

# Dynamic Screening with Verifiable Bankruptcy

Daniel Krähmer and Roland Strausz

June 28, 2022

## Abstract

We consider a dynamic screening model where the agent may go bankrupt due to, for example, cash constraints. We model bankruptcy as a verifiable event that occurs whenever the agent makes a per period loss. This gives rise to less stringent truth-telling constraints than merely requiring that the agent has to obtain a non-negative per period utility. This is so because misreports become verifiable if they force the agent into bankruptcy. Moreover, we develop a novel method for deriving the optimal contract in a setting with cash constraints by ranking contracts in terms of the spread of the distribution of the induced continuation values for the agent. In a setting with continuous types, we derive a regularity condition that ensures that the optimal contract is deterministic.

Keywords: Dynamic Screening, Bankruptcy, Verifiability, Mean Preserving Spread

JEL: D82, H57

## 1 Introduction

We consider bankruptcy constraints in a dynamic screening model where a procurer (the principal) in each period procures one unit of a good or service from a supplier (the agent) whose costs evolve dynamically over time and are the supplier's private information. These bankruptcy constraints capture the fact that, in practice, suppliers are frequently unable to sustain short-term losses during the relationship, for example due to cash or credit constraints.

---

Krahmer: Universität Bonn (kraehmer@hcm.uni-bonn.de); Strausz: Humboldt Universität Berlin (roland.strausz@hu-berlin.de); We thank Nima Hagpanah, Mathijs Janssen, and Rohit Lambda for useful comments as well as seminar participants in Berlin, Bonn, Duisburg, Jerusalem/Tel-Aviv, Montreal, Peking, and Singapore. We gratefully acknowledge financial support from the German Research Foundation (DFG) through Germany's Excellence Strategy EXC 2126/1-390838866 and CRC TR 224 (Krahmer) and CRC TR 190 (Strausz).

Our paper makes two contributions to the recent literature that studies such bankruptcy constraints (e.g. Krishna et al., 2010, Mirrokni et al., 2020, Krasikov and Lamba, 2021, Ashlagi et al., 2022).

First, we explicitly model bankruptcy as a *verifiable* event that occurs whenever the agent obtains a negative per-period utility. On the one hand, this reflects existing institutional rules.<sup>1</sup> On the other hand, by explicitly modeling verifiable bankruptcy as part of the underlying economic environment, we provide a micro-foundation that enables us to derive the contractual feasibility constraints endogenously. In contrast, the existing literature simply posits that a contract has to guarantee the agent a non-negative per period utility on the equilibrium path. Compared to this approach, our approach gives rise to a weaker notion of incentive compatibility.

To understand this difference, note that a contract which guarantees a non-negative per period utility after the agent reveals her cost honestly, may force the agent into bankruptcy if she were to (incorrectly) claim that she could produce more cheaply, thus revealing that she did not report truthfully. Therefore, if bankruptcy is verifiable, truth-telling constraints are less stringent, as misreports become partially verifiable. We show that as a result, an optimal contract only has to ensure that the supplier does not overstate her true costs so that incentive compatibility constraints only have to hold in one direction. This links our dynamic setting with bankruptcy constraints to the literature that considers such one-sided incentive constraints in static settings (e.g., Moore, 1984, and Celik, 2006).

Our second contribution is to offer a novel solution method to identify an optimal contract. In the absence of bankruptcy constraints, dynamic screening are typically solved using a local or first order approach that rests on the fact that, when payments can be chosen freely, incentive compatibility is a feature of the allocation rule alone. This approach is no longer applicable in our setting, because bankruptcy constraints effectively impose a bound on payments.

The basic idea behind our method is based on the observation that every dynamic contract induces a continuation value for the agent which, from the principal's perspective, is a random variable, as it depends on the agent's privately known type. A standard argument from dynamic programming implies that the principal's continuation profit is concave in the agent's continuation value. This observation allows us to rank contracts in terms of second order stochastic dominance of the induced continuation value. As a result, we can identify an optimal contract as a contract

---

<sup>1</sup>Indeed, in modern societies bankruptcy is a legal process formally verified and declared by the court system. For instance, bankruptcy is enshrined by the US Constitution in Article 1, Section 8, Clause 4, and in the case of business debtors further specified in its Bankruptcy Code under Chapter 11. In the UK, the first statute of law dealing with bankruptcy is the Statute of Bankrupts dating back to 1542.

that, among the set of feasible contracts, displays minimal dispersion in the second order sense.

We show that, under a regularity condition, an optimal contract has a simple, deterministic cutoff structure where cost types below a cutoff produce the good and types above the cutoff do not. The regularity condition differs from the more familiar monotone virtual surplus kind of conditions, and also appears in the (static) multi-dimensional screening literature (e.g. Manelli and Vincent (2006)). The connection is that, as in this literature, we write the principal's optimization problem in terms of the agent's (continuation) value rather than the allocation rule.

Our paper contributes to the large literature on dynamic screening/mechanism design (see, e.g., Baron and Besanko, 1984, Battaglini, 2005, Pavan et al., 2014, Esö and Szentes, 2017). While most of this literature focuses on the case that agents can sustain unbounded losses after having accepted a contract, our paper belongs to a set of papers which assume that the agent cannot sustain losses in any period, most notably, Krishna et al. (2010), Krasikov and Lamba (2021), Ashlagi et al. (2022). These papers model bankruptcy constraints by the requirement that, under a direct revelation mechanism, the agent must obtain non-negative utility only on the equilibrium path where she reports truthfully. This allows for the possibility that an agent who misreports his type can still be punished with a negative utility, effectively violating cash constraints.

In contrast, we assume that bankruptcy can also occur off the equilibrium path. As explained above, this implies that we obtain weaker, one-sided incentive compatibility constraints. As we will argue, however, these weaker incentive constraints may only give rise to different predictions in interdependent values settings.<sup>2</sup> Thus, our analysis, on the one hand, validates the existing literature's approach to ignore off-path bankruptcy constraints for private values settings, but, on the other hand, makes clear that neglecting off-path bankruptcy constraints is not without loss in interdependent values settings. An additional contribution of our paper is that we consider a setting with a continuum of types whereas the previous literature primarily deals with the two types case.<sup>3</sup>

In the context of sequential screening problems with a single trading period, Kräbmer and Strausz (2015) consider ex post participation constraints that, for example, arise when agents have withdrawal rights (see also Bergemann et al., 2020). These constraints are conceptually different from the ones considered here, because the agent can voluntarily decide whether to

---

<sup>2</sup>This is in line with the mechanism design literature that considers the effect of such one-sided incentive constraints in static settings, e.g. Celik (2006).

<sup>3</sup>Krasikov et al. (2021) consider a dynamic screening model with cash constraints that do not arise in the form of bankruptcy constraints but in the sense that the agent has a higher discount rate than the principal.

sustain a loss ex post or not. In fact, in contrast to verifiable bankruptcy, voluntary participation leads, if anything, to stricter incentive constraints, as it weakly increases an agent's utility from a misreport.<sup>4</sup>

## 2 The model

A principal (the buyer, she) and an agent (the seller, he) interact over two periods  $\tau = 1, 2$ .<sup>5</sup> In each period, the principal seeks to procure one good from the agent. In period  $\tau$ , the terms of trade are the probability of trade  $x_\tau$  and a transfer  $t_\tau$  from the principal to the agent.<sup>6</sup> The principal's valuation for the good is  $v_\tau \geq 0$ , and the agent's cost to produce the good is  $\theta_\tau$ . While  $v_\tau$  is commonly known,  $\theta_\tau$ , the agent's cost type in period  $\tau$ , is privately known to the agent in period  $\tau$ , and it is commonly known that  $\theta_\tau$  is distributed with cdf  $F_\tau$  with support  $\Theta_\tau \equiv [\underline{\theta}_\tau, \bar{\theta}_\tau]$  and differentiable pdf  $f_\tau$ . We assume that  $\theta_1$  and  $\theta_2$  are stochastically independent.

The parties have time-separable quasi-linear utilities. That is, under the terms of trade  $x_\tau, t_\tau$  the principal's utility in period  $\tau$  is  $v_\tau x_\tau - t_\tau$ , and the agent's utility is  $t_\tau - \theta_\tau x_\tau$ . A party's overall utility is the sum over the per-period utilities.

The novelty of our paper is to consider a situation in which the event that the agent makes a loss is verifiable. That is, if the agent were to make losses in period  $\tau$  under the prevailing terms of trade, the agent would go bankrupt and this is publicly verifiable. In this case, both parties receive their reservation utility of zero.

The timing is as follows:

1. At the outset, the principal commits to a long-term contract which specifies the terms of trade over the two periods. If the agent rejects the contract, both parties receive their reservation utility of 0 and the game ends.
2. If the agent accepts, then in period 1, he privately learns  $\theta_1$ . If  $t_1 - \theta_1 x_1 \geq 0$ , the terms of trade  $x_1, t_1$  are implemented. If  $t_1 - \theta_1 x_1 < 0$ , bankruptcy occurs and both parties receive 0.<sup>7</sup>

---

<sup>4</sup>On this point see also Compte and Jehiel (2009) who show that in mechanism design settings with ex post veto rights the potential to punish agents for misreports is limited because they can quit the mechanism ex post.

<sup>5</sup>In section 5, we show that our analysis extends to a setting with infinitely many periods.

<sup>6</sup>As is standard, we interpret  $t_\tau$  as the expected payment  $t_\tau^{(0)}(1-x_\tau) + t_\tau^{(1)}x_\tau$ , where  $t^{(0)}$  (resp.  $t^{(1)}$ ) is the payment when trade does not (resp. does) occur. Alternatively, for a divisible good, we may interpret  $x_\tau$  as the share of the good traded.

<sup>7</sup>Related to footnote 6, if  $x_1 \in (0, 1)$ , bankruptcy occurs if  $t^{(0)} < 0$  and the mechanism does not prescribe trade, and if  $t^{(1)} - \theta_1 < 0$  and the mechanism does prescribe trade.

3. In period 2, the agent privately learns  $\theta_2$ . If  $t_2 - \theta_2 x_2 \geq 0$ , the terms of trade  $x_2, t_2$  are implemented. If  $t_2 - \theta_2 x_2 < 0$ , bankruptcy occurs and both parties receive 0.

*Example:* To illustrate our analysis, we use the uniform example, where  $\theta_1$  and  $\theta_2$  are both uniformly distributed over the interval  $[0, 1]$ , and  $v_1 = v_2 = \bar{\theta} = 1$ . For this example, trade is efficient for all types and the per-period first-best surplus equals  $S^{FB} = S_1^{FB} = S_2^{FB} = \int_0^1 1 - \theta d\theta = 1/2$ , yielding an aggregate surplus of  $S_1^{FB} + S_2^{FB} = 1$ . In the static second best, the optimal mechanism is a posted price of  $1/2$ , yielding the principal a per-period profit of  $\Pi^{SB} \equiv (1 - 1/2) * 1/2 = 1/4$  and the agent a per-period second best utility of  $U^{SB} \equiv \int_0^{1/2} 1/2 - \theta d\theta = 1/8$ . Implementing a posted price of  $1/2$  for each of the two periods, yields an overall profit of  $2\Pi^{SB} = 1/2$  to the principal and an overall utility of  $2U^{SB} = 1/4$  to the agent, resulting in aggregate surplus of  $3/4$ .

In the benchmark case in which there is an interim participation constraint in period 1 but no bankruptcy constraint, the optimal mechanism implements a posted price of  $p = 1/2$  for the first period, and extracts the whole surplus in the second period. This yields an overall profit of  $\Pi^{SB} + S^{FB} = 3/4$  to the principal, an overall utility of  $U^{SB} = 1/8$  to the agent, resulting in aggregate surplus of  $7/8$ .  $\square$

### 3 The principal's problem

The principal's objective is to design a contract to maximize her profits. Because the principal has full commitment, the revelation principle applies, implying that an optimal contract is in the class of direct mechanisms where, on the equilibrium path, the agent reports his type truthfully in every period (Myerson, 1986). Moreover, because bankruptcy in period 1 is verifiable, a mechanism can condition the terms of trade in period 2 on whether bankruptcy has occurred in period 1 or not. Without loss, we can therefore restrict attention to contracts of the form  $(x_1, t_1, x_2^N, t_2^N, x_2^B, t_2^B)$ , where

$$(x_1, t_1) : [\underline{\theta}_1, \bar{\theta}_1] \rightarrow [0, 1] \times \mathbb{R}, \quad (x_2^b, t_2^b) : [\underline{\theta}_1, \bar{\theta}_1] \times [\underline{\theta}_2, \bar{\theta}_2] \rightarrow [0, 1] \times \mathbb{R}, \quad (1)$$

where  $b \in \{B, N\}$  indicates whether bankruptcy has ( $b = B$ ) or has not ( $b = N$ ) occurred in period 1.

To state the incentive compatibility constraints, we denote for  $b \in \{N, B\}$  the agent's expected

period 2 utility from a report  $\hat{\theta}_1$ , conditional on truthfully reporting in period 2, by

$$U^b(\hat{\theta}_1) = \int_{\underline{\theta}_2}^{\bar{\theta}_2} \max\{0, t_2^b(\hat{\theta}_1, \theta_2) - \theta_2 x_2^b(\hat{\theta}_1, \theta_2)\} dF_2(\theta_2). \quad (2)$$

Moreover, let

$$\Theta_1^N = \{\theta_1 \mid t_1(\theta_1) - \theta_1 x_1(\theta_1) \geq 0\} \quad (3)$$

be the set of period 1 types where bankruptcy does not occur in period 1 under a given mechanism.

