume that the borrower does not receive information on the past outcomes of the lender — in Section 7.4 we show that such information would be useless in

[17]The assumption that the lender's shocks are independently distributed across periods is not essential.

[18]Thus, the designer cannot dictate the actions to be taken by any agent, and in particular cannot direct lenders to refrain from lending to defaulters.

[19]We define the designer's social payoff target more precisely after discussing the constraints on efficiency in Section 3.

any equilibrium, since no borrower would condition on it. Information structures fall into two broad categories.

A *deterministic* information (or signal) structure consists of a finite signal space S and a mapping $\tau : O^K \to S$. More simply, it consists of a partition of the set of K-period histories, O^K, with each element of the partition being associated with a distinct signal in S, and can also be called a *partitional* information structure.

A *random* information (or signal) structure allows the range of the mapping to be the set of probability distributions over signals, so that $\tau : O^K \to \Delta(S)$.

Note that in both cases, the signal *does not* depend on past signal realizations, since otherwise one could smuggle in infinite memory on outcomes. Most of our analysis will focus on partitional information structures, for two reasons. First, we will see that the efficiency gains from random information are restricted to overcoming integer problems, and are therefore of less interest. Second, we deem a random information structure to be more vulnerable to manipulation, especially in a large society — if a borrower with a given history gets a higher continuation value from one signal realization than another, she may wish to expend resources to influence the outcome.

3 Benchmarks

3.1 The Infinite Memory Benchmark

Suppose that each lender can observe the entire history of transactions of each borrower he is matched with. That is, a lender matched with a borrower at date t observes the outcome of the borrower in periods $1, 2, .., t-1$. We assume that payoff parameters are such that there exists an equilibrium where lending takes place.[20] Assume also that the borrower does not observe any information about the lender, so that incentives for the lender have to be provided within the period.

Consider an equilibrium where a borrower who is in good standing has an incentive to repay when she is able to. Her expected gain from intentional default is $(1-\delta)g$.[21] The deviation makes a difference to her continuation value only when she is able to repay, i.e. with probability $1-\lambda$. Suppose that after a default, wilful or involuntary, she is excluded

[20]That is, we assume that permanent exclusion is sufficiently costly that the Bulow and Rogoff (1989) problem, whereby a lender always finds it better to default and re-invest the sum, does not arise. For example, costs of filing for bankruptcy could be non-trivial. The precise condition is $g < \frac{\delta(1-\lambda)}{1-\delta(1-\lambda)}$.

[21]Per-period payoffs are normalized by multiplying by $(1-\delta)$.

from the lending market for K periods. The incentive constraint ensuring that she prefers repaying when able is then

$$(1-\delta)g \leq \delta(1-\lambda)[V^K(0) - V^K(K)], \tag{1}$$

where $V^K(0)$ denotes her payoff when she is in good standing, and $V^K(K)$ her payoff at the beginning of the K periods of punishment. These are given by

$$V^K(0) = \frac{1-\delta}{1-\delta[\lambda\delta^K + 1 - \lambda]}, \tag{2}$$

$$V^K(K) = \delta^K V^K(0). \tag{3}$$

The most efficient equilibrium in this class has K large enough to provide the borrower incentives to repay when she is in good standing, but no larger. Call this value $\bar{K}$, and assume that the incentive constraint (1) holds as a strict inequality when $K = \bar{K}$ — this assumption will be made throughout the paper, and is satisfied for generic values of the parameters (δ, g, λ). The payoff of the borrower when she is in good standing is $\bar{V} := V^{\bar{K}}(0)$, i.e. it is given by equation (2) with $K = \bar{K}$. We evaluate the payoffs of any lender by his per-period payoff in the steady state corresponding to this equilibrium. Since the lender earns an expected payoff of 1 on meeting a borrower in good standing, and 0 otherwise, his payoff $\bar{W}$ equals the fraction of borrowers in good standing, i.e. $\bar{W} = \frac{1}{1+\lambda\bar{K}}$.

It is useful at this point to examine the incentives of the lender, given that future play cannot be conditioned on her behavior. We want to ensure that a borrower who defaults, and who should be excluded for K periods, is not offered a loan. To do this, we must distinguish between defaults that occur when a loan should be made, and those that arise when the lender should not have lent in the first place. This is illustrated in the equilibrium described by the automaton in Figure 2, where a defaulting borrower is excluded for K periods — the figure depicts the case of $K = 2$. Depending on the entire history, the borrower is either in a good state or in one of K distinct bad states. The lender extends a loan if and only if the borrower is in the good state. A borrower begins in the good state, and stays there unless she defaults, in which case she transits to the first of the bad states. The borrower then transits through the remaining $K - 1$ bad states, spending exactly one period in each, and then back to the good state. The transition out of any bad state is *independent of the outcome in that period*, thus ensuring that the borrower's actions in a bad state do not affect her continuation value. Since the borrower is never punished for a default when she is in a bad state, she will always choose to default, ensuring that no lender will lend to her when

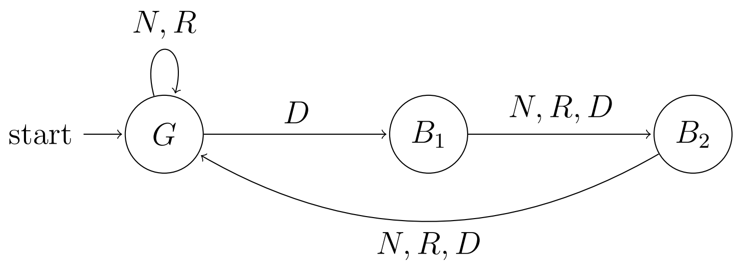


Figure 2: *Strategy profile with two periods of exclusion.*

she is in a bad state. Note that this equilibrium requires that every lender should be able to observe the entire history of every borrower he is matched with. Otherwise, he cannot deduce whether the borrower defaulted in a period where she was supposed to be lent to, or one in which she was supposed to be excluded.

The equilibrium with $\bar{K}$ periods of exclusion can be improved upon — due to integer constraints, the punishment is strictly greater than what is required to ensure borrower repayment. In Appendix A.1 we show that the highest payoff the borrower can achieve in *any equilibrium*, V^*, is strictly less than 1 due involuntary default, and is given by the following expression:[22]

$$V^* = 1 - \frac{\lambda}{1-\lambda}\, g. \tag{4}$$

To sustain the equilibrium payoff V^*, we assume that players observe the realization of a public randomization device at the beginning of each period, and that past realizations of the randomization device are also a part of the public history. The payoff V^* can be achieved by the borrower being excluded for $\bar{K}-1$ periods with probability x^* and for $\bar{K}$ periods with probability $1-x^*$. This gives rise to a steady-state proportion of borrowers in good standing equal to $\frac{1}{1+\lambda(\bar{K}-x^*)}$, and since the lender gets a payoff of 1 whenever he meets a borrower in good standing, and 0 otherwise, this proportion equals the lender's expected payoff, W^*.

To summarize: $\bar{V}$ and $\bar{W}$ will be called the constrained efficient payoffs for the borrower and lender respectively, that reflect both the integer constraint and the incentive constraint due to imperfect monitoring. V^* and W^* will be called the fully efficient payoffs – these

[22]In deriving this bound, we assume that borrower mixed strategies are not observable. If mixed strategies are observable we can sustain a borrower payoff higher than V^*, as in Fudenberg, Kreps, and Maskin (1990). The borrower in good standing must have access to a private randomization device that allows her to wilfully default with some probability, and such defaults are not punished. Furthermore, past realizations of the randomization device must also be a part of the infinite public history. The assumption that mixed strategies are observable seems strong and possibly unrealistic.

include the incentive constraint for the borrower, but no integer constraints. We assume that the designer's objective is to achieve a payoff no less than $\bar{V}$ for the borrower. In Section 5 we show that this is always possible, though it sometimes results in low payoffs for the lender. In Sections 6.1 and 6.2 we show how the designer can correct this, and also achieve $\bar{W}$ for the lender.

3.2 Perfect Bounded Memory

Henceforth, we shall assume that lenders have bounded memory, i.e. we assume that at every stage, the lender observes a bounded history of length K of past play of the borrower she is matched with in that stage. We assume that the lender does not observe any information regarding other lenders. Specifically, he does not observe any information regarding the lenders with whom the borrower he currently faces has been matched in the past.

Our first proposition is a negative one — if we provide the lender full information regarding the past K interactions of the borrower, then no lending can be supported.

Proposition 1 *Suppose that $K \geq 2$ is arbitrary and the lender observes the finest possible partition of O^K, or that $K = 1$ and the information partition is arbitrary. The unique purifiable equilibrium corresponds to the lender never lending and the borrower never repaying.*

The proof does not follow directly from Bhaskar, Mailath, and Morris (2013), but is an adaptation of that argument, and so we do not present it here. The intuition is as follows. Suppose that the information partition is the finest possible. Consider a candidate equilibrium where a borrower who defaults is excluded for $K \geq \bar{K}$ periods, so that a borrower with a clean record prefers to repay. Consider a borrower with exactly one default which occurred exactly K periods ago. Such a borrower has incentives identical to those of a borrower with a clean record, and will therefore also repay. Therefore, a lender has every incentive to lend to such a borrower, undermining the punishment. An induction argument then implies that no length of punishment can be sustained.

The role of purification is to extend this argument to all possible equilibria. When memory length is K, the borrower knows that the lender tomorrow cannot condition his behavior on events that happened K period ago, since he does not observe these events. The payoff shocks faced by the borrower imply that for any strategies of the lenders, the borrower is indifferent between R and D only on a set of measure zero. Thus, the borrower will also not condition her behavior on what happened K periods ago. In consequence, the lender today will not condition his lending decision on events K periods ago, and an induction argument ensures that there can be no conditioning on history.

The second part of the proposition, that there cannot be conditioning upon history if $K = 1$, does not need an induction argument and applies to any information structure. So we need $K \geq 2$, since otherwise no information structure sustains lending. Even if $g < \frac{\delta(1-\lambda)}{1+\delta\lambda}$, so that only one period of memory is required to satisfy (1), we need at least two period memory. Underlying this second result is a more general point, that will recur frequently in our analysis – the borrower will never condition her behavior on what happened K periods ago, under *any* information structure.

Total breakdown of lending does not occur under all information structures. Surprisingly, *less information* may support cooperative outcomes, as we shall see below. Although it still remains the case that the borrower will not condition on events that happened exactly K periods ago, a coarser information structure prevents the lender from knowing this, and thus the induction argument underlying the above proposition (and the main theorem in Bhaskar, Mailath, and Morris (2013)) does not apply. The main contribution of this paper is to show that coarse information can be appropriately chosen in order to sustain efficient or near-efficient outcomes, in repeated game type environments where fine information leads to a breakdown of cooperation.

4 A Simple Coarse Information Structure

We shall assume henceforth that the exogenous bound on the length of memory, $\tilde{K}$, is finite but large enough so that it is never a binding constraint. So the length of effective memory, K, can be chosen without constraints.[23] Assume that $K \geq \max\{\bar{K}, 2\}$,[24] and let the information structure be given by the following binary partition of O^K. The lender observes a "bad credit history" signal B if and only if the borrower has had an outcome of D in the last K periods, and observes a "good credit history" signal G otherwise. Since this information structure will recur through this paper, it will be convenient to label it the *simple* information partition/structure. In this section we show that lending can be supported under the simple information structure.

[23] Observe that K can be set less than $\tilde{K}$ by not disclosing any information about events that occurred more than K periods ago. More subtly, this can also be achieved by *full disclosure* of events that occurred between K and $\tilde{K}$ periods ago – this follows from arguments similar to those underlying Proposition 1.

[24] We also examined how lending can be sustained when $\tilde{K} < \bar{K}$, but for reasons of space do not present these results here.

The borrower has complete knowledge of her own private history, since she knows the entire history of past transactions. Information on events that occurred more than K periods ago is irrelevant, since no lender can condition on it. Under the simple information structure, the following partition of K-period private histories will be used to describe the borrower's incentives. Partition the set of private histories into $K + 1$ equivalence classes, indexed by m. More precisely, let t' denote the date of the most recent incidence of D in the borrower's history, and let $j = t - t'$, where t denotes the current period. Define $m := \min\{K + 1 - j, 0\}$. Under the simple information structure, if $m = 0$ the lender observes G while if $m \geq 1$ the lender observes B. Thus, m represents the number of periods that must elapse without default before the borrower gets a good history. When $m \geq 1$, this value is the borrower's private information. In particular, among lenders with a bad credit history, the lender is not able to distinguish those with a lower m from those with a higher m.

Consider a candidate equilibrium where the lender lends after G but not after B, and the borrower always repays when the lender observes G. Let $V^K(m)$ denote the value of a borrower at the beginning of the period, as a function of m. When her credit history is good, the borrower's value is given by $V^K(0)$ defined in (2). For $m \geq 1$, the borrower is excluded for m periods before getting a clean history, so that

$$V^K(m) = \delta^m V^K(0), \qquad m \in \{1, \ldots, K\}. \tag{5}$$

Since $K \geq \bar{K}$, the borrower strictly prefers to repay at a good credit history. Let us examine the borrower's repayment incentives when the lender sees a bad credit history. Note that this is an unreached information set at the candidate strategy profile, since the lender is making a loan when he should not. Repayment incentives depend upon the borrower's private information, and are summarized by m. Observe that the borrower's incentives at $m = 1$ are identical to those at $m = 0$ — for both types of borrower, their current action has identical effects on their future signal. Therefore, a borrower of type $m = 1$ will always choose R. Now consider the incentives of a borrower of type $m = K$. We need this borrower to default, since otherwise every type of borrower would repay and lending after observing signal B would be optimal for the lender. Thus we require

$$(1 - \delta)g > \delta(1 - \lambda)\left[V^K(K - 1) - V^K(K)\right]. \tag{6}$$

The left-hand side above is the one-period gain from default, whereas the right-hand side reflects the gain in continuation value from repayment, since the length of exclusion is reduced by one period. In Appendix A.2 we show that (6) is satisfied whenever $K \geq \bar{K}$.

