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Abstract: A contract with multiple agents may be susceptible to collusion. We show that agents' collusion imposes no cost in a large class of circumstances with risk neutral agents, including both uncorrelated and correlated types. In those circumstances, any payoff the principal can attain in the absence of collusion, including the second-best level, can be attained in the presence of collusion in a way robust to many aspects of collusion behavior. The collusion-proof implementation generalizes to a setting in which only a subset of agents may collude, provided that noncollusive agents' incentives can be protected via an ex post incentive compatible and ex post individually rational mechanism. Our collusion-proof implementation also sheds light on the extent to which hierarchical delegation of contracts can optimally respond to collusion.

Keywords: Robustly collusion-proof implementation, pairwise identifiability, subgroup collusion, ex post implementability.

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1 Introduction

There has been a growing interest in studying collusion among asymmetrically informed agents, in various settings ranging from internal organization, regulation, auctions, to oligopolistic competition.[1] While most of these studies explore how agents can effectively collude against exogenously given institutions, a few recent studies have begun to investigate an *optimal* organizational/contractual response to agents' collusion. In particular, Laffont and Martimort (1997, 2000) have developed a modeling framework that integrates collusion as part of the general mechanism design analysis.[2] An important insight gained from this framework is that agents' asymmetric information imposes transaction costs on their abilities to carry out collusive arrangements.

Just how far these transaction costs can be exploited in contract design is still unknown. In procurement/public good settings, Laffont and Martimort (hereafter LM) have shown that the optimal outcome can be made collusion-proof at no cost to the principal if the agents' types are uncorrelated (LM, 1997), but, if the types are correlated, preventing collusion entails strict cost to the principal (LM, 2000). The former result — i.e., collusion is preventable at no cost with uncorrelated types — is reproduced by Quesada (2004) with a different coalition formation process, and by Jeon and Menicucci (2005) in a nonlinear pricing model that allows collusive consumers to arbitrage on their purchases. These models have special structures, though. LM and Quesada (2004) assume two agents with two possible types and Leontief production technologies/preferences, and Jeon and Menicucci (2005) assume $n \geq 2$ agents with two types or two agents with three types, along with several preference restrictions.

[1] Tirole (1986), Baliga and Sjostrom (1998), Celik (2004), Faure-Grimaud, Laffont, and Martimort (2003), Severinov (2003) and Mookherjee and Tsumagari (2004) study collusion in internal organization and the value of delegation. Graham and Marshall (1987), McAfee and McMillan (1992), Mailath and Zemsky (1991), Marshall and Marx (2004), Brusco and Lopomo (2002) and Caillaud and Jehiel (1998) study collusion in one-shot auctions of various formats, while Aoyagi (2003), Blume and Heidhues (2002), Skrzypacz and Hopenhayn (2004) and Abdulkadiroğlu and Chung (2003) study collusion in repeated auctions.

[2] An earlier literature concerned about coalition formation in Groves mechanisms includes Green and Laffont (1979) and Crémer (1996). The former paper envisions a coalition of symmetrically informed agents, whereas the latter allows for their possible asymmetric information. While the latter framework resembles that of Laffont-Martimort and even considers subgroup collusion, it restricts attention to dominant strategy implementation (at both grand and coalitional mechanism design) and does not consider participation constraints.

Intriguing as these results are, their reliance on special structures raises several questions. First, it is unclear whether the results are generalizable beyond the assumed environments. Second, even if the results are generalizable, the method of collusion-proof implementation is specific to the assumed setting, so it does not provide a general method that may work in other settings. Third, the specificity of the models and the lack of a general method make it also difficult to isolate the economic insight explaining under what circumstances collusion is preventable and why it is preventable in those circumstances.

The current paper advances on these fronts by developing a general method for collusion-proofing a mechanism. Using this method, we show that any payoff attainable by the principal in the absence of collusion, including the second-best level, can be attained in the presence of collusion, in a large class of environments with risk neutral agents, for both uncorrelated and correlated types cases. Our collusion-proof implementation does not rest on any special assumptions about preferences/technologies or type structures. For example, the agents' types can be discrete or continuous (at least for the uncorrelated types case) or even multidimensional, and no special features on preferences or technology, such as single crossing, are needed for our results.

Furthermore, our collusion-proof implementation is robust to many aspects of collusion behavior, such as the identity of the agent organizing/initiating collusion, the manipulation technology employed by the coalition (e.g., whether the coalition can arbitrage on an initial allocation), the coalition's objective and the bargaining power of its members (e.g., whether the coalition caters to the interests of some agents more than others), and the exact makeup of the coalition (e.g., whether collusion involves all agents or only some agents). In fact, the principal need not even know how the collusion operates along many of these dimensions.

Our method of collusion-proof implementation utilizes the idea of "selling the firm to the coalition." Specifically, for any expected payoff level that the principal can attain in the absence of collusion, we construct a new mechanism that gives the principal an *ex post* constant payoff equal to the original expected payoff. This mechanism forces the (grand) coalition to become a residual claimant of the entire surplus, after paying off the principal an ex post constant surplus, when it manipulates the outcome. That such a mechanism is implementable in the adverse selection setting is not obvious, and will be an important part of our analysis. Also not obvious is that such a mechanism, if implementable, is immune to collusion. In fact, being the residual claimant, the coalition would prefer the first-best allocation over the intended allocation in case the latter involves distortion, so it will try to manipulate so that the former arises. Yet, such a manipulation never succeeds. The reason is that the coalition faces an asymmetric information problem just like the principal in the original noncollusive mechanism design. This informational asymmetry means that an appropriate amount of information rent must be given to the members of the coalition to implement a particular allocation. But since the principal is paid off to realize a desired level of surplus irrespective of the induced allocation, implementing any other allocation by the coalition would violate budget balancing.[3] (This intuition will become more transparent in Section 5, with the aid of a figure.) In short, by making the agents residual claimants, our mechanism forces them to internalize precisely the same amount of informational cost that the principal faces in noncollusive mechanism design, and in this sense exploits the coalitional transaction cost fully.

This idea of collusion-proof implementation does not rely on the agents' types being uncorrelated, although making the agents residual claimants while preserving their incentives proves more challenging in a correlated type environment. If there are only two agents, our method of collusion-proofing indeed does not work, much consistent with LM (2000)'s finding in their two agents model. With more than two agents, however, given a reasonable type structure, our collusion-proof implementation works quite generally, implying again that the principal can attain any noncollusive payoff in a robustly collusion-proof fashion even with correlation. An important corollary of this result is that the principal can typically implement the first-best allocation and extract the entire rents from the agents even in the presence of collusive agents.

We then extend our analysis to consider a mechanism that would prevent collusion by a subgroup of agents. Although the issue of preventing collusion by a subgroup has rarely been analyzed before, it is practically relevant since in many settings, only a subgroup of agents are often in a position to collude. Collusion-proofing in this environment poses a new challenge since the coalition may prey on noncollusive agents as much as on the principal. Protecting the interests of noncollusive agents thus becomes an important consideration for the principal. Our collusion-proof implementation idea generalizes in a remarkable way to this problem: If *at least two* collusive agents are identified, then we can construct a mechanism that can handle *any* collusion involving these two, including the grand collusion.

[3]The intuition is the same as the one showing that implementing the first-best allocation would run a budget deficit in Myerson-Satthertwaite bargaining. The difference is that this problem is endogenously/deliberately created by our design to prevent collusion from being feasible.

This result strengthens the robustness in the way the collusion problem is thwarted since the principal need not know the exact size or makeup of the coalition. While this result requires an additional condition that the outcome must be ex post implementable in the noncollusive setup (i.e., ex post incentive compatible and ex post individually rational), the condition is known to hold in a large class of uncorrelated types environments.

The collusion-proof implementation result also advances our understanding of the value of hierarchical delegation of contracts. Despite its practical significance, delegation of contracting authority has been difficult to justify, since it involves a loss of control for the principal (see Melumad, Mookherjee and Reichelstein (1995), for instance). Whether collusion can change this view has been the subject of much recent research (see Laffont and Martimort (1998), Faure-Grimaud, Laffont and Martimort (2003), Celik (2004), Mookherjee and Tsumagari (2004)). Since collusion creates control loss even with centralized contracts, delegation may be relatively more attractive and may even serve as an optimal response to collusion. This latter conjecture turns out not to be true, however. Our results imply that collusion imposes no real cost to centralized contracting, which suggests that delegation cannot be more justifiable in the presence of collusion than in its absence.

The rest of the paper is organized as follows. Section 2 illustrates the idea of the main results using a simple example. Section 3 describes the model, including the economic environments studied. Section 4 describes the noncollusive benchmark. Section 5 develops the notion of robust collusion-proofness. Section 6 constructs a robustly collusion-proof mechanism that implements any noncollusive payoff for the principal, in the uncorrelated type environment. Section 7 generalizes the analysis to the correlated type environment. Section 8 then studies collusion-proofing when only a subset of agents may collude. Section 9 establishes robustness of the result to an alternative modeling of coalition formation. Section 10 draws implications for hierarchical delegation of contracts. Section 11 concludes.

2 An Illustrative Example

It is useful to begin with an example that illustrates our main idea. Suppose a buyer procures a good from one of two suppliers, agents 1 and 2. Agent $i = 1, 2$ can supply the good at a cost θ_i, which is drawn uniformly from $[0, 1]$, and the buyer values the good more than 2. If the agents cannot collude, it is optimal for the buyer to use a standard auction, such as a second-price auction. (No binding reserve price is employed since the seller's valuation of the object is sufficiently high.) Specifically, the agents bid supply prices, and the low bidder wins and performs the job at the payment that equals the high bid. Consequently, the buyer procures the good at the expected price of 2/3, which is the best the buyer can do, as is well known from Myerson (1981).

Suppose now the agents can collude. It is easily seen that the second-price auction is susceptible to collusion. Prior to bidding, the firms can organize a knockout auction wherein the agents bid for the right to participate in the second-price auction uncontested; i.e., the loser bids 1, and the winner bids his cost.[4] Hence, with collusion, the buyer essentially pays the price of 1 to the winner of the knockout auction.

Now consider a different mechanism. The buyer holds an auction in which the agents bid for a payment, b_i, and again the low bidder wins. The mechanism differs in the payment arrangement: The buyer pays a fixed amount, 2/3, to the losing (high) bidder, say j, who then pays the winning bidder its bid b_i to perform the job. Intuitively, the losing bidder is a "prime contractor" who "outsources" the job to the winning bidder and in the process finances the difference, $b_i - 2/3$.

Absent collusion, the bidding game has a unique equilibrium in which the agents adopt a symmetric increasing bidding strategy, $\frac{1}{2} + \frac{1}{3}\theta$, for each type $\theta \in [0, 1]$. Consequently, the job is allocated efficiently as in the optimal mechanism, and the buyer procures the good at the fixed price of 2/3. Since the allocation is the same and the buyer pays the same on average as in the (noncollusive) second-price auction, the revenue equivalence theorem implies that the interim payoffs of both firms are the same as in that game. Hence, it is equilibrium for both agents to participate in the auction game. In sum, the proposed mechanism implements the optimal procurement policy, in the absence of collusion. More importantly, the new mechanism is not susceptible to collusion. In the bidding game, the agents become residual claimants of the social surplus after paying a fixed amount of 2/3 to the buyer. Since the allocation is efficient, they have no incentive to collude in that bidding game.

This example illustrates the main idea of preventing collusion, namely that of "selling

[4]More precisely, they can organize a knockout auction in which the agents bid to pay their rivals for the "uncontested bidding" in the official auction. This knockout auction game has a unique symmetric equilibrium in which an agent with cost θ bids $\frac{1}{3} - \frac{1}{3}\theta$. This equilibrium implements the direct revelation (strong) cartel mechanism studied by McAfee and McMillan (1992). A similar problem arises with the first-price auction.

the firm" to the agents. In what follows, this idea will be used to construct a general collusion-proof mechanism that works in a more complicated environment. The example also illustrates another feature of our collusion-proof mechanism, distinguished from the existing literature (e.g., LM, 1997, 2000). Unlike the traditional approach, our mechanism guarantees the buyer a desired level of ex post surplus, whether collusion actually occurs or not. Hence, in the example the buyer could achieve the same outcome, by delegating the procurement job to a "consortium" of the agents (run by some uninformed third party), at a fixed price of 2/3; the consortium will then organize its own auction to allocate the job efficiently. Such delegation may provide a more practically relevant implementation of our mechanism.