**Definition 1** A contract  $(x_1, t_1, x_2^N, t_2^N, x_2^B, t_2^B)$  is feasible if:

(i) It is incentive compatible in period 2, that is, for  $b \in \{N, B\}$ :<sup>8</sup>

$$\max\{0, t_2^b(\theta_1, \theta_2) - \theta_2 x_2^b(\theta_1, \theta_2)\} \geq \max\{0, t_2^b(\theta_1, \hat{\theta}_2) - \theta_2 x_2^b(\theta_1, \hat{\theta}_2)\} \quad \forall \theta_1, \theta_2, \hat{\theta}_2. \quad (4)$$

(ii) It is incentive compatible in period 1, that is:

◊ For all  $\theta_1 \in \Theta_1^N$ , we have:

$$t_1(\theta_1) - \theta_1 x_1(\theta_1) + U^N(\theta_1) \geq t_1(\hat{\theta}_1) - \theta_1 x_1(\hat{\theta}_1) + U^N(\hat{\theta}_1) \quad \forall \hat{\theta}_1 : t_1(\hat{\theta}_1) - \theta_1 x_1(\hat{\theta}_1) \geq 0, \quad (5)$$

$$t_1(\theta_1) - \theta_1 x_1(\theta_1) + U^N(\theta_1) \geq U^B(\hat{\theta}_1) \quad \forall \hat{\theta}_1 : t_1(\hat{\theta}_1) - \theta_1 x_1(\hat{\theta}_1) < 0, \quad (6)$$

◊ For all  $\theta_1 \notin \Theta_1^N$ , we have:

$$U^B(\theta_1) \geq t_1(\hat{\theta}_1) - \theta_1 x_1(\hat{\theta}_1) + U^N(\hat{\theta}_1) \quad \forall \hat{\theta}_1 : t_1(\hat{\theta}_1) - \theta_1 x_1(\hat{\theta}_1) \geq 0, \quad (7)$$

$$U^B(\theta_1) \geq U^B(\hat{\theta}_1) \quad \forall \hat{\theta}_1 : t_1(\hat{\theta}_1) - \theta_1 x_1(\hat{\theta}_1) < 0. \quad (8)$$

Part (i) of the definition captures the truth-telling constraints for the agent in period 2, taking into account that bankruptcy in period 2 occurs whenever the terms of trade would impose a loss on the agent. Similarly, part (ii) describes the truth-telling constraints for the agent in period 1. This requires a distinction between four cases, depending on whether truth-telling does or does not induce bankruptcy in period 1 and whether deviating from truth-telling does or does not induce bankruptcy in period 1.

---

<sup>8</sup>The revelation principle for dynamic games requires truthful reporting in period 2 only after a truthful report in period 1 (see Myerson, 1986). In our context, where types are independent, the support of period 2 types is “non-shifting”, that is, is independent of the period 1 type. It then follows with standard arguments that if truth-telling in period 2 is optimal for the agent after telling the truth in period 1, then it is so after any report in period 1.

The principal's problem is thus to select a feasible contract that maximizes her profits

$$\int_{\Theta_1^N} \left[ v_1 x_1(\theta_1) - t_1(\theta_1) + \int_{\Theta_2^{N,N}(\theta_1)} v_2 x_2^N(\theta_1, \theta_2) - t_2^N(\theta_1, \theta_2) dF_2(\theta_2) \right] dF_1(\theta_1) \quad (9)$$

$$+ \int_{\Theta_1 \setminus \Theta_1^N} \left[ 0 + \int_{\Theta_2^{N,B}(\theta_1)} v_2 x_2^B(\theta_1, \theta_2) - t_2^B(\theta_1, \theta_2) dF_2(\theta_2) \right] dF_1(\theta_1), \quad (10)$$

where

$$\Theta_2^{N,b}(\theta_1) \equiv \{\theta_2 \in \Theta_2 \mid t_2^b(\theta_1, \theta_2) - \theta_2 x_2^b(\theta_1, \theta_2) \geq 0\} \quad (11)$$

denotes the set of period 2 types  $\theta_2$  for whom bankruptcy does not occur in period 2 given the period 1 type  $\theta_1$  and given that bankruptcy has not ( $b = N$ ) or has ( $b = B$ ) occurred in period 1.

To solve the principal's problem, we first show that it is without loss to focus on contracts under which bankruptcy never occurs on the equilibrium path where the agent tells the truth.

The intuition is simply that the bankruptcy outcome is equivalent to not trading the good ( $x = 0$ ) and making no payments ( $t = 0$ ). Thus, the outcome of a mechanism  $\gamma$  in which bankruptcy occurs on the equilibrium path can be replicated by the mechanism which differs from  $\gamma$  only in that it specifies no trade and zero payments (and hence no bankruptcy) in case bankruptcy would occur under  $\gamma$ .

Second, it is without loss to focus on mechanisms in which the agent exactly breaks even in the first period, and backloads any potential profit for the agent in that it accrues only in the second period.<sup>9</sup> The reason is that if the agent were to make a profit in the first period, the principal could deduct it from the agent's first period 1 payments and pay it out in period 2 instead. This would not affect the principal's profit and would maintain truth-telling incentives for which only total payments matter.

We summarize these considerations in the next lemma.

**Lemma 1** *For any feasible contract there is a payoff-equivalent feasible contract  $(x_1, t_1, x_2^N, t_2^N, x_2^B, t_2^B)$  with the following properties:*

- *The agent exactly breaks even, and there is no bankruptcy in period 1 (on path):*

$$t_1(\theta_1) - \theta_1 x_1(\theta_1) = 0 \quad \text{for all } \theta_1. \quad (12)$$

---

<sup>9</sup>This argument also appears in Ashlagi et al. (2022).

- There is no bankruptcy in period 2 (on path):

$$t_2^N(\theta_1, \theta_2) - \theta_2 x_2^N(\theta_1, \theta_2) \geq 0 \quad \text{for all } \theta_1, \theta_2. \quad (13)$$

- After the off-path event that there is bankruptcy in period 1, the relationship is terminated:

$$x_2^B(\theta_1, \theta_2) = t_2^B(\theta_1, \theta_2) = 0 \quad \text{for all } \theta_1, \theta_2. \quad (14)$$

Lemma 1 implies that we can find an optimal contract in the class of feasible contracts that satisfy (12)-(14). Since properties (12) and (14) pin down  $t_1$ ,  $x_2^B$ , and  $t_2^B$ , we are actually left to determine only the triple  $(x_1, x_2^N, t_2^N)$ . We therefore introduce the following definition.

**Definition 2** A triple  $(x_1, x_2, t_2) : [\underline{\theta}_1, \bar{\theta}_1] \rightarrow [0, 1]^2 \times \mathbb{R}$  is called a *backloaded contract* if

$$NB_2 : \quad t_2(\theta_1, \theta_2) - \theta_2 x_2(\theta_1, \theta_2) \geq 0 \quad \forall \theta_1, \theta_2. \quad (15)$$

A backloaded contract uniquely induces a contract  $(x_1, t_1, x_2^N, t_2^N, x_2^B, t_2^B)$  with the properties (12)-(14) by setting  $t_1 = \theta_1 x_1$ ,  $x_2^N = x_2$ ,  $t_2^N = t_2$ , and  $x_2^B = t_2^B = 0$ . For a backloaded contract, we write

$$U(\theta_1) = \int_{\underline{\theta}_2}^{\bar{\theta}_2} t_2(\theta_1, \theta_2) - \theta_2 x_2(\theta_1, \theta_2) dF_2(\theta_2) \quad (16)$$

for the agent's expected period 2 utility. The next lemma characterizes when a backloaded contract is feasible.

**Lemma 2** A backloaded contract  $(x_1, x_2, t_2)$  induces a feasible contract  $(x_1, t_1, x_2^N, t_2^N, x_2^B, t_2^B)$  if and only if

$$IC_2 : \quad t_2(\theta_1, \theta_2) - \theta_2 x_2(\theta_1, \theta_2) \geq t_2(\theta_1, \hat{\theta}_2) - \theta_2 x_2(\theta_1, \hat{\theta}_2) \quad \forall \theta_1, \theta_2, \hat{\theta}_2 \quad (17)$$

$$IC_1 : \quad U(\theta_1) \geq (\hat{\theta}_1 - \theta_1)x_1(\hat{\theta}_1) + U(\hat{\theta}_1) \quad \forall \theta_1 \leq \hat{\theta}_1 \quad (18)$$

Constraint  $IC_2$  corresponds to the period 2 truth-telling constraints (4). The more interesting constraint is  $IC_1$  which corresponds to the period 1 truth-telling constraints.<sup>10</sup>

---

<sup>10</sup>To see that  $IC_1$  replaces the period 1 truth-telling constraints (5)-(8) note that because under a backloaded contract there is no bankruptcy in period 1 for any  $\theta_1$ , constraints (6), (7) and (8) are all redundant, and the only relevant constraint is (5), which now has to hold for all  $\theta_1$ , leading to  $IC_1$ .



The novelty is that  $IC_1$  only requires that the agent does not report a higher type than his true type, but not that he does not report a lower type. The reason for this asymmetry is that if the agent reported lower costs in the first period, then, because any cost type breaks even in period 1, the agent would go bankrupt after such a lie. But, bankruptcy does not occur on path and is verifiable. Consequently, such a lie would be detected, and under a backloaded mechanism, the relationship would be terminated. This prospect is enough to dissuade the agent from understating his costs, and extra incentives are not needed to induce truth-telling.

We can now re-state the principal's problem as selecting an optimal backloaded contract. Under a backloaded contract, the principal's period 1 profit equals  $v_1x_1(\theta_1) - \theta_1x_1(\theta_1)$  for all  $\theta_1$ , because the agent breaks even in period 1. Moreover, her profit in period 2 is equal to  $v_2x_2(\theta_1, \theta_2) - t_2(\theta_1, \theta_2)$  for all  $(\theta_1, \theta_2)$ , because no bankruptcy occurs in period 2. Thus, the principal's problem is

$$P : \quad \max_{x_1, x_2, t_2} \int_{\underline{\theta}_1}^{\bar{\theta}_1} \int_{\underline{\theta}_2}^{\bar{\theta}_2} v_1x_1(\theta_1) - \theta_1x_1(\theta_1) + v_2x_2(\theta_1, \theta_2) - t_2(\theta_1, \theta_2) dF_2(\theta_2) dF_1(\theta_1)$$

$$s.t. \quad IC_2, NB_2, IC_1,$$

where  $IC_2$  and  $IC_1$  are the feasibility constraints, and  $NB_2$  ensures that the contract is a backloaded contract

Intuitively, for given  $\theta_1$ , the principal faces the standard (intra-temporal) rent-efficiency trade-off in period 2, because she has to grant low cost types an information rent for truth-telling due to the presence of the no-bankruptcy constraint  $NB_2$ . Moreover, because a backloaded contract uses the *expected* period 2 information rent for incentivizing low cost types in period 1 to reveal the truth, the principal also faces an inter-temporal trade-off between maximizing profits in period 1 and 2.

Before solving problem  $P$ , we note that the no-bankruptcy constraint  $NB_2$  is formally equivalent to a period 2 participation constraint. Hence, problem  $P$  is equivalent to a two-period dynamic mechanism design problem with ex post participation constraints, but with the novelty that the first period incentive constraints are asymmetric in that they only require higher types not to mimic lower types.

## 4 Solution to the principal's problem

We solve the principal's problem by the well-known technique in dynamic programming to reduce the dynamic problem  $P$  to a sequence of static problems (Spear and Srivastava, 1987, Thomas and Worrall, 1990). Consequently, we proceed in two steps. In the first step, we solve for optimal period 2 terms of trade  $(x_2^U, t_2^U)$  that promise the agent a certain exogenously given expected period 2 utility  $U$ . In the second step, we then solve for an optimal period 1 allocation  $x_1$  and an optimal continuation value  $U$  taking as given optimal period 2 terms of trade  $(x_2^U, t_2^U)$  from step 1 that supply the agent with  $U$ .

### Step 1: Optimal period 2 terms of trade

Note first that the principal can promise any positive utility  $U \geq 0$ . Indeed, by  $NB_2$ , the principal cannot promise a negative utility while she can offer any utility  $U \geq 0$  by, for example, offering the terms of trade  $(x_2, t_2) = (0, U)$ . Thus, the set of feasible promised utilities is  $\{U \mid U \geq 0\}$ .

For a given report  $\theta_1$ , the principal's problem to optimally promise  $U \geq 0$  is

$$P_2 : \quad \Pi(U) \equiv \max_{x_2, t_2} \int_{\underline{\theta}_2}^{\bar{\theta}_2} v_2 x_2(\theta_1, \theta_2) - t_2(\theta_1, \theta_2) dF_2(\theta_2) \quad s.t \quad (19)$$

$$IC_2 : \quad t_2(\theta_1, \theta_2) - \theta_2 x_2(\theta_1, \theta_2) \geq t_2(\theta_1, \hat{\theta}_2) - \theta_2 x_2(\theta_1, \hat{\theta}_2) \quad \forall \theta_2, \hat{\theta}_2 \quad (20)$$

$$NB_2 : \quad t_2(\theta_1, \theta_2) - \theta_2 x_2(\theta_1, \theta_2) \geq 0 \quad \forall \theta_2 \quad (21)$$

$$PK : \quad \int_{\underline{\theta}_2}^{\bar{\theta}_2} t_2(\theta_1, \theta_2) - \theta_2 x_2(\theta_1, \theta_2) dF_2(\theta_2) = U. \quad (22)$$

While the constraints  $IC_2$  and  $NB_2$  carry over from problem  $P$ , the constraint  $PK$  ensures that the agent receives his promised utility  $U$ .