Now consider the incentives to repay for a borrower with an arbitrary $m > 1$. By repaying, the length of exclusion is reduced to $m-1$, while by defaulting, it increases to K. Thus the difference in overall payoffs from defaulting as compared to repaying equals

$$(1-\delta)g - \delta(1-\lambda)[V^K(m-1) - V^K(K)] = (1-\delta)g - (1-\lambda)(\delta^m - \delta^{K+1})V^K(0). \quad (7)$$

We have seen that when $m = K$, the above expression is positive, while when $m = 1$, the expression is negative. Thus there exists a real number, denoted $m^\dagger(K) \in (1, K)$, that sets the payoff difference equal to zero. We assume that $m^\dagger(K)$ is not an integer, as will be the case for generic payoffs.[25] Let $m^*(K) = \lfloor m^\dagger(K) \rfloor$, i.e. m^* denotes the integer value of $m^\dagger$. If $m > m^*(K)$, the borrower chooses D when offered a loan. If $m \leq m^*(K)$, she chooses R. Intuitively, a borrower who is close to getting a clean history will not default, just as a convict nearing the end of his sentence has incentives to behave.

Since the lender has imperfect information regarding the borrower's K-period history, we will have to compute the lender's beliefs about those histories. These beliefs will be determined by Bayes rule, from the equilibrium strategy profile. We will focus on lender beliefs in the steady state, i.e. under the invariant distribution over a borrower's private histories induced by the strategy profile. In Appendix A.3 we set out the conditions under which the strategies set out here are optimal in the initial periods of the game, when the distribution over borrower types may be different from the steady state one.

We now describe the beliefs of the lender when he observes B. In every period, the probability of involuntary default is constant, and equals λ. Furthermore, under the candidate strategy profile, a borrower with a bad credit history never gets a loan and hence transits deterministically through the states $m = K, K-1, .., 1$. Therefore, the invariant (steady state) distribution over values of m induced by this strategy profile gives equal probability to each of these states.[26] Consequently, the lender attributes probability $\frac{m^*(K)}{K}$ to a borrower with signal B repaying a loan. Simple algebra shows that making a loan to a borrower with a bad credit history is strictly unprofitable for the lender if

$$\frac{m^*(K)}{K} < \frac{\ell}{1+\ell}. \quad (8)$$

Suppose that ℓ is large enough that the lender's incentive constraint (8) is satisfied. Then

[25] This ensures that the equilibrium is sequentially strict, permitting a simple proof of purifiability.

[26] The invariant distribution $(\mu_m)_{m=0}^K$ has $\mu_0 = \frac{1}{1+K\lambda}$ and $\mu_1 = \cdots = \mu_K = \frac{\lambda}{1+K\lambda}$.

he finds it strictly optimal not to lend after B, and to lend after G. We have seen that, since $K \geq \bar{K}$, it is optimal for the borrower to repay when she has a clean history G. Moreover, if granted a loan after B, she has strict incentives to repay as long as $m \leq m^*(K)$ and to default if $m > m^*(K)$. Thus, there exists an equilibrium that is sequentially strict, and is therefore purifiable. In other words, providing the borrower with coarse information, so that he does not observe the exact timing of the most recent default, overcomes the impossibility result in Proposition 1. Even though those types of borrowers who are close to "getting out of jail" would choose to repay a loan, the lender is unable to distinguish them from those whose sentence is far from complete. He therefore cannot target loans to the former. In other words, coarse information endogenously generates borrower adverse selection that mitigates *lender moral hazard*.

It remains to investigate the conditions on the parameters that ensure that the incentive constraint (8) is satisfied. In Appendix A.2, we show that $\frac{m^*(K)}{K} \to 0$ as $K \to \infty$. We therefore have the following proposition:

Proposition 2 *An equilibrium where the lender lends after observing G and does not lend after observing B exists as long as K is sufficiently large. Such an equilibrium is sequentially strict and therefore purifiable.*

Discussion: This result highlights the novel role of coarse information, in preventing the complete breakdown of cooperation, by preventing unravelling due to a backwards induction argument, as in Proposition 1. Coarse information therefore makes a qualitative difference and plays a more important role as compared with Kamenica and Gentzkow (2011) and the subsequent literature on information design. There, it serves to increases the probability with which the agent takes the action desired by the principal, by pooling states where the agent's incentive to take this action is strict with states where the incentive constraint is violated. In our context, there may be but a single history where the lender has an incentive to supply a loan when she should not. With perfect information, this violation causes unravelling so that no lending can be supported at all. Coarse information, by preventing the lender from detecting this single history, prevents unravelling.

Coarse information also generates *endogenous adverse selection* among lenders with the signal B. Our underlying model assumes borrower moral hazard but no exogenous adverse selection. Nonetheless, borrowers with different histories have different repayment incentives. By pooling borrowers with different histories, we are able to endogenously generate adverse selection, so as to solve the lender moral hazard problem.[27]

How would our analysis be altered if we allowed the lender to charge a higher interest rate from a borrower with a bad record? A higher interest rate would make such a loan more profitable, conditional on repayment; however, it also increases the borrower's incentive to default. Nevertheless, a revealed preference argument implies that the individual lender must be better off from being able to tailor interest rates to the borrower's record. Thus, the first order effect is to undermine borrower exclusion.

One may conjecture that since a defaulting borrower is subject to higher interest rates, this serves as an alternative form of punishment. However, this cannot be the case: higher interest rates alone cannot serve as a sufficient punishment, since a defaulter who is charged higher rates can default once again. Thus borrower exclusion is necessary, and allowing for variable terms does not significantly affect the analysis. Section 7.3 provides a more systematic analysis of how our results extend to other extensive form games, including ones where the lender has a choice between several forms of loan contract.

5 Efficiency Under the Simple Information Structure

In this section we investigate the conditions under which an equilibrium with punishments of minimal length, $\bar{K}$, exists, for $\bar{K} \geq 2$, under the simple information structure. We show that for all parameter values, the borrower's constrained efficient payoff $\bar{V}$ can always be achieved.

5.1 Pure strategy equilibrium when ℓ is large

Consider first the pure strategy profile set out in the previous section, with $\bar{K}$ memory. In the appendix, in lemma A.1 we show that $m^*(\bar{K}) = 1$, so that every borrower with type $m > 1$ defaults, giving rise to a steady state repayment probability of $\frac{1}{\bar{K}}$. The lender has strict incentives not to lend to a borrower with a bad credit history if

$$\frac{1}{\bar{K}} < \frac{\ell}{1+\ell} \Leftrightarrow \ell > \frac{1}{\bar{K}-1}. \tag{9}$$

Given that punishments are of length $\bar{K}$, a borrower with a good credit history has a strict incentive to repay. Thus we have a sequentially strict equilibrium that achieves the payoff

[27] As we have discussed in Section 1.1, the role of exogenous adverse selection in mitigating moral hazard problems has already been pointed out by Ghosh and Ray (1996).

$\bar{V}$ for the borrower and $\bar{W}$ for the lender. We can also achieve the fully efficient payoffs V^* and W^* by using a random signal structure, to induce a punishment length between $\bar{K}$ and $\bar{K}-1$. We define the *random version of the simple information structure* as follows. If there is no instance of D in the last $\bar{K}$ periods, signal G is observed by the lender. If there is any instance of D in the last $\bar{K}-1$ periods, then signal B is observed. Finally, if there is a single instance of D in the last $\bar{K}$ periods and this occurred exactly $\bar{K}$ periods ago, signal G is observed with probability $(1-x)$, and B is observed with probability x. We assume $x > x^*$, where x^* denotes the value where the borrower is indifferent between repaying and defaulting when she has signal G. In Appendix A.2 we show that under this random signal structure, $m^* = 1$, so that the repayment probability after a bad signal remains low enough and lending is not profitable, thereby proving the following proposition.

Proposition 3 *Suppose $\bar{K} \geq 2$. If loans are not too profitable, so that $\frac{1}{\bar{K}} < \frac{\ell}{1+\ell}$, there exist sequentially strict equilibria that can a) achieve constrained efficient payoffs $\bar{V}$ and $\bar{W}$ under the simple information structure, and b) approximate the fully efficient payoffs V^* and W^* under a random signal structure.*

5.2 Mixed equilibrium when ℓ is small

Consider now the case where $\ell < \frac{1}{\bar{K}-1}$. Suppose that lenders lend with positive probability on observing B, and lend with probability one after G.[28] We now show that this permits an equilibrium where the length of exclusion after a default is no greater than $\bar{K}$ — indeed, the effective length is strictly less, since exclusion is probabilistic. This may appear surprising — if a lender is required to randomize after B, then not lending must be optimal, and so the necessary incentive constraint for an individual lender should be no different from the pure strategy case. However, the behavior of the population of lenders changes the relative proportions of different types of borrower among those with signal B. It raises the proportion of those with larger values of m, thereby raising the default probability at B and disciplining lenders. Thus, other lenders lending probabilistically to borrowers with a bad history exacerbates the adverse selection faced by the individual lender.

Let $p \in (0,1)$ denote the probability that a borrower with history B gets a loan (a borrower with history G gets a loan for sure). Recall that if $p = 0$ and $K = \bar{K}$, then it is strictly optimal for a borrower with a good signal, i.e. $m = 0$, to repay. By continuity,

[28] To recast in the language of information design, it may be worth clarifying that the lender is recommended to take a *random* action when the borrower's history is B, rather than the information system recommending each pure action to the lender with positive probability.

repayment is also optimal for a borrower with $m = 0$ for an interval of values, $p \in [0, \tilde{p}]$, where $\tilde{p} > 0$ is the threshold where such a borrower is indifferent between repaying and defaulting. We restrict attention to values of p in this interval in what follows. Note that the best responses of a borrower with $m = 1$ are identical to those of a borrower with $m = 0$, for any p, since their continuation values are identical. Also, any increase in p increases the attractiveness of defaulting, and so a borrower with $m > 1$ will continue to default when $p > 0$.

The value function for a borrower with a good signal, i.e. $m = 0$, is given by:

$$\tilde{V}^{\bar{K}}(0,p) = (1-\delta) + \delta\left[\lambda \tilde{V}^{\bar{K}}(\bar{K},p) + (1-\lambda)\tilde{V}^{\bar{K}}(0,p)\right], \tag{10}$$

while the value function of a borrower with signal B is given by

$$\tilde{V}^{\bar{K}}(m,p) = \begin{cases} p(1-\delta) + \delta\left[p\lambda V^{\bar{K}}(\bar{K},p) + (1-p\lambda)V^{\bar{K}}(m-1,p)\right] & \text{if } m = 1, \\ p(1-\delta)(1+g) + \delta\left[pV^{\bar{K}}(\bar{K},p) + (1-p)V^{\bar{K}}(m-1,p)\right] & \text{if } m > 1. \end{cases} \tag{11}$$

Any $p \in [0, \tilde{p}]$, in conjunction with the borrower responses and exogenous default probability λ, induces a unique invariant distribution μ on the state space $\{0, 1, 2, \ldots, \bar{K}\}$. A borrower with $m > 1$ transits to $m - 1$ if she does not get a loan, and to $m = \bar{K}$ if she does get a loan, and thus

$$\mu_{m-1} = (1-p)\mu_m \quad \text{if } m > 1. \tag{12}$$

The measure $\mu_{\bar{K}}$ equals both the inflow of involuntary defaulters, who defect at rate λ, and the inflow of deliberate defaulters from states $m > 1$, so that

$$\mu_{\bar{K}} = \lambda\left(\mu_0 + p\mu_1\right) + p\sum_{m=2}^{\bar{K}} \mu_m. \tag{13}$$

Finally, a borrower with $m = 1$ transits to $m = 0$ unless she gets a loan and suffers involuntary default. Thus, the measure of agents with $m = 0$, i.e. with a good credit history, equals

$$\mu_0 = (1-\lambda)\mu_0 + (1-p\lambda)\mu_1. \tag{14}$$

Since μ_m depends on p and also on the repayment probability for borrowers with types $m \in \{0, 1\}$, which equals 1, we write it henceforth as $\mu_m(p, 1)$. Figure 3 depicts the invariant distribution over the values of $m \in \{1, 2.., \bar{K}\}$, conditional on signal B, for two values of p. The horizontal line depicts the conditional distribution when $p = 0$, which is uniform. The

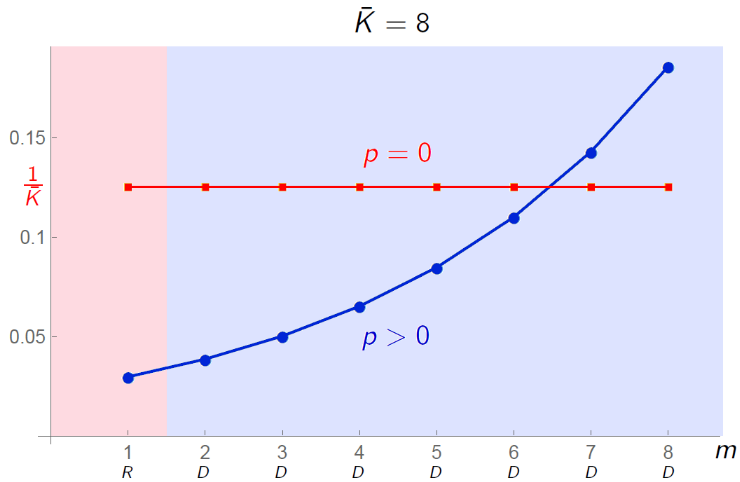


Figure 3: *Stationary probabilities conditional on signal B:* $\mu_m/(1-\mu_0)$ *for* $m = 1, \ldots, \bar{K}$. *Illustrated for* $p = 0$ *and* $p = 0.23$.

distribution conditional on $p > 0$ is upward sloping since higher values of p increase $\mu_{\bar{K}}$ and depress μ_1.

