Renegotiation-Proof Mechanism Design*

Zvika Neeman† and Gregory Pavlov‡

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Abstract

A mechanism is said to be renegotiation-proof if it is robust against renegotation both before and after it is played. We ask the following three related questions: (1) what kind of environments or mechanism design problems admit renegotiation-proof implementation? (2) what kind of social choice rules are implementable in a way that is renegotiation-proof? and (3) what kind of mechanisms are renegotiation-proof?

We provide characterization results for environments, social choice rules, and mechanisms that facilitate renegotiation-proof implementation in complete information settings, and in incomplete information settings with independent private values. For incomplete information settings with correlated interdependent values we provide sufficient conditions for renegotiation-proof implementation. Importantly, our results imply that some common mechanism design problems do not admit the existence of any renegotiation-proof mechanism.

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† Department of Economics, Boston University, 270 Bay State Road, Boston, MA 02215, and the Eitan Berglas School of Economics, Tel-Aviv University, Tel-Aviv, Israel 69978; Email `zvika@BU.edu`, http://people.bu.edu/zvika, http://www.tau.ac.il/ zvika/.

‡ Department of Economics, Boston University, 270 Bay State Road, Boston, MA 02215; Email `gpavlov@BU.edu`, http://people.bu.edu/gpavlov.

1. Introduction

It is widely recognized that in order for mechanism design theory to realize its potential as a theory of institutional design it must be robust. At least five different notions of robustness have been discussed in mechanism design literature: robustness against the cost and complexity of communication and computation, robustness against collusion, robustness against uncertainty about higher order beliefs, and robustness against renegotiation.[1] This paper is devoted to the latter subject of robustness against renegotiation.

The reason that robustness against renegotiation is important is that mechanism design theory attempts to answer the question of when and how it is possible to design a game form (a mechanism) whose equilibrium outcomes are optimal with respect to some given criterion of social welfare. If a proposed mechanism might be renegotiated then it is impossible to ensure that it indeed achieves the goal it was designed to accomplish. Hence, if the objective of mechanism design theory is to suggest practicable methods for achieving certain social goals, then, not withstanding the fact that renegotiation may sometimes help improve efficiency, renegotiation-proofness of the mechanisms that are designed to achieve these goals must be ensured.[2]

Renegotiation might either involve renegotiation of just the decision reached by the mechanism, or renegotiation of the equilibrium that is played under the mechanism, or renegotiation of the entire mechanism and equilibrium to be played. Renegotiation may take place either before the mechanism is played, when each player knows only his own type, or after the mechanism is played, when each player knows both his own type and the decision reached by the mechanism, but not necessarily the other players' types.

In the former case, when renegotiation is done at the interim stage, the players might renegotiate the equilibrium they intended to play under the mechanism, or the mechanism itself. In the latter case, when renegotiation is done at the ex-post stage, the players may

[1] The literature on robust mechanism design has become quite voluminous. The interested reader may consult Nisan et al. (2007) and the references therein on robustness against the cost and complexity of communication and computation (see Palfrey and Srivastava (1991) for discussion of the robsutness against the possibility of additional communication), Che and Kim (2006) and the references therein on robustness against collusion, and Bergemann and Morris (2005) and the references therein on robustness against uncertainty about higher order beliefs. The literature about robustness against renegotiation is surveyed below. Although it is not usually interpreted as such, the work on multidimensional mechanism design (see, e.g., Jehiel et al., 2006, and the references therein) may also be interpreted as part of the literature on robust mechanism design, namely, robustness against higher dimensions of the type space.

[2] The literature distinguishes between two different versions of the impossibility to commit. Under the stronger version, one party has the ability to unilateraly change the mechanism in pursuit of unilateral gains. Under the more moderate version, only voluntary and hence Pareto-improving changes of the mechanism are permitted. In this paper we focus on the latter case.

wish to renegotiate the decision or recommendation that is made by the mechanism. The possibility of ex-post renegotiation may also have another, more subtle, effect: namely, players may be induced to play the mechanism differently than they originally intended in anticipation of future renegotiation.

A mechanism that is immune against renegotiation before it is played is said to be interim renegotiation-proof, and a mechanism that is immune against renegotiation after it is played is said to be ex-post renegotiation-proof. A mechanism that is both interim and ex-post renegotiation-proof is said to be renegotiation-proof.

The literature about renegotiation-proofness can thus be distinguished according to whether it addresses the subject of interim or ex-post renegotiation-proofness, and according to the assumptions that are imposed on the information and preferences of the players: complete information versus independent information versus correlated information; and private versus interdependent valuations.

The three main questions that are addressed in this paper are (1) what kind of environments or mechanism design problems admit renegotiation-proof implementation? (2) what kind of social choice rules are implementable in a way that is renegotiation-proof? and (3) what kind of mechanisms are renegotiation-proof?

We provide characterization results for environments, social choice rules, and mechanisms that facilitate renegotiation-proof implementation in complete information settings, and in incomplete information settings with independent private values. For complete information environments with three or more players, this characterization is in terms of ex-post efficient decision rules; and for complete information environments with two players, and for incomplete information environments with independent private values, this characterization is in terms of Groves mechanisms. For incomplete information settings with correlated, and possibly interdependent, values we provide sufficient conditions for renegotiation-proof implementation.

Importantly, our results imply that some common mechanism design problems, such as the bilateral trade problem studied by Myerson and Satterthwaite (1983), *do not* admit the existence of *any* renegotiation-proof mechanism. Some readers may interpret this impossibility result as a sign that our notion of renegotiation is too permissive, but we do not think so.[3] Rather, we believe that our results show that more work needs to be devoted to understanding how renegotiation might be blocked and how it is actually blocked in different institutions in practice.

The literature on renegotiation under complete information (see especially Maskin and Moore (1999), and Segal and Whinston (2002), but also Chung (1988), Green and Laffont (1987, 1994), Hart and Moore (1988), Aghion et al. (1989), and Che and Hausch (1999))

[3]Indeed, there are several senses in which our notion of renegotiation can be made even more permissive.

has characterized the class of implementable social choice rules given some exogenous "renegotiation function" that for every outcome specifies another outcome to which the original outcome can be renegotiated.[4] This approach is in line with the standard approach in microeconomic theory, which is to assume that the players can foresee perfectly the outcome of any future renegotiation (see, e.g., Bolton (1990) and Dewatripont and Maskin (1990) for surveys of the early literature) and is different from the approach taken here according to which the only constraint on renegotiation is that the players have to consent to it.

Rubinstein and Wolinsky (1992) also wrote about renegotiation under complete information. However, they have followed the approach that is common in the literature about renegotiation under incomplete information, which is to define a notion of renegotiation-proofness and to study the mechanisms that are renegotiation-proof given that definition. Rubinstein and Wolinsky have examined a specific buyer seller problem, and have focused their attention on the question of how the cost of renegotiation affects the set of renegotiation-proof social choice rules.

The literature on renegotiation-proofness under incomplete information (see the seminal contribution by Holmström and Myerson (1983), as well as Crawford (1985), Palfrey and Srivastava (1991), Lagunoff (1995), and Cramton and Palfrey (1995)) has mostly confined its attention to the subject of interim renegotiation-proofness. Each paper in this literature has presented a different notion of interim renegotiation-proofness that has the property that for any mechanism design problem, there exists a mechanism that is renegotiation-proof. The subject of ex-post renegotiation-proofness under incomplete information received considerably less attention. It was examined by Forges (1993, 1994) who concluded that the question of whether there exists a renegotiation-proof mechanism for *every* mechanism design problem remains open (1994, p. 241).[5]

The rest of the paper proceeds as follows. In the next section, we present the basic set up of our model. Section 3 is devoted to the subject of renegotiation-proofness under complete information, and Section 4 is devoted to renegotiation-proofness under incomplete information. All proofs are relegated to the appendix.

[4] Of related interest is the work by Bernheim et al. (1987) and Moreno and Wooders (1996) who studied coalition-proof equilibria in strategic form games. The problem of renegotiation in such environments is simpler because the players have no informational advantage vis-a-vis the designer of the mechanism.

[5] On interim renegotiation proofness, see also Maskin and Tirole (1992). On ex-post renegotiation proofness, see also Green and Laffont (1987). Beaudry and Poitevin (1995) deal with both interim and ex-post renegotiation proofness, but in a simpler model with only one privately informed player. Krasa (1999) introduced a concept of unimprovability that combines some features of interim and ex-post renegotiation proofness.

2. Set Up

A group of n players, indexed by $i \in N = \{1, 2, ..., n\}$, must reach a decision that involves the choice of a social alternative $a \in A$ together with the determination of monetary transfers to the players, $t = (t_1, ..., t_n) \in \mathbb{R}^n$. We require that the sum of these monetary transfers be non-positive.[6] A decision of the players (a, t), or rather an outcome (a, t) of the process of negotiation among the players, is said to be feasible if $a \in A$ and $\sum_{i=1}^{n} t_i \leq 0$.

The players' preferences over the set $A \times \mathbb{R}^n$ as well as their beliefs about each other's preferences are determined by their types. The set of player i's types is denoted Θ_i. For simplicity, we assume that the sets Θ_i, $i \in N$, are finite, however, our results would continue to hold, with appropriate adjustments, if the players each has a continuum of types. We denote $\Theta = \Theta_1 \times \cdots \times \Theta_n$, and $\Theta_{-i} = \prod\limits_{j \neq i} \Theta_j$, with typical elements θ and θ_{-i}, respectively. A profile of types $\theta \in \Theta$ is also called a state of the world. We denote the common prior distribution over the set of states of the world Θ by P.

Each player i is assumed to be an expected utility maximizer with a quasi-linear payoff function that is given by $u_i(a, t_i, \theta) = v_i(a, \theta) + t_i$ where $v_i : A \times \Theta \to \mathbb{R}$ denotes player i's preferences over the set of social alternatives A as a function of his type and t_i denotes a possibly additional monetary transfer to player i.

In a complete information environment, the state of the world θ is commonly known among the players, although not necessarily by the mechanism designer.[7] In an incomplete information environment, each player i knows his type θ_i, and derives his beliefs by conditioning the common prior P on his own type. A complete information *mechanism design environment* is thus fully described by a four-tuple $\left\langle N, A, \Theta, (u_i)_{i \in N} \right\rangle$.[8] An incomplete information *mechanism design environment* is described by a five-tuple $\left\langle N, A, \Theta, P, (u_i)_{i \in N} \right\rangle$.

A mechanism is a game form $\langle S, m \rangle$ that specifies a message set S_i for each player $i \in N$, and a mapping $m : S \to \Delta(A \times \mathbb{R}^n)$ from the set of message profiles $S = S_1 \times \cdots \times S_n$ into the set of lotteries over the product of the set of social alternatives A and monetary transfers

[6] Otherwise, the players may wish to renegotiate any decision just for the purpose of generating large transfer payments for themselves. Also, observe that it is possible to incorporate non budget balanced monetary transfers into the social alternative $a \in A$. For example, the social alternative a may describe whether or not a bridge is built, and how much each player is supposed to pay for it. Suppose that the cost of building the bridge is given by $c > 0$. The set of social alternatives can then include an alternative where the bridge is not built and no one pays anything, an alternative where the bridge is built and each player pays $\frac{c}{n}$, an alternative where the bridge is built, players 1 and 2 pay $\frac{c}{2}$ each while other players pay nothing and so on. The transfers t can then be added to a to facilitate contracting among the players.

[7] A mechanism designer who knows the state of the world can easily implement any social choice function she likes.

[8] The fact that the state of the world is commonly known among the players in such an environment obviates the common prior.