Problem  $P_2$  corresponds to a static monopoly problem where the agent has an interim outside option of 0 after learning  $\theta_2$  (as reflected by  $NB_2$ ), and an ex-ante outside option of  $U$  before learning  $\theta_2$  (as reflected by  $PK$ ). The solution is well-known from Samuelson (1984); for details see our Remark 1 below. We state the features that will be key for our purposes in the next lemma. In order to avoid uninteresting case distinctions, we impose the following mild condition.<sup>11</sup>

<sup>11</sup>It is well-known (e.g. Riley and Zeckhauser, 1983) that in the absence of  $PK$ , the solution to  $P_2$  can be implemented by a posted price  $p$  given by

$$p \in \arg \max_{\bar{p}} \int_{\underline{\theta}_2}^{\bar{p}} v_2 - \theta_2 - \frac{F_2(\theta_2)}{f_2(\theta_2)} dF_2(\theta_2). \quad (23)$$

**Assumption 1:** The second best solution  $(x_2^{SB}, t_2^{SB})$  to the relaxed version of  $P_2$  where  $PK$  is missing is unique.

Given Assumption 1, the utilities in the second best solution for both the principal and the agent are unique and we denote them, respectively, by  $\Pi_2^{SB}$  and  $U_2^{SB}$ . Moreover, we denote the surplus associated with the period 2 first-best allocation  $x_2^{FB}(\theta_1, \theta_2) \equiv \mathbf{1}_{[\underline{\theta}_2, \min\{v_2, \bar{\theta}_2\}]}(\theta_2)$  by<sup>12</sup>

$$S_2^{FB} = \int_{\underline{\theta}_2}^{\min\{v_2, \bar{\theta}_2\}} v_2 - \theta_2 dF_2. \quad (24)$$

Clearly,  $U_2^{SB} \in (0, S_2^{FB})$ .

**Lemma 3** *The value of problem  $P_2$  as a function of  $U$ ,  $\Pi(U)$ , is concave in  $U$  with  $\Pi(0) = \Pi(S_2^{FB}) = 0$  and attains a unique maximum  $\Pi_2^{SB}$  at  $U_2^{SB}$ , that is,  $\Pi(U_2^{SB}) = \Pi_2^{SB}$ .*

The concavity of the value follows from a standard mixing argument. Specifically, given two promises  $U'$  and  $U''$ , the principal can promise the agent the convex mixture  $\bar{U} = \alpha U' + (1 - \alpha)U''$  by appropriately randomizing between the optimal terms of trade for  $U'$  and  $U''$ . This would yield the principal a profit  $\alpha\Pi(U'_2) + (1 - \alpha)\Pi(U''_2)$ , but by re-optimizing, the principal can promise  $\bar{U}$  at a higher profit, implying that  $\Pi$  is concave.

To see why  $\Pi(0) = 0$ , note that  $IC_2$  and  $NB_2$  imply that the only way to provide the agent with expected utility  $U = 0$  is through no trade ( $x_2 = t_2 = 0$ ), resulting in zero profits for the principal. To see that  $\Pi(S_2^{FB}) = 0$ , observe that the principal's profit  $\Pi$  is the total surplus generated minus the utility  $U$  supplied to the agent. Hence, if the principal promises the entire first-best surplus to the agent,  $U = S_2^{FB}$ , she cannot make a strictly positive profit. But she can at least guarantee herself zero profits by selecting terms of trade that generate the first-best surplus. Therefore,  $\Pi(S_2^{FB}) = 0$ . Finally, that the principal's profit is uniquely maximized at  $U^{SB}$  follows directly from the definition of the second best and Assumption 1.

**Remark 1 (Period 2 implementation)** We briefly discuss how the period 2 contract can be implemented. If the principal promises more than the second best surplus,  $U \geq S_2^{FB}$ , then it follows from the proof of Lemma 3 that the optimal contract displays the first-best allocation  $x_2^{FB}(\theta_1, \theta_2)$ . The intuition is that when guaranteeing the agent a utility exceeding the first-best level  $S_2^{FB}$ , the principal does not face the standard rent-efficiency trade-off anymore. Now, if the principal promises

---

Notice that the right hand side is generically a singleton in the sense that whenever it is not a singleton, a slight perturbation of  $\frac{F_2(\theta_2)}{f_2(\theta_2)}$  would remove all but one solution. Hence, Assumption 1 is mild in that it holds generically.

<sup>12</sup>Given a set  $A$ , the indicator function  $\mathbf{1}_A(a)$  is 1 if  $a \in A$  and 0 otherwise.

exactly  $U = S_2^{FB}$ , this can be indirectly implemented by an offer from the principal to procure the good at a price of  $v_2$ . If the principal promises strictly more,  $U > S_2^{FB}$ , then an optimal contract can be indirectly implemented by a two-part tariff. In particular, the principal makes an unconditional payment  $U - S_2^{FB}$  and offers to procure the good at a price of  $v_2$ . This two-part tariff yields her an expected profit  $\Pi(U) = S_2^{FB} - U$ .

If, on the other hand,  $U < S_2^{FB}$ , it follows from Samuelson (1984) that an optimal trading probability is of the form

$$x_2(\theta_1, \theta_2) = \begin{cases} 1 & \text{if } \theta_2 \in [0, \theta'_2] \\ \xi & \text{if } \theta_2 \in (\theta'_2, \theta''_2] \\ 0 & \text{else} \end{cases} \quad (25)$$

for some  $\xi \in [0, 1]$ ,  $\underline{\theta} \leq \theta'_2 \leq \theta''_2 < v_2$  which all depend on  $U$ . If  $\xi = 0$ , the optimal contract can be implemented by an offer from the principal to procure the good at price  $\theta'_2$ . If  $\xi > 0$ , the optimal contract can be implemented by a menu of three options for the agent: to not produce the good at a price of 0; to produce a “fraction”  $\xi$  of the good for a price of  $\xi \theta'_2$ ,<sup>13</sup> or to produce the good at price  $\theta''_2$ .

Whether  $\xi$  is strictly positive or not, depends on the distribution  $F_2$  and on the size of  $U$ . For the special case that the hazard rate  $F_2/f_2$  is increasing, we have that  $\xi = 0$  for all  $U$  so that the optimal contract can be implemented with a posted price.

*Example:* For our uniform example, the hazard rate  $F_2(\theta_2)/f_2(\theta_2) = \theta_2$  is increasing so that, as noted in Remark 1, a posted price in period 2 is optimal. In particular, for  $U \in [0, S_2^{FB}] = [0, 1/2]$ , the optimal contract for  $U \in [0, S_2^{FB}] = [0, 1/2]$  corresponds to a posted price  $p_2$  which maximizes  $p_2(v - p_2)$  subject to the promise keeping constraint  $\int_0^{p_2} p_2 - \theta \, d\theta = U$ . This constraint simplifies to  $p_2^2/2 = U$  and therefore pins down  $p_2(U) = \sqrt{2U}$ . The resulting profit is  $\Pi(U) = p_2(v - p_2) = \sqrt{2U}(1 - \sqrt{2U}) = \sqrt{2U} - 2U$ . Moreover, for  $U > 1/2$ , we have  $\Pi(U) = 1/2 - U$ . Taken together, we thus have:

$$\Pi(U) = \begin{cases} \sqrt{2U} - 2U & \text{if } U \leq 1/2; \\ 1/2 - U & \text{if } U > 1/2. \end{cases} \quad (26)$$

Note that  $\Pi(U)$  is not only continuous but also differentiable at  $U = 1/2$ .

<sup>13</sup>For an indivisible good the contract randomizes between trade and no trade and the agent is paid  $\theta'_2$  if trade is the outcome.

## Step 2: Optimal period 1 terms of trade

Step 1 allow us to re-write the principal's problem  $P$  as a static maximization problem over the period 1 terms of trade  $x_1$  and the agent's promised utility  $U$ . More specifically, any combination  $(x_1(\theta_1), U(\theta_1))$  with  $U(\theta_1) \geq 0$  corresponds to a backloaded contract  $(x_1(\theta_1), x_2(\theta_1, \cdot), t_2(\theta_1, \cdot))$  where  $(x_2(\theta_1, \cdot), t_2(\theta_1, \cdot))$  is the solution to  $P_2$  with  $U = U(\theta_1)$ . We refer to  $(x_1, U)$  as a *reduced* backloaded contract (and simply as backloaded contract if there is no risk of confusion). Clearly, only contracts corresponding to reduced backloaded contracts can be optimal.

Recall that under a backloaded contract, the agent breaks even in period 1, that is,  $t_1(\theta_1) = \theta_1 x_1(\theta_1)$ . Consequently, the principal receives the profit  $v_1 x_1(\theta_1) - \theta_1 x_1(\theta_1)$  in period 1 and the profit  $\Pi(U(\theta_1))$  in period 2. Suppressing the time index for period 1, we can therefore rewrite the principal's problem as

$$P' : \quad \max_{x, U} \int_{\underline{\theta}}^{\bar{\theta}} [v - \theta] x(\theta) + \Pi(U(\theta)) dF(\theta) \quad s.t \quad (27)$$

$$IR : \quad U(\theta) \geq 0 \quad \forall \theta \quad (28)$$

$$IC : \quad U(\theta) \geq (\hat{\theta} - \theta)x(\hat{\theta}) + U(\hat{\theta}) \quad \forall \theta \leq \hat{\theta} \quad (29)$$

$$UG : \quad x(\theta) \in [0, 1] \quad \forall \theta. \quad (30)$$

The constraint  $IR$  is simply the feasibility constraint that the agent's expected utility cannot be negative, and the constraint  $IC$  is inherited from the original formulation of  $P$ .

Problem  $P'$  looks similar to a standard monopoly problem where  $U(\theta)$  is agent type  $\theta$ 's information rent, and constraint  $IR$  corresponds to a standard (interim) participation constraint. There are, however, two important differences.

First, unlike in the static monopoly problem with transferable utility, the principal's objective is not linear in the agent's information rent. This is due to the period 2 bankruptcy constraint which results in a rent-efficiency trade-off in period 2. In fact, if the principal did not face a bankruptcy constraint in period 2, her objective would be linear in the information rent because she would then optimally implement the first-best allocation in period 2 and could award the agent any (possibly negative) level of rent through an appropriate transfer.

To shed more light on the principal's costs of providing incentives, recall that  $\Pi$  is single-peaked with a maximum at  $U^{SB}$ . Therefore, if the period 1 type were publicly known, the principal would maximize the objective by picking an efficient  $x(\theta)$  and setting  $U(\theta)$  equal to the second best information rent  $U^{SB}$ . But since the period 1 type  $\theta$  is private information, the principal

has to create a spread in the information rents and award a higher information rent to low cost than to high cost types to induce the former to report truthfully. As a result, the cost of providing incentives through promising a certain information rent  $U$  in period 2 is not monotone in  $U$ . For example, "punishing" the agent with a zero information rent in period 2 is extremely costly, since  $\Pi(0) = 0$  means that the principal has to sacrifice the entire surplus in period 2. Likewise, to reward the agent with a rent higher than  $U^{SB}$ , then because  $\Pi$  is maximal at  $U^{SB}$ , the principal has to give the agent a surplus share that exceeds the second best share of the surplus in period 2.

Second, the incentive compatibility constraints  $IC$  are uni-directional, only requiring that the agent does not report a less efficient type. In contrast to the setting with bi-directional incentive constraints, the uni-directional constraints prevent us from employing familiar solution techniques that are based on the characterization of incentive compatibility in terms of monotonicity of the trading probability and revenue equivalence. In fact, it is easy to see that  $IC$  does not even imply that  $x(\theta)$  is monotone.<sup>14</sup> To address this issue, the next lemma provides necessary conditions for  $IC$  that allow us to relax problem  $P'$ .

**Lemma 4** *If  $(x, U)$  satisfies  $IC$ , then it satisfies the two following conditions:*

$M$ :  $U$  is decreasing.

$IC_L$ :  $U'(\theta) \leq -x(\theta)$  for all  $\theta$  where the derivative exists.

Property  $M$  is straightforward and simply reflects that lower cost types can guarantee themselves at least the utility of a higher cost type by pretending to be that type. As to condition  $IC_L$ , note first that because  $U$  is decreasing,  $U$  is differentiable almost everywhere. Recall that in the standard case where  $IC$  is required for *all* reports  $\hat{\theta}$ , the derivative of the agent's utility is actually pinned down by the allocation  $x$ . In our case, where  $IC$  is required only for reports  $\hat{\theta} > \theta$ , it is only necessary that the derivative of the agent's utility is bounded by the allocation  $x$ .

The lemma implies that we obtain a relaxed version of  $P'$  if we replace  $IC$  with the monotonicity condition  $M$  and the "localized" condition  $IC_L$ :

$$R : \quad \max_{x, U} \int_{\underline{\theta}}^{\bar{\theta}} [v - \theta]x(\theta) + \Pi(U(\theta)) dF(\theta) \quad s.t \quad IR, M, IC_L, UG \quad (31)$$

We now solve  $R$  and then show that its solution also solves  $P'$ . We proceed in two steps. We

---

<sup>14</sup>Analyzing a screening problem with uni-directional incentive constraints and discrete types, Celik (2006) makes the same observation. His techniques for solving the subsequent problem do not apply to our framework with continuous types.

first show that at a solution to  $R$ , trade never happens if it is inefficient, and the constraint  $IC_L$  is binding. In the second step, we use these properties to establish a solution to  $R$ . To establish the first step, let  $\Phi$  be the (non-empty) feasible set for problem  $R$ . We then obtain the following result.