The probability that a loan made at history B is repaid is

$$\pi(p, 1) := \frac{\mu_1(p, 1)}{1 - \mu_0(p, 1)}. \tag{15}$$

In Appendix A.4.1 we show that this is a continuous and strictly decreasing function of p. Intuitively, higher values of p result in more defaults at B, increasing the slope of the conditional distribution. Thus if $\pi(\tilde{p}, 1) \leq \frac{\ell}{1+\ell}$, the intermediate value theorem implies that there exists a value of $p \in (0, \tilde{p}]$ such that $\pi(p, 1) = \frac{\ell}{1+\ell}$. This proves the existence of a mixed strategy equilibrium where all borrowers have pure best responses.

If loans are so profitable that $\pi(\tilde{p}, 1) > \frac{\ell}{1+\ell}$, then an equilibrium also requires mixing by the borrower. At $\tilde{p}$, the borrower with $m = 1$ is indifferent between repaying and defaulting on a loan. In this case, a borrower with a good signal (i.e. with $m = 0$) is also indifferent between repaying and defaulting, and there is a continuum of equilibria where these two types repay with different probabilities. However, only the equilibrium in which both types, $m = 1$ and $m = 0$, repay with the same probability, q, is purifiable. We focus our analysis on this equilibrium.

Let $\mu(\tilde{p}, q)$ denote the invariant distribution over values of m induced by this strategy

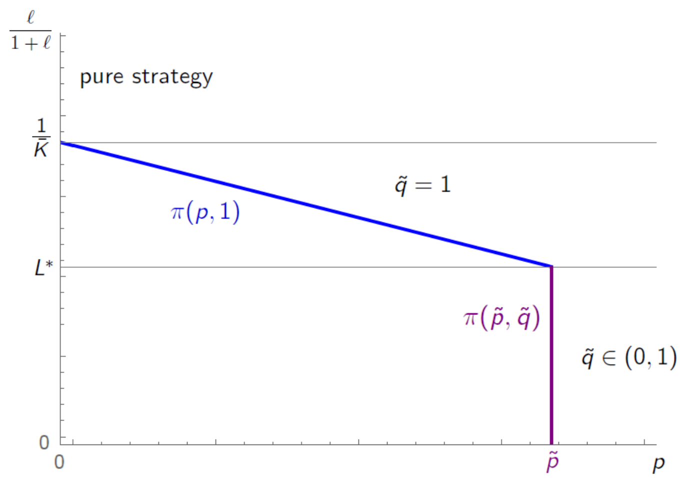


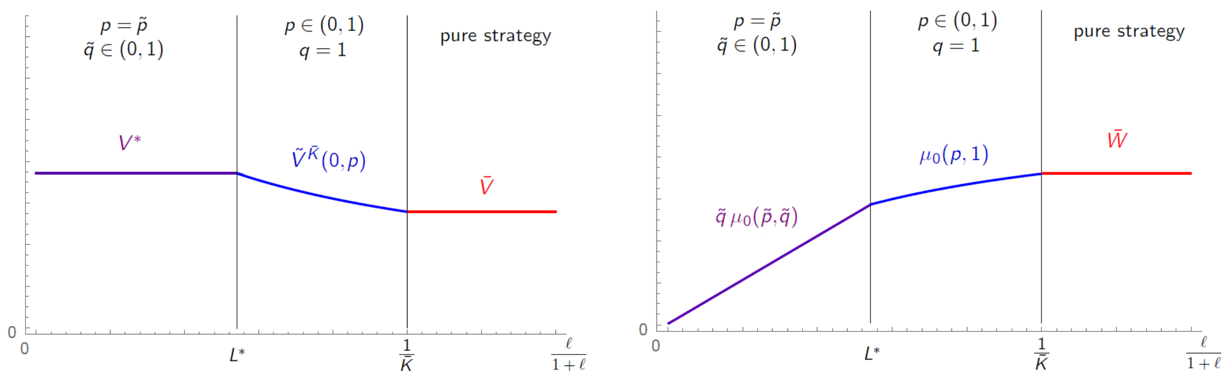
Figure 4: *The functions $\pi(p,1)$ and $\pi(\tilde{p},q)$. Let $L^* = \frac{\ell^*}{1+\ell^*}$. When $L^* \le \ell/(1+\ell) \le 1/\bar{K}$ there exists a mixed strategy equilibrium in which all types of borrowers use a pure strategy. When $0 < \ell/(1+\ell) < L^*$, there exists a mixed strategy equilibrium in which types $m=0$ and $m=1$ repay with probability q setting $\pi(\tilde{p},q) = \ell/(1+\ell)$.*

profile. The probability that a loan made at history B is repaid is now

$$\pi(\tilde{p},q) := \frac{q\,\mu_1(\tilde{p},q)}{1-\mu_0(\tilde{p},q)} = q\,\pi(\tilde{p},1). \tag{16}$$

We establish the second equality in Appendix A.4.2. Clearly, $\pi(\tilde{p},q)$ is a continuous and strictly increasing function of q. Since we are considering the case where $\pi(\tilde{p},1) > \frac{\ell}{1+\ell}$, and since $\pi(\tilde{p},0) = 0$, the intermediate value theorem implies that there exists a value of q setting the repayment probability $\pi(\tilde{p},q)$ equal to $\frac{\ell}{1+\ell}$, so that lenders are indifferent between lending and not lending to a borrower with signal B. Figure 4 illustrates our analysis, with p on the horizontal axis and the repayment probability after B, $\pi(p,q)$, on the vertical axis. When $q=1$, so that a borrower with $m=1$ repays for sure, $\pi(p,1)$ is given by the downward sloping (blue) line. This stops at $\tilde{p}$, and further declines of the repayment probability are achieved by reducing q, along the (purple) vertical line. Figure 5 illustrates the corresponding equilibrium payoff for the borrower and the lender. We have therefore established the following proposition.

Proposition 4 *Suppose $\bar{K} \ge 2$. If $0 < \ell < \frac{1}{\bar{K}-1}$, there exists a purifiable mixed equilibrium under the simple information structure and $\bar{K}$ memory, where the borrower's payoff is strictly greater than $\bar{V}$. If ℓ is strictly greater than a threshold value ℓ^*, then the borrower plays a pure*



(a) *Borrower's equilibrium payoff.* (b) *Lender's equilibrium payoff.*

Figure 5: *Equilibrium payoffs under the simple information structure with $\bar{K}$ period memory.*

strategy, where she repays if $m \in \{0,1\}$. If $\ell \in (0,\ell^*]$, then loans are made with probability $\tilde{p}$ after B, and borrower types $m \in \{0,1\}$ repay with probability $\tilde{q}$ so as to make the lender indifferent between lending and not lending at B.

The borrower payoff in the mixed equilibrium lies between $\bar{V}$ and V^*. It is strictly greater than $\bar{V}$ since the exclusion for $\bar{K}$ periods is random, and she gets a loan with positive probability. When ℓ is so low that the borrower also mixes, then she gets the payoff V^* – this follows from the fact that her incentive constraint is satisfied with equality when she has a good signal. Thus, when lending becomes more profitable, the borrower's payoff increases in the mixed equilibrium. However, payoffs for the lender are strictly less than $\bar{W}$. Since the lender only makes positive profits when she lends to a borrower with a good signal, steady state profits equal the proportion of borrowers with signal G. This proportion falls as p increases. When the borrower also mixes, and defaults after a good signal with some probability, the lender's profits fall further, and as ℓ tends to zero, so do profits.

Appendix A.4.3 proves that the equilibria described in the proposition are purifiable. In the case where both lenders and borrowers with $m \in \{0,1\}$ mix, it is worth noting that the equilibrium is not *regular* — it is not isolated, since it is one of a continuum of equilibria.[29] Here, we give a brief intuition for why purification selects a unique mixed equilibrium. When the lending probability after B equals $\tilde{p}$, and borrower types $m \in \{0,1\}$ are indifferent between defaulting and repaying, there is a continuum of equilibria in the unperturbed game. The borrower repayment probability $\tilde{q}$ at $m=1$ is pinned down by the

[29]The standard proofs for purifiability, in Harsanyi (1973), Govindan, Reny, and Robson (2003) and Doraszelski and Escobar (2010), apply for regular equilibria.

equilibrium condition $\pi(\tilde{p}, \tilde{q}) = \frac{\ell}{1+\ell}$, but the repayment probability at $m = 0$ can take any value in some interval. In particular, one can have the borrower repaying with probability one at $m = 1$, but with probability $\tilde{q}$ at $m = 0$. However, the difference between borrower histories at these two values of m is payoff-irrelevant for the borrower, since no future lender can see this difference. The payoff shocks prevent any such conditioning, and only one of these equilibria can be purified, namely the one where the repayment probability at $m = 0$ also equals $\tilde{q}$. Thus, although the equilibrium where the borrower repays for sure when $m = 1$ is better for the lenders (and no worse for the borrowers), it cannot be sustained.

An Example: We consider parameter values such that $\bar{K} = 4$.[30] Consider the pure strategy profile when $K = \bar{K}$, where the lender extends a loan only after G. From our previous analysis, the invariant distribution over $\{1, \ldots, K\}$ is uniform, and the probability that the lender is repaid if lending at B equals $\frac{1}{4}$. So if $\ell > \frac{1}{3}$, a pure strategy equilibrium exists. The expected payoff to a borrower with a good history is $\bar{V} = 0.763$. The lender's expected payoff equals the probability of encountering a borrower with a good history, which is $\bar{W} = 0.714$.

If $\ell < \frac{1}{3}$, lending after B is too profitable and a pure strategy equilibrium with $\bar{K}$-period memory does not exist. A pure strategy equilibrium with longer memory exists, but can be very inefficient. For example, if $\ell = 0.315$, we need $K = 30$, in which case $m^*(K) = 7$ and the lender strictly prefers not lending at B. The invariant distribution over borrower types has only a quarter of the population with a clean history, so that the lender's payoff equals 0.25, strictly less than $\bar{W}$. Since exclusion is very long, the borrower's payoff at a clean history is also low, at 0.537, which is strictly less than $\bar{V}$.

In the mixed strategy equilibrium with 4-period memory, the lender offers a loan with probability $\tilde{p} = 0.028$ to a borrower on observing B. This equilibrium is considerably more efficient than the pure equilibrium with 30-period memory. The proportion of borrowers with clean histories is $\mu_0 = 0.705$, and this is also the lender's expected payoff. The expected payoff to a borrower with a clean history is $0.775 > \bar{V}$, since she sometimes gets a loan even when the signal is B.

If ℓ is smaller, say 0.1, then the mixed equilibrium also requires random repayment by borrowers of types $m \in \{0, 1\}$.[31] The lending probability after B is $\tilde{p} = 0.034$, and the repayment probability is $\tilde{q} = 0.383$ for $m = 0$ and $m = 1$. The lender's payoff in this

[30] Specifically, $\delta = 0.9, \lambda = 0.1$ and $g = 2$.

[31] If $\ell = 0.1$, $K = 89$ periods of exclusion are needed to support a pure strategy equilibrium. In this case $m^*(K) = 8$. The lender's payoff is $\mu_0 = 0.1$ and the borrower's payoff at a clean history is 0.526.

equilibrium is substantially lower: $\mu_0(\tilde{q} - \ell(1 - \tilde{q})) = 0.084$. This is largely because a lower fraction of the population has a good history: $\mu_0 = 0.262$. The payoff to the borrower with a clean history equals $V^* = 0.778$.

At the same value of ℓ, there exists another equilibrium at which the lending probability at G is one and at B is $\tilde{p} = 0.034$, and where the borrower with $m = 0$ repays the loan with certainty, while the borrower with $m = 1$ repays it with probability $q_1 = 0.383$. The lender's payoff in this equilibrium, $\mu_0 = 0.699$, is substantially higher than in the equilibrium where both $m = 0$ and $m = 1$ mix with the same probability. The borrower's payoff at $m = 0$ remains V^*. Notice that this equilibrium is not purifiable, but it Pareto-dominates the purifiable equilibrium at which $m = 0$ and $m = 1$ repay a loan with the same probability. □

Taking stock: we have demonstrated that for any parameter values, the simple binary information structure can ensure a borrower payoff of at least $\bar{V}$, no matter how profitable loans are (or, equivalently, how small ℓ is). When ℓ is large, a pure strategy equilibrium exists, and yields borrower payoffs of $\bar{V}$ and lender payoffs of $\bar{W}$. We can also achieve fully efficient payoffs V^* and W^* with a random signal structure. When ℓ is small, the mixed strategy equilibrium yields borrower payoffs greater than $\bar{V}$, but lender payoffs strictly below $\bar{W}$. For very small values of ℓ, lender payoffs can be extremely low.