$\mathbb{R}^n$. As mentioned above, we assume that the mechanism that is employed by the players is such that the sum of monetary transfers to the players is non-positive, for any profile of messages that are sent by the players. If the monetary transfers to the players sum up to zero for any profile of messages that are sent by the players then the monetary transfers are said to be budget balanced.

The combination of a mechanism $\langle S, m\rangle$ and a state of the world θ defines a complete information game $\left\langle N, S, (u_i(\cdot,\cdot,\theta)\circ m)_{i\in N}\right\rangle$. The combination of a mechanism $\langle S, m\rangle$ and a prior distribution over the states of the world P defines a Bayesian game $\left\langle N, S, \Theta, P, (u_i \circ m)_{i\in N}\right\rangle$. We denote a Nash or a Bayesian Nash equilibrium of the complete information or Bayesian game that is induced by the mechanism $\langle S, m\rangle$ by $\sigma = (\sigma_1, ..., \sigma_n)$.

A social choice rule is a mapping $f : \Theta \rightrightarrows A \times \mathbb{R}^n$ from the set of states of the world into outcomes. A social choice rule is said to be implementable by a mechanism $\langle S, m\rangle$ in a complete or incomplete information environment, respectively, if the equilibrium outcomes that are induced by the mechanism belong to $f(\theta)$, for every $\theta \in \Theta$. We thus employ a weak notion of implementation.

Definition. A social alternative $a \in A$ is said to be *ex-post efficient* if it is such that:

$$a \in \arg\max_{a'\in A} \sum_{i=1}^{n} v_i(a', \theta).$$

An equilibrium σ is said to be ex-post efficient if it leads to the choice of ex-post efficient social alternatives.

We assume that for every state of the world $\theta \in \Theta$, there is a single social alternative $a \in A$ that maximizes social welfare $\sum_{i=1}^{n} v_i(a, \theta_i)$. Observe that if the players' type spaces are finite, then this assumption is generically satisfied.

Finally, to simplify the discussion, we do not discuss the subject of individual rationality. However, all of our results continue to hold if individual rationality is added as a constraint to the analysis.

3. Renegotiation-Proofness Under Complete Information

3.1. Ex-Post Renegotiation-Proofness Under Complete Information

We model the process of ex-post renegotiation in an environment with complete information in the following way: a mechanism $\langle S, m\rangle$ is chosen before the state of the world becomes known. This mechanism is played after the state of the world $\theta \in \Theta$ is realized and becomes commonly known among the players, but not known to the mechanism designer. Consider a Nash equilibrium $\sigma = (\sigma_1, ..., \sigma_n)$ of the complete information game that is induced by the mechanism $\langle S, m\rangle$ when the state of the world is θ. Denote the Nash equilibrium outcome by $(a, t_1, ..., t_n)$.

Suppose that the process of renegotiation assumes the following form. Suppose that a different social alternative $a' \in A$, together with a profile of monetary transfers $t' = (t'_1, ..., t'_n)$ that sum up to zero (or less) is exogenously proposed to the players instead of the outcome $(a, t_1, ..., t_n)$ that was obtained under the mechanism $\langle S, m\rangle$.[9] If the players all agree to switch to the renegotiated proposal, then alternative a' is implemented, and each player i receives a monetary transfer of t'_i. Otherwise, the original outcome (a, t) is implemented.[10]

We assume that if the outcome (a', t') Pareto dominates the outcome (a, t), which means that the former outcome is weakly preferred by all the players and strictly preferred by at least one player to the latter outcome, then the original outcome (a, t) is renegotiated to the new outcome (a', t'). Otherwise, the original outcome (a, t) is implemented. This assumption leads to the following definition.

Definition. A Nash equilibrium σ of the complete information game that is induced by a mechanism $\langle S, m\rangle$ when the state of the world is θ that generates an outcome (a, t) is ex-post renegotiation-proof if:

1. there does not exist an alternative feasible outcome (a', t') that Pareto dominates (a, t), and

2. there does not exist an alternative feasible outcome (a', t') that player i prefers to (a, t), and that if anticipated by i, would lead i to deviate from σ in such a way that the outcome that is generated by (σ'_i, σ_{-i}) is Pareto dominated by (a', t').[11]

The first part of the definition is straightforward. If an outcome (a, t) that is generated by an equilibrium σ is not Pareto efficient in a given state of the world $\theta \in \Theta$, then the players would agree to renegotiate it to another outcome (a', t') that Pareto dominates (a, t). This result is stated in the following lemma, which is given without proof.

[9] The set of social alternatives A may include lotteries. If so, ex-post renegotiation takes place before these lotteries are carried through.

[10] We assume that both the original and alternative outcomes (a, t) and (a', t') are public outcomes that can be imposed directly by the mechanism designer. We also assume that the outcomes are durable in the sense that there is no fixed date by which the outcome has to be implemented in order to yield the specified payoffs to the players. Watson (2007) (see also Noldeke and Schmidt (1995) and Lyon and Rasmusen (2004)) has demonstrated that the effect of ex-post renegotiation may be significantly reduced in environments with inalienable actions and nondurable trade opportunities.

[11] Observe that because player i may also choose not to deviate or $\sigma'_i = \sigma_i$ the first part of the definition is subsumed in the second.

Lemma 1. *In a complete information mechanism design environment, an ex-post renegotiation-proof Nash equilibrium is ex-post efficient and budget balanced.*

The second part of the definition is more subtle. Even though there may not exist any alternative outcome that Pareto dominates (a, t), there may still exist another outcome (a', t') that some player i prefers to (a, t) and that player i can bring about by deviating from σ in such a way that the outcome that is produced after the deviation is Pareto dominated by (a', t'). If such a profitable deviation exists for some player then σ cannot be ex-post renegotiation-proof.

The following example illustrates the second part of the definition by demonstrating that an equilibrium may fail to be ex-post renegotiation-proof in spite of being ex-post efficient and in dominant strategies.

Example 1. Suppose that there are two players, a buyer and a seller. The seller owns an object that the buyer may want to buy. The buyer is equally likely to value this object at either 1 or 5. The seller's reservation value for the object is 2. The state of the world is thus determined by the buyer's valuation for the object. The set of social alternatives consists of three alternatives: "no trade," "trade at the price 3," and "trade at the price 4."

Consider the following mechanism: the buyer announces whether he wants to trade or not. If he announces he wants to trade, then the buyer and seller trade at the price 4; otherwise, there is no trade. Observe that in each one of the two states of the world, the game that is induced by this mechanism has a trivial unique Nash equilibrium in dominant strategies. If the buyer's valuation for the object is 1, then in equilibrium the buyer declines to trade and the object is not traded. If the buyer's valuation for the object is 5, then in equilibrium the buyer agrees to trade and the object is traded at the price 4.

However, despite the fact that the Nash equilibrium that is played when the buyer's valuation is high is both ex-post efficient and in dominant strategies, it is not ex-post renegotiation-proof according to our definition. To see this, suppose that in the event of no trade, the buyer and seller may renegotiate the outcome to trading at the price of 3 if they so wish. A buyer who values the object at 5 and who anticipates the possibility of such renegotiation might announce that he declines to trade in the hope of renegotiating the outcome to trading at a price that is better for him. Since such renegotiation would also make the seller strictly better off compared to no trade, the seller may well agree to renegotiate the outcome. Thus, the Nash equilibrium in which the object is traded at the price 4 may be renegotiated away – the fact that the buyer's valuation for the object in this case is commonly known to be larger than 4 does not prevent this renegotiation from taking place.[12]

[12] See Forges (1993, p. 142) and (1994, p. 260) for another example in which an ex-post efficient equilibrium

A mechanism may give rise to different equilibria in different states of the world, and even to different equilibria in the same state of the world. We define what it means for a mechanism to be ex-post renegotiation-proof as follows.

Definition. A mechanism $\langle S, m \rangle$ is *ex-post renegotiation-proof* if it has an ex-post renegotiation-proof Nash equilibrium σ^{θ} for every state of the world $\theta \in \Theta$.[13]

Remark. The difference between our notion of ex-post renegotiation-proofness and the one that is implied by Maskin and Moore (1999) (and Segal and Whinston, 2002) stems from their assumption that renegotiation is commonly known to proceed according to a given reduced form renegotiation mapping $h : A \times \mathbb{R}^n \times \Theta \to A \times \mathbb{R}^n$ that maps an outcome and a state of the world into a possibly different outcome. A mechanism is ex-post renegotiation-proof according to our definition if it is robust against renegotiation according to *any* such renegotiation procedure. Our notion of renegotiation-proofness is thus stronger, and is satisfied by fewer mechanisms.

The following proposition provides a characterization of ex-post renegotiation-proof mechanisms for the case where the number of players is larger than or equal to three.

Proposition 1. *Consider a complete information mechanism design environment with $n \geq 3$ players. In such an environment there exists an ex-post renegotiation-proof mechanism that implements the outcome (a, t) if and only if the social alternative a is ex-post efficient and the transfers t are budget balanced.*

The idea of the proof of Proposition 1 is the following. In order to implement a given social choice rule, a mechanism designer needs to know the state of the world. If there are three or more players, then it is possible to use the report of player 2 about the state of the world to verify that player 1 is telling the truth about the state of the world, to use the report of player 1 about the state of the world to verify that player 2 is telling the truth, and to use player 3 as a budget breaker. Since this method ensures that both players 1 and 2 will reveal the true state of the world, it is possible to implement any ex-post efficient outcome given this state.

When there are only two players, it is impossible to separate the provision of incentives for telling the truth about the state of the world from budget balance, which makes this case harder to analyze. We therefore proceed to analyze this case under two additional simplifying assumptions:

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can be renegotiated.

[13] A stronger definition would have required that every equilibrium is ex-post renegotiation proof in every state of the world.

1. **Private Values:** Players' payoffs depend only on their own types, namely $v_i(a,(\theta_i,\theta_{-i})) = v_i\left(a,\left(\theta_i,\theta'_{-i}\right)\right)$ for every $a \in A$, $\theta_i \in \Theta_i$, and pairs $\theta_{-i}, \theta'_{-i} \in \Theta_{-i}$. In order to simplify the notation, henceforth, until the end of this subsection, we suppress mention of other players' types in player i's payoff function and simply write $v_i(a,\theta_i)$ instead.

2. **Full Support:** Every profile of states of the world $(\theta_1, ..., \theta_n) \in \Theta_1 \times \cdots \times \Theta_n$ is feasible ex-ante.

We show that when there are only two players a mechanism is ex-post renegotiation-proof if and only if it is a Groves mechanism (Groves, 1973).

Definition. A mechanism $\langle S,(a,t)\rangle$ is a Groves mechanism if it is such that players are asked to report their types, that is $S_i = \Theta_i$ for every player i, the decision rule $a : \Theta \to A$ is ex-post efficient, and transfers $t_i : \Theta \to \mathbb{R}$, $i \in N$, are given by

$$t_i(\theta_i,\theta_{-i}) = \sum_{j \neq i} v_j(a(\theta_i,\theta_{-i}),\theta_j) + H_i(\theta_{-i})$$

for some functions $H_i : \Theta_{-i} \to \mathbb{R}$, $i \in N$.