**Lemma 5** *Let  $(\tilde{x}, \tilde{U}) \in \Phi$ . Then there is  $(x, U) \in \Phi$  which delivers the principal a (weakly) higher profit than  $(\tilde{x}, \tilde{U})$  and has the following properties:*

- (i) *If  $v < \bar{\theta}$ , then  $x(\theta) = 0$  for all  $\theta > v$ .*
- (ii)  *$U'(\theta) = -x(\theta)$  for all  $\theta$ .*

The first part makes the familiar point that an optimal contract induces a downward distortion. To understand the second part, recall that  $\Pi$  is concave with a maximum at  $U^{SB}$ . For a given trading probability  $x$ , the principal therefore seeks to choose  $U$  as closely as possible to  $U^{SB}$  while maintaining the incentive compatibility requirement that  $U'(\theta) \leq -x(\theta)$ . Thus, an optimal choice of  $U$  is maximally flat, implying that  $U'(\theta) = -x(\theta)$ .

We emphasize that although property (ii) corresponds to the revenue equivalence property from standard screening models where  $IC$  is required for *all* reports  $\hat{\theta}$ , in our setting, property (ii) expresses an optimality rather than a feasibility condition.

In standard screening models, property (ii) is useful, because it pins down the agent's utility  $U$  as an integral over the trading probability  $x$ . If, in addition,  $\Pi$  is linear, an integration by parts argument can be used to replace  $U$  in the objective function of (31), and the problem can then be solved by point-wise maximization over  $x(\theta)$ . In our case, because  $\Pi$  is concave, this approach does not work.

Our alternative approach is to instead use property (ii) to replace the trading probability  $x$  by the agent's utility function  $U$  in the objective function of (31) and then maximize over  $U$ . This allows us to show that an optimal contract is in the class of *cutoff-contracts* where the good is traded if and only if that agent's cost is below a cutoff  $\theta_0 \in [\underline{\theta}, \bar{\theta}]$ .

**Definition 3** *A cutoff-contract  $(x, U)$  is characterized by two parameters: a cutoff  $\theta_0 \in [\underline{\theta}, \bar{\theta}]$  and an intercept  $U_0 \geq \theta_0 - \underline{\theta}$  such that*

$$x(\theta) = \begin{cases} 1 & \text{if } \theta \leq \theta_0 \\ 0 & \text{else} \end{cases}, \quad U(\theta) = \begin{cases} U_0 - (\theta - \underline{\theta}) & \text{if } \theta \leq \theta_0 \\ U_0 - (\theta_0 - \underline{\theta}) & \text{else.} \end{cases} \quad (32)$$

We denote by  $\Lambda$  the set of cutoff contracts. Clearly,  $\Lambda \subset \Phi$ . We now state the main result of this

section that, under a regularity condition, a cutoff-contract is a solution to the relaxed problem  $R$ .

**Proposition 1** *Let  $(v - \theta) \frac{f'(\theta)}{f(\theta)}$  be increasing on the range  $[\underline{\theta}, \min\{v, \bar{\theta}\}]$ . Consider  $(\tilde{x}, \tilde{U}) \in \Phi$ . Then there is a cutoff-contract  $(x, U) \in \Lambda$  which delivers a (weakly) higher profit than  $(\tilde{x}, \tilde{U})$ .*

While we prove the proposition in the appendix, the underlying logic is best understood in the context of our uniform example. Note that the uniform example satisfies the regularity condition trivially, as  $f'(\theta) = 0$ .

*Example:* Consider some  $(\tilde{x}, \tilde{U}) \in \Phi$ . As indicated earlier, we can use part (ii) of Lemma 5 to replace  $\tilde{x}$  by  $\tilde{U}'$  in the objective of (31). Using integration by parts, the objective then rewrites as

$$\int_{\underline{\theta}}^{\bar{\theta}} [v - \theta] \tilde{x}(\theta) + \Pi(\tilde{U}(\theta)) dF(\theta) = \int_0^1 [v - \theta] \tilde{U}'(\theta) + \Pi(\tilde{U}(\theta)) d\theta \quad (33)$$

$$= -\tilde{U}(0) + \int_0^1 \tilde{U}(\theta) d\theta + \int_0^1 \Pi(\tilde{U}(\theta)) d\theta. \quad (34)$$

We now construct a function  $U$  belonging to a cutoff-contract for which expression (34) is at least as large as for  $\tilde{U}$ . To do so, note that Lemma 5 implies that  $\tilde{U}$  is a decreasing continuous function with a slope between  $-1$  and  $0$ . Therefore, because under a cutoff-contract,  $U$  has slope  $-1$  up to the cutoff  $\theta_0$  and then slope  $0$ , an intermediate value argument implies that we can find  $U$  so that

$$U_0 = \tilde{U}(0), \quad \int_0^1 U(\theta) d\theta = \int_0^1 \tilde{U}(\theta) d\theta. \quad (35)$$

In particular, there is a  $\tilde{\theta} \in [0, 1]$  so that

$$U(\theta) \leq \tilde{U}(\theta) \text{ for } \theta \leq \tilde{\theta} \text{ and } U(\theta) \geq \tilde{U}(\theta) \text{ for } \theta \geq \tilde{\theta}. \quad (36)$$

The first panel of Figure 1 illustrates the construction graphically.

By (35), the first two terms in (34) are the same for  $U$  and  $\tilde{U}$ . The key idea to analyze the third term in (34) is to interpret the agent's utility as a random variable which induces a probability distribution in utility space (the pushforward). Formally, and as illustrated in the second panel of Figure 1, the distributions induced by  $\tilde{U}$  and  $U$  correspond to the cumulative distribution functions

$$F^{\tilde{U}}(u) = Pr(\theta \in [0, 1] : \tilde{U}(\theta) \leq u) \quad \text{and} \quad F^U(u) = Pr(\theta \in [0, 1] : U(\theta) \leq u). \quad (37)$$



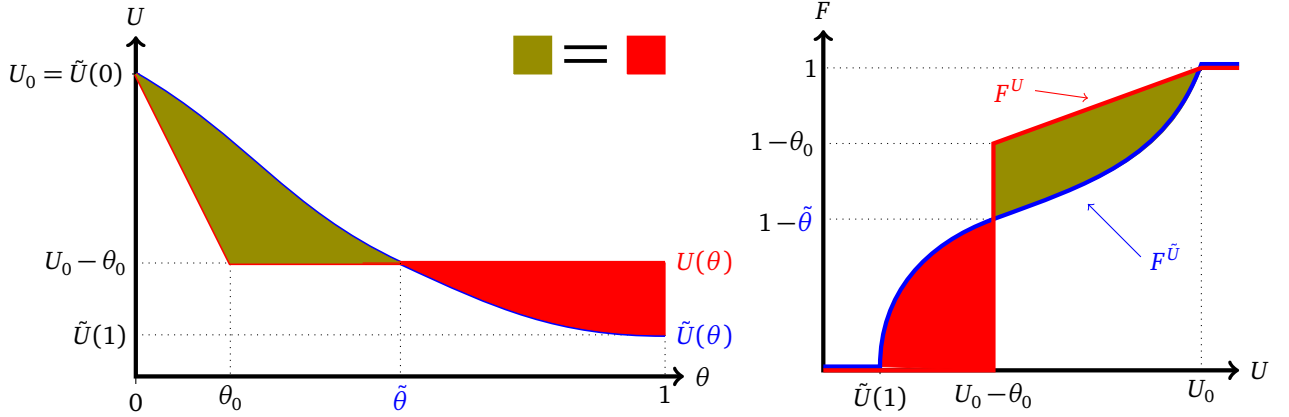


Figure 1: The left panel illustrates, given  $\tilde{U}$  and that  $\theta$  is uniformly distributed over  $[0, 1]$ , the construction of the cutoff contract  $U(\cdot)$  such that  $U_0 = \tilde{U}(0)$  and  $\int_0^1 U(\theta) d\theta = \int_0^1 \tilde{U}(\theta) d\theta$ . The right panel shows the associated probability distributions  $F^U$  and  $F^{\tilde{U}}$  of  $U$  and  $\tilde{U}$  in utility space.  $F^{\tilde{U}}$  is a mean preserving spread of  $F^U$ .

The key observation is now that the second part of (35) and (36) imply that  $F^{\tilde{U}}$  is a mean preserving spread of  $F^U$ . Therefore, because  $\Pi$  is concave, the third term in (34) is larger for  $U$  than for  $\tilde{U}$ .  $\square$

For the general case without uniform distribution, the construction is analogous. The mean preserving spread argument carries over unchanged. The role of the regularity condition is to sign what corresponds to the first and second terms in (34), since these terms depend in general on the density  $f$ .

The regularity condition in Proposition 1 is not entirely new to the literature. In a context where the principal is a seller and the agent is a buyer, Manelli and Vincent (2006, Theorem 4) impose an equivalent regularity condition when characterizing the profit maximizing solution in a multi-dimensional screening problem. A sufficient condition for the regularity condition is that jointly  $f' \leq 0$  and  $f$  is log-convex.<sup>15</sup> Examples include the family of power distributions  $F(\theta) = \theta^\alpha$ ,  $\theta \in [0, 1]$ , for  $\alpha \leq 1$  or of exponential distributions  $F(\theta) = 1 - e^{-\lambda\theta}$ ,  $\theta \geq 0$ ,  $\lambda \geq 0$ .

Proposition 1 shows that a cutoff-contract is a solution to the relaxed problem  $R$ . It is straightforward to verify that any cutoff-contract satisfies the constraints  $IC$  of the original problem.

<sup>15</sup>To see this, note

$$\frac{d}{d\theta}(v - \theta) \frac{f'(\theta)}{f(\theta)} = -\frac{f'(\theta)}{f(\theta)} + (v - \theta) \frac{d}{d\theta} \frac{f'(\theta)}{f(\theta)} = -\frac{f'(\theta)}{f(\theta)} + (v - \theta) \frac{d}{d\theta} \log(f(\theta)). \quad (38)$$

Because  $v - \theta$  is positive on the range  $[\underline{\theta}, \min\{v, \bar{\theta}\}]$ , this expression is positive if  $f' \leq 0$  and  $\log f$  is increasing, that is,  $f$  is log-convex.

Therefore, we have:

**Proposition 2** *Let  $(v - \theta) \frac{f'(\theta)}{f(\theta)}$  be increasing on the range  $[\underline{\theta}, \min\{v, \bar{\theta}\}]$ , then there is a cutoff-contract  $(x, U) \in \Lambda$  which solves the original problem  $P'$ .*

Since a cutoff-contract consists only of the two parameters  $\theta_0, U_0$ , finding the optimal cutoff-contract comes down to solving an optimization problem in two variables. We illustrate this exercise in our running example.

*Example:* For our uniform example, the principal's objective is

$$W(\theta_0, U_0) = \int_0^{\theta_0} 1 - \theta \, d\theta + \int_0^{\theta_0} \Pi(U_0 - \theta) \, d\theta + \int_{\theta_0}^1 \Pi(U_0 - \theta_0) \, d\theta \quad (39)$$

with  $U_0 \geq \theta_0$  and where  $\Pi$  is given by (26). To determine the maximizer, we first determine an optimal  $\theta_0^*(U_0)$  for a given  $U_0$ . A tedious but otherwise straightforward analysis of the first and second order condition with respect to  $\theta_0$  yields<sup>16</sup>

$$\theta_0^*(U_0) = U_0 - 1/18. \quad (42)$$

Next, we maximize  $W(\theta_0^*(U_0), U_0) = W(U_0 - 1/18, U_0)$  with respect to  $U_0$ . For  $U_0 \leq 1/2$ , this expression reduces to the quadratic expression  $163/648 + 5/6 \cdot U_0 - U_0^2$  which is strictly increasing for  $U_0 \leq 1/2$  so that a maximum exhibits  $U_0 \geq 1/2$ . For  $U_0 > 1/2$ , the expression  $W(U_0 - 1/18, U_0)$  reduces to the quadratic expression  $41/324 + 4/3 \cdot U_0 - U_0^2$  which attains a maximum at  $U_0 = 2/3$ .

We therefore conclude that  $(\theta_0^*, U_0^*) = (11/18, 2/3)$  maximizes  $W(\theta_0, U_0)$  with a payoff of  $185/324 \approx 0.571$ , exceeding by 14% the principal's payoff of  $2\Pi^{SB} = 1/2$ , from charging twice the static optimal price  $p = 1/2$ .

Recall from above that in the uniform example, the period 2 terms of trade can be implemented by offering the agent a period 2 price  $p_2 = \sqrt{2U}$ . With this in mind, period 1 cost types  $\theta$

<sup>16</sup>The first order condition with respect to  $\theta_0$  is:

$$\frac{\partial W}{\partial \theta_0} = (1 - \theta_0)(1 - \Pi'(U_0 - \theta_0)) = 0 \quad \Leftrightarrow \quad \theta_0 = 1 \text{ or } \Pi'(U_0 - \theta_0) = 1. \quad (40)$$

It is easy to check that  $\theta_0 = 1$  is not a maximizer of  $W$ . By (26), the unique solution to  $\Pi'(U_0 - \theta_0) = 1$  is  $\theta_0 = U_0 - 1/18$ . This is indeed a maximizer of  $W(\theta_0, U_0)$ , because the second order condition is

$$\frac{\partial^2 W}{\partial \theta_0^2} = -1 + \Pi'(U_0 - \theta_0) + \Pi''(U_0 - \theta_0)(1 - \theta_0) < 0, \quad (41)$$

is satisfied for  $\theta_0 = U_0 - 1/18$ , since the first two terms cancel, while  $\Pi''(U) = -\sqrt{2}U^{-3/2}/4 < 0$  for  $U \leq 1/2$  and  $U_0 - \theta_0 = 1/18 < 1/2$ .