The next sections examine how outcomes may be improved for lenders without compromising on achieving a borrower payoff of $\bar{V}$. In Section 6.1 we show that a non-monotone information structure can be used to support a pure strategy equilibrium with minimal borrower exclusion. In Section 6.2 we show that preventing lenders from chasing borrowers, by requiring initial applications from the latter, can also do the same under the simple information structure. In both cases, pure strategy equilibria achieve the constrained efficient payoffs $\bar{V}$ and $\bar{W}$.

6 Improving Lender Payoffs

We now explore two ways to increase lender payoffs when ℓ is small. First, we consider non-monotone information structures. that pool multiple defaulters with non-defaulters, Then we consider the implications of legislation that prevents lenders from "chasing" borrowers.

6.1 Non-monotone Information

How can we discipline lenders when ℓ is small? One idea is as follows: suppose that we reward borrowers for defaulting on a lender who should not have made a loan. This makes it more likely that a borrower with a bad credit history will default, and dissuades lending to them. We can implement this idea, under bounded memory, by assigning a good credit history to borrowers with *two* defaults, while those with a single default are assigned a bad credit history. We call such an information structure *non-monotone*, since borrowers with no defaults are pooled with borrowers with two defaults, while one-default borrowers are excluded from this pool.

There still remains the problem identified in Section 3.2, that the incentives of a borrower with a single default which occurred exactly K periods ago (i.e. a borrower with $m = 1$) are identical to that of a borrower with no defaults. Thus in any purifiable equilibrium, the behavior of the two borrowers must be identical, and if the borrower with no defaults repays for sure, so must the borrower with a single default and $m = 1$. This suggests that the probability of repayment of a lender with a bad credit history cannot be reduced below $\frac{1}{K}$. Nonetheless, the following proposition constructs an information structure where this repayment probability is zero. The trick here is to allow for memory that is one period longer than is required for borrower incentives, so that $K = \bar{K} + 1$. The additional period is not used to punish the borrower, but instead to retain information for disciplining the lender.

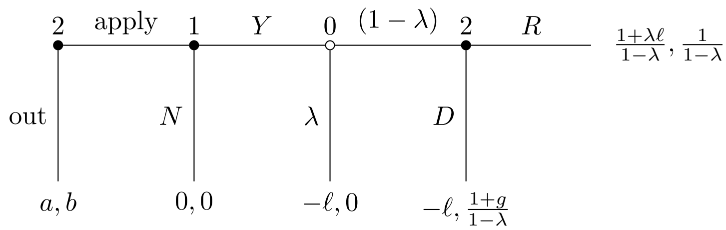
Proposition 5 *For any $\ell > 0$, there exists a non-monotone informational structure, and a sequentially strict equilibrium that achieves borrower payoff $\bar{V}$ and lender payoff $\bar{W}$.*

Proof. Let the length of memory be $K = \bar{K}+1$, and let N_D denote the number of instances of D in the last K periods. The lender observes credit history G if $N_D \in \{0, 2\}$, or if $N_D = 1$ and $m = 1$. Otherwise, the credit history is B — in particular, if $N_D = 1$ and $m > 1$. The lender lends after G and does not lend after B. Consequently, a defaulting lender with no instance of D in the past is excluded for $\bar{K}$ periods, and thus repayment is optimal on being given a loan. Consider a borrower with $N_D = 1$ and $m > 1$, who has credit history B. If she receives a loan, this borrower will default, since by doing so she gets a good credit history in the next period (since $N_D = 2$ in the next period). Thus defaulting raises her continuation value as well as current payoff, relative to repayment. Consequently, the probability of repayment of a loan made to a borrower with history B is zero, and thus for any $\ell > 0$, lending at B is strictly unprofitable. Since exclusion is for $\bar{K}$ periods, the payoffs are as stated in the proposition. ■

Remark 1 *The proposition applies also when $\bar{K} = 1$ — in contrast with Proposition 3, which does not.*

Non-monotonicity of the information is an unrealistic feature, since a borrower with a worse default record is given a better rating than one with a single default. Furthermore, it may be vulnerable to manipulation, if we take into account real-world considerations that are not explicitly modeled. A borrower with two defaults in the last $K-1$ periods is ensured of a continuation value corresponding to being able to default without consequence twice in every K periods. This is very attractive, and a borrower with a single default may be willing to pay a large bribe to a lender, in exchange for the privilege of defaulting once more.

6.2 Banning Loan Chasing



We now investigate the effects of laws mandating that lenders cannot "chase" borrowers, by requiring that borrowers must first make an application to the lender before a loan is made. Making an application involves a slight cost to the borrower.[32] We model the interaction between borrower and lender as the extensive form game set out in the figure above. First, the borrower may apply for a loan, at a small cost. If she does not apply, the game ends, with payoffs a for the lender and $b > 0$ for the borrower. Once she applies, the game is as before; i.e. the lender chooses between Y and N, and if the borrower is able to repay, he must choose between R and N. Thus the backwards induction outcome is *out*, and the borrower does not apply. We assume the simple information structure with $\bar{K}$ periods memory.[33]

Requiring prior application transforms the interaction between an individual lender and borrower into a signaling game. In particular, a borrower with credit history B has private information regarding m, the number of periods without default that must elapse before her credit history becomes good. Since the informed party moves first, we have a signaling game. Consider the following strategy profile, σ^*. Borrowers with history G apply, are given a loan and repay. Borrowers of type B do not apply; if they do make an application, the lender rejects their application; if the lender accepts their application, the borrower defaults

[32] And possibly to the lender, although this plays no role in the analysis.

[33] For the full efficiency result, we use the random version of the simple information structure, under which the borrower gets a good signal either if she has not defaulted in the last $\bar{K}$ periods, and has defaulted exactly once $\bar{K}$ periods ago, in which case she gets signal G with probability x.

if $m > m^*$ and repays if $m \leq m^*$. The following proposition shows that if $K = \bar{K} \geq 2$, then this strategy profile is a sequentially strict equilibrium, where the lender believes that an applicant with signal B will default with probability one, and these beliefs are implied by the D1 criterion of Cho and Kreps (1987). In other words, punishments are of minimal length, no matter how profitable loans are.

Proposition 6 *Assume that $K = \bar{K} \geq 2$ and the random version of the simple information structure. For any $\ell > 0$, σ^* is a sequentially strict perfect Bayesian equilibrium, that approximates payoffs V^* and W^*, with borrower beliefs satisfying the D1 criterion that assigns probability one to an applicant with a bad credit history defaulting.*

Proof. The borrower's strategy is a strict best response to the lender's strategy, since application is costly ($a > 0$). Given the lender's beliefs, his strategy is (strictly) sequentially rational. It remains to verify that the beliefs of the lender are implied by the D1 criterion. Suppose that a borrower with a bad credit history applies for a loan, and gets it. Since $m^* = 1$, only this type of borrower will repay, (cf. Section 4). Consider a mixed response of the lender to a loan application, whereby he gives a loan with probability q on observing a B applicant, where q is chosen so that the type of applicant who intends to repay (i.e. one with $m = m^* = 1$) is indifferent between applying or not. Thus, q satisfies

$$(1-\delta)a = q\big[1 - \delta + \delta\lambda\big(V(K) - V(0)\big)\big]. \tag{17}$$

Now consider a borrower of type $m' > 1$, whose optimal strategy is to default on the loan, if she receives it. Since default is optimal, her net benefit from applying, relative to not applying, equals

$$q\big[(1-\delta)(1+g) + \delta\big(V(K) - V(m'-1)\big)\big] - (1-\delta)a. \tag{18}$$

We now show that expression (18) above is strictly positive. Substituting for $(1-\delta)a$ from (17), and dividing by q, we see that the sign of (18) is the same as that of

$$(1-\delta)g + \delta(1-\lambda)\big(V(K) - V(m'-1)\big) + \delta\lambda\big(V(0) - V(m'-1)\big). \tag{19}$$

Since default is optimal for type m',

$$(1-\delta)g + \delta(1-\lambda)[V(K) - V(m'-1)] > 0,$$

establishing that the sum of the first two terms in (19) is strictly positive. Also, $V(0) > V(m')$, and so the third term as well as the overall expression in (19) is strictly positive. Thus, type m' has a strict incentive to apply whenever m^* is indifferent.

We conclude therefore that a borrower who intends to default strictly prefers to apply, if q is such that any type of borrower who does not intend to default is indifferent. Thus the D1 criterion implies that in the above equilibrium, the lender must assign probability one to defaulting types when he sees an application from a borrower with a B credit history. ■

We conclude that when loans are very profitable, so that a mixed equilibrium results in low lender payoffs, banning loan chasing is in the interests of the lenders.In the resulting signaling game, the fully efficient payoffs V^* and W^* are equilibrium payoffs.

7 Extensions

7.1 Adverse Selection

In focusing on borrower moral hazard, we have assumed away adverse selection. We now show that moderate adverse selection among borrowers may actually improve matters, by mitigating lender moral hazard. In other words, exogenous borrower adverse selection can augment the adverse selection that is endogenously generated by the coarse information on borrower histories.

Suppose that there are two types of borrowers, who differ only in their rates of involuntary default, λ and λ'. Let $\lambda' > \lambda$, so that the former corresponds a high-risk borrower. Given the payoffs in Figure 1a, the expected payoff of lending to a high-risk borrower who intends to repay is $\pi := \frac{1+(\lambda'-\lambda)\ell-\lambda'}{(1-\lambda)} < 1$. The payoff from lending to a borrower who intends to default is $-\ell$, independent of her type. Let θ denote the fraction of high-risk borrowers. Assume K-period memory, and the simple information structure. Consider a pure strategy profile where lenders lend after signal G, but not after B. Suppose that K is large enough that borrowers of either type find it optimal to repay at credit history G. The steady state probability that a high-risk borrower has a bad credit history equals $\frac{K\lambda'}{1+K\lambda'}$, which exceeds the steady state probability that a normal borrower has signal B, $\frac{K\lambda}{1+K\lambda}$. Thus the probability assigned by the lender to a borrower with a bad signal being high-risk is greater than θ. Since high-risk borrowers are less profitable even when they intend to repay (i.e. when $m \leq m^*$), this reduces the lender's incentive to lend after a bad signal. Thus borrower adverse selection mitigates lender moral hazard, even though we have shown that it is not essential.

7.2 Empirical evidence

We examine the empirical work on the functioning of the credit scoring system, which we briefly reviewed in Section 1.1. Two points are in order. First, the declared objective of a credit bureau is to provide lenders with the best predictions of borrower delinquency. Its goal is *not* to sustain the overall functioning of the credit system. Our analysis demonstrates that these goals are in conflict, since providing more information may undermine borrower exclusion. Second, adverse selection may well play a role in disciplining lenders.

Musto (2004) uses panel data to document the effects of expunging Chapter 7 bankruptcy flags. Musto finds that the removal of flags boosts credit scores and credit card limits, especially for those with relatively good credit scores. He also finds that the removed information on bankruptcy flags is predictive of future defaults, even conditional on the same credit score, and argues that this legislation has adverse consequences for resource allocation, by removing information from the market.

Gross, Notowidigdo, and Wang (2016) find that the removal of bankruptcy flags raises credit scores by 15 points, and results in substantial increase in borrowing, both on credit cards and in mortgages. They find that this increase is *not* associated with any increase in delinquencies or collection inquiries, i.e. there is no increased risk of default.

Dobbie, Goldsmith-Pinkham, Mahoney, and Song (2016) use a difference-in-difference design, comparing Chapter 13 filers, whose bankruptcy flags are removed after 7 years, with Chapter 7 filers whose flags are not removed at that point.[34] They find that the removal of bankruptcy flags leads to a jump in credit scores in the quarter of removal, which corresponds to an implied 3 percentage point reduced default risk, on a pre-flag removal risk of 32 percent. This leads to a large increase in the credit limits and credit card balances, and on mortgage borrowings. They document that the removed bankruptcy flags are strongly predictive of future credit card and delinquency.

To summarize: a common empirical finding is that the removal of bankruptcy flags is associated with a sharp jump in credit scores. Such a jump is not plausibly consistent with any real change in default probability — it is hard to think of a model where there is 3 percentage points decline in default probability over a single quarter. Instead, it suggests that bounded memory constraints are binding, and information does indeed leave the market.

Second, the empirical evidence does not examine whether lending increases in anticipation of the removal of bankruptcy flags, since it focuses on the before-after comparison. Third, the findings on the informational content of hidden past defaults are contradictory — Gross,

[34] Recall that Chapter 7 flags are removed at 10 years.