Proposition 2. *Consider a complete information mechanism design environment with two players. In such an environment, a budget balanced mechanism is ex-post renegotiation-proof if and only if it is a Groves mechanism.*

The intuition for Proposition 2 is the following. The possibility of renegotiation implies that a player can deviate from equilibrium play in order to induce an inefficient decision and then renegotiate the outcome to one that is ex-post efficient while capturing the difference in social surplus. This implies that the possibility of ex-post renegotiation allows any player to capture the surplus or externality that he generates up to a constant. It therefore follows that a mechanism in which players already get the surplus or externality they generate is ex-post renegotiation-proof, and conversely, any mechanism that is ex-post renegotiation-proof must be a mechanism in which each player obtains a payoff that is equal to the surplus he generates up to a constant. Thus, Proposition 2 follows from the fact that the class of mechanisms in which players' payoffs are equal to the surplus they generate up to a constant coincides with the class of Groves mechanisms.[14]

Example 1 (continued). If the set of social alternatives in example 1 is expanded to allow for trade at any price, then inspection of the proof of Proposition 2 reveals that any profile of ex-post renegotiation-proof Nash equilibria (one equilibrium for each state of the world)

[14] We do not have an intuitive explanation for the reason that the mechanism must ignore the players' reports about the other player's type.

must be such that it is the buyer who determines if there is trade or not, and the price paid by the buyer when there is trade must be larger by exactly 2 than the price paid by the buyer when there is no trade (this is the Groves payment for the buyer). It follows that if we add the participation constraint that in the event of no trade the buyer does not pay anything, then in any ex-post renegotiation-proof mechanism, it is the buyer who decides if there is trade or not, and the price that is paid for the object in the event of trade is equal to 2.

It is easy to construct a budget balanced Groves mechanism if the preferences of one of the players are independent of the state of the world. However, there are several results in the literature that demonstrate that in two player environments with sufficiently rich type spaces there does not exist any budget balanced Groves mechanism (see for example, Green and Laffont (1979), Walker (1980), and Hurwicz and Walker (1990)).

The next example demonstrates that some complete information mechanism design problems with two players may fail to admit the existence of an ex-post renegotiation-proof mechanism even in a very simple environment.

Example 2. There are two players, a buyer and a seller. The seller owns an object that the buyer may want to buy. The buyer is equally likely to value the object at either 1 or 5. The seller's reservation value for the object is equally likely to be either 2 or 6. The state of the world is thus determined both by the buyer's valuation for the object and by the seller's reservation value. The set of social alternatives consists of a continuum of alternatives: "no trade," and "trade at the price p with probability q," where $p \in (-\infty, \infty)$ and $q \in [0, 1]$.

Inspection of the proof of Proposition 2 reveals that the possibility of ex-post renegotiation implies that the buyer can ensure that he does not pay more than 2 when he buys the object compared to when he does not buy it, and the seller can ensure that the buyer pays at least 5 when he buys the object compared to when he does not buy it, respectively (the two requirements are a consequence of the fact that the buyer's and seller's payments are Groves payments, respectively). Since these two requirements are inconsistent, it follows that there does not exist any ex-post renegotiation-proof mechanism for this mechanism design problem.

Finally, we want to emphasize that the "Full Support" assumption is necessary for Proposition 2. In environments where it is not satisfied, the requirements of ex-post renegotiation-proofness are weaker, and thus there may exist ex-post renegotiation-proof mechanisms that are not budget balanced Groves mechanisms.

Example 3. Suppose that there are two players, a buyer and a seller. The seller owns an object that the buyer may want to buy. There are two states of the world, L and H. In state L the buyer's valuation for the object is 2 and the seller's reservation value is 1. In state H the buyer's valuation for the object is 6 and the seller's reservation value is 5.

It is straightforward to show that no budget balanced Groves mechanism exist in this environment. Nevertheless, there exist many ex-post renegotiation-proof mechanisms. For example, a mechanism that prescribes trade with probability 1 at a constant price that is independent of the players' messages is ex-post renegotiation-proof.

3.2. Interim renegotiation-proofness Under Complete Information

Ex-post renegotiation takes place after the mechanism has been played. Interim renegotiation takes place before the mechanism is to be played. In a complete information environment, the players do not learn anything about the state of the world from the play of the mechanism. It therefore follows that any equilibrium that the players would want to renegotiate in the interim stage they would also want to renegotiate ex-post. Thus any mechanism that is ex-post renegotiation-proof is also interim renegotiation-proof.[15,16]

4. Renegotiation-Proofness Under Incomplete Information

4.1. Ex-Post Renegotiation-Proofness Under Incomplete Information

Consider an equilibrium σ of a mechanism $\langle S, m\rangle$. Let $\psi : A \times \mathbb{R}^n \to A \times \mathbb{R}^n$ denote an alternative outcome generating function from the set of possible outcomes into itself that for every outcome (a, t) that may be obtained under the mechanism $\langle S, m\rangle$ specifies an alternative outcome $\psi(a, t)$. A mapping ψ is feasible if it maps outcomes into feasible outcomes.

Suppose that the process of renegotiation assumes the following form. After an outcome (a, t) is produced by an equilibrium σ of a mechanism $\langle S, m\rangle$ and is communicated to the players, a different feasible outcome $\psi(a, t)$ is proposed to the players. The players vote simultaneously on whether to accept the alternative outcome $\psi(a, t)$. If all the players vote

[15] Segal and Whinston (2002) made the same observation with respect to their notions of interim and ex-post renegotiation proofness.

[16] A mechanism may be interim renegotiation-proof but not ex-post renegotiation proof. Consider the environment described in Example 1 above where the buyer can have a value of 1 or 5, and the seller has a reservation value of 2. Consider the following mechanism: the buyer announces his value, if he says "1" then there is no trade and no payment, and if he says "5" then there is trade at a price of 3. As explained above, this mechanism is not ex-post renegotiation-proof. However, this mechanism is interim renegotiation-proof. If the buyer's value is 5, then by rejecting any alternative mechanism the seller can guarantee himself a payoff of 1 and the buyer can guarantee himself a payoff of 2. Any alternative mechanism would just redistribute the surplus of 3 between the buyer and seller, and would therefore necessarily be blocked by either the buyer or seller. The same argument applies in the case when the buyer's value is 1.

unanimously in favor of the alternative outcome $\psi(a,t)$, then it is implemented instead of the originally proposed outcome (a,t). Otherwise, the outcome (a,t) is implemented.

Under complete information or when players have private values, each player can easily tell which of any two given outcomes he prefers. But when there is incomplete information and players have interdependent valuations, whether or not a player prefers one outcome to another may depend on what types of the other players vote in favor of the alternative outcome. Furthermore, when the players observe an outcome that is consistent with play of the equilibrium σ it is reasonable to assume that they will update their beliefs about the types of the other players in a way that is consistent with σ (except, of course, for a player who deviated from σ who believes that other players played according to σ but knows he played differently); if, on the other hand, the players observe an outcome that is inconsistent with play of the equilibrium σ, then it is reasonable to assume that they will update their beliefs about the types of the other players taking into account that one of them deviated and played a different strategy.[17] These considerations lead to the following definition.

Let $P_{\sigma}(a,t)$ denote the probability distribution over players' types conditional on having produced the outcome (a,t) when players employ the equilibrium strategies σ, and let $P_{\sigma'_i,\sigma_{-i}}(a,t)$ denote the probability distribution over players' types conditional on having produced the outcome (a,t) when player i employs the strategy σ'_i and all the other players employ the equilibrium strategies σ_{-i}.

Definition. An alternative (a,t) that is produced under an equilibrium σ of a mechanism $\langle S,m\rangle$ when one of the players i may have possibly played a different strategy σ'_i is said to be *renegotiated away with a positive probability* if either one of the the following conditions is satisfied:

1. If the players have all played the equilibrium strategies σ, then (a,t) is *renegotiated away with a positive probability* if there exists a set of types $T = T_1 \times \cdots \times T_n$ that has a positive P_{σ} probability such that:

    1. All the types in T prefer the alternative outcome $\psi(a,t)$ to the outcome (a,t) conditional on the event T and for at least one type in T this preference is strict, where the beliefs of all the players are given by $P_{\sigma}(a,t)$,

    2. All the types outside the set T prefer the outcome (a,t) to the alternative outcome $\psi(a,t)$ conditional on the event T and their own type, where the beliefs of all the players are given by $P_{\sigma}(a,t)$.

[17] Note that we do not require that the beliefs of the different types be consistent with each other. That is, two types of two different players may have different beliefs about what produced the outcome (a,t) when the latter is inconsistent with the equilibrium σ.

2. If player i has played a strategy $\sigma_i' \neq \sigma_i$, all the other players have played the equilibrium strategies σ_{-i}, and the outcome (a,t) is consistent with play of σ, then (a,t) is *renegotiated away with a positive probability* if there exists a set of types $T = T_1 \times \cdots \times T_n$ that has a positive $P_{\sigma_i',\sigma_{-i}}$ probability such that:

    1. All the types in T prefer the alternative outcome $\psi(a,t)$ to the outcome (a,t) conditional on the event T and for at least one type in T this preference is strict, where the beliefs of all the players other than i are given by $P_\sigma(a,t)$ and player i's beliefs are given by $P_{\sigma_i',\sigma_{-i}}(a,t)$,
    2. All the types outside the set T prefer the outcome (a,t) to the alternative outcome $\psi(a,t)$ conditional on the event T and their own type, where, again, the beliefs of all the players other than i are given by $P_\sigma(a,t)$ and player i's beliefs are given by $P_{\sigma_i',\sigma_{-i}}(a,t)$.

3. If player i has played a strategy $\sigma_i' \neq \sigma_i$, all the other players have played the equilibrium strategies σ_{-i}, and the outcome (a,t) is inconsistent with play of σ, then (a,t) is *renegotiated away with a positive probability* if there exists a set of types $T = T_1 \times \cdots \times T_n$ that has a positive $P_{\sigma_i',\sigma_{-i}}$ probability such that:

    1. All the types in T prefer the alternative outcome $\psi(a,t)$ to the outcome (a,t) conditional on the event T and for at least one type in T this preference is strict, where the beliefs of all the players other than i can be any arbitrary belief that is consistent with observation of the outcome (a,t) and player i's beliefs are given by $P_{\sigma_i',\sigma_{-i}}(a,t)$,
    2. All the types outside the set T prefer the outcome (a,t) to the alternative outcome $\psi(a,t)$ conditional on the event T and their own type, where, again, the beliefs of all the players other than i can be any arbitrary belief that is consistent with observation of the outcome (a,t) and player i's beliefs are given by $P_{\sigma_i',\sigma_{-i}}(a,t)$.

Remark. If players have private values, then their beliefs about the other players are irrelevant for the purpose of comparing the outcome that was obtained under the mechanism (a,t) and the alternative outcome $\psi(a,t)$. In this case, the definition of "renegotiated away with a positive probability" can be much simplified in that it is enough that there exists a profile of types that all prefer the alternative $\psi(a,t)$ to (a,t) in order to ensure that (a,t) would be renegotiated away with a positive probability. This case is analyzed in Section 4.1.1 below.

Definition. An equilibrium σ of a mechanism $\langle S, m \rangle$ is ex-post renegotiation-proof relative to an alternative outcome generating function ψ if none of the outcomes that can be obtained under the mechanism $\langle S, m \rangle$ when some player i adopts a strategy σ_i' while all the other players follow the strategies σ_{-i} can be renegotiated away with a positive probability in a way that benefits player i at the interim stage when i considers how to play the mechanism.

Remark. As in the case of renegotiation under complete information, there are two ways in which an equilibrium σ of a mechanism $\langle S, m \rangle$ can be undermined. First, following the equilibrium play in the mechanism the players may renegotiate away from the mechanism's recommended decision in favor of some alternative decision, and second, the players may have an incentive to deviate from their equilibrium strategies under the mechanism in anticipation of future renegotiation, and then renegotiate as anticipated. The definition captures both of these possibilities.

Definition. An equilibrium σ of a mechanism $\langle S, m \rangle$ is said to be ex-post renegotiation-proof if it is ex-post renegotiation-proof against every feasible ψ.