3 Primitives

There are a principal and $n \geq 2$ agents, with $N := \{1, ..., n\}$ representing the total set of agents. Each agent i has type θ_i drawn from some arbitrary measurable set Θ_i. A vector of realized types is denoted $\theta := (\theta_1, ..., \theta_n) \in \times_{i=1}^n \Theta_i =: \Theta$. Until more specific cases are considered, we maintain a general assumption that θ is distributed according to some prior distribution $\mu^0 \in \Delta\Theta$. Hence, θ can be discrete or continuous (or a mixture of those), or multidimensional. The realized value of θ_i is private information observed only by agent i; all others, including the principal, only know its distribution along with other aspects of the game structure. We adopt the following notation: $\tilde{\theta}$, $\tilde{\theta}_i$, $\tilde{\theta}_{-i}$ represent random variables, $\mathbb{E}[\cdot] := \int_\Theta [\cdot] d\mu^0(\tilde{\theta})$ and $\mathbb{E}_{\tilde{\theta}_{-i}}[\cdot] := \int_{\Theta_{-i}} [\cdot] d\mu^0(\theta_i, \tilde{\theta}_{-i})$ are expectation operators based on the prior distribution; and $\mathbf{E}_\mu[\cdot] := \int_\Theta [\cdot] d\mu(\tilde{\theta})$ represents an expectation operator based on an arbitrary probability distribution $\mu \in \Delta\Theta$.

An economic decision is described by $x \in \mathcal{X}$, for some arbitrary set $\mathcal{X}$. Given a profile of types, $\theta \in \Theta$, and a decision $x \in \mathcal{X}$, agent $i \in N$ realizes gross surplus of $a_i(x, \theta)$ and the principal obtains $w(x)$. We allow for a random decision, so we focus on a probability measure q on $\mathcal{X}$ and call it an *allocation*. Let $\mathcal{Q} = \Delta\mathcal{X}$ be the set of all allocations (i.e., all probability measures on $\mathcal{X}$). Then, any allocation q (or randomization over x) yields gross surplus of $s_i(q, \theta) := \int_\mathcal{X} a_i(x, \theta) dq(x)$, and of $v(q) = \int_\mathcal{X} w(x) dq(x)$ to agent i and to the principal, respectively, given type profile $\theta \in \Theta$.

All players are risk neutral.[5] Hence, given types θ, if allocation $q \in \mathcal{Q}$ is chosen and the principal pays t_i to agent i in expected value, he receives expected payoff of

$$s_i(q, \theta) + t_i,$$

and the principal receives expected payoff,[6]

$$v(q) - \sum_{i \in N} t_i.$$

If there is no contract, agent i with type θ_i collects a reservation utility of $\overline{U}_i(\theta_i)$.

Virtually all known adverse selection problems with "quasilinear preferences" satisfy the above preference and information structure. The following is the list of some well-known examples.

- *Internal organization, procurement and regulation:* An employer/regulator procures a set, K, of goods in varying quantities from a set N of workers/firms. The decision $x := (x_i^k)_{k \in K, i \in N}$ then represents vectors of goods supplied by the workers. This situation easily fits into our model, with $a_i(x_i, \theta_i)$ representing worker $i \in N$'s payoff (i.e., negative of cost) associated with supplying a vector of quantities, $x_i = (x_i^k)_{k \in K} \geq \mathbf{0}$ given his realized type, θ_i, (which can be multidimensional), and $w(x)$ representing the the seller's value of procuring x. An allocation then is a probability distribution over different production assignments.

- *Nonlinear pricing:* A firm produces/markets a set of goods, K, in varying quantities to a set N of consumers. This is just the mirror image of the procurement problem, with a decision x representing the bundles of goods consumed by the buyers, and with

[5] As will be remarked, our results continue to hold even if the principal is risk averse.

[6] In several models including LM, the principal is a government agency which cares about the agents' welfare. In that case, the principal's payoff is described as

$$v(q) - \sum_{i \in N} t_i + \lambda \sum_{i \in N} [s_i(q, \theta) + t_i],$$

for some $\lambda \in (0, 1]$. This objective function is relevant for a public good problem or Baron and Myerson (1982)'s regulation problem where $\lambda > 0$ reflects the government's shadow value of firms' revenue. Our method works even in this case for the optimal noncollusive mechanism, but according to the LM's weak collusion-proofness criterion, which is weaker than the one that will be developed here. The precise notion and the result are discussed in Appendix A of our working paper version (Che and Kim (2004)).

$a_i(x, \theta_i)$ representing consumer i's utility from consumption and $w(x)$ the negative of firm's cost of producing x.

- *Auctions:* An auctioneer allocates a (finite) set of goods or procurement projects, K, to n bidders and possibly to herself. Let $\mathcal{X}$ be the set of all partitions, or "assignments," of K into the set of all players, including the auctioneer. Suppose that $a_i(x, \theta)$, $i \in N$, is bidder i's gross surplus and $w(x)$ is the auctioneer's gross surplus, when partition $x \in \mathcal{X}$ is chosen and the bidders realize types θ. This model covers many situations of interest, ranging from a one unit IPV (seller or buyer) auction as the simplest form, to interdependent valuations (seen by the possible dependence of a_i on θ_{-i}), bundling, and Jehiel-Moldovanu-Stacchetti (1999) type allocation externalities. In such a model, an allocation $q = (q_x)_{x \in \mathcal{X}}$ denotes a vector of probabilities of different partitions being chosen, and $s_i(q, \theta) = \sum_{x \in \mathcal{X}} q_x a_i(x, \theta)$, $i = 1, ..., n$, and $v(q) = \sum_{x \in \mathcal{X}} q_x w(x)$.

To describe the sequence of events, it is useful to begin with a time line under a *non-collusive game*:

- At date -1, each agent learns his type, θ_i, which is drawn from Θ_i.
- At date 0, the principal proposes a mechanism.
- At date 1, each agent either accepts or rejects the mechanism.
- At date 2, the game form proposed in the mechanism is played if the agents all accepted the mechanism, or else the agents collect their respective reservation utilities.

To study possible collusion among the agents, we follow LM (2000) by considering possible coalition formation *between* date 1 and date 2, initiated by a third party[7]:

- At date $1\frac{1}{4}$, a third party proposes a collusive arrangement.
- At date $1\frac{1}{2}$, each agent accepts or rejects the collusive mechanism.
- At date $1\frac{3}{4}$, the game form specified in the collusive mechanism is played, which binds the play of the coalition members at date 2, if all agents accepted the collusive

[7] In Section 9, we will study a variation in which collusion is initiated by one of the agents.

mechanism at date $1\frac{1}{2}$. If at least one agent rejects the collusive mechanism, no collusion occurs, so the agents play the game at date 2 noncooperatively.

Note that the coalition is formed after the agents make participation decisions. The implication of this formulation will be discussed in Conclusion. Further details of how collusion operates will be discussed in Section 5.

4 Benchmark: A Noncollusive Environment

We first analyze the noncollusive game, with no action between date 1 and date 2. Absent collusion by agents, the Revelation principle guarantees that an equilibrium consequence of any contract that the principal offer can be studied by a direct revelation mechanism (DRM). In our setup, a direct mechanism, or shortly *"mechanism,"* consists of measurable functions, $(q, t) : \Theta \mapsto \mathcal{Q} \times \mathbb{R}^n$, which determines an allocation $q(\theta)$ and a vector of transfers $t(\theta) = (t_1(\theta), ..., t_n(\theta))$ to the agents when they report $\theta \in \Theta$. The function, $q(\cdot)$, is called an *allocation rule*, and $t(\cdot)$ is called a *transfer rule*. Any such pair (q, t) also represents an outcome realized at each state θ and will be sometimes referred to as an "*outcome*," below.

Absent collusion, a mechanism $M = (q, t)$ is *feasible* if it is *individually rational*:

$$(IR) \qquad U_i^M(\theta_i) := \mathbb{E}_{\tilde{\theta}_{-i}}[s_i(q(\theta_i, \tilde{\theta}_{-i}), \theta_i, \tilde{\theta}_{-i}) + t_i(\theta_i, \tilde{\theta}_{-i})|\theta_i] \geq \overline{U}_i(\theta_i) \quad \forall i, \theta_i,$$

and *incentive compatible*:

$$(IC) \qquad U_i^M(\theta_i) \geq \mathbb{E}_{\tilde{\theta}_{-i}}[s_i(q(\theta_i', \tilde{\theta}_{-i}), \theta_i, \tilde{\theta}_{-i}) + t_i(\theta_i', \tilde{\theta}_{-i})|\theta_i] =: u_i^M(\theta_i', \theta_i), \quad \forall i, \theta_i, \theta_i',$$

where $\overline{U}_i(\theta_i)$ is the reservation utility level of agent i with type θ_i. Notice that both incentive compatibility and individual rationality are required at the interim level. Let $\mathcal{M}$ be the set of all feasible mechanisms, i.e., the set of all allocation and transfer rules, $M := (q, t)$, satisfying (IC) and (IR). We assume that the set $\mathcal{M}$ is nonempty.[8]

A mechanism $M = (q, t) \in \mathcal{M}$ *implements* an (expected) payoff of $V \in \mathbb{R}$ for the principal if

$$V = \mathbb{E}[v(q(\tilde{\theta})) - \sum_{i \in N} t_i(\tilde{\theta})],$$

[8]It is reasonable in most of the situations that the principal has an option of offering a null contract, in which case this assumption holds trivially.

in which case we say a payoff V is *implementable.* Let $\mathcal{V}$ denote the set of all implementable payoffs for the principal. Of special interest is the highest implementable payoff, $V^* = \sup \mathcal{V}$. This payoff, henceforth referred to as "*noncollusive optimal*" or "*second-best*" payoff, is implementable, namely, $V^* \in \mathcal{V}$, under very weak conditions (see Balder (1996) for example). Below, we will be interested in the collusion-proof implementability of any arbitrary $V \in \mathcal{V}$, but particularly the second-best payoff V^*.

For any payoff $V \in \mathcal{V}$, there may be more than one mechanism implementing it. For the most part, how we select a mechanism in such a case does not matter. In a couple of occasions (Propositions 2 and 3), however, we select a mechanism $M = (q, t)$ that *efficiently implements* $V \in \mathcal{V}$ in the sense that M yields the highest total surplus among all feasible mechanisms implementing V:

$$\mathbb{E}[v(q(\tilde{\theta})) + \sum_{i \in N} s_i(q(\tilde{\theta}), \tilde{\theta})] \geq \mathbb{E}[v(q'(\tilde{\theta})) + \sum_{i \in N} s_i(q'(\tilde{\theta}), \tilde{\theta})],$$

for any mechanism $M' = (q', t')$ implementing V. Existence of such a mechanism for any given $V \in \mathcal{V}$ involves a restriction but is a very weak one.[9] In particular, the second-best allocation — the allocation rule implementing V^* — is often unique, in which case any optimal mechanism will implement V^* efficiently.

5 Model of Collusion and Collusion-Proofness

The Laffont-Martimort model of collusion postulates that the agents can commit, via an uninformed benevolent representative, to a mechanism that manipulates their reports to the principal. Below, we will expand this modeling framework to accommodate a much broader range of collusion possibilities. We will then develop a notion of collusion-proofness that requires a mechanism to be robust against all such collusion possibilities.

5.1 Modeling Collusive Behavior

We study a collusive arrangement that allows the agents to (1) collectively manipulate their reports to the principal, to (2) reallocate q assigned by the grand contract and to

[9]For instance, if the set of allocation rules associated with mechanisms implementing V is compact, then there exists a mechanism that efficiently implements V since the principal and agents' payoff functions are linear in q.

(3) exchange transfers among the agents in the budget-balanced way. Following LM, we assume that such an arrangement is enforced by a side contract proposed by a benevolent representative. By the Revelation Principle, a side contract is described without loss of generality by a pair of functions, $(\mu, y) : \Theta \mapsto \Delta\Theta \times \mathbb{R}^n$, that maps from the agents' types into (possibly random) reports they will submit to the principal and side-transfers they will exchange with one another. Specifically, a side contract (μ, y) asks the agents to report their types, and, for any profile θ of reported types, it instructs them to randomize their reports over Θ according to a probability measure $\mu(\theta)$ and to exchange side-transfers $y(\theta) = (y_1(\theta), ..., y_n(\theta))$ among them. We require a side contract to be *budget balanced:* $\sum_{i\in N} y_i(\cdot) = 0$.[10]

For our purpose, it is more convenient to work directly with the outcome that is implemented *as a result of* enforcing a balanced-budget side contract. Given any grand mechanism M, we say a mechanism $\tilde{M} := (\tilde{q}(\cdot), \tilde{t}(\cdot))$ is a *reallocational manipulation of* M if there exists a balanced-budget side contract $(\mu, y) : \Theta \mapsto \Delta\Theta \times \mathbb{R}^n$ such that, for each $\theta \in \Theta$,

$$\tilde{t}(\theta) = \mathbf{E}_{\mu(\theta)}[t(\tilde{\theta})] + y(\theta) \text{ and } v(\tilde{q}(\theta)) = \mathbf{E}_{\mu(\theta)}[v(q(\tilde{\theta}))] \tag{1}$$

and let $\mathcal{RM}_M$ denote the set of all reallocational manipulations of M. In words, a reallocational manipulation of M is any outcome $\tilde{M} = (\tilde{q}, \tilde{t})$ that the coalition can induce from grand contract M by manipulating the reports from θ via randomization $\mu(\theta)$ and reallocating the resulting assignment in any way that gives rise to the same gross surplus to the principal (the second equation of (1)), and by redistributing transfers to the agents in a budget-balanced way (the first equation of (1)).