Notowidigdo, and Wang (2016) find no informational content, while Dobbie, Goldsmith-Pinkham, Mahoney, and Song (2016) find that these predict future delinquent behavior. The latter suggests significant residual adverse selection, so that past defaults are informative, while the former suggests not. Our analysis implies that whether residual adverse selection remains or not is an important question, since it would discipline lenders and dissuade them from lending to borrowers whose bankruptcy flags are on the verge of being removed, just as its absence can result in an reduction of punishments once lenders recognize the profitable opportunities available in lending to those borrowers who are on the verge of having their flags removed.

Thus our analysis offers suggestions for further empirical work. First, do lenders increase lending to borrowers whose bankruptcy flags are on the verge of being removed? Second, there is scope for an estimatable model that combines moral hazard with residual adverse selection, which could be used predict lender and borrower behavior.[35] Third, what are the moral hazard implications of bankruptcy law, the credit scoring system, and the constraints on memory? Although Fay, Hurst, and White (2002) address this question at the level of the individual borrower and document the importance of moral hazard, answering it fully requires general equilibrium analysis. The US bankruptcy system provides social insurance on a larger scale than the unemployment insurance system (Dobbie and Song (2015)); however, its moral hazard implications have received comparatively little attention (at least, in comparison with unemployment insurance).

7.3 Generalizing our Results

How robust are our results to various modeling choices? For example, the interaction between lender and borrower could involve many choices — the lender may offer loans of various sizes or interest rates. Second, how may it be extended to other contexts, beyond the credit market?

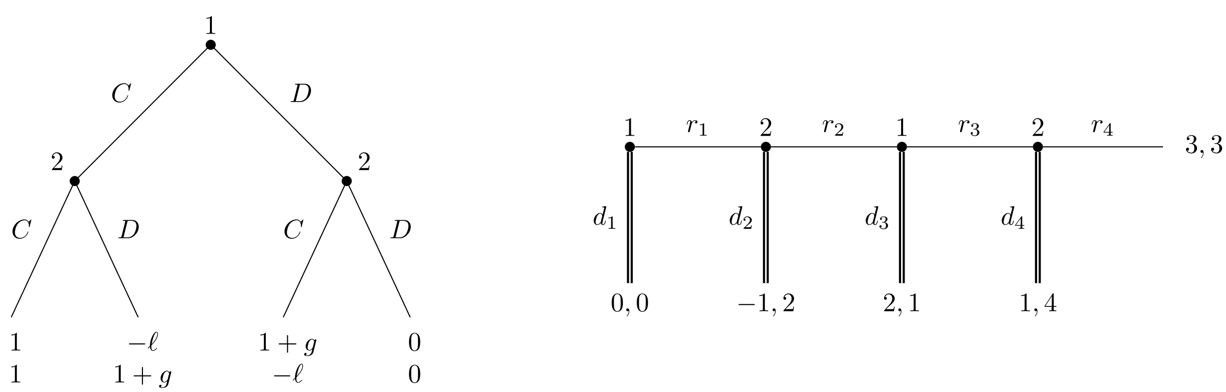
First, we note that the analysis of this paper applies to many large markets with one-sided moral hazard. This includes, for example, the interaction between a buyer and a seller when the seller decides which quality to provide after the buyer places the order. If

[35] Chatterjee, Corbae, Nakajima, and Ríos-Rull (2007) have a quantitative model of default behavior, where the expunging of records is modelled as stochastic, and there is no residual adverse selection. Developing a model where the removal of bankruptcy flags is deterministic and with residual adverse selection is beyond the scope of this paper for two reasons. First, theoretical models are not intended to be realistic, but to sharply identify economic forces at work. Second, any such empirical work would be a substantial project in its own right.

information about the past outcomes of the seller is subject to a bounded memory, our analysis applies. We now show that our analysis also applies to a larger class of stage games of perfect information.

Consider the prisoner's dilemma with sequential moves, as depicted in the Figure 6a, where $g, \ell > 0$. If both players expect the efficient outcome CC to be played, then player 1 has no incentive to deviate to D, if she expects player 2 to respond by continuing with the backwards induction strategy, i.e. by also playing D. On the other hand, player 2 has an incentive to deviate from the path CC. In the Appendix A.5, we show that the analysis of this paper applies to the sustainability of efficient outcomes in any game of perfect information in which each player moves at most once. Thus, it applies to the prisoner's dilemma game.

More generally, consider a generic two-player game of perfect information, and a Pareto-efficient outcome, z^*, that is individually rational. Let both players conjecture that any deviation from the path to z^* is followed by players continuing with the backward induction strategies. Suppose now that only one player has an incentive to deviate from the path to z^* given this conjecture about continuation play, and this incentive arises at a single node. Then the analysis of this paper applies. Thus our results are robust to alternative specifications of the lender-borrower interaction. We can allow the lender to choose between several different loan contracts. Since only the borrower has an incentive to deviate from any efficient role contract, this modified game satisfies our assumption.



(a) Prisoners' dilemma.

(b) Centipede game.

Figure 6: Two admissible games.

To illustrate how general these results are, consider the centipede game in Figure 6b, where the backwards induction strategy profile has players choosing *down* (d_t) at every history. Consider the Pareto-efficient terminal node z^* that is reached when players choose *right* (r_t) at every history. *If players expect the outcome* z^*, then only one player has an incentive to deviate along the path to z^*: player 2. Furthermore, there is only a single decision node at which 2 has an incentive to deviate: the last one.

Now suppose that this game is played repeatedly in a random matching environment. Consider an information structure where, before the game is played in a match, player 1 is provided coarse information on the last K outcomes of player 2. Specifically, signal B is observed if and only if 2 has played d_4 in at least one of the last K periods; signal G is observed otherwise. Suppose that 1 plays d_1 upon observing signal B, and let $\bar{K}$ denote the smallest punishment length that suffices to incentivize player 2 to play r_4 at G.[36] As long as $K \geq \max\{\bar{K}, 2\}$, there exists an equilibrium that supports the efficient outcome z^* under this information structure. Furthermore, it is costly for player 2 to choose r_2 at her first decision node if she expects player 1 to continue with his backwards induction action d_3. This ensures that if 2 plays r_2 and has a bad signal, then the D1 criterion implies that, at his second information set, 1 believes that if he plays r_3, 2 will continue with d_4.

In Appendix A.5, we show that this argument generalizes. Fix a Pareto-efficient terminal node z^* that differs from the backwards induction outcome in a two-player game of perfect information. Suppose that:

- Only one player, $\hat{i}$, has an incentive to deviate from the path to z^*.
- This incentive to deviate exists only at a single node, $\hat{x}$.
- Player $\hat{i}$ has a decision node x that precedes $\hat{x}$ on the path to z^* where her backwards induction strategy prescribes deviating from $\phi(z^*)$ at x.

Under these assumptions, there exists a simple information structure and an equilibrium that sustains play of the efficient outcome z^*.[37] In this equilibrium, players play the outcome z^* when the signal about player $\hat{i}$ is good, and they play the backwards induction outcome when the signal is bad. Players' beliefs satisfy the D1 criterion, and it suffices to pick punishments of a minimum length that is sufficient to discipline player $\hat{i}$.

If the last of the above assumptions is not satisfied, then one also needs to ensure that the player who does not have an incentive to deviate from the path to z^* does indeed punish player $\hat{i}$ when he sees a bad signal regarding her. This concern has been the focus of most of

[36]If g denotes player 2's payoff gain from playing d_4 instead of r_4, then $\bar{K}$ is the smallest integer K that satisfies the inequality $g \leq \frac{\delta(1-\delta^K)}{1-\delta}$, where δ is player 2's discount factor.

[37]In fact, our analysis applies to stage games of perfect information with an arbitrary finite number of players, provided that these conditions hold, but we prove this only for the case of two players.

this paper, and methods similar to those set out in the context of the lender-borrower game can be used. To avoid repetition, we do not present the details here.

If the first of these assumptions is not satisfied, and both players have an incentive to deviate from the path to z^*, then providing incentives for both players becomes more difficult. This would be the case, for example, if the payoff of player 1 after r_3 was changed to 4. As we will see in Section 7.4, it is difficult to provide incentives for a player to condition his behavior on a signal regarding his opponent via *future play.* Incentives for such conditioning have to be provided within the period. (In the lender-borrower game, the lender has only within-period incentives to condition his behavior on the borrower's signal). This makes the analysis of this case more difficult, and we leave this for future work.

7.4 The Irrelevance of Information on Lenders

Can information on lender behavior be used to prevent lenders from making loans to borrowers who have recently defaulted? Suppose that the borrower also observes information on the past outcomes of the lender. It is easy to see that this additional information is not useful, since observing the outcome in any interaction of the lender does not convey information on whether the lender should have made the loan or not in the first place.

Now, suppose that the borrower not only observes the outcomes in the lender's past interactions, but also the information that the lender received about the borrowers he interacted with. For example, if the lender's information regarding a borrower is a binary signal, then the borrower today observes the outcome in each past K interaction plus the K realizations of the binary signal observed by the lender. In particular, if the lender lent yesterday to a borrower with a bad signal, the borrower today can see this. The question is: can we leverage this additional information in order to discipline the lender, so that he does not lend to borrowers with a bad signal?

Unfortunately, the answer is no. Consider a borrower's repayment decision conditional on obtaining a loan. While the borrower can observe information on the lender's past behavior, in any purifiable equilibrium, she will not condition her behavior on this information. Since no future lender will observe this information, but will only observe the outcome in this and past interactions of the borrower, information on the lender's past behavior is payoff-irrelevant.

Thus in the perturbed game where the borrower is subject to payoff shocks, the borrower can play differently after two different lender histories, h_1 and h_1', only for a set of payoff shocks that have Lebesgue measure zero. Hence, in any purifiable equilibrium of the unperturbed game, a borrower cannot condition her repayment behavior on any information regarding the lender. So our assumption that the borrower observes no information regarding the lender is without loss of generality.

This discussion also illuminates the interplay between information and incentives that underlies our analysis. Since a lender's future continuation value cannot depend on his current behavior, incentives have to be provided *within the period.* This is possible, since borrowers with a bad signal have a higher incentive to default than those with a good signal. This also explains why our results extend to general games where only one player has an incentive to deviate from the path to an efficient outcome, but not to games where both players have an incentive to deviate.

Finally, one might ask whether our analysis is robust to different forms of bounded memory. For example, suppose that loans that are defaulted on are expunged from the record, but otherwise, there is no uniform bound on memory. In the appendix A.6, we show that would get similar results under this formulation.

8 Conclusion

Excessive lending by financial institutions has been the focus of attention during the recent financial and sub-prime crises. Economists and policy-makers (e.g. Admati and Hellwig (2014)) have argued that government guarantees for banks, whether implicit or explicit, induce lending to high-risk borrowers, the cost of which is borne by the government. This paper identifies a different form of excessive lending, whereby lenders undermine borrower repayment incentives by providing defaulters with credit. The negative externality imposed by such behavior falls upon other lenders, and ultimately upon the credit system as a whole. While this problem is general, our specific focus has been on the question: how should information be optimally provided when records are bounded? Providing incentives for a lender to exclude a defaulting borrower turns out to be critical, and for this purpose, one may need to limit information. More generally, there is need for further research, theoretical as well as empirical, on the incentive effects of the bankruptcy code, and its interaction with the credit scoring system. Credit scoring has the declared purpose of allowing lenders to better predict borrower behavior. But better predictions may be a mixed blessing, since they may well undermine incentives.

A Appendix: For Online Publication

A.1 Proofs related to Section 3.1

We derive the upper bound on the borrower's value in any equilibrium, when the borrower's mixed strategies are not observable. Let V^* be the supremum value of the borrower's payoff in any equilibrium. Note that in any period when her value is near V^*, the borrower must receive a loan. For the lender to agree to lend, the borrower must repay with positive probability. Thus repaying for sure in the current period must be optimal. Thus V^* satisfies the inequality:

$$V^* \leq (1-\delta) + \delta\left[\lambda\, V^P + (1-\lambda)\, V^*\right]. \tag{A.1}$$

The right-hand side above is an upper bound on the borrower's value when she chooses to repay, and is derived as follows. When the borrower is able to repay, she gets no more than V^* tomorrow, since this is the supremum value in any equilibrium. V^P denotes the borrower's value following involuntary default. Since repaying must optimal in the current period, we have the following necessary incentive constraint

$$(1-\delta)(1+g) + \delta\, V^P \leq (1-\delta) + \delta\left[\lambda\, V^P + (1-\lambda)\, V^*\right],$$

where the left-hand side is the borrower's payoff from voluntary default. Rearranging gives

$$(1-\delta)\, g \leq \delta\,(1-\lambda)\,[V^* - V^P]. \tag{A.2}$$

By substituting inequality A.2 in A.1, we get

$$V^* \leq 1 - \frac{\lambda}{1-\lambda}\, g. \tag{A.3}$$

To see that the above bound on V^* is indeed achievable, let the difference $V^* - V^P$ be such that A.2 holds with equality. It is straightforward to verify that this implies that A.1 holds with equality. This yields the expression for V^* in equation 4.