The definition of ex-post renegotiation-proofness that was given above is quite strong, since it requires a mechanism to be robust against the possibility of switching away to any feasible alternative. Nevertheless, it might be argued that it is not nearly strong enough because it does not allow the alternative proposals that are generated by ψ to depend on the private information of the players beyond what is revealed by the outcome that was produced by the mechanism. Indeed, in realistic settings renegotiation proposals result from some communication process during which the players may choose to reveal some additional private information. To capture this feature we introduce a stronger notion of renegotiation-proofness, which we call "oracle renegotiation-proofness."

Let $\widehat{\psi} : \Theta \times A \times \mathbb{R}^n \to A \times \mathbb{R}^n$ denote an alternative outcome generating function that for every profile of players' types θ and every outcome (a, t) that may be obtained under the mechanism $\langle S, m \rangle$ specifies an alternative outcome $\psi(\theta, (a, t))$. A mapping $\widehat{\psi}$ is feasible if it maps profiles of types and outcomes into feasible outcomes.

Definition. An equilibrium σ of a mechanism $\langle S, m \rangle$ is ex-post oracle renegotiation-proof relative to a mapping $\widehat{\psi}$ if none of the outcomes that can be obtained under the mechanism $\langle S, m \rangle$ when some player i adopts a strategy σ_i' while all the other players follow the strategies σ_{-i} can be renegotiated away with a positive probability in a way that benefits player i.

The notion of "renegotiated away with a positive probability" is defined as above, with obvious modifications. Namely, the players may learn about other players' types from the proposed alternative $\psi(\theta, (a, t))$.

Definition. An equilibrium σ of a mechanism $\langle S, m\rangle$ is said to be ex-post oracle renegotiation-proof if it is ex-post renegotiation-proof against every feasible mapping $\widehat{\psi}$.

The definition of ex-post oracle renegotiation envisions an "oracle" that given the mechanism's decision and the players' types, recommends an alternative decision that the players are likely to prefer to the mechanism's original recommendation. The players treat the oracle's recommendation as exogenous.

As mentioned above, the oracle device is meant to capture the possibility that the alternative proposals may depend on the private information beyond what is revealed by the outcome that is produced by the mechanism. We conjecture that it is possible to show (at least for the case of private values) that if an equilibrium of a mechanism is ex-post oracle renegotiation-proof, then it is also robust against renegotiation in any model with an explicit renegotiation protocol, according to which the players communicate with each other when deciding on an alternative proposal. We postpone further investigation of this issue to future research.

Another justification for the oracle device is that in some realistic settings the state of the world may become commonly known at the ex-post stage. Thus to ensure the renegotiation-proofness of the equilibrium of a mechanism ex-post oracle renegotiation-proofness is required.

The difference between ex-post renegotiation-proofness and ex-post oracle renegotiation-proofness is illustrated in the following example that describes a mechanism that is ex-post renegotiation-proof, but not ex-post oracle renegotiation-proof.

Example 4. There are two players, a buyer and a seller. The buyer is equally likely to value an object at either 0 or 3. The seller's reservation value is equally likely to be 1 or 2. The buyer's valuation and the seller's reservation value are stochastically independent. The buyer is privately informed about his valuation and the seller is privately informed about his reservation value. The set of decisions is given by $A = \{$"no trade," "trade at price 1," "trade at price 2"$\}$. Consider the following mechanism: the buyer announces his value. If he announces the value 0, then there is no trade; if he announces the value 3, then there is trade at the price 2. Observe that truth-telling is a dominant strategy for the buyer under this mechanism.

This mechanism is ex-post renegotiation-proof. The equilibrium payoff of the buyer whose valuation is 3 is 1. The payoff of a buyer with valuation 3 from announcing that his type is zero and then renegotiating to trade at the price 1 is $\frac{1}{2} \cdot 2 + \frac{1}{2} \cdot 0 = 1$ because the seller whose reservation value is 2 would object to renegotiation. However, the mechanism is not ex-post oracle renegotiation-proof because the expected payoff to the buyer whose valuation is 3 if he announces that his valuation is zero and then renegotiates to trade at the price 1 when the seller's reservation value is 1 and to trade at the price 2 when the seller's reservation value is 2 is $\frac{1}{2} \cdot 2 + \frac{1}{2} \cdot 1 = \frac{3}{2} > 1$.

4.1.1. The Case of Independent Private Values

The main difficulty in the analysis of the process of ex-post renegotiation is due to the fact that at the voting stage the players compare their payoff from the alternative outcome $\psi(a,t)$ with their payoff from the original outcome (a,t) *conditional on the other players voting in favor of the alternative.* This analysis becomes much simpler in the case of independent private values because the additional information revealed by the other players' voting behavior is payoff irrelevant.

The fact that an outcome that is not ex-post efficient can be renegotiated to one that is in such a way that strictly benefits all the players implies that,

Lemma 2. *In an incomplete information mechanism design environment with independent private values, an ex-post renegotiation-proof Bayesian-Nash equilibrium is ex-post efficient.*

The lemma is straightforward if we use the notion of ex-post oracle renegotiation-proofness. The point of the lemma is that it is enough to require ex-post renegotiation-proofness.

The next example, which is the incomplete information version of Example 1, demonstrates that the converse of the Lemma does not hold. Namely, an ex-post efficient mechanism may fail to be ex-post renegotiation-proof.

Example 1'. There are two players, a buyer and a seller. The seller owns an object that the buyer may want to buy. The buyer is equally likely to value this object at either 1 or 5. The seller's reservation value for the object is 2. The state of the world is thus determined by the buyer's valuation for the object. The set of social alternatives consists of three alternatives: "no trade," "trade at the price 3," and "trade at the price 4."

Consider the following mechanism: the buyer announces whether he wants to trade or not. If he announces he wants to trade, then the buyer and seller trade at the price 4; otherwise, there is no trade. Observe that the Bayesian game that is induced by this mechanism has a trivial unique Bayesian-Nash equilibrium in dominant strategies. If the buyer's valuation for the object is 1, then the buyer declines to trade. If the buyer's valuation for the object is 5, then in equilibrium the buyer agrees to trade and the object is traded at the price 4.

However, despite the fact that the Bayesian-Nash equilibrium is both ex-post efficient and in dominant strategies, it is not ex-post renegotiation-proof according to our definition. To see this, suppose that in the event of no trade, the buyer and seller may renegotiate the outcome to trading at the price of 3. A buyer who values the object at 5 and who anticipates such a renegotiation possibility might announce that he declines to trade hoping to renegotiate the outcome to trade at a price that is better for him. Since such renegotiation would also make the seller strictly better off compared to no trade, the seller may well agree to renegotiate the outcome. Thus, the Bayesian-Nash equilibrium outcome in which the object is traded at the price 4 may be renegotiated away.

The next example, which is the incomplete information version of Example 2, shows that ex-post renegotiation-proof mechanisms may fail to exist also in incomplete information environments.

Example 2'. There are two players, a buyer and a seller. The seller owns an object that the buyer may want to buy. The buyer is equally likely to value the object at either 1 or 5. The seller's reservation value for the object is equally likely to be either 2 or 6. The state of the world is thus determined both by the buyer's valuation for the object and by the seller's reservation value. The set of social alternatives consists of a continuum of alternatives: "no trade," and "trade at the price p with probability q," where $p \in (-\infty, \infty)$ and $q \in [0, 1]$.

The proof of this is a little involved, but it can be shown, in a manner that is similar to the type of argument used in Example 1' above, that the possibility of ex-post renegotiation implies that the buyer can ensure that he does not pay more than 2 when he buys the object, and the seller can ensure that the buyer pays at least 5 when he buys the object, respectively. Since these two claims are inconsistent, it follows that there does not exist any ex-post renegotiation-proof mechanism for this environment.

The next proposition provides a characterization of the set of environments that admit the existence of an ex-post oracle renegotiation-proof mechanism under the assumption of independent private values. The characterization is in terms of mechanisms that are "Groves in expectation."

Definition. A direct revelation mechanism $\langle a, t \rangle$ is said to be *Groves in expectation* if a is an ex-post efficient decision rule and for every type $\theta_i \in \Theta_i$ of every player $i \in N$,

$$E_{\theta_{-i}}\left[t_i\left(\theta_i, \theta_{-i}\right)\right] = E_{\theta_{-i}}\left[\sum_{j \neq i} v_j\left(a\left(\theta_i, \theta_{-i}\right), \theta\right)\right] + H_i$$

for some constant $H_i \in \mathbb{R}$.

Proposition 3. *Consider an incomplete information mechanism design environment with independent private values. In such a problem, a budget balanced mechanism is ex-post oracle renegotiation-proof if and only if it is Groves in expectation.*

Observe that in a mechanism that is Groves in expectation the expected payment to each player i as a function of his type is equal to the expected payment to the player as a function of his type under some Groves mechanism.[18]

The intuition for the proof of Proposition 3 is the following. The way we defined the process of renegotiation implies that a player can misrepresent his type when a mechanism is played and then renegotiate to an ex-post efficient outcome and capture the difference in social surplus. This implies that the possibility of ex-post renegotiation allows any player to capture the surplus or externality that he generates up to a constant. It therefore follows that a mechanism in which each player already gets the surplus or externality he generates is ex-post renegotiation-proof, and conversely, any mechanism that is ex-post renegotiation-proof must be a mechanism in which each player obtains a payoff that is equal to the surplus he generates up to a constant.

Hence, Proposition 3 is a consequence of the fact that the class of mechanisms in which players' payoff are equal to the externality they generate is the class of mechanisms that are Groves in expectation. It is the class of mechanisms that are Groves in expectation rather than Groves because the players contemplate how best to misrepresent their types at the interim rather than at the ex-post stage, and this implies that the interim expected transfer to each player has to be equal to the interim expected externality, rather than the ex-post transfer equal to the ex-post externality.

Remark. Williams (1999) showed that if the sets of players' types are connected open subsets of $\mathbb{R}^n$ and the players' interim expected valuations are continuously differentiable in their types then any mechanism that is both ex-post efficient and Bayesian incentive compatible is payoff equivalent to a Groves mechanism at the interim stage. When this equivalence holds, Proposition 3 implies that an ex-post oracle renegotiation-proof mechanism exists if and only if there exists a feasible, ex-post efficient, Bayesian incentive compatible, direct revelation mechanism. The fact that for several economically important mechanism design problems, such as bilateral trade (see, e.g., Myerson and Satterthwaite, 1983), regulation (see, e.g., Baron and Myerson, 1982), and litigation and settlement (see, e.g., Spier 1994 and Klement and Neeman, 2005), no ex-post efficient mechanisms exists implies that no ex-post oracle renegotiation-proof mechanisms exist in such mechanism design problems either.

[18] Thus, the class of mechanisms that are Groves in expectation includes the class of Groves mechanisms, AGV mechanisms (after Arrow, 1979, and d'Aspremont and Gerard-Varet, 1979), as well as other mechanisms.

4.1.2. The Case of Correlated Interdependent Players' Types

The case of interdependent values is considerably more complicated than the case of private values. The difference is that when players have private values, they do not need to know anything about other players' types in order to decide whether an alternative outcome (a', t') Pareto dominates the mechanism's decision (a, t). In contrast, when players have interdependent valuations, whether or not it is in a player's best interest to renegotiate the outcome may depend on another player's type. And since other players willingness to renegotiate the outcome depends on their types, players have to take into account what types of other players are likely to agree to renegotiate the outcome.

The next example illustrates some of the difficulty by showing that Lemmas 1 and 2 may not hold when players have interdependent valuations. Namely, in such a case a mechanism may be ex-post renegotiation-proof in spite of not being ex-post efficient.