	(no A.I.) FB	2xSB	No bankruptcy	bankruptcy
P's payoff	1	0.5	0.75	0.571
U's ex ante payoff	0	0.25	.125	0.242
ex ante surplus	1	0.75	.875	0.813

Table 1: Payoff comparisons

above the cutoff  $\theta_0^* = 11/18$  do not produce in period 1 and obtain expected period 2 utility of  $U(\theta) = U_0^* = 2/3$ , corresponding to a period 2 price offer  $p_2 = 1/3$ . All period 1 cost types  $\theta$  below the cutoff  $\theta_0^* = 11/18$  produce in the first period and obtain expected period 2 utility  $U(\theta) = U_0^* - \theta = 2/3 - \theta$ , corresponding to a period 2 price offer  $p_2 = \min\{4/3 - 2\theta_1, 1\}$ . Interestingly, period 1 cost types  $\theta < 1/6$  obtain more than the utility  $1/2$ . These types always produce in period 2, since they receive the offer to produce at a price of 1 in period 2.

The ex ante expected utility of the agent is  $157/648$  so that expected aggregate surplus is  $185/324 + 157/648 = 527/648 \approx 0.813$ , compared to the first best surplus of 1. Without bankruptcy constraints, aggregate surplus is  $7/8 = .875$ , while the twice repeated static second best contract yields aggregate surplus of  $.75$ . Table 1 summarizes.  $\square$

**Remark 2 (Implementation)** We now briefly discuss how an optimal cutoff contract can be indirectly implemented by a menu of prices. For simplicity, suppose that the optimal period 2 terms of trade can be implemented by a posted price. Recall from Remark 1 that this is the case if, for example,  $F_2/f_2$  is increasing.

An optimal contract can then be implemented by a menu  $\{(r, p_2(r)) \mid r \in [\underline{\theta}, \theta_0]\}$  where the agent can choose to produce the good in period 1 for a price  $r$  and conditional on not going bankrupt in period 1, obtains the option to produce the good in period 2 for the price  $p_2(r)$  where  $p_2$  is decreasing in  $r$ . Moreover, if the agent goes bankrupt in period 1, the relationship is terminated.

To see this, recall that under a backloaded contract, the agent breaks even in period 1. Under a cutoff contract, the agent therefore receives in period 1 the transfer  $\hat{\theta}_1$  and produces the good if he announces  $\hat{\theta}_1 \in [\underline{\theta}, \theta_0]$  and does not go bankrupt. If he announces  $\hat{\theta}_1 \in (\theta_0, \bar{\theta}]$  he receives the transfer 0 and does not produce the good. This corresponds to choosing a price  $r = \hat{\theta}_1 \in [\underline{\theta}, \theta_0]$  at which to deliver the good in period 1. Moreover, after announcing  $\hat{\theta}_1$ , the agent obtains expected utility  $U(\hat{\theta}_1)$  in period 2 which can be implemented by a posted price  $p_2(\hat{\theta}_1)$  which is decreasing in  $\hat{\theta}_1$  because  $U(\hat{\theta}_1)$  is decreasing in  $\hat{\theta}_1$ . This corresponds to obtaining the option to produce the good at  $p_2(r) = p_2(\hat{\theta}_1)$  in period 2 after choosing the price  $r$  in period 1.

## 5 Extensions

In this section, we discuss how our analysis extends to settings where there are multiple time periods and to a model with interdependent types.

### *Extension to more than two periods*

While we performed our analysis only for two periods, the extension to multiple periods is straightforward. To illustrate, suppose that there are infinitely many periods and that cost types  $\theta_\tau$  are i.i.d. with time-independent cdf  $F$  on the support  $[\underline{\theta}, \bar{\theta}]$ .<sup>17</sup> For the problem to be well-defined, assume that both parties discount future payoffs with a discount factor  $\delta \in [0, 1)$ . Under the dynamic programming formulation, the principal's choice variables are a probability of trade  $x(\theta)$  for the current period and the expected continuation utility for the agent  $U(\theta)$  that both depend on a report  $\theta$  by the agent about his current type (as well as on the history of past reports which we suppress). The principal's value function  $\Pi(V)$  is now defined recursively as a function of the agent's expected utility  $V$  (starting as of now) according to the dynamic program:

$$P_\infty : \quad \Pi(V) = \max_{x, U} \int_{\underline{\theta}}^{\bar{\theta}} (v - \theta)x(\theta) + \delta \Pi(U(\theta)) dF(\theta) \quad s.t. \quad (43)$$

$$IR : \quad U(\theta) \geq 0 \quad \forall \theta \quad (44)$$

$$IC : \quad U(\theta) \geq (\hat{\theta} - \theta)x(\hat{\theta}) + U(\hat{\theta}) \quad \forall \theta \leq \hat{\theta} \quad (45)$$

$$UG : \quad x(\theta) \in [0, 1] \quad \forall \theta \quad (46)$$

$$PK : \quad \int_{\underline{\theta}}^{\bar{\theta}} \delta U(\theta) dF(\theta) = V. \quad (47)$$

While problem  $P_\infty$  yields the principal's value functions, the solution to the principal's overall problem starting in the initial period is obtained by maximizing  $\Pi$  with respect to  $V$ .

The essential difference between  $P_\infty$  and  $P'$  is the presence of the promise keeping constraint  $PK$  which ensures that the agent's expected utility from the contract is  $V$ . As above, we consider a relaxed problem where we localize  $IC$  and replace it with the constraints  $M$  and  $IC_L$  as stated in Lemma 4:

$$R_\infty : \quad \tilde{\Pi}(V) = \max_{x, U} \int_{\underline{\theta}}^{\bar{\theta}} (v - \theta)x(\theta) + \delta \tilde{\Pi}(U(\theta)) dF(\theta) \quad s.t. \quad IR, M, IC_L, UG, PK. \quad (48)$$

It follows from standard arguments (see Stockey and Lucas, 1989, or Krishna et al. 2013) that  $\tilde{\Pi}$

---

<sup>17</sup>The extension to an arbitrary finite time horizon is analogous but all expressions are time-dependent.

exists. Crucially, as in the two-period case,  $\tilde{\Pi}$  is concave. Recall that to establish the optimality of a cutoff contract for the two-period problem  $R$ , we exploited the concavity of  $\tilde{\Pi}$  to construct for a every feasible contract  $(\tilde{x}, \tilde{U})$  a feasible cutoff-contract  $(x, U)$  that is an improvement. Note that, in contrast to problem  $R$ , feasibility in problem  $R_\infty$  requires that a contract, in addition, satisfies  $PK$ . Therefore, to extend the argument from  $R$  to  $R_\infty$ , we have to ensure that the cutoff contract  $(x, U)$  that improves a given feasible contract does satisfy  $PK$ .

However, note that the cutoff contract  $(x, U)$  constructed in the two-period problem to improve upon  $(\tilde{x}, \tilde{U})$  has the property that<sup>18</sup>

$$\int_{\underline{\theta}}^{\bar{\theta}} U(\theta) dF(\theta) = \int_{\underline{\theta}}^{\bar{\theta}} \tilde{U}(\theta) dF(\theta). \quad (49)$$

Therefore, as  $(\tilde{x}, \tilde{U})$  is an arbitrary feasible contract and thus satisfies  $PK$  by definition, so does  $(x, U)$ . This shows that a cutoff contract is optimal also when there are more than two periods.

*Interdependent types* We have modelled bankruptcy as a verifiable event, thus distinguishing it from the event that the agent voluntarily takes an outside option. Bankruptcy constraints therefore affect the incentive compatibility constraints because the verifiability of bankruptcy allows the principal to detect misreports that lead to bankruptcy. As a result, the incentive constraints in our problem  $P$  are only one-sided. This is in contrast to the existing literature, where bankruptcy constraints are imposed only on path, and incentive constraints are two-sided.

Despite this conceptual difference, the solution of problem  $P$  would not change if we imposed the more standard two-sided incentive constraints. Intuitively, the reason is that the relaxation we consider to solve the problem would also relax, and ultimately yield a solution to, the problem with two-sided incentive constraints. This is so because the principal's valuation for the good does not depend on the agent's type. This implies that the solution to the relaxed problem is monotone, and thus satisfies the stronger two-sided incentive constraints. A similar observation has been made in the static mechanism design literature on one-sided incentive constraints. In particular, Celik (2006) shows that, whenever the efficient solution is monotone, the solution with one-sided incentive constraints coincides with the one for two-sided incentive constraints, even with interdependent valuations.

The monotonicity of the efficient solution however rules out a strong negative correlation between the principal's and the agent's valuation. In such a case, it might well be that the solution to the relaxed problem violates the two-sided, but satisfies the one-sided incentive constraints.

---

<sup>18</sup>This corresponds to the right part of (35) where we defined  $(x, U)$  in the uniform example.

Whenever this is the case, the prediction of a model where bankruptcy constraints are verifiable differ significantly from the those of a model where bankruptcy constraints are imposed only on path. Since a characterization of one-sided incentive constraints is not even available in the static setting, a comprehensive analysis of the interdependent values case in our dynamic model lies outside the scope of the current paper.

## 6 Conclusion

We study bankruptcy constraints in an otherwise standard dynamic screening model. We model bankruptcy as a verifiable event and show that it affects contractual feasibility constraints not only through participation but also incentive compatibility constraints. Thus, our analysis highlights the importance of spelling out explicitly the economic consequences of bankruptcy in terms of the underlying economic environment.

While our paper assumes that bankruptcy occurs whenever the agent makes short term losses, in practice the occurrence and consequences of bankruptcy may be more complicated than that, since bankruptcy may, for example, be partially discretionary or involve restructuring processes. It is an interesting avenue for future research to capture such richer forms of bankruptcy.

Our paper also makes a methodological contribution. In particular, we solve for an optimal contract using a new method that ranks contracts in terms of the spread of the distribution of the induced continuation values for the agent. An open question is to what extent our approach can be employed in a model with correlated cost types (as in Krasikov and Lamba, 2021). Such an extension is beyond the scope of the current paper because it implies that the agent's continuation value becomes type dependent, thus constraining the principal's choice of continuation values. Another interesting avenue is to apply our solution method to static mechanism design problems in which the principal's payoff is not linear in the agent's information rent.

## Appendix

**Proof of Lemma 1** Let  $\tilde{\gamma} = (\tilde{x}_1, \tilde{t}_1, \tilde{x}_2^N, \tilde{t}_2^N, \tilde{x}_2^B, \tilde{t}_2^B)$  be a feasible contract. Our proof strategy is to first define an auxiliary contract  $\hat{\gamma}$  that is feasible and payoff-equivalent to  $\tilde{\gamma}$  but under which no bankruptcy occurs. In a second step, we modify  $\hat{\gamma}$  to obtain the desired contract  $\gamma$  that has the properties stated in the lemma. In what follows, we indicate all variables pertaining to  $\tilde{\gamma}$  and  $\hat{\gamma}$  with a tilde and a hat.

Step 1: Define the auxiliary contract  $\hat{\gamma} = (\hat{x}_1, \hat{t}_1, \hat{x}_2^N, \hat{t}_2^N, \hat{x}_2^B, \hat{t}_2^B)$  by

$$(\hat{x}_1(\theta_1), \hat{t}_1(\theta_1)) = \begin{cases} (\tilde{x}_1(\theta_1), \tilde{t}_1(\theta_1)) & \text{if } \theta_1 \in \tilde{\Theta}_1^N, \\ (0, 0) & \text{otherwise} \end{cases} \quad (50)$$

$$(\hat{x}_2^N(\theta_1, \theta_2), \hat{t}_2^N(\theta_1, \theta_2)) = \begin{cases} (\tilde{x}_2^N(\theta_1, \theta_2), \tilde{t}_2^N(\theta_1, \theta_2)) & \text{if } \theta_1 \in \tilde{\Theta}_1^N, \theta_2 \in \tilde{\Theta}_2^{N,N}(\theta_1) \\ (\tilde{x}_2^B(\theta_1, \theta_2), \tilde{t}_2^B(\theta_1, \theta_2)) & \text{if } \theta_1 \notin \tilde{\Theta}_1^N, \theta_2 \in \tilde{\Theta}_2^{N,B}(\theta_1) \\ (0, 0) & \text{otherwise,} \end{cases} \quad (51)$$

$$(\hat{x}_2^B(\theta_1, \theta_2), \hat{t}_2^B(\theta_1, \theta_2)) = (0, 0) \quad \forall \theta_1, \theta_2. \quad (52)$$

We show that  $\hat{\gamma}$  is feasible and payoff-equivalent to  $\tilde{\gamma}$ . To see this, note first that, by construction, we have  $\hat{\Theta}_1^N = \Theta_1$  and  $\hat{\Theta}_2^{N,N}(\theta_1) = \Theta_2$  for all  $\theta_1$ . Furthermore,

$$\hat{U}^N(\theta_1) = \tilde{U}^N(\theta_1) \text{ for } \theta_1 \in \tilde{\Theta}_1^N \quad \text{and} \quad \hat{U}^N(\theta_1) = \tilde{U}^B(\theta_1) \text{ for } \theta_1 \notin \tilde{\Theta}_1^N. \quad (53)$$

To see feasibility, observe that  $\hat{\gamma}$  trivially satisfies (4) for  $b = B$ , and inherits (4) for  $b = N$  by construction. To see (5), let  $\hat{t}_1(\hat{\theta}_1) - \theta_1 \hat{x}_1(\hat{\theta}_1) \geq 0$ . Consider first the case that  $\theta_1 \in \tilde{\Theta}_1^N$  and  $\hat{\theta}_1 \in \tilde{\Theta}_1^N$ . Then, we have:

$$\hat{t}_1(\theta_1) - \theta_1 \hat{x}_1(\theta_1) + \hat{U}^N(\theta_1) = \tilde{t}_1(\theta_1) - \theta_1 \tilde{x}_1(\theta_1) + \tilde{U}^N(\theta_1) \quad (54)$$

$$\geq \tilde{t}_1(\hat{\theta}_1) - \theta_1 \tilde{x}_1(\hat{\theta}_1) + \tilde{U}^N(\hat{\theta}_1) \quad (55)$$

$$= \hat{t}_1(\hat{\theta}_1) - \theta_1 \hat{x}_1(\hat{\theta}_1) + \hat{U}^N(\hat{\theta}_1), \quad (56)$$

where the inequality follows, because  $\tilde{\gamma}$  satisfies (5) and the two equalities follow from (53). The other cases can be shown analogously.