It is worth noting that the second equation of (1) encompasses all standard scenarios of reallocation. In an auction, for instance, a bidding ring may be able to reallocate the goods among themselves after they are initially auctioned off by the seller. This power to reallocate matters only when the good is sold to one of the members, however. The equation captures (a weaker form of) this restriction. To be more concrete, consider a single-unit auction with n bidders and a seller with a reservation value of $v_0 \geq 0$. Suppose

[10] In fact, all results, except Proposition 1, hold with a weaker, *ex ante* version of budget balancedness, i.e., $\mathbb{E}[\sum_{i\in N} y_i(\theta)] = 0$. This means that all our collusion-proof implementation method works even when the coalition is allowed to obtain financing from outside the coalition. Likewise, our collusion-proof implementation of optimal mechanisms works even when the coalition is allowed to burn money, i.e., with a weaker requirement $\sum_{i\in N} y_i(\cdot) \leq 0$.

the seller wishes to implement an allocation rule, $q(\cdot) = (q_1(\cdot), ..., q_n(\cdot))$, where $q_i(\cdot)$ is the probability of the object being allocated to agent i (as a function of θ). If the bidders can reallocate the object once it is assigned, they can induce any $\tilde{q}(\theta) = (\tilde{q}_1(\theta), ..., \tilde{q}_n(\theta))$ as long as $\sum_{i\in N} \tilde{q}_i(\theta) = \mathbf{E}_{\mu(\theta)}[\sum_{i\in N} q_i(\tilde{\theta})]$, for some $\mu(\theta) \in \Delta\Theta$; i.e., the probability of at least one of them getting the good matches that under some (possibly randomized) reports. But this condition implies

$$v(\tilde{q}(\theta)) = v_0 \cdot \left(1 - \sum_{i\in N} \tilde{q}_i(\theta)\right) = v_0 \cdot \left(1 - \mathbf{E}_{\mu(\theta)}[\sum_{i\in N} q_i(\tilde{\theta})]\right) = \mathbf{E}_{\mu(\theta)}[v(q(\tilde{\theta}))],$$

which is precisely what we require under reallocational manipulation. In another example, as Jeon and Menicucci (2005) or Mookherjee and Tsumagari (2004) envisioned, consumers facing nonlinear pricing or suppliers facing nonlinear contracts may be able to reallocate their initial allocation/assignment to increase their joint surplus. In this case, our equation corresponds to the restriction that the reallocation cannot affect the total amount of the goods/outputs being (re)allocated to all consumers/suppliers.

For feasible collusive behavior, we focus on a reallocational manipulation that satisfies (IC) and (IR), and let

$$\mathcal{M}_M := \mathcal{RM}_M \cap \mathcal{M}$$

be the set of *feasible* (reallocational) manipulations. Conditions (IC) and (IR) are sensible properties to assume for coalitional manipulation. First of all, (IC) is necessary as long as the coalition faces an adverse selection problem, regardless of how the coalition is formed. For instance, if the coalition is proposed by an (uninformed or informed) agent, the proposal must be incentive compatible for all agents, including the proposer (see Quesada (2004) and Mookherjee and Tsumagari (2004)). Likewise, (IR) is necessary for a collusion proposal to be acceptable to the agents in many circumstances. Whether a particular collusion proposal is acceptable depends on the belief formed when the proposal is (unexpectedly) rejected. A standard treatment for this is to assume "passivity of beliefs:" i.e., no new inferences about the agents' types are made in such an event. Given passive beliefs, a manipulation, $\tilde{M}$, would be acceptable if

$$(IR_M) \qquad U_i^{\tilde{M}}(\theta_i) \geq U_i^M(\theta_i), \quad \forall i, \forall \theta_i.$$

Clearly, any manipulation of M satisfying (IR_M) would also satisfy (IR) as long as M satisfies (IR). Hence, requiring (IR) accommodates all acceptable collusive arrangements given passive beliefs, but it also includes arrangements supported by other, possibly extreme, beliefs. In particular, it means that the coalition can hold the members down to the same outside options, regardless of the principal's contract offer, thus limiting her ability to undermine collusion via manipulating their outside options. In fact, endowing the coalition with the ability to enforce any manipulation subject only to (IC) and (IR) is tantamount to assuming that the coalition enjoys the same commitment power as the principal. Although some may view this approach as assuming unrealistically powerful collusion, it can only strengthen our case if our implementation is robust against all such manipulations — a requirement we formalize as follows:

Definition 1 *A mechanism $M \in \mathcal{M}$ is **robustly collusion-proof** (or **RCP**) if every $\tilde{M} \in \mathcal{M}_M$ gives the same expected payoff to the principal as mechanism M. A payoff $V \in \mathcal{V}$ is **RCP implementable** if there exists an RCP mechanism that implements V.*

We next explore several features of our collusion-proof notion. Readers who wish to get to the main results may skip the remainder of this section.

5.2 Implications and Comparison with Existing Notions

- ***Objective of the coalition:***

Our collusion-proofness notion imposes no restriction on the behavioral objective of the coalition. To see this, suppose, facing grand mechanism M, the coalition solves

$$[C_M(\alpha)] \qquad \max_{M' \in \mathcal{M}_M} \mathbb{E}\left[\sum_{i \in N} \alpha_i(\tilde{\theta}) U_i^{M'}(\tilde{\theta}_i)\right],$$

for some $\alpha := (\alpha_1, ..., \alpha_n) : \Theta \mapsto \mathbb{R}_+^n$. This formulation of the collusion problem encompasses a broad class of collusion possibilities, nesting many existing formulations as special cases. For instance, with $\alpha(\cdot) \equiv \mathbf{1}$, the objective function treats the agents rather symmetrically, as was assumed by LM. With $\alpha_i(\cdot) \equiv 1$ and $\alpha_j(\cdot) \equiv 0$ for all $j \neq i$, the representative caters to the interest of agent i at the expense of others, as will happen if agent i proposes a contract (see Mookherjee and Tsumagari (2004), for instance). In fact, any individually rational collusion agreement must correspond to some $\alpha(\cdot) \in \mathcal{A}$, where $\mathcal{A}$ is the set of all mappings, $\alpha : \Theta \mapsto \mathbb{R}_+^n$. All these possible scenarios are captured in our notion: *if M is RCP, then $\forall \alpha \in \mathcal{A}$, every solution of $[C_M(\alpha)]$ gives the same expected payoff to the* *principal as mechanism M.* In fact, the principal need not even know the precise objective of the coalition.

- ***Collusion prevention:***

Our collusion-proofness requirement does not rule out collusion occurring on the equilibrium path, but rather ensures that the principal will not be harmed by collusion, even if it occurs. Clearly, this latter requirement is all that matters as far as the principal is concerned. Our requirement is in fact natural when the principal does not know the precise objective of the coalition (i.e., α). If the principal *does* know the objective, however, she can prevent collusion, given RCP:

PROPOSITION 1 *If a mechanism $M \in \mathcal{M}$ is RCP, then for each α with a nonempty solution to $[C_M(\alpha)]$, there exists a mechanism M_α that gives the same payoff as M to the principal and solves $[C_{M_\alpha}(\alpha)]$.*

PROOF: Suppose that $M = (q(\cdot), t(\cdot))$ is RCP, and let $M_\alpha = (q_\alpha(\cdot), t_\alpha(\cdot))$ be a solution of $[C_M(\alpha)]$. Since M is RCP, M_α gives the same expected payoff to the principal as M. We prove that M_α solves $[C_{M_\alpha}(\alpha)]$. Since $M_\alpha \in \mathcal{RM}_M$, there exists a balanced-budget side contract $(\mu_\alpha(\cdot),\ y_\alpha(\cdot))$ such that $\forall \theta \in \Theta$,

$$v(q_\alpha(\theta)) = \mathbf{E}_{\mu_\alpha(\theta)}[v(q(\tilde{\theta}))] \text{ and } t_\alpha(\theta) = \mathbf{E}_{\mu_\alpha(\theta)}[t(\tilde{\theta})] + y_\alpha(\theta). \tag{2}$$

Now pick any $\tilde{M} = (\tilde{q}(\cdot), \tilde{t}(\cdot)) \in \mathcal{RM}_{M_\alpha}$. Then, there exists a balanced-budget side contract $(\mu(\cdot), y(\cdot))$ such that $\forall \theta$,

$$v(\tilde{q}(\theta)) = \mathbf{E}_{\mu(\theta)}[v(q_\alpha(\tilde{\theta}))] = \mathbf{E}_{\mu(\theta)}[\mathbf{E}_{\mu_\alpha(\tilde{\theta})}[v(q(\tilde{\tilde{\theta}}))]]$$

and

$$\tilde{t}(\theta) = \mathbf{E}_{\mu(\theta)}[t_\alpha(\tilde{\theta})] + y(\theta) = \mathbf{E}_{\mu(\theta)}[\mathbf{E}_{\mu_\alpha(\tilde{\theta})}[t(\tilde{\tilde{\theta}})]] + \mathbf{E}_{\mu(\theta)}[y_\alpha(\tilde{\theta})] + y(\theta),$$

where the last equalities follow from (2). Note $\mathbf{E}_{\mu(\theta)}[\mathbf{E}_{\mu_\alpha(\tilde{\theta})}[\cdot]] = \mathbf{E}_{\bar{\mu}(\theta)}[\cdot]$ for some $\bar{\mu}(\theta) \in \Delta\Theta$ and, if we let $\bar{y}(\theta) := \mathbf{E}_{\mu(\theta)}[y_\alpha(\tilde{\theta})] + y(\theta)$, then $\sum_{i \in N} \bar{y}_i(\theta) = \mathbf{E}_{\mu(\theta)}[\sum_{i \in N} y_{\alpha i}(\tilde{\theta})] + \sum_{i \in N} y_i(\theta) = 0$, for each $\theta \in \Theta$. Hence, $\tilde{M}$ is a reallocational manipulation of M, or $\tilde{M} \in \mathcal{RM}_M$. We have thus shown that $\mathcal{RM}_{M_\alpha} \subset \mathcal{RM}_M$, which in turn implies $\mathcal{M}_{M_\alpha} \subset \mathcal{M}_M$. Since $M_\alpha \in \mathcal{M}_{M_\alpha}$, M_α must then solve $[C_{M_\alpha}(\alpha)]$. ▌

- ***Relationship with other concepts:***

The most standard approach follows LM's *weak collusion-proofness.* This notion posits collusion organized by an uninformed third party who manipulates agents' reports in a way that is acceptable to the agents given their passive beliefs and maximizes their joint payoffs, but has no ability to reallocate their assignment. This notion can be formally stated in a way comprable to RCP. Given any grand mechanism M, say $\tilde{M} = (\tilde{q}, \tilde{t})$ is a *communicative manipulation*, if there exists a balanced-budget side contract $(\mu, y) : \Theta \mapsto \Delta\Theta \times \mathbb{R}^n$ such that, for each $\theta \in \Theta$,

$$\tilde{t}(\theta) = \mathbf{E}_{\mu(\theta)}[t(\tilde{\theta})] + y(\theta) \text{ and } \tilde{q}(\theta) = \mathbf{E}_{\mu(\theta)}[q(\tilde{\theta})]. \tag{3}$$

The second requirement shows inability to reallocate: the agents can influence the allocation only through manipulating their reports. Letting $\mathcal{CM}_M$ be the set of all communicative manipulations, we thus have $\mathcal{CM}_M \subset \mathcal{RM}_M$.