Example 5. There are two players. Player 1 is equally likely to be of type a or type b, player 2 has no private information. There are two decisions $\{\alpha, \beta\}$. The payoffs of the two players (u_1, u_2) are given by the following table:

	type a	type b
decision α	$0, 0$	$0, 0$
decision β	$5, -5$	$1, 1$

A mechanism that always reaches the decision α is ex-post renegotiation-proof against the alternative decision β (the fact that player 1 has a dominant strategy to vote in favor of β implies that β is unattractive for player 2). Such a mechanism is not ex-post efficient in state b.

Nevertheless, when there are at least three players who have private or interdependent valuations and correlated types, then the technique of Crémer and McLean (1985, 1988), which exploits the correlation among the players' types to relax the players' incentive compatibility constraints, can be adapted to establish the existence of an ex-post oracle renegotiation-proof mechanism that implements any ex-post efficient decision rule. The idea is that in order to implement a given social choice rule, the mechanism designer needs to know the state of the world, or the players' true types. In order to induce player i to reveal his type truthfully, it is possible to "stochastically compare" his report to the report of player j while using player k as a budget-breaker. Because in such a scheme player i's report does not affect player j's payoff, this does not influence player j's incentive to report the truth. And it is possible to "rotate" the roles of players i, j, and k, so as to provide every player with a strong incentive to report the truth while maintaining budget balance. Once the players are induced to report their types truthfully, the fact that the decision rule is ex-post efficient prevents them from renegotiating the outcome.[19]

Proposition 4. *Consider an incomplete information mechanism design environment with $n \geq 3$ players. Suppose that the beliefs of every player i about all the other players are linearly independent. Let $a : \Theta \rightarrow A$ be an ex-post efficient decision rule, and let $t : \Theta \rightarrow \mathbb{R}^n$ be a budget balanced vector of transfer functions, then there exists an incentive compatible, budget balanced, and ex-post renegotiation-proof mechanism that implements (a, t).*

As shown by Neeman (2004) and Heifetz and Neeman (2006) the condition that players' beliefs about other players be linearly independent is satisfied generically in type spaces with a given finite number of types, but it fails generically when the collection of all finite type spaces is considered.[20] The question of what can be done when players' beliefs are not linearly independent and so the techniques of Crémer and McLean cannot be used remains open.

4.2. Interim Renegotiation-Proofness Under Incomplete Information

The process of interim renegotiation is modeled in a similar way to the process of ex-post renegotiation except that renegotiation of the mechanism takes place before the mechanism is played. In this case, the beliefs of the players about how an alternative mechanism will be played and about how the original mechanism will be played after the rejection of an alternative mechanism are important. We say that an equilibrium of a mechanism is interim renegotiation-proof if it is never renegotiated for whatever rational beliefs that the players might hold.

Suppose that the process of renegotiation at the interim stage, before the mechanism is played, assumes the following form. Fix a mechanism $\langle S, m \rangle$ and a Bayesian-Nash equilibrium of this mechanism $\sigma = (\sigma_1, ..., \sigma_n)$. Suppose that an alternative mechanism $\langle S', m' \rangle$ (that has at least one equilibrium for any subset of types that choose to play it) is exogenously proposed to the players. The players vote simultaneously whether to retain the original mechanism $\langle S, m \rangle$, or to replace $\langle S, m \rangle$ by the new mechanism $\langle S', m' \rangle$. If all the players vote in favor of the alternative mechanism $\langle S', m' \rangle$, then it is played instead of $\langle S, m \rangle$. Otherwise, the players continue to play the original mechanism $\langle S, m \rangle$ using possibly different strategies than σ that reflect what they have learned about other players' types from

[19] The penalty to player i if he misreports its type can be made sufficiently large to discourage misreporting because the efficiency gain from misrepresentation and renegotiation to an ex-post outcome can be made arbitrarily small relative to the penalty.

[20] Linear independence is a special case of what Heifetz and Neeman (2006) called the "belief determine preferences" or BDP property. Heifetz and Neeman established their result for private values environments, but the logic of their argument extends to environments with interdependent valuations as well.

the rejection of the alternative mechanism $\langle S', m' \rangle$. In either case, players are only informed about the outcome of the vote, not about the votes of individual players.

A pair of mechanisms $\langle S, m \rangle$ and $\langle S', m' \rangle$ thus defines an interim renegotiation game. Player i's strategy in this interim renegotiation game is given by (i) a voting strategy $\rho_i : \Theta_i \to [0,1]$ that denotes the probability that player i votes to reject $\langle S, m \rangle$ in favor of the alternative mechanism $\langle S', m' \rangle$ as a function of player i's true type θ_i; (ii) a strategy $\sigma_i : \Theta_i \to \Delta S_i$ used in the mechanism $\langle S, m \rangle$ if it is retained; (iii) a strategy $\sigma_i' : \Theta_i \to \Delta S_i'$ used in the mechanism $\langle S', m' \rangle$ if it replaces $\langle S, m \rangle$.

Definition. A profile of players' strategies $(\rho_i, \sigma_i, \sigma_i')_{i \in N}$ is a sequential equilibrium of the interim renegotiation game that is induced by the two mechanisms $\langle S, m \rangle$ and $\langle S', m' \rangle$ if

1. Every type's strategy is a best response to the other players' strategies;
2. Players update their beliefs about the other players' types using Bayes rule whenever possible, taking $(\rho_i, \sigma_i, \sigma_i')_{i \in N}$ into account.

Definition. An equilibrium σ of a mechanism $\langle S, m \rangle$ is said to be *interim renegotiation-proof* if there does not exist a mechanism $\langle S', m' \rangle$ and a sequential equilibrium of the interim renegotiation game that is induced by the two mechanisms $\langle S, m \rangle$ and $\langle S', m' \rangle$ in which (i) the players vote in favor of the alternative mechanism $\langle S', m' \rangle$ with a positive probability; and (ii) at least one of the types who votes in favor of the alternative mechanism $\langle S', m' \rangle$ with a positive probability strictly prefers $\langle S', m' \rangle$ to $\langle S, m \rangle$.

Remark. The renegotiation game described above is similar to the one described in Holmström and Myerson (1983). The main difference between the definition presented here and Holmström and Myerson's (1983) definition of "durability" is that Holmström and Myerson defined a mechanism to be "durable" if for every alternative mechanism there is a (non trivial) voting equilibrium in which this alternative mechanism is rejected. In contrast, we define a mechanism to be interim renegotiation-proof if every alternative mechanism is rejected *in every equilibrium* in which it is preferred by at least some players' types. As shown by the next example, which is due to Holmström and Myerson (1983), our definition of interim renegotiation-proofness is strictly stronger than their definition of durability.

Example 6 (Holmström and Myerson, 1983). Suppose that there are two players with independent and equally likely types $(1a, 1b; 2a, 2b)$. There are two social alternatives A and B. The players' payoffs are:

$$u_1(A, \theta) = u_2(A, \theta) = 2 \qquad \forall \theta \in \Theta$$

and

$$u_1(B,\theta) = u_2(B,\theta) = \begin{cases} 3 & \text{if} \quad \theta = (1a, 2a) \text{ or } \theta = (1b, 2b) \\ 0 & \text{if} \quad \theta = (1a, 2b) \text{ or } \theta = (1b, 2a) \end{cases}$$

The constant mechanism that selects the alternative A in every state of the world is durable because in any voting game with any alternative mechanism there is always an equilibrium rejection in which both players use uninformative voting and reporting strategies. For example, suppose that the following mechanism is suggested to the players as an alternative mechanism. The players report their types. If the types match, then alternative B is chosen; if they don't, then alternative A is chosen. This alternative mechanism has an equilibrium in which the players report their types truthfully that Pareto dominates the constant mechanism, which implies that the constant mechanism is not interim renegotiation-proof. But this alternative mechanism also has another equilibrium in which the players randomize on their type reports and where the expected payoff to each type is $\frac{7}{4}$. If the players believe that this is the equilibrium that will be played under the alternative mechanism rather than the Pareto efficient equilibrium then they would vote against the alternative mechanism.

The question of whether every mechanism design problem admits the existence of an interim renegotiation-proof mechanism is difficult and remains open at this stage. A partial answer to this question is given by the following proposition.

Proposition 5. *A budget balanced ex-post efficient equilibrium of a mechanism is interim renegotiation-proof. In particular, budget balanced Groves mechanisms are interim renegotiation-proof in private values environments.*

4.3. Renegotiation-Proofness Under Incomplete Information

Recall that a mechanism is said to be renegotiation-proof if it is both ex-post and interim renegotiation-proof. Our results imply that in independent private values environments any Groves mechanism gives rise to a dominant strategy equilibrium that is both ex-post and interim renegotiation-proof and hence also renegotiation-proof. In particular, in private values environments with sufficiently rich type spaces, an incomplete information mechanism design problem admits the existence of a renegotiation-proof mechanism if and only if it admits the existence of a budget balanced Groves mechanism.

Appendix

Proof of Proposition 1.

Fix an ex-post efficient decision rule a and a budget balanced vector of transfers $t : \Theta \rightarrow \mathbb{R}^n$. Consider a mechanism (α, τ) that requires each player to report the state of the world, and that determines the outcome as a function of the players' reports $\left(\widehat{\theta}_1, ..., \widehat{\theta}_n\right)$ as follows:

$$(\alpha, \tau_1, ..., \tau_n)\left(\widehat{\theta}_1, ..., \widehat{\theta}_n\right) = \begin{cases} (a(\theta), t_1(\theta), ..., t_n(\theta)) & \text{if } \widehat{\theta}_1 = \widehat{\theta}_2 = \theta \in \Theta \\ (a_0, -M, -M, 2M, 0, ..., 0) & \text{if } \widehat{\theta}_1 \neq \widehat{\theta}_2 \end{cases}$$

where $a_0 \in A$ is some fixed social alternative, and the constant M is chosen such that $M > 2n\left(\max_{i \in N, a \in A, \theta \in \Theta} |v_i(a, \theta)| + \max_{i \in N, \theta \in \Theta} |t_i(\theta)|\right)$. The (direct revelation) mechanism (α, τ) is incentive compatible, budget balanced, and ex-post renegotiation-proof, and it implements the decision rule and the vector of transfers (a, t). ■

Proof of Proposition 2.

<**IF**> Let $\langle a, t\rangle$ be a budget balanced Groves mechanism. We show that $\langle a, t\rangle$ is ex-post renegotiation-proof.

Suppose that $\langle a, t\rangle$ is not ex-post renegotiation-proof. We show that this leads to a contradiction. The fact that a is ex-post efficient implies that if the two players report their types truthfully, then they would not be able then to renegotiate the outcome. It therefore follows that there exists a state of the world $\theta = (\theta_1, \theta_2)$, a player $i \in \{1, 2\}$, and a type of player i, $\theta_i' \neq \theta_i$ such that when the state of the world is θ, player i, whose type is commonly known between the players to be θ_i, would benefit from reporting that his type is θ_i' and then renegotiating the outcome from $(a(\theta_i', \theta_j), t(\theta_i', \theta_j))$ to $\left(a(\theta_i, \theta_j), \widehat{t}(\theta_i, \theta_j)\right)$ where $\widehat{t}$ is some ex-post budget balanced transfer function (by renegotiating the outcome to the ex-post efficient outcome $a(\theta_i, \theta_j)$, θ_i is able to capture the greatest possible surplus for himself, and so would prefer that to any other outcome $a \in A$; the transfers $\widehat{t}$ facilitate this renegotiation).