To see (6), note that the left hand side of (6) is non-negative by definition of  $\hat{\gamma}$ . Moreover, because  $\hat{x}_2^B = \hat{t}_2^B = 0$ , we have  $\hat{U}^B(\hat{\theta}_1) = 0$  for all  $\hat{\theta}_1$  so that the right hand side is zero. Therefore, (6) follows. To complete the proof of feasibility, note that (7) and (8) are void for  $\hat{\gamma}$ , because

$$\hat{\Theta}_1^N = \Theta_1.$$

Finally,  $\hat{\gamma}$  and  $\tilde{\gamma}$  are payoff-equivalent, because by construction, if bankruptcy does not occur under  $\tilde{\gamma}$ , then  $\hat{\gamma}$  implements the same terms of trade as  $\tilde{\gamma}$ , and when bankruptcy occurs under  $\tilde{\gamma}$ , no trade occurs under  $\hat{\gamma}$  so that under either contract both the principal and the agent get zero.

Step 2: We now construct a feasible contract  $\gamma = (x_1, t_1, x_2^N, t_2^N, x_2^B, t_2^B)$  which is payoff-equivalent to  $\hat{\gamma}$  and satisfies (12)-(14). To do so, note first that  $\hat{\gamma}$  satisfies (13) and (14), but may violate (12) and display  $\hat{t}_1(\theta_1) - \theta_1 \hat{x}_1(\theta_1) > 0$  for some  $\theta_1$ .

Define  $\gamma$  as the contract that differs from  $\hat{\gamma}$  only in that the period 1 profits for the agent are backloaded to period 2. Formally,  $\gamma$  displays  $x_1 = \hat{x}_1, x_2^N = \hat{x}_2^N, x_2^B = \hat{x}_2^B, t_2^B = \hat{t}_2^B$  and payments

$$t_1(\theta) = \theta_1 x_1(\theta_1), \quad t_2^N(\theta_1, \theta_2) = \hat{t}_2^N(\theta_1, \theta_2) + \hat{t}_1(\theta_1) - t_1(\theta_1). \quad (57)$$

Note first that  $\gamma$  satisfies (12) by construction. Moreover, it inherits (14) from  $\hat{\gamma}$  and also property (13) because

$$t_2^N(\theta_1, \theta_2) - \theta_2 x_2^N(\theta_1, \theta_2) = \hat{t}_2^N(\theta_1, \theta_2) + \hat{t}_1(\theta_1) - t_1(\theta_1) - \theta_2 \hat{x}_2^N(\theta_1, \theta_2) \quad (58)$$

$$= \hat{t}_2^N(\theta_1, \theta_2) - \theta_2 \hat{x}_2^N(\theta_1, \theta_2) + \hat{t}_1(\theta_1) - \theta_1 \hat{x}_1(\theta_1) \geq 0, \quad (59)$$

where the inequality follows since under  $\hat{\gamma}$  no bankruptcy occurs.

We next show that  $\gamma$  is feasible. Indeed,  $\gamma$  trivially satisfies (4) for  $b = B$  because  $x_2^B = t_2^B = 0$ . For  $b = N$ , we have for all  $\theta_1, \theta_2, \hat{\theta}_2$ :

$$t_2^N(\theta_1, \theta_2) - \theta_2 x_2^N(\theta_1, \theta_2) = \hat{t}_2^N(\theta_1, \theta_2) + \hat{t}_1(\theta_1) - t_1(\theta_1) - \theta_2 x_2^N(\theta_1, \theta_2) \quad (60)$$

$$\geq \hat{t}_2^N(\theta_1, \hat{\theta}_2) + \hat{t}_1(\theta_1) - t_1(\theta_1) - \theta_2 x_2^N(\theta_1, \hat{\theta}_2) \quad (61)$$

$$= t_2^N(\theta_1, \hat{\theta}_2) - \theta_2 x_2^N(\theta_1, \hat{\theta}_2), \quad (62)$$

where the first and the third lines use the definition of  $t_2^N$ , and the second line follows because  $\hat{\gamma}$  satisfies (4) for  $b = N$  and since  $x_2^N = \hat{x}_2^N$ .

To see (5), consider  $\theta_1, \hat{\theta}_1$  so that  $t_1(\hat{\theta}_1) - \theta_1 x_1(\hat{\theta}_1) \geq 0$ . Because  $\hat{t}_1(\hat{\theta}_1) \geq t_1(\hat{\theta}_1)$  and  $\hat{x}_1(\hat{\theta}) = x_1(\hat{\theta})$ , this implies that also  $\hat{t}_1(\hat{\theta}_1) - \theta_1 \hat{x}_1(\hat{\theta}_1) \geq 0$ . Therefore, since  $\hat{\gamma}$  satisfies (5), we have

$$\hat{t}_1(\theta) - \theta_1 \hat{x}_1(\theta_1) + \hat{U}^N(\theta_1) \geq \hat{t}_1(\hat{\theta}) - \theta_1 \hat{x}_1(\hat{\theta}_1) + \hat{U}^N(\hat{\theta}_1). \quad (63)$$

Moreover, by construction, we have that  $t_1(\theta_1) + U^N(\theta_1) = \hat{t}_1(\theta_1) + \hat{U}^N(\theta_1)$ . These two observa-



tions imply that

$$t_1(\theta_1) - \theta_1 x_1(\theta_1) + U^N(\theta_1) = \hat{t}_1(\theta) - \theta_1 \hat{x}_1(\theta_1) + \hat{U}^N(\theta_1) \quad (64)$$

$$\geq \hat{t}_1(\hat{\theta}) - \theta_1 \hat{x}_1(\hat{\theta}_1) + \hat{U}^N(\hat{\theta}_1) \quad (65)$$

$$= t_1(\hat{\theta}) - \theta_1 x_1(\hat{\theta}_1) + U^N(\hat{\theta}_1). \quad (66)$$

Furthermore,  $\gamma$  satisfies (6), because  $U^B(\hat{\theta}_1) = 0$  for all  $\hat{\theta}_1$  and the left hand side of (6) is non-negative. Finally, (7) and (8) are void for  $\gamma$ , because  $\Theta_1^N = \hat{\Theta}_1^N = \Theta_1$ .

It remains to show that  $\gamma$  and  $\hat{\gamma}$  are payoff-equivalent. But this follows, because the only difference between the contracts is that the payments have been moved between periods, but the sum of payments over the two periods is the same. qed

**Proof of Lemma 2** Let  $\gamma = (x_1, t_1, x_2^N, t_2^N, x_2^B, t_2^B)$  be the contract induced by the backloaded contract  $(x_1, x_2, t_2)$ . Hence,  $t_1 = \theta_1 x_1$ ,  $x_2^N = x_2$ ,  $t_2^N = t_2$ ,  $x_2^B = t_2^B = 0$ . We have to show that  $\gamma$  is feasible if and only if  $IC_2$  and  $IC_1$  hold. To see this, observe first that  $\gamma$  trivially satisfies (4) for  $b = B$  because  $x_2^B = t_2^B = 0$ . Moreover, for any backloaded-induced contract  $\gamma$ , the constraint (4) for  $b = N$  rewrites as  $IC_2$ . Hence  $\gamma$  satisfies (4) if and only if it satisfies  $IC_2$ .

We next show that constraint (5) is equivalent to  $IC_1$ . Indeed, since  $t_1(\hat{\theta}_1) = \hat{\theta}_1 x_1(\hat{\theta}_1)$  for all  $\hat{\theta}_1$ , we have

$$t_1(\hat{\theta}_1) - \theta_1 x_1(\hat{\theta}_1) \geq 0 \iff (\hat{\theta}_1 - \theta_1) x_1(\hat{\theta}_1) \geq 0 \iff \theta_1 \leq \hat{\theta}_1. \quad (67)$$

Hence,  $\gamma$  satisfies (5) if and only if for all  $\theta_1 \leq \hat{\theta}_1$ , we have  $t_1(\theta_1) - \theta_1 x_1(\theta_1) + U(\theta_1) \geq t_1(\hat{\theta}_1) - \theta_1 x_1(\hat{\theta}_1) + U(\hat{\theta}_1)$ . But because  $t_1(\theta'_1) - \theta'_1 x_1(\theta'_1) = 0$  for all  $\theta'_1$  holds for any contract  $\gamma$  that is induced by some backloaded contract, this is equivalent to  $IC_1$ .

Moreover,  $\gamma$  always satisfies (6) because the right hand side of (6) is zero, and the left hand side is non-negative. Finally, (7) and (8) are void for  $\gamma$  because  $\Theta_1^N = \Theta_1$ . This completes the proof. qed

**Proof of Lemma 3** To simplify notation, we omit  $\theta_1$  and suppress the time subindex. With standard screening arguments, we can write  $P_2$  as a maximization problem that maximizes the virtual

surplus with respect to the allocation  $x(\cdot)$  and the rent of the most inefficient type  $u(\bar{\theta})$  as follows:

$$P_2 : \quad \Pi(U) \equiv \max_{x, u(\bar{\theta})} \int_{\underline{\theta}}^{\bar{\theta}} \left( v - \theta - \frac{F(\theta)}{f(\theta)} \right) x(\theta) dF(\theta) - u(\bar{\theta}) \quad s.t \quad (68)$$

$$M : \quad x(\theta) \text{ is decreasing in } \theta \quad (69)$$

$$NB_2 : \quad u(\bar{\theta}) \geq 0 \quad (70)$$

$$PK : \quad u(\bar{\theta}) + \int_{\underline{\theta}}^{\bar{\theta}} x(\theta) \frac{F(\theta)}{f(\theta)} dF(\theta) = U \quad (71)$$

That  $\Pi(U)$  attains a maximum  $\Pi_2^{SB}$  at  $U_2^{SB}$  is explained in the main text.

To see the further claims of the Lemma note that PK pins down  $u(\bar{\theta})$ , and by substituting out  $u(\bar{\theta})$  in the objective (69) and  $NB_2$ , the problem simplifies to

$$\hat{P}_2 : \quad \Pi(U) \equiv \max_x \int_{\underline{\theta}}^{\bar{\theta}} (v - \theta) x(\theta) dF(\theta) - U \quad s.t \quad (72)$$

$$M : \quad x(\theta) \text{ is decreasing in } \theta \quad (73)$$

$$NB_2 : \quad \int_{\underline{\theta}}^{\bar{\theta}} x(\theta) \frac{F(\theta)}{f(\theta)} dF(\theta) \leq U \quad (74)$$

To see that  $\Pi(0) = 0$ , note that (74) implies that the only way to supply  $U = 0$  is to have  $x(\theta) = 0$  for all  $\theta$ , resulting in zero profits, hence:  $\Pi(0) = 0$ .

To see that  $\Pi$  is concave, let  $x'$  resp.  $x''$  be solutions to  $\hat{P}_2$  for  $U'$  resp.  $U''$ . Then the allocation  $\bar{x} = \alpha x' + (1 - \alpha)x''$  satisfies  $M$  and  $NB_2$  for  $U = \alpha U' + (1 - \alpha)U''$ . Moreover,  $\bar{x}$  yields profit  $\alpha \Pi(U') + (1 - \alpha)\Pi(U'')$ . The solution to  $\hat{P}_2$  for  $U = \alpha U' + (1 - \alpha)U''$  must therefore yield at least  $\bar{\Pi}$ . Thus, we have  $\Pi(\alpha U' + (1 - \alpha)U'') \geq \alpha \Pi(U') + (1 - \alpha)\Pi(U'')$ , which establishes concavity of  $\Pi$ .

To see that  $\Pi(S^{FB}) = 0$ , note that, by definition,  $\Pi + U \leq S^{FB}$  for any allocation  $x(\cdot)$ . Hence, we have  $\Pi(S^{FB}) \leq 0$ . To show  $\Pi(S^{FB}) = 0$ , it therefore suffices to show that, for  $U = S^{FB}$ , the first-best allocation  $x^{FB}(\theta) = 1_{[\underline{\theta}, \min\{v, \bar{\theta}\}]}(\theta)$  satisfies (73) and (74) and yields 0 for the objective (72). Indeed,  $x^{FB}(\theta)$  clearly satisfies (73) and, together with  $U = S^{FB}$ , yields 0 for the objective (72). To see that the first-best allocation also satisfies (74) for  $U = S^{FB} \int_{\underline{\theta}}^{\min\{v, \bar{\theta}\}} v - \theta dF(\theta)$ , note

that by integration by parts:

$$\int_{\underline{\theta}}^{\bar{\theta}} x^{FB}(\theta) \frac{F(\theta)}{f(\theta)} dF(\theta) = \int_{\underline{\theta}}^{\min\{v, \bar{\theta}\}} \frac{F(\theta)}{f(\theta)} dF(\theta) \quad (75)$$

$$= -(v - \theta)F(\theta) \Big|_{\underline{\theta}}^{\min\{v, \bar{\theta}\}} + \int_{\underline{\theta}}^{\min\{v, \bar{\theta}\}} v - \theta dF(\theta) \leq S^{FB}. \quad (76)$$

qed

**Proof of Lemma 4** That  $U$  is decreasing is immediate from  $IC$ . Since  $U$  is decreasing,  $U$  has a derivative almost everywhere by Lebesgue's Theorem. Now suppose that  $U'$  exists at  $\theta$ . Note that for  $h > 0$ , we can write  $IC$  as  $U(\theta - h) - U(\theta) \geq hx(\theta)$ . Thus,

$$U'(\theta) = \lim_{h \rightarrow 0} \frac{U(\theta) - U(\theta - h)}{h} \leq -x(\theta), \quad (77)$$

as desired.

qed

**Proof of Lemma 5** Let  $(\tilde{x}, \tilde{U}) \in \Phi$  be such that it does not satisfy (i) or (ii). We construct an improvement  $(x, U) \in \Phi$  that satisfies (i) and (ii).