Formally, a mechanism M is *weakly collusion-proof* if it maximizes the objective of $[C_M(\mathbf{1})]$ among all communicative manipulations satisfying (IC) and (IR_M). As LM show, when a mechanism is weakly collusion-proof, its outcome can be sustained in a collusive environment as a Perfect Bayesian equilibrium. Our RCP notion encompasses this notion since we allow for any arbitrary α in the coalition's objective function and reallocational manipulations, and we assume (IR) instead of (IR_M) for collusive agreements.[11]

PROPOSITION 2 *If a mechanism M efficiently and RCP implements a payoff $V \in \mathcal{V}$, then it is weakly collusion-proof.*

PROOF: Suppose to the contrary that M is not weakly collusion-proof. Then, there must be a mechanism $\tilde{M} \in \mathcal{CM}_M$ which satisfies (IC) and (IR_M) and generates a higher (expected) joint payoffs for agents than M. Since $\mathcal{CM}_M \subset \mathcal{RM}_M$ and (IR_M) implies (IR), we have $\tilde{M} \in \mathcal{M}_M = \mathcal{RM}_M \cap \mathcal{M}$. Since M is RCP, $\tilde{M}$ yields the same payoff, V, to the principal. Consequently, $\tilde{M}$ must generate a strictly higher total surplus than M. But this contradicts the fact that M efficiently implements V. ▌

Our notion does not subsume LM's *strong collusion-proofness*, which requires collusion-proofness against all possible out-of-equilibrium beliefs. Our notion allows for a range of

[11] Jeon and Menicucci (2005) adopt the same notion except that they allow for reallocation by the agents. Hence, an RCP implementation will imply their notion as well.

reasonable out-of-equilibrium beliefs, including passive beliefs, but it implicitly rules out some extreme beliefs inconsistent with the agents' individual rationality.[12] Our concept is also incompatible with a notion that requires agents' participation constraints to hold at the ex post, rather than interim, level. Ex post participation constraints are motivated either by agents' colluding on participation decisions (Dequiedt (2004)) or by their having an exit option from the grand mechanism ex post (Mookherjee and Tsumagari (2004)). These latter possibilities are not allowed in our model of collusion, so the ex post participation constraint is not required in our notion of collusion proofness. Note that these other notions do not subsume our notion since we require robustness to many aspects of collusion discussed earlier.

6 RCP Implementation: Uncorrelated Types

We now present our main collusion-proof implementation result. We begin with the case in which the types are uncorrelated. Except for the type-independence, we maintain the generality of the environments presented in Section 2.

THEOREM 1 *Suppose that types are uncorrelated. Then, every $V \in \mathcal{V}$ is implementable by a robustly collusion-proof mechanism.*

PROOF: Fix any $V \in \mathcal{V}$, and suppose mechanism $M = (q, t) \in \mathcal{M}$ implements V. We now construct a RCP mechanism $\hat{M} = (\hat{q}, \hat{t}) \in \mathcal{M}$ that also implements V. Define $\hat{M} = (\hat{q}, \hat{t})$ such that $\hat{q}(\cdot) := q(\cdot)$ and that, for each $\theta \in \Theta$,

$$\begin{aligned}\hat{t}_i(\theta) := \kappa_i v(q(\theta)) + \mathbb{E}_{\tilde{\theta}_{-i}} \left[t_i(\theta_i, \tilde{\theta}_{-i}) - \kappa_i v(q(\theta_i, \tilde{\theta}_{-i})) \right] \\ - \frac{1}{n-1} \sum_{j \neq i} \mathbb{E}_{\tilde{\theta}_{-j}} \left[t_j(\theta_j, \tilde{\theta}_{-j}) - \kappa_j v(q(\theta_j, \tilde{\theta}_{-j})) \right] - \rho_i, \quad (4)\end{aligned}$$

where

$$\rho_i := \frac{1}{n-1} \mathbb{E} \left[(1 - \kappa_i) v(q(\tilde{\theta})) - \sum_{j \neq i} t_j(\tilde{\theta}) \right] \text{ and } \sum_{i \in N} \kappa_i = 1.$$

[12] If such beliefs are admitted, the third party representative may be able to force a collusive proposal that may not guarantee a reservation utility for some agent. This will undermine implementation since the latter agent will refuse to participate the grand contract.

Observe first that $\hat{t}(\cdot)$ gives the same interim transfers to the agents as $t(\cdot)$: $\forall i\ \forall \theta_i \in \Theta_i$,

$$\begin{aligned}\mathbb{E}_{\tilde{\theta}_{-i}}[\hat{t}_i(\theta_i,\tilde{\theta}_{-i})] = \mathbb{E}_{\tilde{\theta}_{-i}}[\kappa_i v(q(\theta_i,\tilde{\theta}_{-i}))] + \mathbb{E}_{\tilde{\theta}_{-i}}\left[t_i(\theta_i,\tilde{\theta}_{-i}) - \kappa_i v(q(\theta_i,\tilde{\theta}_{-i}))\right] \\ -\frac{1}{n-1}\sum_{j\neq i}\mathbb{E}_{\tilde{\theta}_j}\left[\mathbb{E}_{\tilde{\theta}_{-j}}\left[t_j(\tilde{\theta}_j,\tilde{\theta}_{-j}) - \kappa_j v(q(\tilde{\theta}_j,\tilde{\theta}_{-j}))\right]\right] - \rho_i \\ = \mathbb{E}_{\tilde{\theta}_{-i}}[t_i(\theta_i,\tilde{\theta}_{-i})]. \end{aligned} \tag{5}$$

It follows from (5) that $\hat{M}$ induces the same interim payoffs to the agents as M, so $\hat{M}$ satisfies (IC) and (IR). Further, (5) means that the principal attains the same expected payoff from $\hat{M}$ as from M:

$$\mathbb{E}[v(q(\tilde{\theta})) - \sum_{i\in N}\hat{t}_i(\tilde{\theta})] = \mathbb{E}[v(q(\tilde{\theta})) - \sum_{i\in N} t_i(\tilde{\theta})].$$

It now remains to show that $\hat{M}$ is RCP. To this end, we observe, $\forall \theta\in\Theta$,

$$\sum_{i\in N}\hat{t}_i(\theta) = v(q(\theta)) - \sum_{i\in N}\rho_i. \tag{6}$$

Consider any arbitrary reallocational manipulation of $\hat{M}$, $\tilde{M} = (\tilde{q}(\cdot),\tilde{t}(\cdot)) \in \mathcal{M}_{\hat{M}}$. Then, there exists a balanced-budget side contract $(\mu, y) : \Theta \mapsto \Delta\Theta \times \mathbb{R}^n$ such that $\tilde{t}(\theta) = \mathbf{E}_{\mu(\theta)}[\hat{t}(\tilde{\theta})] + y(\theta)$ and $v(\tilde{q}(\theta)) = \mathbf{E}_{\mu(\theta)}[v(q(\tilde{\theta}))]$, for each $\theta\in\Theta$. Thus, for each $\theta\in\Theta$,

$$\begin{aligned}\sum_{i\in N}\tilde{t}_i(\theta) &= \sum_{i\in N}\mathbf{E}_{\mu(\theta)}[\hat{t}_i(\tilde{\theta})] + \sum_{i\in N} y_i(\theta) = \mathbf{E}_{\mu(\theta)}[\sum_{i\in N}\hat{t}_i(\tilde{\theta})] \\ &= \mathbf{E}_{\mu(\theta)}[v(q(\tilde{\theta}))] - \sum_{i\in N}\rho_i = v(\tilde{q}(\theta)) - \sum_{i\in N}\rho_i, \end{aligned} \tag{7}$$

where the first and the last equalities follow from the definition of the reallocational manipulation, the second follows from the budget-balancedness of $y(\cdot)$, and the third follows from (6). It then follows from (7) that

$$\mathbb{E}[v(\tilde{q}(\tilde{\theta})) - \sum_{i\in N}\tilde{t}_i(\tilde{\theta})] = \sum_{i\in N}\rho_i = \mathbb{E}[v(q(\tilde{\theta})) - \sum_{i\in N} t_i(\tilde{\theta})], \tag{8}$$

thus proving that $\hat{M}$ is RCP. ▌

As seen from the proof, two features of our mechanism, $\hat{M}$, are central to its RCP implementation of an arbitrary mechanism M: First, as seen in (5), $\hat{M}$ preserves the same interim transfers as M, thus satisfying both (IR) and (IC) and giving the same expected payoff as M to the payoff. Second, as seen in (6), the transfers $\hat{t}_i(\cdot)$ are aggregated so that the principal collects the ex post constant payoff equal to the expected payoff he would have enjoyed under M. This feature forces the coalition to become a "residual claimant" when it manipulates M, ensuring that the principal will attain the desired payoff regardless of how the agents behave, once they participate. The first feature, i.e., (IC) and (IR), guarantees an equilibrium in which the agents indeed participate in the mechanism.

Since every feasible payoff for the principal can be RCP implementable, the following result is immediate.

Corollary 1 *If $V^* \in \mathcal{V}$, then there exists an RCP mechanism that implements the non-collusive optimal payoff for the principal.*

The intuition behind our results can be made more transparent with the aid of the following figure.

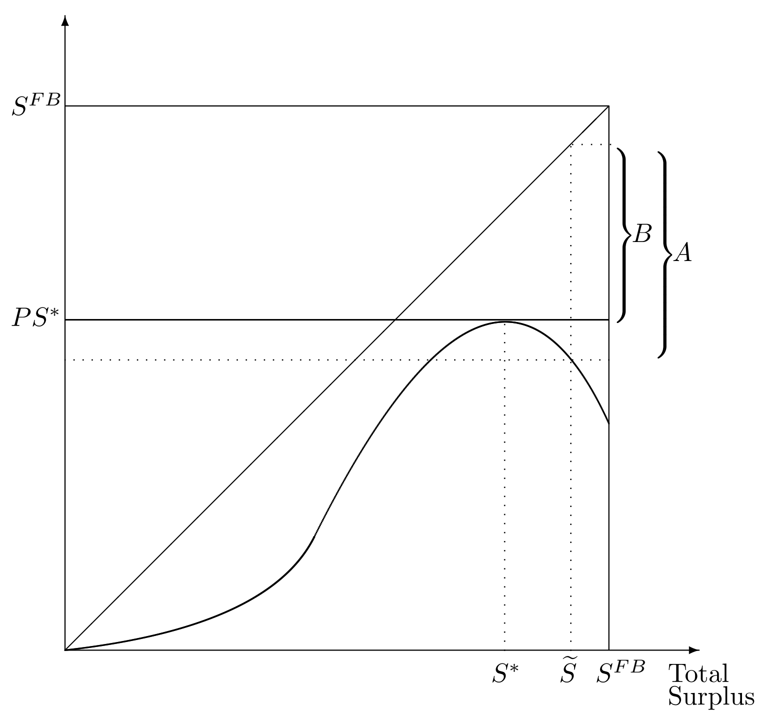

Figure 1

Assume for a moment that there is no collusion problem. It is useful to think of the mechanism design problem as that of implementing a particular (expected) social surplus level, $\mathbb{E}[v(\tilde{q}(\theta)) + \sum_{i\in N} s_i(\tilde{q}(\theta), \theta)]$, i.e., the sum of all players' payoffs including that of the principal. The horizontal axis of Figure 1 depicts all implementable (expected) social surplus levels, with the highest level marking the first-best level, say.[13] Obviously, to achieve a given social surplus level, say $\tilde{S}$, requires a particular allocation rule, $\tilde{q}(\cdot)$, and to implement the latter in turn requires giving away a certain amount (depicted by A in the Figure 1) of information rent to the agents. Suppose the difference between the 45 degree line and the curve below represents the minimal information rent that must be paid to the agents to implement the corresponding social surplus level. The curve below the 45 degree line then represents the (expected) surplus accruing to the principal after paying off the rents to the agents. The figure depicts a common situation in which the principal's surplus is maximized at a below-first-best social surplus level, S^*, because of the rent-saving benefit gained from distorting the allocation.[14] In the absence of collusion, the principal would thus choose to implement S^*.

We now introduce collusion and suppose that the principal proposes mechanism $\hat{M}$. Given mechanism $\hat{M}$, by inducing $(\tilde{q}(\cdot), \tilde{t}(\cdot))$ via manipulation say, the coalition members receive the joint payoff of

$$\sum_{i\in N}[\tilde{t}_i(\theta) + s_i(\tilde{q}(\theta), \theta)] = v(\tilde{q}(\theta)) + \sum_{i\in N} s_i(\tilde{q}(\theta), \theta) - \sum_{i\in N} \rho_i, \tag{9}$$

where the equality follows from (7). Hence, $\hat{M}$ forces the coalition to become residual claimants of the social surplus, after guaranteeing the principal an ex post constant surplus of

$$\sum_{i\in N} \rho_i = \mathbb{E}\left[v(q^*(\tilde{\theta})) - \sum_{i\in N} t_i^*(\tilde{\theta})\right],$$

described in the figure by the maximized level of the curve, PS^*. Hence, given $\hat{M}$, the coalition receives the difference between the 45 degree line and the horizontal line tangent at the principal's maximized surplus, PS^*. Clearly, the mechanism does not eliminate the potential for coalitional manipulation, since the coalition now prefers S^{FB} over S^*, which the principal wishes to implement.

[13] In general, the first-best allocation may not be implementable even in the noncollusive environment. See Jehiel and Moldovanu (2001), for instance. In such a case, S^{FB} should be taken to mean the highest implementable surplus level.

[14] This situation is quite common in many mechanism design problems. For instance, an optimal auction often involves a binding reserve price or handicapping, both of which entail an inefficient allocation. Likewise, nonlinear pricing often induces too little consumption by the buyers.