A report of θ_i' that is followed by such renegotiation is beneficial for player i if

$$v_i(a(\theta_i, \theta_j), \theta_i) + \widehat{t}_i(\theta_i, \theta_j) > v_i(a(\theta_i, \theta_j), \theta_i) + t_i(\theta_i, \theta_j) \tag{1}$$

if and only if

$$\widehat{t}_i(\theta_i, \theta_j) > t_i(\theta_i, \theta_j). \tag{2}$$

Player j agrees to the proposed renegotiation if and only if the transfer $\widehat{t}$ is such that:

$$v_j(a(\theta_i, \theta_j), \theta_j) + \widehat{t}_j(\theta_i, \theta_j) \geq v_j(a(\theta_i', \theta_j), \theta_j) + t_j(\theta_i', \theta_j),$$

or

$$\widehat{t}_j(\theta_i, \theta_j) \geq v_j(a(\theta_i', \theta_j), \theta_j) - v_j(a(\theta_i, \theta_j), \theta_j) + t_j(\theta_i', \theta_j). \tag{3}$$

The fact that both t and $\widehat{t}$ are ex-post budget balanced implies that $t_j(\theta_i', \theta_j) = -t_i(\theta_i', \theta_j)$ and $\widehat{t}_j(\theta_i, \theta_j) = -\widehat{t}_i(\theta_i, \theta_j)$. Plugging these two equations into (3) implies:

$$\widehat{t}_i(\theta_i, \theta_j) \leq v_j(a(\theta_i, \theta_j), \theta_j) - v_j(a(\theta_i', \theta_j), \theta_j) + t_i(\theta_i', \theta_j) \tag{4}$$

The fact that $\langle a, t\rangle$ is a Groves mechanism implies that

$$t_i\left(\theta_i, \theta_j\right) = v_j\left(a\left(\theta_i, \theta_j\right), \theta_j\right) + h_i\left(\theta_j\right)$$

or

$$v_j\left(a\left(\theta_i, \theta_j\right), \theta_j\right) = t_i\left(\theta_i, \theta_j\right) - h_i\left(\theta_j\right)$$

and

$$t_i\left(\theta_i', \theta_j\right) = v_j\left(a\left(\theta_i', \theta_j\right), \theta_j\right) + h_i\left(\theta_j\right)$$

or

$$v_j\left(a\left(\theta_i', \theta_j\right), \theta_j\right) - t_i\left(\theta_i', \theta_j\right) = -h_i\left(\theta_j\right)$$

for some function $h_i : \Theta_j \to \mathbb{R}$. Plugging the two equations above into (4) it follows that:

$$\begin{aligned} \widehat{t}_i\left(\theta_i, \theta_j\right) &\leq \left[t_i\left(\theta_i, \theta_j\right) - h_i\left(\theta_j\right)\right] + h_i\left(\theta_j\right) \\ &= t_i\left(\theta_i, \theta_j\right). \end{aligned}$$

A contradiction to (2).

<**Only If**> Let m be a mechanism that is ex-post budget balanced and ex-post renegotiation-proof, and let $\langle a, t\rangle$ denote its associated incentive compatible direct revelation mechanism. We show that $\langle a, t\rangle$ is a budget balanced Groves mechanism.

For every $\theta_1 \in \Theta_1$ and $\theta_2 \in \Theta_2$ define

$$S\left(\theta_1, \theta_2\right) = \max_{a \in A} \left\{v_1\left(a, \theta_1\right) + v_2\left(a, \theta_2'\right)\right\}.$$

The fact that $\langle a, t\rangle$ is ex-post renegotiation-proof implies that $a\left(\theta, \theta\right)$ must be ex-post efficient for every $\theta \in \Theta$. That is, whenever the players agree on the state of the world, the mechanism must choose efficiently given the players' reports. It therefore follows that

$$S\left(\theta_1, \theta_2\right) = v_1\left(a\left(\theta, \theta\right), \theta_1\right) + v_2\left(a\left(\theta, \theta\right), \theta_2\right) \tag{5}$$

for every $\theta \in \Theta$. But when the players fail to agree, renegotiation-proofness imposes no such obvious restriction on the mechanism $\langle a, t\rangle$, and so the definition of S implies that

$$S\left(\theta_1, \theta_2'\right) \geq v_1\left(a\left(\theta, \theta'\right), \theta_1\right) + v_2\left(a\left(\theta, \theta'\right), \theta_2'\right) \tag{6}$$

for any pair of states of the world $\theta, \theta' \in \Theta$.

Suppose that it is commonly known between the players that the state of the world is $\theta = \left(\theta_1, \theta_2\right)$. Player 1 can report that the state of the world is $\theta' = \left(\theta_1', \theta_2'\right) \in \Theta_1 \times \Theta_2$ and then offer to renegotiate the outcome from $\left(a\left(\theta', \theta\right), t\left(\theta', \theta\right)\right)$ to $\left(a\left(\theta, \theta\right), \widehat{t}\left(\theta, \theta\right)\right)$ where $\widehat{t}$ is some ex-post budget balanced transfer function.

Player 2 would agree to this renegotiation if the transfer $\widehat{t}_2$ is such that:

$$v_2(a(\theta,\theta),\theta_2)+\widehat{t}_2(\theta,\theta)\geq v_2(a(\theta',\theta),\theta_j)+t_2(\theta',\theta),$$

or

$$\widehat{t}_2(\theta,\theta)\geq v_2(a(\theta',\theta),\theta_2)-v_2(a(\theta,\theta),\theta_2)+t_2(\theta',\theta).$$

The payoff player 1 can therefore get through renegotiation is equal to

$$v_1(a(\theta,\theta),\theta_1)-\widehat{t}_2(\theta,\theta)=v_1(a(\theta,\theta),\theta_1)-v_2(a(\theta',\theta),\theta_2)+v_2(a(\theta,\theta),\theta_2)-t_2(\theta',\theta).$$

The fact that $\langle a,t\rangle$ is ex-post renegotiation-proof implies that when player 1 contemplates whether to misreport and then renegotiate, he concludes that this cannot increase his expected payoff, or:

$$v_1(a(\theta,\theta),\theta_1)+t_1(\theta,\theta)\geq v_1(a(\theta,\theta),\theta_1)-v(a(\theta',\theta),\theta_2)+v_2(a(\theta,\theta),\theta_2)-t_2(\theta',\theta)$$

or $\{t_1(\theta',\theta)+t_2(\theta',\theta)\leq 0\}$

$$t_1(\theta,\theta)+t_2(\theta',\theta)\geq -v_2(a(\theta',\theta),\theta_2)+v_2(a(\theta,\theta),\theta_2) \tag{7}$$

for every $\theta'\neq\theta$. By repeating the argument for player 2, it follows that

$$t_2(\theta,\theta)+t_1(\theta,\theta')\geq -v_1(a(\theta,\theta'),\theta_1)+v_1(a(\theta,\theta),\theta_1) \tag{8}$$

for every $\theta'\neq\theta$.

Adding (7) and (8) together and using budget balance implies that:

$$t_2(\theta',\theta)+t_1(\theta,\theta')\geq -v_2(a(\theta',\theta),\theta_2)+v_2(a(\theta,\theta),\theta_2)-v_1(a(\theta,\theta'),\theta_1)+v_1(a(\theta,\theta),\theta_1) \tag{9}$$

and by switching θ and θ' also:

$$t_2(\theta,\theta')+t_1(\theta',\theta)\geq -v_2(a(\theta,\theta'),\theta_2')+v_2(a(\theta',\theta'),\theta_2')-v_1(a(\theta',\theta),\theta_1')+v_1(a(\theta',\theta'),\theta_1') \tag{10}$$

Adding (9) and (10) together, using $t_1(\theta',\theta)+t_2(\theta',\theta)\leq 0$ and $t_1(\theta,\theta')+t_2(\theta,\theta')\leq 0$, and rearranging, implies that:

$$\begin{aligned}&v_1(a(\theta,\theta'),\theta_1)+v_2(a(\theta,\theta'),\theta_2')+v_1(a(\theta',\theta),\theta_1')+v_2(a(\theta',\theta),\theta_2)\\&\qquad\geq v_2(a(\theta,\theta),\theta_2)+v_1(a(\theta,\theta),\theta_1)+v_2(a(\theta',\theta'),\theta_2')+v_1(a(\theta',\theta'),\theta_1')\end{aligned}$$

Thus, (6) implies that a necessary condition for ex-post renegotiation proofness is that:

$$S(\theta_1,\theta_2')+S(\theta_1',\theta_2)\geq S(\theta_1,\theta_2)+S(\theta_1',\theta_2').$$

Repeating the previous argument for the pair of states (θ_1, θ_2') and (θ_1', θ_2) instead of the pair (θ_1, θ_2) and (θ_1', θ_2') implies:

$$S(\theta_1', \theta_2') + S(\theta_1, \theta_2) \geq S(\theta_1, \theta_2') + S(\theta_1', \theta_2)$$

from which it follows that a necessary condition for ex-post renegotiation proofness is that:

$$S(\theta_1', \theta_2') + S(\theta_1, \theta_2) = S(\theta_1, \theta_2') + S(\theta_1', \theta_2). \tag{11}$$

Hence, all the possible inequalities in (6) must hold as equalities. For the decision rule $a : \Theta^N \to A$ this implies that:

$$\begin{aligned}
a((\theta_1, \theta_2), (\theta_1', \theta_2')) &\in \underset{a \in A}{\operatorname{argmax}} \{v_1(a, \theta_1) + v_2(a, \theta_2')\} \\
a((\theta_1', \theta_2'), (\theta_1, \theta_2)) &\in \underset{a \in A}{\operatorname{argmax}} \{v_1(a, \theta_1') + v_2(a, \theta_2)\} \\
a((\theta_1', \theta_2), (\theta_1, \theta_2')) &\in \underset{a \in A}{\operatorname{argmax}} \{v_1(a, \theta_1') + v_2(a, \theta_2')\} \\
a((\theta_1, \theta_2'), (\theta_1', \theta_2)) &\in \underset{a \in A}{\operatorname{argmax}} \{v_1(a, \theta_1) + v_2(a, \theta_2)\}
\end{aligned}$$

Our assumption that there is a unique decision that maximizes social welfare for any state of the world therefore implies that in a mechanism that satisfies ex-post renegotiation-proofness, players' reports about the other player's type are ignored by the mechanism, or that for any $\theta_1, \theta_1' \in \Theta_1$ and for any $\theta_2, \theta_2' \in \Theta_2$,

$$a((\theta_1, \theta_2'), (\theta_1', \theta_2)) = a((\theta_1, \theta_2), (\theta_1, \theta_2)). \tag{12}$$

Furthermore, the fact that (11) holds as an equality implies that all the inequalities that were used to generate it hold as equalities as well. In particular, $t_1(\theta', \theta) + t_2(\theta', \theta) \leq 0$ and $t_1(\theta, \theta') + t_2(\theta, \theta') \leq 0$, as well as (7) and (8) must hold as equalities, which implies

$$\begin{aligned}
& t_1((\theta_1, \theta_2), (\theta_1, \theta_2)) - t_1((\theta_1', \theta_2'), (\theta_1, \theta_2)) \qquad (13) \\
= \; & -v_2(a((\theta_1', \theta_2'), (\theta_1, \theta_2)), \theta_2) + v_2(a((\theta_1, \theta_2), (\theta_1, \theta_2)), \theta_2) \\
= \; & -v_2(a((\theta_1', \cdot), (\cdot, \theta_2)), \theta_2) + v_2(a((\theta_1, \cdot), (\cdot, \theta_2)), \theta_2)
\end{aligned}$$

for every $\theta' \neq \theta$, and

$$\begin{aligned}
& t_2((\theta_1, \theta_2), (\theta_1, \theta_2)) - t_2((\theta_1, \theta_2), (\theta_1', \theta_2')) \qquad (14) \\
= \; & -v_1(a((\theta_1, \theta_2), (\theta_1', \theta_2')), \theta_1) + v_1(a((\theta_1, \theta_2), (\theta_1, \theta_2)), \theta_1) \\
= \; & -v_1(a((\theta_1, \cdot), (\cdot, \theta_2')), \theta_1) + v_1(a((\theta_1, \cdot), (\cdot, \theta_2)), \theta_1)
\end{aligned}$$

for every $\theta' \neq \theta$, where in both cases, the second equality follows from (12). Hence, it follows that the reports of the players about the other player's type do not affect their transfer payments under the mechanism either, or that

$$t_i((\theta_1, \theta_2'), (\theta_1', \theta_2)) = t_i((\theta_1, \theta_2), (\theta_1, \theta_2)). \tag{15}$$

for $i \in \{1,2\}$, and for any $\theta_1, \theta_1' \in \Theta_1$ and any $\theta_2, \theta_2' \in \Theta_2$. Thus, (13) and (14) imply that

$$t_1((\theta_1,\cdot),(\cdot,\theta_2)) - t_1((\theta_1',\cdot),(\cdot,\theta_2)) = -v_2(a((\theta_1',\cdot),(\cdot,\theta_2)),\theta_2) + v_2(a((\theta_1,\cdot),(\cdot,\theta_2)),\theta_2)$$

and

$$t_2((\theta_1,\cdot),(\cdot,\theta_2)) - t_2((\theta_1,\cdot),(\cdot,\theta_2')) = -v_1(a((\theta_1,\cdot),(\cdot,\theta_2')),\theta_1) + v_1(a((\theta_1,\cdot),(\cdot,\theta_2)),\theta_1).$$