Suppose that  $v < \bar{\theta}$  and  $(\tilde{x}, \tilde{U})$  violates (i). Consider first the case that  $\tilde{U}(v) \leq U^{SB}$ , and define  $(x, U)$  as

$$x(\theta) = \begin{cases} \tilde{x}(\theta) & \text{if } \theta \leq v \\ 0 & \text{if } \theta > v \end{cases}, \quad U(\theta) = \begin{cases} \tilde{U}(\theta) & \text{if } \theta \leq v \\ \tilde{U}(v) & \text{if } \theta > v. \end{cases} \quad (78)$$

Clearly,  $(x, U) \in \Phi$  and satisfies (i). We next argue that  $(x, U)$  is a (weak) improvement over  $(\tilde{x}, \tilde{U})$  by showing that

$$\int_{\underline{\theta}}^{\bar{\theta}} (v - \theta)x(\theta) dF(\theta) \geq \int_{\underline{\theta}}^{\bar{\theta}} (v - \theta)\tilde{x}(\theta) dF(\theta), \text{ and} \quad (79)$$

$$\int_{\underline{\theta}}^{\bar{\theta}} \Pi(U(\theta)) dF(\theta) \geq \int_{\underline{\theta}}^{\bar{\theta}} \Pi(\tilde{U}(\theta)) dF(\theta). \quad (80)$$

Inequality (79) is immediate from the definition of  $x$ . To see (80), note that because  $U$  is decreasing and  $U(v) \leq U^{SB}$  by assumption, it follows by construction that for all  $\theta > v$ , we have  $U^{SB} \geq U(\theta) \geq \tilde{U}(\theta)$ . Thus, because  $\Pi$  is concave and uniquely maximized at  $U^{SB}$  by Lemma 3, this implies that  $\Pi(U(\theta)) \geq \Pi(\tilde{U}(\theta))$  for all  $\theta > v$ . Since  $U(\theta) = \tilde{U}(\theta)$  for all  $\theta \leq v$ , (80) follows.

Next consider the case that  $\tilde{U}(v) > U^{SB}$ . Define  $(x, U)$  as

$$x(\theta) = \begin{cases} \tilde{x}(\theta) & \text{if } \theta \leq v \\ 0 & \text{if } \theta > v \end{cases}, \quad U(\theta) = \begin{cases} \tilde{U}(\theta) & \text{if } \theta \leq v \\ U^{SB} & \text{if } \theta > v. \end{cases} \quad (81)$$

Clearly,  $(x, U) \in \Phi$  and satisfies (i). It follows with similar arguments as in the previous paragraph that  $(x, U)$  is a (weak) improvement over  $(\tilde{x}, \tilde{U})$ .

Finally, suppose  $(\tilde{x}, \tilde{U})$  violates (ii). Define

$$\tau = \sup\{\theta \mid \tilde{U}(\theta) \geq U^{SB}\}. \quad (82)$$

Because  $U$  is decreasing, we have that

$$\tilde{U}(\theta) \geq U^{SB} \text{ for all } \theta < \tau, \quad \text{and} \quad \tilde{U}(\theta) < U^{SB} \text{ for all } \theta > \tau. \quad (83)$$

Define  $(x, U)$  as  $x(\theta) = \tilde{x}(\theta)$  for all  $\theta$ , and

$$U(\theta) = U^{SB} - \int_{\tau}^{\theta} x(t) dt. \quad (84)$$

Clearly,  $(x, U) \in \Phi$  and satisfies (ii). To show that  $(x, U)$  yields a higher profit than  $(\tilde{x}, \tilde{U})$ , observe that because  $(\tilde{x}, \tilde{U})$  and  $(x, U)$  specify the same allocation  $x$ , it is sufficient to show that

$$\Pi(\tilde{U}(\theta)) \leq \Pi(U(\theta)) \text{ for almost all } \theta. \quad (85)$$

To see this, consider first the case that  $\theta < \tau$ . It is well-known that the derivative of a decreasing function is (Lebesgue) integrable and that  $\tilde{U}(\theta) - \tilde{U}(\tilde{\theta}) \geq \int_{\tilde{\theta}}^{\theta} \tilde{U}'(t) dt$  for all  $\theta, \tilde{\theta}$ . Hence, for all  $\epsilon > 0$  with  $\theta < \tau - \epsilon$ :

$$\tilde{U}(\theta) \geq \int_{\tau-\epsilon}^{\theta} \tilde{U}'(t) dt + \tilde{U}(\tau - \epsilon) \quad (86)$$

$$= - \int_{\theta}^{\tau-\epsilon} \tilde{U}'(t) dt + \tilde{U}(\tau - \epsilon) \quad (87)$$

$$\geq \int_{\theta}^{\tau-\epsilon} \tilde{x}(t) dt + \tilde{U}(\tau - \epsilon) \quad (88)$$

$$= - \int_{\tau-\epsilon}^{\theta} x(t) dt + \tilde{U}(\tau - \epsilon), \quad (89)$$

where the second inequality follows from  $IC_L$ , and the final equality from  $x = \tilde{x}$ . Because the inequality holds for all  $\epsilon > 0$  and since  $\tilde{U}(\tau - \epsilon) \geq U^{SB}$  by (83), we can infer that

$$\tilde{U}(\theta) \geq - \int_{\tau}^{\theta} x(t) dt + U^{SB} = U(\theta). \quad (90)$$

Moreover, since  $\theta < \tau$ , we have  $U(\theta) \geq U^{SB}$ , and accordingly,  $\tilde{U}(\theta) \geq U(\theta) \geq U^{SB}$ . Because  $\Pi$  is concave and uniquely maximized at  $U^{SB}$  by Lemma 3, these inequalities imply (85) for  $\theta < \tau$ . A symmetrical argument works to show (85) for  $\theta > \tau$ , and this completes the proof.  $\quad \text{qed}$

**Proof of Proposition 1** To avoid case distinctions, we only consider the case  $v < \bar{\theta}$ .<sup>19</sup> By Lemma 5, it is sufficient to prove the statement for  $(\tilde{x}, \tilde{U}) \in \Phi$  which satisfies properties (i) and (ii) from Lemma 5. Consequently, we have:

(i')  $\tilde{U}(\theta) = \tilde{U}(v)$  for all  $\theta \geq v$ .

We first construct a contract  $(\hat{x}, \hat{U})$  which is *not* necessarily in  $\Lambda$  that delivers a (weakly) more profit than  $(\tilde{x}, \tilde{U})$ . In a second step, we then construct  $(x, U)$  which is in  $\Lambda$  that delivers a (weakly) higher profit than  $(\hat{x}, \hat{U})$ .

As to the first step, define for  $\alpha \in [\tilde{U}(v), \tilde{U}(\underline{\theta})]$  the two functions

$$\hat{U}_{\alpha}(\theta) = \begin{cases} \tilde{U}(\underline{\theta}) - (\theta - \underline{\theta}) & \text{if } \theta \in [\underline{\theta}, \hat{\theta}] \\ \alpha & \text{if } \theta \in (\hat{\theta}, v) \\ \tilde{U}(\theta) & \text{if } \theta \in [v, \bar{\theta}] \end{cases}, \quad \Delta(\alpha) \equiv \int_{\underline{\theta}}^{\bar{\theta}} \hat{U}_{\alpha}(\theta) - \tilde{U}(\theta) dF(\theta),$$

where  $\hat{\theta} \equiv \underline{\theta} + \tilde{U}(\underline{\theta}) - \alpha \in [\underline{\theta}, v]$ .

In words,  $\hat{U}_{\alpha}$  starts at  $\tilde{U}(\underline{\theta})$ , then decreases with slope  $-1$  until it attains the value  $\alpha$  at the point  $\hat{\theta}$ , then stays constant equal to  $\alpha$  until it reaches the point  $\theta = v$ , at which it jumps downwards to  $\tilde{U}(v)$  and stays constant from then on (since it coincides with  $\tilde{U}$  which is constant on  $[v, \bar{\theta}]$  by (i') above)

Next, we show that there is  $\hat{\alpha} \in [\tilde{U}(v), \tilde{U}(\underline{\theta})]$  so that

$$\int_{\underline{\theta}}^{\bar{\theta}} \hat{U}_{\hat{\alpha}}(\theta) dF(\theta) = \int_{\underline{\theta}}^{\bar{\theta}} \tilde{U}(\theta) dF(\theta). \quad (91)$$

Indeed, by construction, for  $\alpha = \tilde{U}(\underline{\theta})$ , we have  $\hat{U}_{\alpha}(\theta) - \tilde{U}(\theta) \geq 0$  for all  $\theta$ , and for  $\alpha = \tilde{U}(v)$ , we

---

<sup>19</sup>The other case, in which  $\bar{\theta} \leq v$ , can be shown with identical arguments, and is actually simpler because step 2 of the proof as presented here is not needed to establish the result.

have  $\hat{U}_\alpha(\theta) - \tilde{U}(\theta) \leq 0$  for all  $\theta$ . It follows that  $\Delta(\tilde{U}(\underline{\theta})) \geq 0$  and  $\Delta(\tilde{U}(v)) \leq 0$ . Because  $\Delta(\alpha)$  is continuous on  $\alpha \in [\tilde{U}(v), \tilde{U}(\underline{\theta})]$ , the intermediate value theorem applies, implying (91).

Moreover, because  $\hat{U}_\alpha$  and  $\tilde{U}$  coincide on  $[v, \bar{\theta}]$  by construction, the previous equality can equivalently be written as

$$\int_{\underline{\theta}}^v \hat{U}_\alpha(\theta) dF(\theta) = \int_{\underline{\theta}}^v \tilde{U}(\theta) dF(\theta). \quad (92)$$

From now on, denote  $\hat{U}_\alpha$  simply by  $\hat{U}$ . Moreover, let

$$\hat{x}(\theta) = \begin{cases} 1 & \text{if } \theta \in [\underline{\theta}, \hat{\theta}] \\ 0 & \text{if } \theta > \hat{\theta}. \end{cases} \quad (93)$$

We now show that  $(\hat{x}, \hat{U})$  yields a (weakly) higher profit than  $(\tilde{x}, \tilde{U})$ . This is trivially the case for  $\hat{\alpha} = \tilde{U}(v)$ , where we have  $(\hat{x}, \hat{U}) = (\tilde{x}, \tilde{U})$ . Hence, suppose  $\hat{\alpha} > \tilde{U}(v)$ . In this case, we have  $\hat{U}(v) > \tilde{U}(v)$ . Therefore, because  $\hat{U}(\underline{\theta}) = \tilde{U}(\underline{\theta})$ ,  $\tilde{U}'(\theta) \geq \hat{U}'(\theta) = -1$  for  $\theta \in [\underline{\theta}, \hat{\theta}]$  and  $\tilde{U}'(\theta) \leq \hat{U}'(\theta) = 0$  for  $\theta \in [\hat{\theta}, v]$ , there is a  $\tilde{\theta} \in [\underline{\theta}, v]$  so that

$$\hat{U}(\theta) - \tilde{U}(\theta) \leq 0 \quad \forall \theta \leq \tilde{\theta} \quad \text{and} \quad \hat{U}(\theta) - \tilde{U}(\theta) \geq 0 \quad \forall \theta \geq \tilde{\theta}. \quad (94)$$

Using the facts that  $\hat{U}' = -\hat{x}$  and  $\tilde{U}' = -\tilde{x}$ , and  $\hat{x}(\theta) = \tilde{x}(\theta) = 0$  for all  $\theta > v$ , we can write the difference in the principal's profits from  $(\hat{x}, \hat{U})$  and  $(\tilde{x}, \tilde{U})$  as

$$\begin{aligned} W(\hat{x}, \hat{U}) - W(\tilde{x}, \tilde{U}) &= \int_{\underline{\theta}}^{\tilde{\theta}} (v - \theta)[\hat{x}(\theta) - \tilde{x}(\theta)] + \Pi(\hat{U}(\theta)) - \Pi(\tilde{U}(\theta)) dF(\theta) \\ &= \int_{\underline{\theta}}^v (v - \theta)[\hat{x}(\theta) - \tilde{x}(\theta)] dF(\theta) + \int_{\underline{\theta}}^{\tilde{\theta}} \Pi(\hat{U}(\theta)) - \Pi(\tilde{U}(\theta)) dF(\theta) \\ &= \int_{\underline{\theta}}^v (v - \theta)[\tilde{U}'(\theta) - \hat{U}'(\theta)] dF(\theta) + \int_{\underline{\theta}}^{\tilde{\theta}} \Pi(\hat{U}(\theta)) - \Pi(\tilde{U}(\theta)) dF(\theta). \end{aligned}$$