The reason the coalition cannot implement, via manipulation, S^{FB} — or any social surplus level other than S^* for that matter — is as follows: Since the coalition faces the same adverse selection problem as the principal faces in $[NC]$, the amount of information rents the coalition must pay to the agents is described as before — by the difference between the 45 degree line and the curve. Under $\hat{M}$, the amount of surplus left to the coalition after paying off the principal is the gap between the 45 degree line and the horizontal tangent line, which is strictly less than the information rents needed to implement such a level, for any social surplus level differing from S^*. If the collusion organizer wishes to implement $\tilde{S}$ (via manipulation), for instance, it will require the information rents of A, but the surplus left over after paying off the principal is only B, so implementing $\tilde{S}$ would entail a budget deficit of $A - B$, and is thus infeasible. Any deviation from S^* is unimplementable for the same reason. This is possible precisely because S^* is optimal for the principal among all implementable social surplus levels.

REMARK 1 *For an RCP implementation, the principal need not deal with the agents at all, opting rather to contract directly with their third-party representative. Fix an RCP mechanism $(\hat{t}, \hat{q})$ implementing any $V \in \mathcal{V}$. The principal can offer a menu $\{\hat{T}(\theta), \hat{q}(\theta)\}_{\theta\in\Theta}$ to the representative, where $\hat{T}(\cdot) := \sum_{i\in N} \hat{t}_i(\cdot)$ is a menu of total budgets. Facing such a contract, the representative will organize the coalition of agents and implement the desired payoff V for the principal. Absent collusion, such "delegation" would be trivial since the representative would act just like the original principal. The significance of the delegation is that it works even in the presence of collusion — i.e., even when the representative cares intrinsically about the welfare of the agents. In fact, such delegation may provide a practical way to implement an RCP mechanism. For instance, instead of hiring and supervising individual suppliers, a buyer may wish to outsource the job to an intermediary (or "prime contractor") of organizing and supervising a network of suppliers (or "subcontractors").*

REMARK 2 *The design of transfer rules in (4) is reminiscent of Arrow-d'Aspremont-Gérard-Varet mechanism (Arrow (1979) and d'Aspremont-Gérard-Varet (1979)). Their transfers preserve the incentives of Vickrey-Clarke-Groves mechanism with zero aggregate transfer. Ours implements the interim payoffs of any original mechanism with an ex post constant "surplus" for the principal. Eso and Frutos (1999) suggested a similar transfer rule giving rise to ex post constant "revenue," as an optimal mechanism for a risk-averse seller in a single-unit auction. See also Bose, Ozdenoren and Pape (2005). These mechanisms* *serve much different purposes in their analysis. Nonetheless, our model is more general and, our mechanism subsumes theirs as a special case (with $v(\cdot)$ being constant). For this reason, our construction would generalize their results. For instance, our RCP mechanism implementing V^* would be (noncollusive) optimal even if the principal were risk averse.*[15]

7 RCP Implementation: Correlated Types

We now turn to the case in which the agents' types are correlated. In this case, we already know from LM (2000) that collusion cannot be prevented for free in a public good model with two agents and two types. As we show below, however, our collusion-proof implementation result holds even in a large class of correlated type environments, if there are more than two agents. Given the well-known result by Crémer and McLean (1985, 1988), this implies that the principal can extract full rents and implement the first-best outcome *even if collusion is possible.*

Consider our general environment in Section 2, but assume that the joint type space, Θ, is finite. (The finite type space will enable us to utilize linear algebra, as will be seen.) Specifically, we assume that the support of agent $i \in N$'s type is given by $\Theta_i = \{\theta_i^1, ..., \theta_i^{\ell_i}\}$ with $\ell_i = |\Theta_i| \geq 2$. Let $L := \prod_{i \in N} \ell_i$. It is useful to index all elements of Θ (i.e., all possible type profiles) in an arbitrary order so that $\Theta = \{\theta^1, ..., \theta^L\}$. We then suppose that each type profile $\theta \in \Theta$ is realized by a joint probability, $\mu^0(\theta) \in [0, 1]$ such that $\sum_{\theta' \in \Theta} \mu^0(\theta') = 1$, with $\mu^0 := (\mu^0(\theta^1), ..., \mu^0(\theta^L))'$ representing the vector of joint probabilities of all type profiles listed in the order mentioned above.

Fix any mechanism $M = (q(\cdot), t(\cdot)) \in \mathcal{M}$, attainable in a noncollusive environment. As before, we consider a new mechanism, $\hat{M} = (q(\cdot), \hat{t}(\cdot))$, that satisfies two properties on the transfer rule: (a) it satisfies both (IC) and (IR) and yields the same interim transfers to the agents as M, and (b) it ensures that the principal enjoys an ex post constant surplus that equals the expected surplus she would enjoy under M.

Formally, (a) holds if,

$$\sum_{\theta_{-i} \in \Theta_{-i}} \mu^0(\theta_i^k, \theta_{-i}) \hat{t}_i(\theta_i^{k'}, \theta_{-i}) = \sum_{\theta_{-i} \in \Theta_{-i}} \mu^0(\theta_i^k, \theta_{-i}) t_i(\theta_i^{k'}, \theta_{-i}), \forall i \text{ and } \forall \theta_i^k, \theta_i^{k'} \in \Theta_i \quad (10)$$

[15] More precisely, the RCP mechanism implementing V^* is the unique optimal mechanism for a principal with a strictly concave von-Neumann Morgenstern utility function, $u_0(a(x) - \sum_{i \in N} t_i)$.

and (b) holds if

$$\sum_{i\in N}\hat{t}_i(\theta')=v(q(\theta'))-\rho,\forall\theta'\in\Theta, \tag{11}$$

where $\rho:=\mathbb{E}[v(q(\tilde{\theta}))-\sum_{i\in N}t_i(\tilde{\theta})]$. Since t satisfies (IC) and (IR), (10) ensures that $\hat{t}$ satisfies (IC) and (IR) and yields the same interim payoffs to all the players as M. Meanwhile, (11) makes the agents residual claimants. Together, these two features guarantee that $\hat{M}$ implements the optimal noncollusive mechanism M in a collusion-proof fashion.

We describe these two restrictions by a system of linear equations. To begin, define for each i and $\theta_i^k,\theta_i^{k'}\in\Theta_i$ with $\theta_i^{k'}\neq\theta_i^k$,

$$\begin{aligned} T_i(\theta_i^k) &:= \sum_{\theta_{-i}\in\Theta_{-i}}\mu^0(\theta_i^k,\theta_{-i})t_i(\theta_i^k,\theta_{-i}) \\ S_i(\theta_i^k,\theta_i^{k'}) &:= \sum_{\theta_{-i}\in\Theta_{-i}}\mu^0(\theta_i^k,\theta_{-i})t_i(\theta_i^{k'},\theta_{-i}). \end{aligned}$$

In words, $T_i(\theta_i^k)$ and $S_i(\theta_i^k,\theta_i^{k'})$ denote the interim transfer agent i of type θ_i^k receives when reporting truthfully and when misreporting to be of type $\theta_i^{k'}$, respectively, given that all other agents report truthfully. We can then form interim transfer vectors as follows:

$$T_i:=(T_i(\theta_i^k))_{\theta_i^k\in\Theta_i} \text{ and } S_i:=(S_i(\theta_i^k,\theta_i^{k'}))_{\theta_i^k,\theta_i^{k'}\in\Theta_i,\ \theta_i^k\neq\theta_i^{k'}}.$$

We next form a vector of transfers for the new mechanism. For each $i\in N$, let

$$\hat{t}_i:=(\hat{t}_i(\theta^1),\ldots,\hat{t}_i(\theta^L))'.$$

(That is, the elements of the vector are listed in the order of $\Theta=\{\theta^1,...,\theta^L\}$.) Next, we form a matrix P_i, of size $\ell_i\times L$, which represents the probabilities over the reported types of all agents when agent i reports truthfully. Specifically, the m-th element of a row corresponding to $T_i(\theta_i^k)$ has probability $\mu^0(\theta_i^k,\theta_{-i})$ if $\theta^m=(\theta_i^k,\theta_{-i})$, and zero otherwise. Similarly, a matrix B_i, of size $\ell_i(\ell_i-1)\times L$, represents the probabilities over the reported types when agent i lies. Specifically, the m-th element of a row corresponding to $S_i(\theta_i^k,\theta_i^{k'})$ has probabilities $\mu^0(\theta_i^k,\theta_{-i})$ if $\theta^m=(\theta_i^{k'},\theta_{-i})$, and zero otherwise.[16] Then, (10) is expressed as:

$$\begin{pmatrix}P_i\\B_i\end{pmatrix}\times\hat{t}_i=\begin{pmatrix}T_i\\S_i\end{pmatrix}\ \forall i\in N.$$

[16]It is useful to consider a specific example. Suppose there are three agents, and each has two types, $\Theta_i=\{1,2\}$, $i=1,2,3$. Suppose Θ is indexed as $\{111,112,121,122,211,212,221,222\}$, where the type

To combine with the second property, we define a vector of length L:

$$v - \rho := (v(q(\theta^1)) - \rho, ..., v(q(\theta^L)) - \rho)'.$$

Then, (10) and (11) are described in matrix forms as:

$$\begin{pmatrix} \Pi_1 & \dots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \dots & \Pi_n \\ I_L & \cdots & I_L \end{pmatrix} \times \begin{pmatrix} \hat{t}_1 \\ \vdots \\ \hat{t}_n \end{pmatrix} = \begin{pmatrix} T_1 \\ S_1 \\ \vdots \\ T_n \\ S_n \\ v-\rho \end{pmatrix} \tag{12}$$

where $\Pi_i := \begin{pmatrix} P_i \\ B_i \end{pmatrix}$ and I_L is the identity matrix of size L.

The next condition proves to be sufficient for the existence of a solution to (12):

CONDITION **(PI′)**: *There exist agents i and j such that*

$$rank \begin{pmatrix} \Pi_i \\ \Pi_j \end{pmatrix} = rank \begin{pmatrix} \Pi_i \end{pmatrix} + rank \begin{pmatrix} \Pi_j \end{pmatrix} - 1. \tag{13}$$

Condition (PI′) requires that the spaces spanned by the rows of Π_i and those spanned by the rows of Π_j should not intersect except for an one-dimensional vector space, which accounts for a redundancy in the system of equations.[17] Intuitively, it requires that the

profile ijk refers to agent 1 being of type i, 2 of type j and 3 of type k. Then,

$$P_2 = \begin{pmatrix} \mu^0(111) & \mu^0(112) & 0 & 0 & \mu^0(211) & \mu^0(212) & 0 & 0 \\ 0 & 0 & \mu^0(121) & \mu^0(122) & 0 & 0 & \mu^0(221) & \mu^0(222) \end{pmatrix} \text{ and}$$
$$B_2 = \begin{pmatrix} 0 & 0 & \mu^0(111) & \mu^0(112) & 0 & 0 & \mu^0(211) & \mu^0(212) \\ \mu^0(121) & \mu^0(122) & 0 & 0 & \mu^0(221) & \mu^0(222) & 0 & 0 \end{pmatrix},$$

where $\mu^0(ijk)$ is the probability of agents 1, 2 and 3 being respectively of types i, j and k. The first and second rows of the above P_2 correspond to $T_2(1)$ and $T_2(2)$, respectively. The first and second rows of B_2 correspond to $S_2(1, 2)$ and $S_2(2, 1)$, respectively.

[17] The redundancy comes from an accounting identity associated with the fact that the equilibrium transfers specified in top and bottom parts of the system must be consistent with each other. To be specific, if we premultiply the equations of (12) corresponding to T_i by the probability vector $\mu^{0\prime}$, we

untruthful reports by agents i and all possible reports by agent j induce distinct probability distributions over the entire report profiles, assuming all others report truthfully. This feature provides the flexibility needed to mimic the incentive design of t and at the same time makes the agents residual claimants.[18]

Our main results follow.

LEMMA 1 *Given Condition (PI′), a solution, $\hat{t} \in \mathbb{R}^{nL}$, to (12) exists.*

PROOF: See Appendix A.