A.2 Proofs Related to Sections 4 and 5.1

First, we show that if $K \geq \bar{K}$, then a borrower with $m = K$ has a strict incentive to default, i.e. we establish the inequality below (a restatement of (6)):

$$g > (1-\lambda)\delta^K V^K(0).$$

Since both δ^K and $V^K(0)$ are strictly decreasing in K, it suffices to prove this for $K = \bar{K}$. Here, we prove a stronger result that implies the first part of Lemma A.1. For $K = \bar{K}$ and for any $m > 1$,

$$(1-\delta)g > \delta(1-\lambda)\left(V^{\bar{K}}(m-1) - V^{\bar{K}}(\bar{K})\right).$$

Since $V^{\bar{K}}(m)$ is strictly decreasing in m, it suffices to prove this for $m = 2$. That is, we need to establish the inequality

$$(1-\delta)g > \delta(1-\lambda)\left(V^{\bar{K}}(1) - V^{\bar{K}}(\bar{K})\right) = \delta(1-\lambda)(\delta - \delta^{\bar{K}})V^{\bar{K}}(0). \tag{A.4}$$

By the definition of $\bar{K}$, the incentive constraint (1) is not satisfied for $K = \bar{K} - 1$, so that

$$(1-\delta)g > \delta(1-\lambda)\left(V^{\bar{K}-1}(0) - V^{\bar{K}-1}(\bar{K}-1)\right) = \delta(1-\lambda)(1-\delta^{\bar{K}-1})V^{\bar{K}-1}(0).$$

Thus, to prove (A.4), it suffices to show that

$$V^{\bar{K}-1}(0) > \delta\, V^{\bar{K}}(0).$$

Since $V^{\bar{K}-1}(0) > V^{\bar{K}}(0)$, the above inequality is proved. We have therefore established (6).

We now solve for $m^\dagger$, the real value of m that sets (7) equal to zero:

$$m^\dagger(K) = \ln\left[\frac{(1-\delta)g}{(1-\lambda)V^K(0)} + \delta^{K+1}\right] / \ln\delta.$$

Lemma A.1 *If $K = \bar{K}$, then $m^\dagger(K) \in (1,2)$. Moreover, $\frac{m^*(K)}{K} \to 0$ as $K \to \infty$.*

Proof. Since

$$\lim_{K\to\infty} V^K(0) = \frac{(1-\delta)}{1-\delta(1-\lambda)},$$

it follows that

$$\lim_{K\to\infty} m^\dagger(K) = \ln\left[\frac{g(1-\delta(1-\lambda))}{1-\lambda}\right] / \ln\delta. \tag{A.5}$$

Therefore, $\frac{m^*(K)}{K} \to 0$ as $K \to \infty$. ■

Proof of Proposition 3

We begin by writing out the value functions of the borrower under the random information structure. Recall that we have $\bar{K}$ memory, and that the borrower is excluded with probability x for $\bar{K}-1$ periods and with complementary probability for $\bar{K}$ periods. The borrower's value function at a clean history has the same form as before:

$$V^{\bar{K},x}(0) = (1-\delta) + \delta \left[\lambda V^{\bar{K},x}(\bar{K}) + (1-\lambda)V^{\bar{K},x}(0)\right].$$

Her value function in the last period of potential exclusion is modified, and is given by:

$$V^{\bar{K},x}(\bar{K}) = \delta^{\bar{K}-1}\ (x\delta + 1 - x)\ V^{\bar{K},x}(0).$$

Using this, we may rewrite her value function at a clean history as

$$V^{\bar{K},x}(0) = \frac{1-\delta}{1-\delta(1-\lambda+\lambda\,\delta^{\bar{K}-1}(x\delta+1-x))}. \tag{A.6}$$

The borrower agrees to repay at G if and only if

$$(1-\delta)g \le \delta(1-\lambda)\left(1-\delta^{\bar{K}-1}(x\delta+1-x)\right)\ V^{\bar{K},x}(0). \tag{A.7}$$

Using the expression in (A.6), the derivative of the right hand side of (A.7) is

$$\frac{(1-\delta)^3\,(1-\lambda)\,\delta^{\bar{K}}}{\left(1-\delta(1-\lambda)-\lambda\,\delta^{\bar{K}}(x\delta+1-x)\right)^2},$$

which is strictly positive for all $x \in [0,1]$. Thus the right hand side of (A.7) is a strictly increasing function of x. By the definition of $\bar{K}$, (A.7) is satisfied when $x=1$, and violated when $x=0$. There therefore exists $x^*(\bar{K}) \in (0,1]$ such that (A.7) is satisfied for every $x \in [x^*(\bar{K}), 1]$.[38]

It remains to examine whether this modification preserves the incentive of lenders not to lend at B. We now show that, while $m^\dagger(\bar{K},x)$ decreases with x, it remains an element of the interval $[1,2)$, so that $m^*(\bar{K},x)=1$ for every $x \in [x^*(\bar{K}),1]$. Thus, the only effect of this modification is to make lending at B less attractive, since the proportion of agents with $m=1$ in the population of agents with a bad signal has been reduced.

[38] In the non-generic case where $\bar{K}$ satisfies (1) with equality, we have that $x^*(\bar{K})=1$.

We first show that $m^\dagger(\bar{K}, x)$ is a strictly decreasing function of x. For every $x \in [x^*(\bar{K}), 1]$, $m^\dagger(\bar{K}, x)$ is the unique value of $m \in (0, K)$ setting

$$(1-\lambda)(1-x(1-\delta))\left(\delta^{m-1}-\delta^{\bar{K}}\right)V^{\bar{K},x}(0)-(1-\delta)g \tag{A.8}$$

equal to zero. The above is a strictly decreasing function of m. It is also a strictly decreasing function of x, as its derivative with respect to x equals

$$(1-\lambda)\left(\delta^{m-1}-\delta^{\bar{K}}\right)\left[-(1-\delta)\,V^{\bar{K},x}(0)+(1-x(1-\delta))\,\frac{\partial}{\partial x}V^{\bar{K},x}(0)\right]<0,$$

where the inequality follows from the fact that $V^{\bar{K},x}(0)$ is positive and strictly decreasing in x. To maintain the expression in (A.8) equal to zero, any increase in x must be compensated by a decrease in $m^\dagger$. The result follows.

We now show that $m^\dagger(\bar{K}, x) \in [1, 2)$ for every $x \in [x^*(\bar{K}), 1]$. Since (A.8) is strictly decreasing in m, it suffices to show that

$$(1-\lambda)(1-x^*(1-\delta))\left(\delta^{2-1}-\delta^{\bar{K}}\right)V^{\bar{K},x^*}(0)<(1-\delta)g, \tag{A.9}$$

and that

$$(1-\lambda)(1-x^*(1-\delta))\left(\delta^{1-1}-\delta^{\bar{K}}\right)V^{\bar{K},x^*}(0)\geq(1-\delta)g. \tag{A.10}$$

Since (A.8) is strictly decreasing in x, we have

$$(1-\lambda)(1-x^*(1-\delta))\left(\delta-\delta^{\bar{K}}\right)V^{\bar{K},x^*}(0)<\delta(1-\lambda)\left(1-\delta^{\bar{K}-1}\right)V^{\bar{K},0}(0),$$

and since the right hand side of (A.7) is strictly increasing in x,

$$\delta(1-\lambda)\left(1-\delta^{\bar{K}-1}\right)V^{\bar{K},0}(0)<\delta(1-\lambda)\left(1-\delta^{\bar{K}-1}(x^*\delta+1-x^*)\right)V^{\bar{K},x^*}(0).$$

By the definition of $x^*(\bar{K})$, the right hand side above equals $(1-\delta)g$, establishing (A.9).

Similarly, since (A.8) is strictly decreasing in x, we have

$$(1-\lambda)(1-x^*(1-\delta))\left(1-\delta^{\bar{K}}\right)V^{\bar{K},x^*}(0)>\delta(1-\lambda)\left(1-\delta^{\bar{K}}\right)V^{\bar{K},1}(0),$$

where $V^{\bar{K},1}(0) = V^{\bar{K}}(0)$, so that the right hand side above is weakly greater than $(1-\delta)g$ by the definition of $\bar{K}$. This establishes (A.10), and completes the proof.

A.3 Non-stationary Analysis

Consider the simple binary partition of Section 4 and the pure strategy equilibrium set out there. Suppose that the game starts at date $t = 1$ with all borrowers having a clean history. The measure of type m borrowers at date t, $\tilde{\mu}_m(t)$, varies over time. Types $m \leq m^*(K)$ repay when extended a loan. Thus, at any date t, the probability that a loan extended at history B is repaid is

$$\tilde{\pi}(t; K) = \frac{\sum_{m=1}^{m^*(K)} \tilde{\mu}_m(t)}{1 - \tilde{\mu}_0(t)}. \tag{A.11}$$

The sufficient incentive constraint ensuring that a lender should never want to lend to a borrower with signal B at any date, is

$$\bar{\pi}(K) := \sup_t \tilde{\pi}(t; K) < \frac{\ell}{1+\ell}. \tag{A.12}$$

To compute $\bar{\pi}(K)$, observe that the measure of type $m = 0$ is maximal at $t = 1$. A fraction λ of those borrowers transit to $m = K$, and then transit deterministically thought the lower values of m. Therefore, the measure of type $m = 1$ is maximal at date $K + 1$, and equals λ. This is also the date where the repayment probability is maximal. At that date,

$$\tilde{\mu}_m(t) = \begin{cases} \lambda(1-\lambda)^{m-1} & \text{for } m \geq 1, \\ (1-\lambda)^K & \text{for } m = 0, \end{cases}$$

so that

$$\bar{\pi}(K) = \frac{\sum_{m=1}^{m^*(K)} \lambda(1-\lambda)^{m-1}}{1-(1-\lambda)^K} = \frac{1-(1-\lambda)^{m^*(K)}}{1-(1-\lambda)^K}.$$

Letting $m^\infty := \lim_{K\to\infty} m^*(K)$, we have that as $K \to \infty$ the maximal repayment probability converges to

$$1 - (1-\lambda)^{m^\infty + 1}.$$

Consider the case of $\bar{K}$-period memory, where $m^*(\bar{K}) = 1$. In this case,

$$\bar{\pi}(\bar{K}) = \frac{\lambda}{1-(1-\lambda)^{\bar{K}}}.$$

Note that $\bar{\pi}(\bar{K}) > \frac{1}{\bar{K}}$ (the steady state repayment probability) and that $\bar{\pi}(\bar{K}) \to \frac{1}{\bar{K}}$ as $\lambda \to 0$.

Consequently, if $\bar{\pi}(\bar{K}) < \frac{\ell}{1+\ell}$, then we have a pure strategy equilibrium where the lender's do not have an incentive to lend to a borrower with signal B at any date. If this condition is violated, but the lender's incentive constraint is satisfied in the steady state, then the transition to the steady state is more complex, and requires mixed strategies along the path, and we do not investigate this here.

A.4 Proof of Claims in Section 5.2

We now prove claims related to the mixed strategy equilibrium.

A.4.1 First Claim

We show that $\pi(p,1)$, defined in (15), is a strictly decreasing function of p. (Continuity for $p \in [0,1]$ is immediate.) For any given $K \geq 2$ and $p \in (0,1)$, the invariant distribution $\mu(p,1)$, is given by equations (12) to (14), together with the condition $\sum_{m=0}^{K} \mu_m = 1$. Solving the above system, we obtain

$$\pi(p,1) = \frac{p\,(1-p)^{K-1}}{1-(1-p)^K},$$

so that

$$\frac{\partial \pi(p,1)}{\partial p} = \frac{(1-p)^{K-2}\; h(p,K)}{\left(1-(1-p)^K\right)^2},$$

where $h(p,K) := 1 - Kp - (1-p)^K$ satisfies, for every $p \in (0,1)$ and $K \geq 1$,

$$h(p,K+1) - h(p,K) = -p\left(1-(1-p)^K\right) < 0,$$

while for every $p \in (0,1)$, $h(p,1) = 0$.

We therefore have that for every $p \in (0,1]$ and $K \geq 2$, $h(p,K) < 0$ so that $\frac{\partial \pi(p,1)}{\partial p} < 0$ and $\pi(p,1)$ is a strictly decreasing function of p.

A.4.2 Second Claim

We now establish the second equality in (16). For any given $K \geq 2$ and $(p,q) \in (0,1)^2$, the invariant distribution $\mu(p,q)$, is given by

$$\mu_0 = q(1-\lambda)\,\mu_0 + \big(1 - p\,(1-q(1-\lambda))\,\big)\,\mu_1,$$

$$\mu_m = (1-p)^{K-m}\mu_K, \quad 1 \leq m \leq K,$$

$$\mu_K = \big(1-q(1-\lambda)\big)\,\mu_0 + p\,(1-q(1-\lambda))\;\mu_1 + p\;\textstyle\sum_{m=2}^{K} \mu_m,$$

together with the condition $\sum_{m=0}^{K} \mu_m = 1$. Solving the above system, we obtain

$$\pi(\tilde{p}, q) = q \, \frac{\tilde{p}\,(1-\tilde{p})^{K-1}}{1-(1-\tilde{p})^{K}} = q \, \pi(\tilde{p}, 1),$$

as in (16).

A.4.3 Purification of the Mixed Equilibrium in Proposition 4

The perturbed stage game Γ^ϵ is defined as follows. Without loss of generality, it suffices to perturb the payoff to one of two actions of each of the players. Accordingly, we assume that the payoff to the lender from lending is augmented by ϵy, where y is the realization of a random variable that is distributed on a bounded support, without loss of generality $[0, 1]$, with a continuous cumulative distribution function F_Y. The expected payoff to the borrower from wilful default is augmented by ϵz, where z is the realization of a random variable that is distributed on $[0, 1]$ with a continuous cumulative distribution function F_Z.