Another way to write the last two equations is the following:

$$\begin{aligned} t_1((\theta_1,\cdot),(\cdot,\theta_2)) &= v_2(a((\theta_1,\cdot),(\cdot,\theta_2)),\theta_2) - v_2(a((\theta_1',\cdot),(\cdot,\theta_2)),\theta_2) + t_1((\theta_1',\cdot),(\cdot,\theta_2)) \\ &= v_2(a((\theta_1,\cdot),(\cdot,\theta_2)),\theta_2) + h_1(\theta_2) \end{aligned}$$

and

$$\begin{aligned} t_2((\theta_1,\cdot),(\cdot,\theta_2)) &= v_1(a((\theta_1,\cdot),(\cdot,\theta_2)),\theta_1) - v_1(a((\theta_1,\cdot),(\cdot,\theta_2')),\theta_1) + t_2((\theta_1,\cdot),(\cdot,\theta_2')) \\ &= v_1(a((\theta_1,\cdot),(\cdot,\theta_2)),\theta_1) + h_2(\theta_1), \end{aligned}$$

which implies that the transfer payments are Groves transfer payments. ■

Example 1 (continued).

We show that the buyer is the one who determines if the trade takes place, and pays exactly 2 more than he pays if there is no trade.

By the revelation principle (for games with complete information), any mechanism can be described as a mapping from the announcements of the players into probabilities of trade q and the buyer's payments p:

B\S	1	5
1	$q_{1,1}, p_{1,1}$	$q_{1,5}, p_{1,5}$
5	$q_{5,1}, p_{5,1}$	$q_{5,5}, p_{5,5}$

Renegotiation-proof constraints require that each player prefers to report the state honestly, rather than misreport and consequently renegotiate to the efficient allocation and capture the efficient surplus ($S(1)$ or $S(5)$) less the utility of the other player prescribed by the mechanism.

$$\begin{aligned} B1 &: q_{1,1} - p_{1,1} \geq S(1) - (p_{5,1} - 2q_{5,1}) \\ B5 &: 5q_{5,5} - p_{5,5} \geq S(5) - (p_{1,5} - 2q_{1,5}) \\ S1 &: p_{1,1} - 2q_{1,1} \geq S(1) - (q_{1,5} - p_{1,5}) \\ S5 &: p_{5,5} - 2q_{5,5} \geq S(5) - (5q_{1,5} - p_{1,5}) \end{aligned}$$

Notice that the efficient surpluses are

$$\begin{aligned} S(1) &= \max_{q\in[0,1]} (1-2)\, q = 0 \\ S(5) &= \max_{q\in[0,1]} (5-2)\, q = 3 \end{aligned}$$

Also notice that by Lemma 1 the allocations must be ex-post efficient:

$$\begin{aligned} q_{1,1} &= 0 \\ q_{5,5} &= 1 \end{aligned}$$

Hence the renegotiation-proof constraints become

$$\begin{aligned} B1 &: -p_{1,1} \geq -p_{5,1} + 2q_{5,1} \\ B5 &: 5 - p_{5,5} \geq 3 - p_{1,5} + 2q_{1,5} \\ S1 &: p_{1,1} \geq -q_{1,5} + p_{1,5} \\ S5 &: p_{5,5} - 2 \geq 3 - 5q_{5,1} + p_{5,1} \end{aligned}$$

Adding up all four constraints we get

$$3 \geq 6 - 3q_{5,1} + q_{1,5}$$

or

$$3q_{5,1} - q_{1,5} \geq 3.$$

Since $0 \leq q_{1,5}, q_{5,1} \leq 1$, the only possibility is to have $q_{1,5} = 0$ and $q_{5,1} = 1$. Moreover, since the resulting equality actually holds as equality, this implies that all renegotiation-proof constraints also must hold as equalities. Rearranging we obtain

$$\begin{aligned} B1 &: p_{5,1} - p_{1,1} = 2 \\ B5 &: p_{5,5} - p_{1,5} = 2 \\ S1 &: p_{1,1} = p_{1,5} \\ S5 &: p_{5,5} = p_{5,1} \end{aligned}$$

Example 2.

We show that no renegotiation-proof mechanism exist in this environment.

By the revelation principle, any mechanism can be described as a mapping from the announcements of the players into probabilities of trade q and the buyer's payments p:

B\S	$(1,2)$	$(5,2)$	$(1,6)$	$(5,6)$
$(1,2)$	$q_{(1,2),(1,2)}, p_{(1,2),(1,2)}$	$q_{(1,2),(5,2)}, p_{(1,2),(5,2)}$	...	...
$(5,2)$	$q_{(5,2),(1,2)}, p_{(5,2),(1,2)}$	$q_{(5,2),(5,2)}, p_{(5,2),(5,2)}$	...	...
$(1,6)$	...	...	...	...
$(5,6)$	...	...	...	...

Replication of the argument from Example 1 yields:

$$p_{(5,2),(5,2)} = p_{(1,2),(1,2)} + 2$$

Repeating the argument from Example 1 for the states $(5,2)$ and $(5,6)$ yields:

$$p_{(5,2),(5,2)} = p_{(5,6),(5,6)} + 5$$

Repeating the argument from Example 1 for the states $(1,2)$ and $(1,6)$ yields:

$$p_{(1,2),(1,2)} = p_{(1,6),(1,6)}$$

Finally, repeating the argument from Example 1 for the states $(1,6)$ and $(5,6)$ yields:

$$p_{(5,6),(5,6)} = p_{(1,6),(1,6)}$$

These equalities are incompatible. Hence no renegotiation-proof mechanism exist for this environment.

Proof of Lemma 2.

Suppose that σ is an ex-post renegotiation-proof equilibrium of the mechanism $\langle S, m \rangle$. Suppose that σ is not ex-post efficient. It follows that there exists a decision $(a, t) \in A \times \mathbb{R}^n$, a profile of types $\theta = (\theta_1, ..., \theta_n)$ such that $m(\sigma(\theta)) = (a, t)$, and a feasible alternative decision $(a', t') \in A \times \mathbb{R}^n$ such that

$$v_i(a', \theta_i) + t'_i \geq v_i(a, \theta_i) + t_i \tag{16}$$

for every type θ_i, $i \in N$, with at least one strict inequality. We show that the ex-post renegotiation subgame has a sequential equilibrium in which the players all vote in favor of the alternative decision (a', t') with a positive probability. Inequality (3) implies that there exists an equilibrium in which the types θ_i, $i \in N$, all vote for the alternative (a', t') with a positive probability, and at least one of these types is made strictly better off by this vote. (Observe that since players are assumed to have private values, if other types also vote in favor of the alternative (a', t') in this equilibrium, this does not affect the payoff of the types θ_i, $i \in N$ conditional on switching to (a', t') and so does not disturb the equilibrium.) ■

Proof of Proposition 3.

<**IF**> Let $\langle a, t \rangle$ be a budget balanced Groves in expectation mechanism. We show that $\langle a, t \rangle$ is ex-post renegotiation-proof.

Suppose that $\langle a, t \rangle$ is not ex-post renegotiation-proof. We show that this leads to a contradiction. The fact that a is ex-post efficient implies that if all the players report their types truthfully, then they would not want to renegotiate the outcome. It therefore follows that there exists a player $i \in N$ and two types $\theta_i, \theta_i' \in \Theta_i$ such that type θ_i would benefit from reporting that his type is θ_i' and then, for every $\theta_{-i} \in \Theta_{-i}$, renegotiating the outcome from $(a(\theta_i', \theta_{-i}), t(\theta_i', \theta_{-i}))$ to $\left(a(\theta_i, \theta_{-i}), \widehat{t}(\theta_i, \theta_{-i})\right)$ where $\widehat{t}$ is some ex-post budget balanced transfer function (by renegotiating the outcome to the ex-post efficient outcome $a(\theta_i, \theta_{-i})$, θ_i is able to capture the greatest possible surplus for himself, and so would prefer that to any other outcome $a \in A$; the transfers $\widehat{t}$ facilitate this renegotiation).

A report of θ_i' that is followed by renegotiation is beneficial for θ_i when he contemplates it in the interim stage if

$$E_{\theta_{-i}}\left[v_i(a(\theta_i, \theta_{-i}), \theta_i) + \widehat{t}_i(\theta_i, \theta_{-i})\right] > E_{\theta_{-i}}\left[v_i(a(\theta_i, \theta_{-i}), \theta_i) + t_i(\theta_i, \theta_{-i})\right]$$

if and only if

$$E_{\theta_{-i}}\left[\widehat{t}_i(\theta_i, \theta_{-i})\right] > E_{\theta_{-i}}\left[t_i(\theta_i, \theta_{-i})\right]. \tag{17}$$

Player j agrees to the proposed renegotiation if and only if the transfer $\widehat{t}_j$ is such that for every $\theta_{-i} \in \Theta_{-i}$:

$$v_j(a(\theta_i, \theta_{-i}), \theta_j) + \widehat{t}_j(\theta_i, \theta_{-i}) \geq v_j(a(\theta_i', \theta_{-i}), \theta_j) + t_j(\theta_i', \theta_{-i}),$$

or

$$\widehat{t}_j(\theta_i, \theta_{-i}) \geq v_j(a(\theta_i', \theta_{-i}), \theta_j) - v_j(a(\theta_i, \theta_{-i}), \theta_j) + t_j(\theta_i', \theta_{-i}).$$

Summing the previous inequalities over $j \neq i$, it follows that

$$\sum_{j \neq i} \widehat{t}_j(\theta_i, \theta_{-i}) \geq \sum_{j \neq i} v_j(a(\theta_i', \theta_{-i}), \theta_j) - \sum_{j \neq i} v_j(a(\theta_i, \theta_{-i}), \theta_j) + \sum_{j \neq i} t_j(\theta_i', \theta_{-i}). \tag{18}$$