THEOREM 2 *Given Condition (PI′), every $V \in \mathcal{V}$ is RCP implementable.*

PROOF: Fix any $M = (q, t) \in \mathcal{M}$. Then, given the Condition (PI′) and Lemma 1, we can consider a mechanism $\hat{M} = (q(\cdot), \hat{t}(\cdot))$, where $\hat{t}(\cdot)$ solves the system of linear equations in (12). Since $\hat{t}(\cdot)$ satisfies (10), the interim transfers, and thus interim payoffs, for the agents are precisely the same under $\hat{M}$ as under M, for any possible report each agent may make, assuming that all other agents report truthfully. This guarantees that $\hat{M}$ satisfies (IC) and (IR) and yields the same interim payoffs to all players as M. Next, since $\hat{t}$ satisfies (11), the same argument as in the proof of Theorem 1 proves that $\hat{M}$ is RCP. ▮

obtain the aggregate expected transfers in equilibrium:

$$\sum_{i \in N} \mu^{0\prime} \cdot \hat{t}_i = \sum_{i \in N} \mathbb{E}[\hat{t}_i(\tilde{\theta})] = LHS = RHS = \sum_{i \in N} \sum_{\theta_i \in \Theta_i} T_i(\theta_i) = \sum_{i \in N} \mathbb{E}[t_i(\tilde{\theta})].$$

This must be consistent with the restrictions on the aggregate transfers in expected value. In particular, we obtain the same equation by premultiplying the bottom L equations of (12) with the probability vector $\mu^{0\prime}$:

$$\sum_{i \in N} \mathbb{E}[\hat{t}_i(\tilde{\theta})] = LHS = RHS = \mu^{0\prime} \cdot (v - \rho) = \mathbb{E}[v(q(\tilde{\theta}))] - \mathbb{E}[v(q(\tilde{\theta})) - \sum_{i \in N} t_i(\theta)] = \sum_{i \in N} \mathbb{E}[t_i(\tilde{\theta})].$$

[18]Similar conditions have appeared in the literature in the context of repeated games and static mechanism design with budget balancing (see Fudenberg, Levine, and Maskin (1994, 1995) and Kosenok and Severinov (2004)). *Pairwise identifiability for a pair of agents i and j*, considered by Fudenberg, et al., requires the same rank condition, except that Π_i represents probability distributions corresponding to different *strategies* rather than all pairs of reports and states. So Π_i has $\ell_i^{\ell_i}$ rows in the pairwise identifiability, whereas Π_i in our (PI′) has ℓ_i^2 rows. In fact, it can be shown that the pairwise identifiability is weaker than (PI′) in the sense that if (13) holds for a pair of agents i and j, then pairwise identifiability holds for the same pair. Several conditions proposed by Kosnok and Severinov (2004) are closely related to (PI′). In fact, the genericity of (PI′) follows from the genericity of one of their conditions, as stated in Lemma 2.

It can be readily checked that Condition (PI′) fails generically if there are only two agents. In that case, generically, the RHS of (13) becomes $\ell_i\ell_j + \min\{\ell_i^2, \ell_j^2\} - 1$, thus exceeding the rank of the stacked matrix on its LHS, which equals $\ell_i\ell_j$ generically.[19] This is consistent with LM (2000), which finds that the principal is strictly worse off from collusion and that the principal's optimized payoff is continuous at zero correlation, if the agents' types are correlated. The latter finding of LM contrasts with the noncollusive mechanism design, which displays a discontinuous shift from a typical second-best outcome to a full-extraction first-best outcome when an arbitrarily small amount of type correlation is added.

If there are more than two agents, however, Condition (PI′) holds quite generally, so LM (2000)'s result does not hold.[20] The following result due to Kosenok and Severinov (2004) makes the statement precise.

LEMMA 2 *(Kosenok and Severinov) Suppose that $n \geq 3$ and that, if $n = 3$, at least one agent has more than two types. Then condition (PI′) holds for generic $\mu^0(\cdot)$.*[21]

PROOF: This result follows from Step 3 through 5 in the proof of Lemma 3 of Kosenok and Severinov (2004, pp. 26-28). In particular, they prove that, given the condition, the matrix on the LHS of (13) has a one-dimensional kernel for a generic $\mu^0(\cdot)$, for $j := \arg\min_{k\in N} \ell_k$ and $i := \arg\min_{k\in N\setminus\{j\}} \ell_k$. Hence, (13) holds for that pair, generically. ▮

Given Lemma 2, our collusion-proof implementation holds generically for any $n \geq 3$, with the additional requirement that an agent must have more than two types if $n = 3$. It is not difficult to see why adding a new agent makes it easier to satisfy the properties required for collusion-proofness. Suppose there are two agents with two possible types. Then the transfer rule specifies 8 transfer amounts: A transfer amount is specified for each of 4 joint realizations of types for each of the two agents. Meanwhile, the number of equations required by (12) is 12, so the system has no solution. Intuitively, the transfer

[19] Generically, each matrix on the RHS has a full rank since different reports by an agent induces a different distributions over the other agent's reports when the latter reports truthfully. Hence, the ranks sum to $(\ell_i + \ell_j)\min\{\ell_i, \ell_j\} - 1 = \ell_i\ell_j + \min\{\ell_i^2, \ell_j^2\} - 1$.

[20] LM's result with two agents means, however, that collusion will matter again if a subgroup of two agents are collusive. As will be noted in Remark 1, our method does not generalize to the subgroup collusion problem, if types are correlated. In this sense, the LM's point remains valid.

[21] This condition means that the probability distributions μ^0 for which the condition holds has full Lebesque measure in the $n-1$ dimensional simplex.

rule does not give a sufficient number of degrees of freedom to "sell the firm to the agents" while preserving the original incentive design of t. As the number of agents increases, the number of unknowns (the transfer amounts to be specified) increases multiplicatively while the number of restrictions increases only additively. The reason is that the restrictions implied by (a) need to hold only at the interim level. To be concrete, suppose that there is another agent with three types.[22] Then, the number of transfer amounts to be specified grows to 36 (i.e., a transfer specified for each of 12 joint type realizations for each of the three agents), whereas the number of equations required by (12) grows only to 29. This creates enough flexibility to satisfy both (a) and (b).[23]

As is well known from Crémer and McLean (1988), the full-extraction first-best outcome is implementable for generic $\mu^0(\cdot)$.[24] Lemma 2 implies that the outcome is attainable even in the collusive environment in a broad set of circumstances.

COROLLARY 2 *Given the condition of Lemma 2, for a generic $\mu^0(\cdot)$, there exists a RCP mechanism that implements the full-extraction first-best outcome.*

8 Collusion by a Subgroup of Agents

So far, we have only considered the possibility of collusion involving all agents. In many situations, however, only a subset of agents may be in a position to collude. For instance, in construction procurement auctions in which both local and non-local firms compete, local firms may be able to collude more effectively, based on their regular contacts and the trade association relationships. Can such collusion be prevented?

[22] If the third agent has two types, then the system in (12) has more unknowns than the number of equations. But, the matrix on its LHS has a two dimensional kernel, whereas the system has only one dimensional redundancy. So, the solution does not exist generically.

[23] As footnote 22 indicates, the comparison between the number of equations and unknowns does not inform us of the existence of a solution because of possible linear dependence across the required equations. Nonetheless, the comparison is suggestive of how the properties required for collusion-proofness can be met.

[24] The full-extraction first-best outcome is defined as in Crémer and McLean (1988). In our context, it means that (IR) is binding for all agents for all types, and implemented allocation rule has

$$q^*(\theta) \in \arg\max_{q\in\mathcal{Q}} v(q) + \sum_{i\in N} s_i(q(\theta),\theta),$$

for all $\theta \in \Theta$. The conditions for that outcome to be implementable is shown to be generic.

Preventing collusion by a subgroup of agents introduces a new consideration in mechanism design, since one has to consider the effect of collusion on the incentives of noncollusive agents. In particular, a coalition may gain from preying on the noncollusive agents by shifting rents away from them.[25] Hence, an important element of a collusion-proof mechanism is to protect noncollusive agents' interests/incentives appropriately. This section discusses how the basic idea of collusion-proof implementation generalizes to this case. We again restrict the economic environment to uncorrelated types; a remark will be made later on the correlated types case.

We begin with the model of subgroup collusion. To this end, consider a coalition, $C \subset N$, of agents with $1 < |C| \leq n$. The time line of the game and its modeling framework are analogous to the case with collusion by the grand coalition. Hence, the robust collusion-proofness concept generalizes naturally to this partial collusion case. To begin, we define a side contract among coalition C, called a *C-side contract*, by a pair of functions, $(\mu^C, y^C) : \Theta_C \mapsto \Delta\Theta_C \times \mathbb{R}^{|C|}$, where μ^C determines the probability distribution of reports on the coalition's types in Θ_C. Then, for any direct mechanism $M = (q(\cdot), t(\cdot))$, we call $\tilde{M} = (\tilde{q}(\cdot), \tilde{t}(\cdot)) \in \mathcal{M}$ its *reallocational manipulation by C* if there exists a balanced-budget C-side contract, $(\mu^C, y^C) : \Theta_C \mapsto \Delta\Theta_C \times \mathbb{R}^{|C|}$, such that $\forall \theta$

$$\tilde{t}_i(\theta) = \begin{cases} \mathbf{E}_{\mu^C(\theta_C)}[t_i(\theta_{N\backslash C}, \tilde{\theta}_C)] + y_i^C(\theta_C), & \text{if } i \in C \\ \mathbf{E}_{\mu^C(\theta_C)}[t_i(\theta_{N\backslash C}, \tilde{\theta}_C)], & \text{if } i \in N\backslash C, \end{cases} \tag{14}$$

$$v(\tilde{q}(\theta)) = \mathbf{E}_{\mu^C(\theta_C)}[v(q(\theta_{N\backslash C}, \tilde{\theta}_C)] \tag{15}$$

and

$$s_i(\tilde{q}(\theta), \theta) = \mathbf{E}_{\mu^C(\theta_C)}[s_i(q(\theta_{N\backslash C}, \tilde{\theta}_C), \theta)], \ \forall i \in N\backslash C. \tag{16}$$

Note that a reallocational manipulation is required to be undetectable not only to the principal (see (15)) but also to the noncollusive agents (see (16)). In a single unit auction with 2 collusive bidders and 1 noncollusive one, for instance, the latter restriction means that reallocation of the object between the two colluders is possible only when the object is initially assigned to one of the two collusive bidders.[26]

[25] Whether this problem arises depends on the grand mechanism in place. For instance, if a subset of bidders collude in a first-price auction, this may actually benefit noncollusive bidders.

[26] Consider for instance a single-unit interdependent value auction in which a bidder $i = 1, 2, 3$ realizes the valuation of $a_i(\theta_1, \theta_2, \theta_3)$ from winning the good (and zero for not winning), and suppose for simplicity that the seller never retains the good. Then, the reallocation ability by a coalition $C = \{1, 2\}$ means that

Similar to the grand coalition case, we say that a reallocational manipulation of M by coalition C, $\tilde{M}$, is *feasible* if it satisfies

$$(IR^C) \qquad U_i^{\tilde{M}}(\theta_i) \geq \overline{U}_i(\theta_i),\ \forall i \in C, \theta_i,$$

and

$$(IC^C) \qquad U_i^{\tilde{M}}(\theta_i) \geq u_i^{\tilde{M}}(\tilde{\theta}_i, \theta_i),\ \forall i \in C, \theta_i, \tilde{\theta}_i,$$

and let $\mathcal{M}_M^C$ denote the set of all feasible reallocational manipulations of M by coalition C. Note that a feasible reallocational manipulation by the coalition need not satisfy incentive compatibility and individual rationality of the agents outside that coalition, since the latter does not care about the noncollusive agents. Instead, we impose these conditions as part of the coalition-proofness requirements.

Definition 2 *A direct mechanism M is* ***robustly collusion-proof*** *(or* ***RCP****)* ***with respect to coalition*** *$C \subset N$ if $\mathcal{M}_M^C \subset \mathcal{M}$ and every manipulation in $\mathcal{M}_M^C$ gives the same expected payoff to the principal as mechanism M.*

The notion of collusion-proofness here is essentially the same as before, except for the additional requirement that every reallocational manipulation by a coalition must be also incentive compatible and individually rational to noncollusive agents.[27] The extra requirement is added to protect the interests/incentives of the noncollusive agents against possible manipulation by the coalition, thus ensuring their participation and ultimately the intended payoff of the principal. Suppose the subcoalition wishes to induce a manipulation $\tilde{M} = (\tilde{q}, \tilde{t}) \in \mathcal{M}_M^C$ that violates either incentive compatibility or individual rationality of some noncollusive agent. If such a manipulation is anticipated, then the latter agent may

a resulting allocation $\tilde{q}$ must satisfy, $\forall \theta = (\theta_1, \theta_2, \theta_3)$,

$$\tilde{q}_1(\theta) + \tilde{q}_2(\theta) = q_1(\tilde{\theta}_1, \tilde{\theta}_2, \theta_3) + q_2(\tilde{\theta}_1, \tilde{\theta}_2, \theta_3)$$

for any manipulation $(\tilde{\theta}_1, \tilde{\theta}_2)$ by C. It then follows that

$$s_3(\tilde{q}(\theta), \theta) = (1 - \tilde{q}_1(\theta) - \tilde{q}_2(\theta))a_3(\theta) = (1 - q_1(\tilde{\theta}_1, \tilde{\theta}_2, \theta_3) - q_2(\tilde{\theta}_1, \tilde{\theta}_2, \theta_3))a_3(\theta) = s_3(q(\tilde{\theta}_1, \tilde{\theta}_2, \theta_3), \theta),$$

which implies (16).