The proof of Lemma 1 is straightforward. Let σ be a stationary sequentially strict equilibrium where each type of player plays the same strategy. At any information set, since a player has strict best responses, if ϵ is small enough, then this best response is also optimal for all realizations of his payoff shock. Since memory is bounded, there are finitely many strategically distinct information sets for each player. Thus there exists $\bar{\epsilon} > 0$, such that if $\epsilon < \bar{\epsilon}$, there is an equilibrium in the perturbed game that induces the same behavior as σ.

We now turn to the mixed equilibria of Proposition 4. The case where only the lender mixes and the borrower has strict best responses is more straightforward. So we consider first the case where both lender and borrower mix. The equilibrium is not *regular*, since it is contained in the relative interior of a one-dimensional manifold of equilibria. Thus we cannot directly invoke, for example, Doraszelski and Escobar (2010), who show that regular Markov perfect equilibria are purifiable in stochastic games.

Assume that $\ell \in (0, \ell^*)$, so that in the unperturbed game, the mixed equilibrium has the lender lending with probability $\tilde{p}$ after credit history B, while the borrower repays with probability $\tilde{q}$ if $m \in \{0, 1\}$ and has strict incentives to default if $m > 1$. Now if ϵ is small enough, and if the lender's lending probability after B is close to $\tilde{p}$, the borrower retains strict incentives to default when $m > 1$ for every realization z. Similarly, the lender retains strict incentives to lend after signal G. Let $\bar{y}$ denote the threshold value of the payoff shock, such that the lender lends after signal B if and only if $y > \bar{y}$, and let $\bar{p} := 1 - F_Y(\bar{y})$. Let $\bar{z}$ denote the threshold value of the payoff shock, such that a borrower with $m \in \{0, 1\}$ defaults if and only if $z > \bar{z}$, and define $\bar{q} := F_Z(\bar{z})$. At $(p,q) = (\bar{p}, \bar{q})$, the value functions in the perturbed game can then be rewritten to take into account the payoff shocks. For $m = 0$, we have

$$\tilde{V}^{\bar{K}}(0,\bar{p}) = (1-\delta)\left(1 + \epsilon\int_{\bar{z}}^{1}(z-\bar{z})\,dF_Z(z)\right) + \delta\left[\lambda\tilde{V}^{\bar{K}}(\bar{K},\bar{p}) + (1-\lambda)\tilde{V}^{\bar{K}}(0,\bar{p})\right]. \quad \text{(A.13)}$$

We derive the above expression as follows. At $\bar{z}$, the borrower is indifferent between defaulting and repaying. Thus the payoff from defaulting, when $z > \bar{z}$, equals the payoff from repaying plus the difference $z - \bar{z}$. Similarly, the value function of a borrower with signal B and $m = 1$ is given by

$$\tilde{V}^{\bar{K}}(1,\bar{p}) = \bar{p}(1-\delta)\left(1 + \epsilon\int_{\bar{z}}^{1}(z-\bar{z})\,dF_Z(z)\right) + \delta\left[\bar{p}\lambda\tilde{V}^{\bar{K}}(\bar{K},\bar{p}) + (1-\bar{p}\lambda)\tilde{V}^{\bar{K}}(0,\bar{p})\right]. \quad \text{(A.14)}$$

For $m > 1$, the borrower always defaults, and hence

$$\tilde{V}^{\bar{K}}(m,\bar{p}) = \bar{p}(1-\delta)\left(1 + g + \epsilon\,\mathbb{E}(z)\right) + \delta\left[\bar{p}\tilde{V}^{\bar{K}}(\bar{K},\bar{p}) + (1-\bar{p})\tilde{V}^{\bar{K}}(m-1,\bar{p})\right] \quad \text{(A.15)}$$

The indifference condition for a borrower with $m \in \{0,1\}$ and $z = \bar{z}$ is

$$(1-\delta)(g + \epsilon\bar{z}) - \delta(1-\lambda)\left(\tilde{V}^{\bar{K}}(0,\bar{p}) - \tilde{V}^{\bar{K}}(\bar{K},\bar{p})\right) = 0. \quad \text{(A.16)}$$

The indifference condition for a lender facing a borrower with history B and having payoff shock $\bar{y}$ is

$$\frac{\bar{q}\mu_1(\bar{p},\bar{q})}{1-\mu_0(\bar{p},\bar{q})} - \frac{\ell}{1+\ell+\epsilon\bar{y}} = 0. \quad \text{(A.17)}$$

When $\epsilon = 0$, equations (A.16) and (A.17) have as solution $(\tilde{p}, \tilde{q})$. In the remainder of this appendix, we establish that the Jacobian determinant of the left hand side of equations (A.16) and (A.17) at $\epsilon = 0$ and $(p,q) = (\tilde{p}, \tilde{q})$ is non-zero. By the implicit function theorem, if ϵ is sufficiently close to zero, there exist $(\bar{p}(\epsilon), \bar{q}(\epsilon))$ close to $(\tilde{p}, \tilde{q})$ that solves equations (A.16) and (A.17). We have then established that the mixed strategy equilibrium where both the lender and the borrower mix is purifiable.

The indifference condition for a borrower with type $m \in \{0,1\}$ in the unperturbed game is given by[39]

$$\gamma(p,q) = (1-\delta)g - \delta(1-\lambda)(V^{\bar{K}}(0,p,q) - V^{\bar{K}}(\bar{K},p,q)) = 0. \tag{A.18}$$

The indifference condition for the lender after B in the unperturbed game is given by

$$\phi(p,q) = q\mu_1(p,q)(1+\ell) - \ell(1-\mu_0(p,q)) = 0. \tag{A.19}$$

Consider the partial derivatives, $\phi_p, \phi_q, \gamma_p, \gamma_q$, as 2×2 matrix. We now prove that the determinant of this matrix is non-zero when evaluated at $(p,q) = (\tilde{p},\tilde{q})$. The value functions of the borrower evaluated at $p = \tilde{p}$ are constant with respect to q. Therefore, $\gamma_q = 0$ when $p = \tilde{p}$. Thus it suffices to prove that γ_p and ϕ_q are both non-zero at $(p,q) = (\tilde{p},\tilde{q})$.

When $q \in (0,1)$, $V^{\bar{K}}(0,p,q)$ and $V^{\bar{K}}(K,p,q)$ satisfy

$$V^{\bar{K}}(0,p,q) = (1-\delta)(1+g(1-q)) + \delta\left((1-(1-\lambda)q)\; V^{\bar{K}}(K,p,q) + (1-\lambda)q\; V^{\bar{K}}(0,p,q)\right).$$

Differentiating with respect to p, we obtain

$$\frac{\partial V^{\bar{K}}(K,p,q)}{\partial p} = \frac{1-\delta(1-\lambda)q}{\delta-\delta(1-\lambda)q}\;\frac{\partial V^{\bar{K}}(0,p,q)}{\partial p},$$

where $(1-\delta(1-\lambda)q)/(\delta-\delta(1-\lambda)q) > 1$. As a result,

$$\gamma_p(p,q) = -\delta(1-\lambda)\left[1 - \frac{1-\delta(1-\lambda)q}{\delta(1-(1-\lambda)q)}\right]\frac{\partial V^{\bar{K}}(0,p,q)}{\partial p}$$

is strictly positive, since $V^{\bar{K}}(0,p,q)$ is a strictly increasing function of p for every $q \in [0,1]$. Thus γ_p is non-zero at $(p,q) = (\tilde{p},\tilde{q})$.

Differentiating ϕ with respect to q gives

$$\phi_q(p,q) = \frac{\partial\mu_1(p,q)}{\partial q}q(1+\ell) + \mu_1(p,q)(1+\ell) + \frac{\partial\mu_0(p,q)}{\partial q}\ell. \tag{A.20}$$

Solving the system for the invariant distribution of types, we have

$$\mu_0(p,q) = \frac{C(1-p+pQ)}{A-QB},$$

[39] Although, for every $m \in \{0,1,\ldots,\bar{K}\}$, the level of $V^{\bar{K}}(m,p)$ is independent of q when $p = \tilde{p}$, its slope is not. We therefore emphasize the dependence of $V^{\bar{K}}$ on q in the remainder of this section.

$$\mu_1(p,q) = \frac{C(1-Q)}{A-QB},$$

where

$$A = (2-p)C + S, \quad B = (1-p)C + S, \quad C = (1-pS),$$

$$Q = q(1-\lambda), \quad S = \sum_{m=2}^{k}(1-p)^{k-m}.$$

Differentiating with respect to q,

$$\frac{\partial \mu_0(p,q)}{\partial q} = \frac{(1-\lambda)C}{(1-Q)(A-QB)} \left(1-\mu_0(p,q)\right),$$

$$\frac{\partial \mu_1(p,q)}{\partial q} = \frac{-(1-\lambda)C}{(1-Q)(A-QB)} \mu_1(p,q).$$

Using these expressions in (A.20), we obtain

$$\phi_q(p,q) = \mu_1(p,q)(1+\ell)\left[1 - \frac{QC}{(1-Q)(A-QB)}\right] + \frac{(1-\lambda)C}{(1-Q)(A-QB)} \left(1-\mu_0(p,q)\right)\ell. \tag{A.21}$$

Since the lender is indifferent between lending and not lending at a bad history when $q=\tilde{q}$, we have that for every $p \in [0,1]$,

$$\mu_1(p,\tilde{q})(1+\ell)\tilde{q} = \left(1-\mu_0(p,\tilde{q})\right)\ell.$$

Using this indifference condition in (A.21) gives

$$\phi_q(p,q)\big|_{q=\tilde{q}} = \mu_1(p,\tilde{q})(1+\ell) > 0$$

for every $p \in [0,1]$, and we have established that ϕ_q is non-zero at $(p,q) = (\tilde{p},\tilde{q})$.

Finally, the equilibrium where only the lender mixes and the borrower has strict best responses is also purifiable, since we have shown that $\gamma_p(p,1) \neq 0$.

A.5 General Games

Let Γ be a two-player (stage) game of perfect information, with finitely many nodes and no chance moves. Let Z be the set of terminal nodes or outcomes, so that each element $z \in Z$ is associated with a utility pair, $u(z) \in \mathbb{R}^2$. Assume that there are no payoff ties, so that if $z \neq z'$, then $u_i(z) \neq u_i(z')$ for every $i \in \{1,2\}$. Thus there exists a unique backwards induction strategy profile, $\bar{\sigma}$ and a unique backwards induction outcome, denoted $\bar{z}$. Normalize payoffs so that $u(\bar{z}) = (0, 0)$ and $u(z^*) = (1, 1)$.

Let X denote the set of non-terminal nodes, partitioned into X_1 and X_2, the decision nodes of the two players. Any pure behavior strategy profile σ induces a terminal node starting at any non-terminal node x. Write $u(\sigma(x))$ for the payoffs so induced. For any $x \in X$, let $\bar{\sigma}(x)$ denote the unique backwards induction path induced by $\bar{\sigma}$ starting at x, and $u(\bar{\sigma}(x))$ denote the payoff vector at the corresponding terminal node. Given any terminal node $z \in Z$, let $\phi(z)$ denote the path to z from the initial node x_0.

Definition 2 *Fix a terminal node z, a path $\phi(z)$, and a node x on this path, where player i moves. Player i has an incentive to deviate at x if $u_i(\bar{\sigma}(x)) > u_i(z)$. Player i has an incentive to deviate from $\phi(z)$ if there exists a node x on this path where he has an incentive to deviate.*

Remark 3 *No player has an incentive to deviate from $\phi(\bar{z})$, the backwards induction path. If $z \neq \bar{z}$, then at least one player has an incentive to deviate from the path to z.*

We focus on the sustainability of outcomes that Pareto-dominate the backwards induction outcome $\bar{z}$. Consider any pair (Γ, z^*), where Γ is a generic two-player game and z^* is a terminal node that strictly Pareto-dominates the backwards induction outcome $\bar{z}$, i.e. where $u_1(z^*) > 0$ and $u_2(z^*) > 0$. We assume that the pair (Γ, z^*) satisfies the following assumptions:

- Only one player (labelled $\hat{i}$) has an incentive to deviate on the path to z^*.
- There is a single node $\hat{x}$ on $\phi(z^*)$ at which $\hat{i}$ has an incentive to deviate.