Integrating the first integral by parts delivers

$$W(\hat{x}, \hat{U}) - W(\tilde{x}, \tilde{U}) = (v - \theta)f(\theta)[\tilde{U}(\theta) - \hat{U}(\theta)] \Big|_{\underline{\theta}}^v \quad (95)$$

$$- \int_{\underline{\theta}}^v \left[ (v - \theta) \frac{f'(\theta)}{f(\theta)} - 1 \right] [\tilde{U}(\theta) - \hat{U}(\theta)] dF(\theta) \quad (96)$$

$$+ \int_{\underline{\theta}}^{\tilde{\theta}} \Pi(\hat{U}(\theta)) - \Pi(\tilde{U}(\theta)) dF(\theta). \quad (97)$$

We now argue that this expression is positive. Observe first that by construction,  $\hat{U}(\underline{\theta}) = \tilde{U}(\underline{\theta})$ , and thus the right hand side of (95) is equal to zero. Moreover, by (92), expression (96) can firstly be written as

$$- \int_{\underline{\theta}}^v \left[ (v - \theta) \frac{f'(\theta)}{f(\theta)} \right] [\tilde{U}(\theta) - \hat{U}(\theta)] dF(\theta) = Y, \quad (98)$$

and we can secondly add  $\int_{\underline{\theta}}^v \left[ (v - \tilde{\theta}) \frac{f'(\tilde{\theta})}{f(\tilde{\theta})} \right] [\tilde{U}(\theta) - \hat{U}(\theta)] dF(\theta) = 0$ , with  $\tilde{\theta}$  defined in (94), to obtain:

$$Y = - \int_{\underline{\theta}}^v \left[ (v - \theta) \frac{f'(\theta)}{f(\theta)} - (v - \tilde{\theta}) \frac{f'(\tilde{\theta})}{f(\tilde{\theta})} \right] [\tilde{U}(\theta) - \hat{U}(\theta)] dF(\theta) \quad (99)$$

$$= - \int_{\underline{\theta}}^{\tilde{\theta}} \left[ (v - \theta) \frac{f'(\theta)}{f(\theta)} - (v - \tilde{\theta}) \frac{f'(\tilde{\theta})}{f(\tilde{\theta})} \right] [\tilde{U}(\theta) - \hat{U}(\theta)] dF(\theta) \quad (100)$$

$$- \int_{\tilde{\theta}}^v \left[ (v - \theta) \frac{f'(\theta)}{f(\theta)} - (v - \tilde{\theta}) \frac{f'(\tilde{\theta})}{f(\tilde{\theta})} \right] [\tilde{U}(\theta) - \hat{U}(\theta)] dF(\theta). \quad (101)$$

Now, the assumption that  $(v - \theta) \frac{f'(\theta)}{f(\theta)}$  is increasing implies that the first bracket under the integral (100) is negative for all  $\theta \in [\underline{\theta}, \tilde{\theta}]$ , and (94) implies that the second bracket under the integral (100) is positive for all  $\theta \in [\underline{\theta}, \tilde{\theta}]$ , so that, overall (100) is positive. Analogously, (101) is positive.

Finally, to see that (97) is positive, define for an arbitrary decreasing function  $U$ , the cdf  $F^U$  as the push-forward measure, that is, the utility distribution induced by  $U$ , given by

$$F^U(u) = \text{Prob}(\{\theta \mid U(\theta) \leq u\}). \quad (102)$$

By (91) and (94),  $F^{\tilde{U}}$  is a mean preserving spread of  $F^{\hat{U}}$ . Thus, because  $\Pi$  is concave by Lemma

3, we have

$$\int_{\underline{\theta}}^{\bar{\theta}} \Pi(\hat{U}(\theta)) - \Pi(\tilde{U}(\theta)) dF(\theta) = \int_{\underline{\theta}}^{\bar{\theta}} \Pi(u) dF^{\hat{U}}(u) - \int \Pi(u) dF^{\tilde{U}}(u) \geq 0. \quad (103)$$

This completes the first step of the proof.

As to the second step, let  $(\hat{x}, \hat{U})$  from the first step be given. We construct  $(x, U) \in \Lambda$  which delivers a (weakly) more profit than  $(\hat{x}, \hat{U})$ . Indeed, let  $(x, U)$  be a cutoff-contract with cutoff  $\theta_0 = \hat{\theta}$  and an intercept  $U_0 \in [\hat{U}(v) + \hat{\theta} - \underline{\theta}, \hat{U}(\underline{\theta})]$  such that<sup>20</sup>

$$\int_{\underline{\theta}}^{\bar{\theta}} U(\theta) dF(\theta) = \int_{\underline{\theta}}^{\bar{\theta}} \hat{U}(\theta) dF(\theta). \quad (104)$$

This also implies that

$$U(\theta) - \hat{U}(\theta) \leq 0 \quad \forall \theta \leq v \quad \text{and} \quad U(\theta) - \hat{U}(\theta) \geq 0 \quad \forall \theta \geq v. \quad (105)$$

Because  $\theta_0 = \hat{\theta}$  implies  $x = \hat{x}$ , the difference in the principal's profit from  $(x, U)$  and  $(\hat{x}, \hat{U})$  can be written as

$$W(x, U) - W(\hat{x}, \hat{U}) = \int_{\underline{\theta}}^{\bar{\theta}} (v - \theta)[x(\theta) - \hat{x}(\theta)] + \Pi(U(\theta)) - \Pi(\hat{U}(\theta)) dF(\theta) \quad (106)$$

$$= \int_{\underline{\theta}}^{\bar{\theta}} \Pi(U(\theta)) - \Pi(\hat{U}(\theta)) dF(\theta). \quad (107)$$

Similarly to the argument at the end of the first step, (104) and (105) imply that  $F^{\hat{U}}$  is a mean preserving spread of  $F^U$ , and hence (107) is positive, and this completes the proof. qed

**Proof of Proposition 2** Note first if there is a solution  $(x, U) \in \Lambda$  to the relaxed problem  $R$ , then because  $(x, U) \in \Lambda$  is obviously feasible for the original problem  $P$ , it is also a solution to  $P$ .

It remains to show existence of a solution  $(x, U) \in \Lambda$  to  $R$ . For this recall that a cutoff contract is characterized by cutoffs  $\theta_0 \in [\underline{\theta}, \bar{\theta}]$  and  $U_0 \geq \theta_0 - \underline{\theta}$ . We first show the auxiliary claim that for any  $(\tilde{x}, \tilde{U}) \in \Lambda$  there is a  $(x, U) \in \Lambda$  which yields a (weakly) higher profit than  $(\tilde{x}, \tilde{U})$  and has the

---

<sup>20</sup>Given  $\theta_0 = \hat{\theta}$ , the cutoff  $U_0$  exists by the intermediate value theorem, because the integral on the left hand side of (104) is strictly larger than the right hand side for  $U_0 = \hat{U}(\underline{\theta})$ , strictly lower for  $U_0 = \hat{U}(v) + \hat{\theta} - \underline{\theta}$ , and changes continuously in  $U_0$ .



property that

$$U_0 \leq U^{SB} + (\bar{\theta} - \underline{\theta}). \quad (108)$$

Indeed, consider a  $(\tilde{x}, \tilde{U})$  with cutoffs  $(\tilde{\theta}_0, \tilde{U}_0)$  that violates (108). Since  $(\tilde{x}, \tilde{U})$  is a cutoff contract, this implies that  $\tilde{U}(\theta) > U^{SB}$  for all  $\theta$ . Define  $(x, U) \in \Lambda$  with cutoffs

$$\theta_0 = \tilde{\theta}_0, \quad U_0 = \tilde{U}_0 - (\tilde{U}(\bar{\theta}) - U^{SB}). \quad (109)$$

By construction, we have that  $U^{SB} \leq U(\theta) \leq \tilde{U}(\theta)$  for all  $\theta$ . Thus, because  $\Pi$  is concave and uniquely maximized at  $U^{SB}$  by Lemma 3, this implies that  $\Pi(U(\theta)) \geq \Pi(\tilde{U}(\theta))$  for all  $\theta$ . Therefore, and since  $x = \tilde{x}$ , we obtain the profit

$$W(x, U) = \int (v - \theta)\tilde{x}(\theta) + \Pi(U(\theta)) dF(\theta) \geq \int (v - \theta)\tilde{x}(\theta) + \Pi(\tilde{U}(\theta)) dF(\theta) = W(\tilde{x}, \tilde{U}) \quad (110)$$

and this proves the auxiliary claim.

Now, let  $\bar{\Lambda}$  be the set of cutoff contracts that satisfy (108). That is,  $(x, U) \in \bar{\Lambda}$  if we can express  $(x, U)$  as a cutoff contract with cutoff  $\theta_0 \in [\underline{\theta}, \bar{\theta}]$  and intercept  $U_0 \in [\theta_0 - \underline{\theta}, U^{SB} + (\bar{\theta} - \underline{\theta})]$ .

The auxiliary claim and Proposition 1 then imply that there is a solution  $(x, U) \in \Lambda$  to  $R$  if there is a solution to the problem

$$Q: \quad \max_{(x, U)} W(x, U) \quad s.t. \quad (x, U) \in \bar{\Lambda}. \quad (111)$$

Because the profit  $W(x, U)$  of a cutoff contract is pinned down by  $(\theta_0, U_0)$ , problem  $Q$  boils down to the problem of choosing a two-dimensional variable  $(\theta_0, U_0)$  from the compact set  $[\underline{\theta}, \bar{\theta}] \times [\theta_0 - \underline{\theta}, U^{SB} + (\bar{\theta} - \underline{\theta})]$ . Because profit is continuous in  $(\theta_0, U_0)$ , there is a solution to  $Q$ . Therefore, there is a solution  $(x, U) \in \Lambda$  to  $R$ , and this completes the proof. qed

## A References

- Ashlagi, Itai, Constantinos Daskalakis, and Nima Haghpanah. 2022. Sequential Mechanisms With ex post Individual Rationality. *Operations Research* (forthcoming).
- Baron, David P, and David Besanko. 1984. Regulation and Information in a Continuing Relationship. *Information Economics and Policy* 1(3), 267-302.

- Battaglini, Marco. 2005. Long-term Contracting with Markovian Consumers. *American Economic Review* 95(3), 637-658.
- Bergemann, Dirk, Francisco Castro, and Gabriel Y. Weintraub. 2020. The Scope of Sequential Screening with Ex Post Participation Constraints. *Journal of Economic Theory* 188, 105055.
- Celik, Gorkem. 2006. Mechanism Design With Weaker Incentive Compatibility Constraints. *Games and Economic Behavior* 56(1), 37-44.
- Compte, Olivier, and Philippe Jehiel. 2009. Veto Constraint in Mechanism Design: Inefficiency with Correlated Types. *American Economic Journal: Microeconomics* 1(1), 182-206.
- Daskalakis, Constantinos, Alan Deckelbaum, and Christos Tzamos. 2017. Strong Duality for a Multiple-Good Monopolist. *Econometrica* 85(3), 735-767.
- Esö, Peter, and Balazs Szentes. 2017. Dynamic Contracting: An Irrelevance Theorem. *Theoretical Economics* 12(1), 109-139.
- Krähmer, Daniel, and Roland Strausz. 2015. Optimal Sales Contracts with Withdrawal Rights. *The Review of Economic Studies* 82(2), 762-790.
- Krasikov, Ilia, and Rohit Lamba. 2021. A Theory of Dynamic Contracting with Financial Constraints. *Journal of Economic Theory* 193, 105196.
- Krasikov, Ilia, Lamba, Rohit, and Thomas Mettal. 2021. Implications of Unequal Discounting in Dynamic Contracting. Discussion Paper Penn State University.
- Krishna, R. Vijay, Giuseppe Lopomo, and Curtis R. Taylor. 2013. Stairway to Heaven or Highway to Hell: Liquidity, Sweat Equity, and the Uncertain Path to Ownership. *The RAND Journal of Economics* 44(1), 104-127.
- Manelli, Alejandro M., and Daniel R. Vincent. 2006. Bundling as an Optimal Selling Mechanism for a Multiple-Good Monopolist. *Journal of Economic Theory* 127(1), 1-35.
- Mirroknii, Vahab, Renato Paes Leme, Pingzhong Tang, and Song Zuo. 2020. Non-Clairvoyant Dynamic Mechanism Design. *Econometrica* 88(5), 1939-1963.
- Moore, John. 1984. Global Incentive Compatibility Constraints in Auction Design. *Econometrica* 52(6), 1523-1535.

- Myerson, Roger B. 1986. Multistage Games with Communication. *Econometrica* 54(2), 323-358.
- Pavan, Alessandro, Ilya Segal, and Juuso Toikka. 2014. Dynamic Mechanism Design: A Myersonian Approach. *Econometrica* 82(2), 601-653.
- Riley, John, and Richard Zeckhauser. 1983. Optimal Selling Strategies: When to Haggle, when to Hold Firm. *The Quarterly Journal of Economics* 98(2), 267-289.
- Rochet, Jean-Charles, and Philippe Choné. 1998. Ironing, Sweeping, and Multidimensional Screening. *Econometrica* 66(4), 783-826.
- Samuelson, William. 1984. Bargaining under Asymmetric Information. *Econometrica* 52(4), 995-1005.
- Spear, Stephen E., and Sanjay Srivastava. 1987. On Repeated Moral Hazard with Discounting. *The Review of Economic Studies* 54(4), 599-617.
- Stokey, Nancy L., Robert E. Lucas, and Edward C. Prescott, 1989, *Recursive Methods in Economic Dynamics*. Cambridge Massachusetts, Harvard University Press.
- Thomas, Jonathan, and Tim Worrall. 1990. Income Fluctuation and Asymmetric Information: An Example of a Repeated Principal-Agent Problem. *Journal of Economic Theory* 51(2), 367-390.