[27] This requirement is superfluous in the case of the grand coalition since a feasible manipulation is assumed to satisfy incentive compatibility and individual rationality for all agents.

lie about his type or not participate in M, in which case the principal may not receive the same expected payoff as M.

The additional requirement in collusion-proofness translates into an additional property to satisfy in mechanism design. We say a mechanism $M = (q(\cdot), t(\cdot))$ is *ex post implementable*, if it is *ex post individually rational*:

$$s_i(q(\theta_i, \theta_{-i}), \theta) - t_i(\theta_i, \theta_{-i}) \geq \overline{U}_i(\theta_i),\ \forall i, \forall \theta_i, \forall \theta_{-i} \tag{17}$$

and *ex post incentive compatible:*

$$s_i(q(\theta_i, \theta_{-i}), \theta) - t_i(\theta_i, \theta_{-i}) \geq s_i(q(\theta_i', \theta_{-i}), \theta) - t_i(\theta_i', , \theta_{-i}),\ \forall i, \forall \theta_i, \forall \theta_i', \forall \theta_{-i}. \tag{18}$$

Let $\mathcal{V}^{EP}$ denote the set of payoffs that the principal can attain by ex post implementable mechanisms. Clearly, $\mathcal{V}^{EP} \subset \mathcal{V}$. Later, we provide a more clear sense about $\mathcal{V}^{EP}$ by presenting a sufficient condition for ex post implementability.

THEOREM 3 *Suppose the types are uncorrelated, and fix any two agents $i, j \in N$. Then, any $V \in \mathcal{V}^{EP}$ is implementable by a mechanism that is RCP with respect to any coalition C containing $\{i, j\}$.*

PROOF: Fix any $V \in \mathcal{V}^{EP}$, and suppose $M = (q, t) \in \mathcal{M}$ ex post implements V. For any two agents, $i, j \in N$, we construct a new mechanism, $\bar{M}_{ij} \in \mathcal{M}$, that would RCP implement V. Let a mechanism, $\bar{M}_{ij} := (q(\cdot), \bar{t}(\cdot))$, be such that, for each $k \neq i, j$, $\forall \theta$,

$$\bar{t}_k(\theta) = t_k(\theta),$$

and, for i, $\forall \theta \in \Theta$,

$$\begin{aligned}
\bar{t}_i(\theta) \quad = \quad & \tfrac{1}{2}[v(q(\theta)) - \sum_{k \neq i,j} t_k(\theta)] + \mathbb{E}_{\tilde{\theta}_{-i}} \left[t_i(\theta_i, \tilde{\theta}_{-i}) - \tfrac{1}{2} \left\{ v(q(\theta_i, \tilde{\theta}_{-i})) - \sum_{k \neq i,j} t_l(\theta_i, \tilde{\theta}_{-i}) \right\} \right] \\
& - \mathbb{E}_{\tilde{\theta}_{-j}} \left[t_j(\theta_j, \tilde{\theta}_{-j}) - \tfrac{1}{2} \left\{ v(q(\theta_j, \tilde{\theta}_{-j})) - \sum_{k \neq i,j} t_k(\theta_j, \tilde{\theta}_{-j}) \right\} \right] \\
& - \mathbb{E} \left[\tfrac{1}{2} \left\{ v(q(\tilde{\theta}) - \sum_{k \neq i,j} t_k(\tilde{\theta}) \right\} - t_j(\tilde{\theta}) \right],
\end{aligned}$$

and symmetrically for j; i.e., $\bar{t}_j$ defined exactly the same with the roles of i and j switched.

Observe first that, $\forall k$, $\forall \theta_k \in \Theta_k$,

$$\mathbb{E}_{\tilde{\theta}_{-k}}\left[\bar{t}_k(\theta_k, \tilde{\theta}_{-k})] = \mathbb{E}_{\tilde{\theta}_{-k}}[t_k(\theta_k, \tilde{\theta}_{-k})\right], \tag{19}$$

so $\bar{M}$ satisfies (IC) and (IR) and attains the same value as M. Hence, $\bar{M}$ implements V.

We next show that $\bar{M}$ is RCP with respect to any coalition C containing agents i and j. To show this, fix any such coalition C and choose any feasible reallocational manipulation of $\bar{M}$ by C, say $\tilde{M} = (\tilde{q}(\cdot), \tilde{t}(\cdot)) \in \mathcal{M}^C_{\bar{M}}$. Then, there exists a balanced-budget C-side contract $(\mu^C(\cdot), y^C(\cdot))$ satisfying (14), (15) and (16). Further, $\tilde{M}$ satisfies (IC^C) and (IR^C), so it is incentive compatible and individually rational for any collusive agent in C. Consider now any $k \in N \backslash C$. Then, $\forall \theta_k, \theta'_k \in \Theta_k, \forall \theta_{-k} \in \Theta_{-k}$,

$$\begin{aligned} s_k(\tilde{q}(\theta_k, \theta_{-k}), \theta) + \tilde{t}_k(\theta_k, \theta_{-k}) &= \mathbf{E}_{\mu^C(\theta_C)}[s_k(q(\theta_k, \theta_{N\backslash C-k}, \tilde{\theta}_C), \theta) + \bar{t}_k(\theta_k, \theta_{N\backslash C-k}, \tilde{\theta}_C)] \\ &= \mathbf{E}_{\mu^C(\theta_C)}[s_k(q(\theta_k, \theta_{N\backslash C-k}, \tilde{\theta}_C), \theta) + t_k(\theta_k, \theta_{N\backslash C-k}, \tilde{\theta}_C)] \\ &\geq \mathbf{E}_{\mu^C(\theta_C)}[s_k(q(\theta'_k, \theta_{N\backslash C-k}, \tilde{\theta}_C), \theta) + t_k(\theta'_k, \theta_{N\backslash C-k}, \tilde{\theta}_C)] \\ &= s_k(\tilde{q}(\theta'_k, \theta_{-k}), \theta) + \tilde{t}_k(\theta'_k, \theta_{-k}), \end{aligned}$$

where the first and last equalities follow from (14) and (16), the second follows from the construction of $\bar{t}_k$ for $k \in N\backslash C$, and the lone inequality follows from ex post implementability of M. Likewise, $\forall k \in N\backslash C$, $\forall \theta_k, \theta_{-k}$,

$$\begin{aligned} s_k(\tilde{q}(\theta), \theta) + \tilde{t}_k(\theta) &= \mathbf{E}_{\mu^C(\theta_C)}[s_k(q(\theta_k, \theta_{N\backslash C-k}, \tilde{\theta}_C), \theta) + t_k(\theta_k, \theta_{N\backslash C-k}, \tilde{\theta}_C)] \\ &\geq \mathbf{E}_{\mu^C(\theta_C)}[\overline{U}_k(\theta_k)] = \overline{U}_k(\theta_k). \end{aligned}$$

These inequalities prove that $\tilde{M}$ is also incentive compatible and individually rational for agent $k \in N\backslash C$. In sum, $\tilde{M}$ must satisfy (IC) and (IR). Since $\tilde{M}$ is an arbitrary element of $\mathcal{M}^C_{\bar{M}}$, this proves that $\mathcal{M}^C_{\bar{M}} \subset \mathcal{M}$.

It now remains to show that $\tilde{M}$ implements V. Observe, $\forall \theta \in \Theta$,

$$\begin{aligned} \sum_{k\in N} \tilde{t}_k(\theta) &= \sum_{k\in N} \mathbf{E}_{\mu^C(\theta_C)}[\bar{t}_k(\theta_{N\backslash C}, \tilde{\theta}_C)] + \sum_{k\in C} y^C_k(\theta_C) \\ &= \sum_{k=i,j} \mathbf{E}_{\mu^C(\theta_C)}[\bar{t}_k(\theta_{N\backslash C}, \tilde{\theta}_C)] + \sum_{k\neq i,j} \mathbf{E}_{\mu^C(\theta_C)}[\bar{t}_k(\theta_{N\backslash C}, \tilde{\theta}_C)] \\ &= \mathbf{E}_{\mu^C(\theta_C)}[\sum_{k=i,j} \bar{t}_k(\theta_{N\backslash C}, \tilde{\theta}_C)] + \mathbf{E}_{\mu^C(\theta_C)}[\sum_{k\neq i,j} t_k(\theta_{N\backslash C}, \tilde{\theta}_C)] \\ &= \mathbf{E}_{\mu^C(\theta_C)}[v(q(\theta_{N\backslash C}, \tilde{\theta}_C)) - \sum_{k\neq i,j} t_k(\theta_{N\backslash C}, \tilde{\theta}_C)] - \mathbb{E}[v(q(\tilde{\theta})) - \sum_{k\in N} t_k(\tilde{\theta})] \end{aligned}$$

$$+\mathbf{E}_{\mu^C(\theta_C)}[\sum_{k\neq i,j} t_k(\theta_{N\setminus C}, \tilde{\theta}_C)]$$

$$= \quad v(\tilde{q}(\theta)) - \mathbb{E}[v(q(\tilde{\theta})) - \sum_{k\in N} t_k(\tilde{\theta})],$$

where the first equality follows from (14), the second from the budget-balancedness of the side contract, the third from (14) and the switching of expectation and summation, the fourth from the construction of $\bar{t}(\cdot)$, and the fifth from collecting terms and from (15). It follows that

$$\mathbb{E}[v(\tilde{q}(\tilde{\theta})) - \sum_{i\in N} \tilde{t}_i(\tilde{\theta})] = \mathbb{E}[v(q(\tilde{\theta})) - \sum_{i\in N} t_i(\tilde{\theta})] = V, \tag{20}$$

proving that $\tilde{M}$ implements V. We thus conclude that $\bar{M}$ is RCP with respect to C. ▌

According to this proposition, the principal need to identify *only* two members of any possible coalition to handle *any* collusion involving the two, including the grand collusion. Hence, neither the principal nor any noncollusive agents need to know the precise size or the membership of the coalition, as long as two core members of collusion are identified. The RCP mechanism that does this has three features: (1) As before, the mechanism involves the selling of the firm to the agents as a whole, thus ensuring an ex post constant surplus to the principal, (2) Unlike before, the mechanism forces the two chosen agents to bear the principal's payment risk toward all other agents, and (3) All other agents' incentive compatibility and participation utility are preserved at the ex post level, for all feasible reallocational manipulations by coalition including the two agents. Features (2) and (3) ensure the participation of noncollusive agents, which, along with (1), ensures the target level of surplus to the principal.[28] The last feature, (3), requires ex post implementability of an outcome. Although that requirement limits the class of allocations/environments to which the above result applies, many plausible environments are known to be in that class. For instance, Mookherjee and Reichelstein (1992) [Proposition 2] and Chung and Ely (2003) [Proposition 4] provide the following sufficient condition.

LEMMA 3 *(Mookherjee-Reichelstein & Chung-Ely) Suppose* $\Theta_i \equiv [\underline{\theta}_i, \overline{\theta}_i]$ *(i.e., one dimensional support) and* $\overline{U}_i(\theta_i) = \overline{U}_i$ *for all* $i \in N$*. Then, for any allocation rule* $q(\cdot)$ *such*

[28] Given that the original mechanism is ex post implementable, a mechanism satisfying (1) can be made ex post implementable for at most $n-2$ agents. This explains why at least two collusive agents need to be identified.

that

$$\frac{\partial}{\partial \theta_i} s_i(q(\theta_i', \theta_{-i}), \theta) \text{ is nonnegative and nondecreasing in } \theta_i', \forall i, \forall \theta_i, \forall \theta_{-i}, \tag{21}$$

there exists a transfer rule $t(\cdot)$ such that $M = (q, t)$ is ex post implementable.[29]

Corollary 3 *If any $V \in \mathcal{V}$ is implementable by M whose allocation rule satisfies the properties of Lemma 3, then, for any two agents i, j, V is implementable by a mechanism that is RCP with respect to any C containing i and j.*

The assumed properties in Lemma 3 hold at the optimal mechanism in many well-known mechanism design problems, such as auctions, procurement, regulation, nonlinear pricing and public goods provision.[30] While the sufficient condition presumes a continuous type space, a discrete type problem can be reformulated as a continuous type problem without any loss (see Skreta (2004), for example). Hence, the result applies to all existing models of collusion.

Remark 3 *(Correlated Types and Subgroup Collusion) We conjecture that a version of Theorem 3 holds generically in a large class of correlated types cases, with $|C| \geq 3$. Ex post implementability appears problematic, however. Even though ex post incentive compatibility alone seems feasible generically (see Mookherjee and Reichelstein (1992)), that requirement combined with ex post individual rationality is difficult to satisfy for the full-extraction first-best outcome. Whether and at what cost collusion by a subset of agents can be prevented remains an open question in the correlated type environment.*

[29] While Proposition 2 of Mookherjee and Reichelstein (1992) from which this lemma is adapted does not prove ex post individual rationality, it is implied as Mookherjee and Reichelstein (1992) and Chung and Ely (2003) argue since the first condition implies that there is a single worst type.