The following lemma shows that the set of pairs (Γ, z^*) satisfying the conditions above includes every outcome that Pareto-dominates the backwards induction outcome in *games where each player moves at most once along any path of play.*

Lemma A.2 *If Γ is a game where each player moves at most once, and z^* Pareto-dominates $\bar{z}$, then only player 2 has an incentive to deviate on the path to z^*.*

Proof. Let Γ be a two-player game of perfect information where each player moves at most once along any paths of play. Without loss of generality, player 1 moves at the initial node, choosing an action from a finite set A_1 and player 2 moves after some choices of player 1. Let a_1^*, a_2^* denote the path to z^* from the initial node. We claim that at a_1^*, player 2 has *an incentive to deviate*, i.e. her optimal action differs from a_2^*. If this were not the case, then since player 1 prefers z^* to $\bar{z}$, z^* would be the unique backwards induction outcome, a contradiction. To see that player 1 does not have an incentive to deviate at the initial node x_0, observe that $u_1(\bar{\sigma}(x_0)) = 0 < u_1(z^*)$. ■

Let the pair (Γ, z^*) satisfy the two assumptions, and let j index the player who does not have an incentive to deviate. If $\hat{i}$ initiates the play of the backwards induction profile at $\hat{x}$, and j continues, the resulting payoff $u_{\hat{i}}(\bar{\sigma}(\hat{x}))$ to $\hat{i}$ is strictly greater than her payoff $u_{\hat{i}}(z^*)$ at z^*, which we normalizes to 1. Thus we may write $1 + g$ for this payoff, where

$$g := u_{\hat{i}}(\bar{\sigma}(\hat{x})) - u_{\hat{i}}(z^*) > 0.$$

Define $\tilde{x}_j$ as the maximal element under the precedence relation $\preceq$ on X (where for $x, y \in X$, $x \preceq y$ signifies that x precedes y) of the set $\tilde{X}_j$, where

$$\tilde{X}_j = \{\, x \in X_j \cap \phi(z^*),\, x \preceq \hat{x},\, u_j(\bar{\sigma}(x)) > u_j(\bar{\sigma}(\hat{x})) \,\}\,.$$

For instance, in the centipede game depicted in Figure 6b, we have $\hat{x} = (r_1, r_2, r_3)$ and $\tilde{x}_j = (r_1, r_2)$.

We show that the set $\tilde{X}_j$ is non-empty, so that $\tilde{x}_j$ is well defined. If $\tilde{X}_j$ is empty, this implies that, for all $x \in X_j \cap \phi(z^*)$ such that $x \preceq \hat{x}$, we have $u_j(\bar{\sigma}(x)) \leq u_j(\bar{\sigma}(\hat{x}))$. Since player $\hat{i}$'s incentive to deviate from $\phi(z^*)$ is maximal at $\hat{x}$, we have that $u_{\hat{i}}(\bar{\sigma}(x)) \leq u_{\hat{i}}(\bar{\sigma}(\hat{x}))$ for every $x \in X_{\hat{i}} \cap \phi(z^*)$ such that $x \preceq \hat{x}$. These two facts imply that $\bar{\sigma}(\hat{x})$ is the backwards induction outcome, $\bar{z}$. But since, by the definition of $\hat{x}$, $u_{\hat{i}}(\bar{\sigma}(\hat{x})) > u_{\hat{i}}(z^*)$, this contradicts the assumption that z^* Pareto-dominates $\bar{z}$.

We may therefore define

$$\ell := u_j(\bar{\sigma}(\tilde{x}_j)) - u_j(\bar{\sigma}(\hat{x})) > 0.$$

In words, ℓ is player j's loss from continuing on the path $\phi(z^*)$ at $\tilde{x}_j$ if player $\hat{i}$ continues with her backwards induction strategy at $\hat{x}$. The argument above established that $\ell > 0$.

The information structure in the repeated random matching game is a generalization of the simple information structure that has been extensively used in this paper in the context of the borrower-lender game. Partition the set of terminal nodes Z in the stage game so that D denotes the set of nodes that arises after a deviation by $\hat{i}$ from $\phi(z^*)$ at $\hat{x}$. Let N denote the complement, $N = Z \setminus D$. The signal regarding player $\hat{i}$ is B if there is any instance of D in any of the last K periods; otherwise, the signal is G. In each period, player j observes the signal regarding $\hat{\imath}$ before the players play the stage game Γ. Player $\hat{\imath}$ observes no information regarding the past play of player j. Given this simple information structure, let $m \in \{1, \ldots, K\}$ denote the number of periods that must elapse before player $\hat{\imath}$'s signal switches back to G given that it is currently B. Under the simple information structure, m is player $\hat{\imath}$'s private information, i.e. her type. Let $m^* \in (1, K)$ be a threshold used in defining player $\hat{\imath}$'s strategy. In equilibrium, it will depend on player $\hat{\imath}$'s payoff function and will generically take non-integer values.

Define the following strategies and strategy profiles in the stage game Γ. Let $\sigma^* = (\sigma^*_{\hat{\imath}}, \sigma^*_j)$ denote the strategy in Γ where $\phi(z^*)$ is played unless some player deviates from $\phi(z^*)$, in which case players continue with $\bar{\sigma}$.

For $i \in \{1, 2\}$, define the strategy $\hat{\sigma}_i$ in Γ as follows. For every $x \in X_i$,

$$\hat{\sigma}_i(x) = \begin{cases} \sigma^*_i(x) & \text{if } x \in \phi(z^*) \text{ and } x \succeq \hat{x}, \\ \bar{\sigma}_i(x) & \text{otherwise.} \end{cases}$$

The repeated game strategies are as follows.

- The players play σ^* at G.
- Player j plays $\hat{\sigma}_j$ at B.
- Player $\hat{\imath}$ plays $\bar{\sigma}_{\hat{\imath}}$ at B if $m > m^*$ and plays $\hat{\sigma}_{\hat{\imath}}$ at B if $m < m^*$.

Given these strategies, it is straightforward to verify that the value of player $\hat{\imath}$ at signal G is $V^K(0) := 1$, while her value at signal B, given her type m, is $V^K(m) := \delta^m$. Since the deviation gain for $\hat{\imath}$ equals g, then if player $\hat{\imath}$'s discount factor δ is large enough, there exists $\bar{K}$ such that if $K \geq \bar{K}$, player $\hat{\imath}$ has no incentive to deviate from $\phi(z^*)$ when she has a good signal.

We now verify the optimality of these repeated game strategies. Consider signal G. If $K \geq \bar{K}$, then player $\hat{\imath}$ has no incentive to deviate from σ^* at G. Given this, neither does player j, since by assumption, j does not have an incentive to deviate from $\phi(z^*)$.

Now consider signal B, and a type m for player $\hat{\imath}$. Consider any node $x \preceq \tilde{x}_j$ on the path $\phi(z^*)$. Given that player j plays $\bar{\sigma}_j$ at $\tilde{x}_j$, backwards induction establishes that $\bar{\sigma}_i$ is optimal for $i \in \{1, 2\}$ at every node x that precedes $\hat{x}$.

Consider next the node $\hat{x}$. If player $\hat{\imath}$ plays $\bar{\sigma}_{\hat{\imath}}$ at this node, the specified continuation strategies imply that she gets a current payoff of $u_{\hat{\imath}}(\bar{\sigma}(\hat{x}))$ and a continuation value of $V^K(K)$. If instead she continues on path $\phi(z^*)$, she gets a current payoff of $u_{\hat{\imath}}(z^*)$ and a continuation value of $V^K(m-1) = \delta^{m-1}$. Thus the payoff difference between these two choices equals

$$(1-\delta)g - \delta[V^K(m-1) - V^K(K)].$$

Since $V^K(m)$ is strictly decreasing in m, there exists a real number m^* such that at $\hat{x}$ it is optimal for $\hat{i}$ to continue with $\sigma^*_{\hat{i}}$ if $m < m^*$ and with $\bar{\sigma}_{\hat{i}}$ otherwise. Furthermore, since the deviation gain for $\hat{i}$ is maximal at $\hat{x}$, it is optimal to also continue with $\sigma^*_{\hat{i}}$ at subsequent nodes on the path $\phi(z^*)$ if $m < m^*$.

There remains the critical node $\tilde{x}_j$. If j continues on the path $\phi(z^*)$ at this node, and $m > m^*$ so that $\hat{i}$ proceeds with her backwards induction strategy, j incurs a strict loss relative to playing his backwards induction strategy at $\tilde{x}_j$, since $u_j(\bar{\sigma}(\hat{x})) - u_j(\bar{\sigma}(\tilde{x}_j)) = -\ell$. On the other hand, if $m < m^*$ so that $\hat{i}$ continues on the path $\phi(z^*)$ at $\hat{x}$, j continuing on $\phi(z^*)$ at $\tilde{x}_j$ rather than playing the backwards induction strategy secures the net gain $u_j(z^*) - u_j(\bar{\sigma}(\tilde{x}_j)) > 0$. (This payoff difference is positive because we assumed that j has no incentive to deviate from $\phi(z^*)$.)

Let π denote the probability assigned by j to player $\hat{i}$'s type m being strictly less than m^*. Then it is optimal for j to play his backwards induction strategy at node $\tilde{x}_j$ if

$$\pi < \frac{u_j(\bar{\sigma}(\tilde{x}_j)) - u_j(\bar{\sigma}(\hat{x}))}{u_j(z^*) - u_j(\bar{\sigma}(\hat{x}))} = \frac{\ell}{1 - u_j(\bar{\sigma}(\tilde{x}_j)) + \ell} =: \bar{\pi}.$$

Suppose that the pair (Γ, z^*) also satisfies the third assumption set out in Section 7.3, i.e.

- Player $\hat{i}$ has a decision node x that precedes $\hat{x}$ on the path to z^* where her backwards induction strategy prescribes deviating from $\phi(z^*)$ at x.

In this case it is costly for $\hat{i}$ to continue on the path $\phi(z^*)$ at x, given that j plays the backwards induction strategy at $\tilde{x}_j$. Thus the D1 criterion implies that if the decision node $\tilde{x}_j$ is reached, the probability π assigned by j must be zero. The arguments for this are identical to those set out in the proof of Proposition 6. Thus we have an equilibrium that supports the outcome z^* without any further assumptions.

If the above assumption is not satisfied, then π is determined by the invariant distribution over the values of m. Ensuring that π is low enough requires arguments similar to those explored in the context of the basic lender-borrower game where the borrower need not make a prior application, and we do not repeat them here.

A.6 An Alternative Specification of Forgetting

We now consider an alternative modeling of forgetting defaults and show that it yields qualitatively similar conclusions. Suppose that the borrower's history is edited, so that any incidence of D is replaced by N after K periods have elapsed, i.e. it is as though the loan never took place. Let us also assume that in each period there is a small probability ρ that a borrower does not meets a lender. When a lender and a borrower are matched, the lender perfectly observes the borrower's entire *edited* history, and that $K \geq \bar{K}$, so that an incidence of default is retained longer in the record than is required for incentivizing the borrower.

Let $\tilde{H}^t = O^t$ denote the space of t-period private histories of the borrower. These are known only to the borrower. Let H^t denote the space of t-period recorded histories. These are the edited histories observed by the lender. If $t \leq K$, then $H^t = O^t$, while it $t > K$, then $H^t = \{R, N\}^{t-K} \times O^K$. The following lemma shows that in any purifiable equilibrium, the borrower will not condition her strategy on her private history, but only on the recorded history. Indeed, the former is payoff irrelevant since no lender that she will ever be matched with has access to it. Consequently, whenever we speak of the history in the rest of this subsection, we mean the recorded history. We now show that there are further restrictions on how the recorded history may be utilized in any purifiable equilibrium.

We define the following equivalence relation on t-period histories. Consider two histories, $h^t = (a_1, ...a_t)$ and $\hat{h}^t = (\hat{a}_1, ..., \hat{a}_t)$. We write that $h^t \sim \hat{h}^t$ if for every $s \in \{1, \ldots, t-K\}$, $\hat{a}_s = a_s$, while for every $s \in \{t-K+1, \ldots, t\}$, $\hat{a}_s \neq a_s \Rightarrow \hat{a}_s, a_s \in \{D, N\}$. That is, two t-period histories are equivalent if:

- The outcomes are identical in any period $s \leq t - K$.
- If the outcomes differ in any period s within the last K periods, then these outcomes are either D or N.

Let σ denote a strategy profile in Γ^∞, i.e. a strategy for borrowers and a strategy for lenders.

Lemma A.3 *If σ is a purifiable equilibrium, then at every date $t+1$, σ is measurable with respect to H^t, the set of possible recorded histories. Further, if $h^t \sim \hat{h}^t$, $\sigma(h^t) = \sigma(\hat{h}^t)$.*

Proof. The strategy of any lender that the borrower meets at any future date cannot condition on the private history $\tilde{h}^t$. Thus the borrower's continuation value does not depend $\tilde{h}^t$, and nor does his current payoff. Hence the borrower can only condition upon $\tilde{h}^t$ if he is indifferent between R and D. However, in the perturbed game, such indifference is possible only for a set of z values that has Lebsegue measure zero. Thus any equilibrium in the unperturbed game where the borrower chooses different mixed actions after different private histories is not purifiable.

The proof of the second part of the lemma is by induction. Let h^t, $\hat{h}^t$ be two recorded histories that are equivalent. At all dates $s > t + K$ the lenders will not be able to condition upon these histories since they will not be distinguishable. Thus in period $s-1$, the borrower will not condition her repayment decision on these histories. As a result, the lender at date $s-1$ will also not condition her lending decision on these histories. By induction, neither lender nor borrower at any previous date will condition their behaviors on these histories. ■

This lemma implies that in any purifiable equilibrium, not obtaining a loan must be treated in the same way as a default. This has important implications. Consider an equilibrium where borrowers are incentivized to repay by $\bar{K}$ periods of exclusion. The above lemma implies that if any period, a borrower fails to get a loan, then she must also be excluded for $\bar{K}$ periods. Thus if $\rho > 0$, so that there is some chance that a borrower might fail to get a loan for exogenous reasons, the fact that such failures must lead to punishment causes additional inefficiencies. Providing the lender with coarse information can improve efficiency in this context as well. In particular, if the borrower is only informed about the last $\bar{K}$ outcomes, and only learns whether the borrower has defaulted or not in this time, then an equilibrium can be sustained under exactly the same conditions as in Section 4.

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