The fact that both t and $\widehat{t}$ are ex-post budget balanced implies that $\sum_{j \neq i} t_j(\theta_i', \theta_{-i}) = -t_i(\theta_i', \theta_{-i})$ and $\sum_{j \neq i} \widehat{t}_j(\theta_i, \theta_{-i}) = -\widehat{t}_i(\theta_i, \theta_{-i})$. Plugging these two equations into (18) implies:

$$\widehat{t}_i(\theta_i, \theta_{-i}) \leq \sum_{j \neq i} v_j(a(\theta_i, \theta_{-i}), \theta_j) - \sum_{j \neq i} v_j(a(\theta_i', \theta_{-i}), \theta_j) + t_i(\theta_i', \theta_{-i})$$

for every $\theta_{-i} \in \Theta_{-i}$. Taking the expectation over $\theta_{-i} \in \Theta_{-i}$ implies

$$E_{\theta_{-i}}\left[\widehat{t}_i(\theta_i, \theta_{-i})\right] \leq E_{\theta_{-i}}\left[\sum_{j \neq i} v_j(a(\theta_i, \theta_{-i}), \theta_j)\right] + E_{\theta_{-i}}\left[t_i(\theta_i', \theta_{-i})\right] - E_{\theta_{-i}}\left[\sum_{j \neq i} v_j(a(\theta_i', \theta_{-i}), \theta_j)\right]. \tag{19}$$

The fact that $\langle a, t \rangle$ is a Groves in expectation mechanism implies that

$$E_{\theta_{-i}}\left[\sum_{j \neq i} v_j(a(\theta_i, \theta_{-i}), \theta_j)\right] = E_{\theta_{-i}}\left[t_i(\theta_i, \theta_{-i})\right] - H_i$$

and

$$E_{\theta_{-i}}\left[t_i\left(\theta_i',\theta_{-i}\right)\right]-E_{\theta_{-i}}\left[\sum_{j\neq i}v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)\right]=H_i$$

for some constant H_i. Plugging the two equations above into (19) it follows that:

$$\begin{aligned}E_{\theta_{-i}}\left[\widehat{t}_i\left(\theta_i,\theta_{-i}\right)\right] &\leq \left[E_{\theta_{-i}}\left[t_i\left(\theta_i,\theta_{-i}\right)\right]-H_i\right]+H_i\\ &= E_{\theta_{-i}}\left[t_i\left(\theta_i,\theta_{-i}\right)\right].\end{aligned}$$

A contradiction to (17).

<**Only If**> Let $\langle a,t\rangle$ be a budget balanced incentive compatible direct revelation mechanism that is ex-post renegotiation proof. We show that $\langle a,t\rangle$ is a Groves in expectation mechanism.

Type $\theta_i\in\Theta_i$ of player i can report he is type $\theta_i'\in\Theta_i$ and then offer to renegotiate the outcome from $\left(a\left(\theta_i',\theta_{-i}\right),t\left(\theta_i',\theta_{-i}\right)\right)$ to $\left(a\left(\theta_i,\theta_{-i}\right),\widehat{t}\left(\theta_i,\theta_{-i}\right)\right)$ where $\widehat{t}$ is some ex-post budget balanced transfer function.

Player j would agree to this renegotiation if the transfer $\widehat{t}_j$ is such that for every $\theta_{-i}\in\Theta_{-i}$:

$$v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)+\widehat{t}_j\left(\theta_i,\theta_{-i}\right)\geq v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)+t_j\left(\theta_i',\theta_{-i}\right),$$

or

$$\widehat{t}_j\left(\theta_i,\theta_{-i}\right)\geq v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)-v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)+t_j\left(\theta_i',\theta_{-i}\right).$$

Summing the previous inequalities over $j\neq i$, it follows that renegotiation would be possible if for every $\theta_{-i}\in\Theta_{-i}$

$$\sum_{j\neq i}\widehat{t}_j\left(\theta_i,\theta_{-i}\right)\geq\sum_{j\neq i}v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)-\sum_{j\neq i}v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)+\sum_{j\neq i}t_j\left(\theta_i',\theta_{-i}\right).$$

The payoff player $\theta_i\in\Theta_i$ can therefore get through renegotiation is equal to

$$\begin{aligned}&v_i\left(a\left(\theta_i,\theta_{-i}\right),\theta_i\right)-\sum_{j\neq i}\widehat{t}_j\left(\theta_i,\theta_{-i}\right)\\ &\quad=v_i\left(a\left(\theta_i,\theta_{-i}\right),\theta_i\right)-\sum_{j\neq i}v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)+\sum_{j\neq i}v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)-\sum_{j\neq i}t_j\left(\theta_i',\theta_{-i}\right)\end{aligned}$$

The fact that $\langle a,t\rangle$ is ex-post renegotiation proof implies that, in the interim stage, when player i considers whether he should misreport and then renegotiate, he concludes that this cannot increase his expected payoff, or:

$$\begin{aligned}&E_{\theta_{-i}}\left[v_i\left(a\left(\theta_i,\theta_{-i}\right),\theta_i\right)+t_i\left(\theta_i,\theta_{-i}\right)\right]\\ &\geq E_{\theta_{-i}}\left[v_i\left(a\left(\theta_i,\theta_{-i}\right),\theta_i\right)-\sum_{j\neq i}v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)+\sum_{j\neq i}v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)-\sum_{j\neq i}t_j\left(\theta_i',\theta_{-i}\right)\right]\end{aligned}$$

or

$$E_{\theta_{-i}}\left[t_i\left(\theta_i,\theta_{-i}\right)\right] \geq E_{\theta_{-i}}\left[-\sum_{j\neq i} v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)+\sum_{j\neq i} v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)-\sum_{j\neq i} t_j\left(\theta_i',\theta_{-i}\right)\right]$$

for every $\theta_i,\theta_i' \in \Theta_i$. Because $t_i\left(\theta_i',\theta_{-i}\right)+\sum_{j\neq i} t_j\left(\theta_i',\theta_{-i}\right)=0$, we have that

$$E_{\theta_{-i}}\left[t_i\left(\theta_i,\theta_{-i}\right)-t_i\left(\theta_i',\theta_{-i}\right)\right] \geq E_{\theta_{-i}}\left[\sum_{j\neq i} v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)-\sum_{j\neq i} v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)\right]$$

for every $\theta_i,\theta_i' \in \Theta_i$. Because type $\theta_i' \in \Theta_i$ of player i can report that he is type $\theta_i \in \Theta_i$ and then offer to renegotiate the outcome as above, we may replace θ_i and θ_i' in the previous inequality to get:

$$E_{\theta_{-i}}\left[t_i\left(\theta_i,\theta_{-i}\right)-t_i\left(\theta_i',\theta_{-i}\right)\right] \leq E_{\theta_{-i}}\left[\sum_{j\neq i} v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)-\sum_{j\neq i} v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)\right]$$

for every $\theta_i,\theta_i' \in \Theta_i$, from which it follows that

$$E_{\theta_{-i}}\left[t_i\left(\theta_i,\theta_{-i}\right)-t_i\left(\theta_i',\theta_{-i}\right)\right] = E_{\theta_{-i}}\left[\sum_{j\neq i} v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)-\sum_{j\neq i} v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)\right]$$

for every $\theta_i,\theta_i' \in \Theta_i$ and $\theta_{-i} \in \Theta_{-i}$. By fixing $\theta_i' \in \Theta_i$, it therefore follows that for every $\theta_i \in \Theta_i$:

$$\begin{aligned}
E_{\theta_{-i}}\left[t_i\left(\theta_i,\theta_{-i}\right)\right] &= E_{\theta_{-i}}\left[\sum_{j\neq i} v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)-\sum_{j\neq i} v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)+t_i\left(\theta_i',\theta_{-i}\right)\right] \\
&= E_{\theta_{-i}}\left[\sum_{j\neq i} v_j\left(a\left(\theta_i,\theta_{-i}\right),\theta_j\right)\right]+H_i
\end{aligned}$$

where

$$H_i = E_{\theta_{-i}}\left[t_i\left(\theta_i',\theta_{-i}\right)-\sum_{j\neq i} v_j\left(a\left(\theta_i',\theta_{-i}\right),\theta_j\right)\right].$$

It follows that $\langle a,t\rangle$ is a Groves in expectation mechanism. ■

Proof of Proposition 4.

Let $a:\Theta\rightarrow A$ be an ex-post efficient decision rule, and let $t:\Theta\rightarrow\mathbb{R}^n$ be a budget balanced vector of transfer functions. Denote the different types of player i by $\theta_i^1,\theta_i^2...,\theta_i^m$, respectively. A common prior distribution over the space of states of the world Θ induces for each type θ_i^j of each player i a belief $b_i\left(\theta_i^j\right) \in \Delta\left(\Theta_{-(i,i+1)}\right)$ about the types of all the other players except for player $i+1$ (to simplify the notation, we adopt the convention that player $n+1$ stands for player 1, and player 0 stands for player n). If these beliefs are linearly independent, then there exists a monetary transfer function $t_i^L : \Theta_{-(i+1)} \to \mathbb{R}$ that solves the following matrix equation:

$$\begin{bmatrix} b_i\left(\theta_i^1\right)(\cdot) \\ \vdots \\ b_i\left(\theta_i^m\right)(\cdot) \end{bmatrix} \cdot \left[t_i^{L\prime}\left(\theta_i^1,\cdot\right),...,t_i^{L\prime}\left(\theta_i^m,\cdot\right)\right] = \begin{bmatrix} 0 & L & \cdots & L \\ L & 0 & \ddots & \vdots \\ \vdots & \ddots & \ddots & L \\ L & \cdots & L & 0 \end{bmatrix}$$

The monetary transfers t_i^L are such that if they are applied to the players' reports about their types, and if all the players except for player i report their types truthfully, then for each type θ_i^j of player i, if θ_i^j reports his type truthfully, then his expected t_i^L payment is 0, but if θ_i^j misrepresents his type, then his expected t_i^L payment is L. Note that the monetary transfers t_i^L are such that player i's payment is independent of the report of player $i+1$. This implies that player $i+1$ has no incentive to misrepresent his type in order to receive a larger t_i^L transfer from player i.

Consider the following mechanism: each player is required to report his type. If the profile of reported types is θ then social alternative $a(\theta)$ is implemented, each player i is paid the transfer t_i, and in addition, each player $i \in \{1,...,n-1\}$ pays $t_i^L(\theta)$ to player $i+1$, and player n pays $t_n^L(\theta)$ to player 1, where L is chosen so that it is larger than the upper bound

$$\overline{E} = \max_{\theta\in\Theta,a,b\in A} \sum_{i=1}^{n} |v_i(a,\theta) - v_i(b,\theta)| + \max_{\theta\in\Theta}\left(\sum_{i=1}^{n} |t_j(\theta)|\right)$$

on the maximum surplus that a player can obtain by renegotiation of any outcome to any other outcome.

Observe that the penalty for misreporting L is chosen to be sufficiently large so that the direct mechanism $\langle a,t\rangle$ is incentive compatible. The fact that $a(\theta)$ is an ex-post efficient decision rule and that t is budget balanced implies that if the players report their types truthfully then they cannot benefit from renegotiation of the outcome of the mechanism. And the fact that $L > \overline{E}$ implies that no player can benefit from misreporting his type and then renegotiating the outcome and capturing the implied increase in the social surplus from renegotiation. This is because misreporting has an expected cost of L to a player, while the increase in social surplus is bounded from above by $\overline{E} < L$. ■

Proof of Proposition 5.

Suppose that an ex-post efficient equilibrium σ of a mechanism $\langle S,m\rangle$ is not interim renegotiation-proof. It follows that there exists a set of profiles of players' types $\Upsilon = \Upsilon_1 \times \cdot\cdot\cdot \times \Upsilon_n$ that has a positive P probability, and an alternative equilibrium σ' of an alternative mechanism $\langle S', m' \rangle$, that the types in Υ all prefer, and some strictly prefer, conditional on their types and the set Υ to the outcome that is obtained when the players all play their equilibrium strategies σ under the mechanism $\langle S, m \rangle$. A contradiction to the ex-post efficiency of the equilibrium σ of the mechanism $\langle S, m \rangle$. ■

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