[30] The connection with literature can be made more clear with the following sufficient conditions due to MR:

(i) One-dimensional condensation: There exists $h_i : \mathcal{Q} \to \mathbb{R}$ and $d_i(\cdot,\cdot) : \mathbb{R} \times \Theta \to \mathbb{R}$, twice differentiable, such that $s_i(q, \theta) = d_i(h_i(q), \theta)$.

(ii) Single crossing: $\frac{\partial^2 d_i}{\partial h_i \partial \theta_i} \geq 0$.

(iii) Ex post monotonicity: $\forall \theta_{-i} \in \Theta_{-i}$, $h_i(q(\theta_{-i}, \cdot))$ is nondecreasing.

9 Collusion Proposed by an Informed Agent

Previous sections have employed the LM's modeling approach whereby a third party representative organizes a collusive agreement on behalf of members of the coalition. Even though this approach serves as a useful metaphor and we have allowed for a variety of scenarios within this approach, this modeling assumption may not be most descriptive of a typical collusion process. In a typical situation, a member of coalition may initiate and propose a collusive agreement. We consider this latter scenario in the current model. The obvious difficulty with modeling this latter scenario is the "informed principal problem," since the agent proposing a collusive scheme is privately informed of his type, and may thus want to use a contract offer to signal his type to the other agent. The implications of such problems for coalition formation as well as for the principal's response to collusion have not been studied, except for the recent work by Quesada (2004). She finds the second-best outcome to be collusion-proof implementable, in the LM setting with a binary type and a perfect complementarity technology.[31] Her result exploits special features of that setting,[32] however, leaving the generality of her result in question. We show below that our RCP design can be made to prevent collusion proposed by an informed agent, in a much more general setting.[33]

To begin, we assume that there are only two agents and that agent 1 (instead of a third party representative) makes a take-it-or-leave-it collusion offer to the other agent at date $1\frac{1}{4}$. The rest of the structure remains the same as before. The analysis of this game, much like Quesada, involves applying Maskin and Tirole (1992)'s characterization of informed principal problem (Theorem 1^* in page 35), with agent 1 taking the role of the informed principal in their setup. Their characterization assumes two agents (i.e., one principal and

[31]Quesada (2004) also considers ex ante collusion (on participation decisions) and finds that the second-best outcome is not collusion-proof implementable.

[32]The features of the LM model allows the second-best outcome to be collusion-proof implementable via ex post individually rational dominant strategies.

[33]A structurally similar problem is "resale" following an auction. Similarly to our problem, the winning bidder is informed about the his type when dealing with the losing bidders in the resale market. In the resale problem, however, the (resale) contract proposal is made after the initial assignment, whereas the collusion proposal is made prior to the "play" of the grand mechanism. This difference turns out to matter. Since the bidders' types are updated after initial allocation, the crucial issue facing the principal is how to "manipulate" the updating of types through initial assignment (see Zheng (2002)). This issue does not arise in our problem.

one agent) and finite types distributed independently across the agents. Using their result thus requires us to restrict our model accordingly. Specifically, each agent $i = 1, 2$ draws a type independently from a finite set. We further assume that the second-best outcome is efficiently implementable via an ex post incentive compatible mechanism.[34] As noted in Lemma 3, this set includes most of the cases considered in the literature.

PROPOSITION 3 *Suppose there are only two agents each with types drawn independently from a finite set. If there is a mechanism M^* which efficiently implements V^* and is ex post incentive compatible, then there exists a RCP mechanism that admits a perfect Bayesian equilibrium in which agent 1 (proposer) offers a null side contract to agent 2 and the principal receives the payoff of V^*.*

PROOF: See Appendix B.

Here, we sketch the main idea behind the result. The mechanism used in this proposition, much like that of Theorem 1, implements the noncollusive optimal outcome in a way ex post incentive compatible for agent 2, and guarantees the principal ex post constant surplus of V^*. The ex post incentives for agent 2 means that each type of agent 1 (the proposer) can earn the noncollusive payoff, regardless of what other types do, by offering the null side contract. This payoff is also the most it can earn from offering any side contract that is incentive compatible for agent 1 and ex post incentive compatible for agent 2 and guarantees the noncooperative payoff to agent 2. In such a case, Maskin and Tirole (1992) ensures that there exists a perfect Bayesian equilibrium supporting that outcome.

While the result holds for the case of $n = 2$, the proof does not depend on that fact. Theorem 1* (and Theorem 1) of Maskin and Tirole (1992) also appears to extend to the case of more than two agents. We thus conjecture that the result holds for more than two agents.

Neither the argument of Proposition 3 nor the result of Maskin and Tirole appears to readily extend to the case of correlated types, however. Nevertheless, we offer another result that will be useful for that case. Consider our general model with $n \geq 2$ and an arbitrary type distribution. Given the condition of Lemma 2, the full-extraction first-best result is generically RCP implementable. The next result implies that such an outcome is collusion proof implementable even when an informed agent proposes collusion.

[34] This is weaker than assuming $V^* \in \mathcal{V}^{EP}$, given that $\mathcal{V}^{EP}$ also requires ex post individual rationality.

Proposition 4 *Suppose a mechanism $M^* = (q^*, t^*) \in \mathcal{M}$ satisfies (6) (or equivalently, (11)) — and is thus RCP — and implements the first-best allocation, i.e.,*

$$q^*(\theta) \in \arg\max_{q \in \mathcal{Q}} v(q) + \sum_{i \in N} s_i(q, \theta), \forall \theta \in \Theta. \tag{22}$$

The mechanism M^* admits a perfect Bayesian equilibrium in which agent 1 offers a null side contract to other agents and the outcome M^* is implemented.

Proof: See Appendix C.

10 Hierarchical Delegation of Contracts

Part of an interest in studying collusion stems from the hope it may offer for explaining some organizational forms that are otherwise difficult to justify. Hierarchical delegation of contracts is one such organizational practice. If a principal delegates to say agent 1 the authority to contract with agent 2, then the principal loses the opportunity to communicate with the latter and to choose his contract terms in her best interest. This control loss makes delegated contracting difficult to justify, despite its popularity. One can at best hope delegated contracting to do as well as centralized contracting — i.e., implement the second-best outcome. If agents' types are uncorrelated, Melumad, Mookherjee and Reichelstein (1995) (hereafter, MMR) show that delegation achieves the second-best outcome if and only if, under delegation, (a) the principal monitors individual output contributions by all agents (q in our model); and (b) agent 1 can be compelled to make his participation decision before he communicates with agent 2.[35] Condition (a) is needed for the principal to be able to counteract a potential monopoly distortion that may arise from the increased bargaining power gained by agent 1. Condition (b) is needed for the individual rationality to hold at the interim level, so as to prevent agent 1 from commanding rents based on the information he learned about agent 2.

Does collusion make a difference? While centralization still confers (weakly) more control to the principal than does delegation,[36] the latter seems relatively more attractive

[35]These conditions are "necessary" for equivalence in the sense that a counter example can be found where failure of either condition leads to nonequivalence (see MMR). Mookherjee and Reichelstein (2001) also extend the sufficiency part to the case with any finite number of agents.

[36]Specifically, a centralized contract may enable the principal to manipulate agents' opportunity cost

when the former is subject to collusion. To what extent collusion justifies hierarchical delegation has been the subject of much recent research, but no general answer has emerged yet. Some authors established equivalence in some cases (Laffont and Martimort, 1998; Faure-Grimaud et al., 2003) while others showed nonequivalence in other cases (Celik, 2004; Mookherjee and Tsumagari, 2004). Our collusion-proof implementation results (under centralization) enable us to provide some general answer on the issue and fill an important gap in the literature.

Specifically, we have shown that the second-best outcome is achievable under centralization in the presence of collusion, whether it is organized by a third party (Corollary 1) or by an informed agent (Propositions 3 and 4). Hence, for delegated contracting to do as well as centralized contracting, the former must implement the second-best outcome. It then follows from MMR that, for uncorrelated types, delegation is inferior to centralization unless conditions (a) and (b) both hold. In other words, conditions (a) and (b) continue to be the relevant requirements for equivalence, even in the presence of collusion.

This perspective explains some of the existing results. For instance, Laffont and Martimort (1998)'s equivalence result follows immediately from the MMR's conditions being satisfied in their model. In particular, their perfect complementarity technology makes it trivial for the principal to observe agents' individual outputs. Also consistent with our perspective, Mookherjee and Tsumagari (2004) showed delegation to be strictly inferior if agents can reallocate output and the agent 1 can postpone his participation decision until after he communicates with agent 2 — i.e., both conditions (a) and (b) fail.[37]

Thus far, no result is available for the case where only one of the MMR condition holds. For instance, whether delegation is optimal is not known for the standard case where agents's participation constraints hold at the interim level but their technologies/preferences are general enough to admit nontrivial reallocational opportunities for the agents. Our results provide an unambiguous answer for this case. It follows from MMR that the agents' reallocational ability, when undetected by the principal, leads to a monopoly distortion under delegation. By contrast, the agents' reallocational ability does not prevent the principal from achieving the second-best outcome via a centralized contract. Hence, delegation

of participating in collusion since it will determine their status quo payoffs. The principal enjoys no such leverage relative to agent 2 under delegation.

[37]Our result does not imply theirs, however, since their model of collusion under centralization permits colluding agents to exit from the grand contract after communicating with each other, so their participation constraints hold ex post even for centralized contracting.

is strictly inferior in this case.[38] In sum, our results suggest that hierarchical delegation is no more justifiable when the agents are collusive than when they are not, at least if their types are uncorrelated.

REMARK 4 *(Correlated Types and Delegation) Our result offers no general perspective when agents' types are correlated, since there is no MMR-like result for the no collusion benchmark. Faure-Grimaud et al (2003) and Celik (2004) consider models in which a non-productive supervisor observes an imperfect signal about the type of a productive agent. Differences in the informational structures have led them to reach different conclusions on the value of delegation. In both cases, however, conditions (a) and (b) are met. In particular, the non-productive role of supervisor makes condition (a) trivial. If the supervisor also had a productive role, there could be additional distortion associated with delegation, rendering it unambiguously inferior.*

11 Conclusion

We have shown that the optimal noncollusive mechanism can be made collusion-proof in a broad class of circumstances, including both uncorrelated and correlated types environments, in a way robust to the specifics of coalition's objective, its manipulation technique or its exact makeup. This result unifies several observations scattered in the literature and provides a general insight into how the transaction cost associated with agents' private information can be exploited to overcome collusion. An equally valuable lesson from the current paper may lie in furthering the understanding of the true scope of collusion. While the mechanism we propose applies to a general class of technologies, preferences, and the agents' type structures, it requires several important conditions. Recognizing these condi-

[38] The comparison could in principle depend on how one models collusion under centralized contracting. Laffont and Martimort (1998) for instance invoke the third-party-initiated collusion which treats the agents symmetrically in terms of their relative bargaining power. Since a delegated agent has the full bargaining power under delegation, the latter then involves a shift in bargaining power within the agents as well as the usual control loss for the principal. Mookherjee and Tsumagari (2004) adopt a different model where a collusive proposal is made by one agent (agent 1 in our discussion) in a take-it-or-leave-it fashion under centralization, so that the two formats differ only in terms of the principal's control loss. Regardless of the differences, our result implies that the second-best outcome is achievable under centralization. So, the non-equivalence result is quite robust.

tions can shed some light on the factors that can make collusion truly problematic.[39]

First, we followed the extensive form of LM (1997, 2000) in which a coalition is formed after the agents sign up for the principal's grand contract. This means that we do not allow the agents to collude on their participation decisions.[40] While this assumption makes sense in many situations, there are circumstances in which agents may be able to collude prior to their participation decisions. To illustrate, consider our example in Section 2 and our collusion-proof mechanism which charges the agents 2/3. If they can collude prior to participating in such a mechanism, they may refuse to participate whenever their costs exceed 2/3, which will undermine the implementation of the second-best outcome. What form of contract, and to what extent, can deal with such an early collusion remains an important question to study.[41]

Second, our collusion-proof implementation relies largely on the risk neutrality of the agents. An important feature of our mechanism is that it makes the agents residual claimants, which means shifting all payoff risks (i.e., the payoff variability) to the agents. Imposing such risks requires providing a risk premium to the agents if they are risk averse. Similarly, our mechanism may sometimes require positive entry fees, which agents may be either unwilling or unable to pay, due to their risk aversion or liquidity constraints. Risk aversion and liquidity constraints will thus introduce a real tradeoff in dealing with collusion.[42]

Third, our collusion-proof implementation relies on a Bayesian mechanism, which cannot generally be made either dominant strategy or ex post implementable for all agents. As

[39]When these conditions fail, our method of collusion-proofing may not provide a useful guide for solving the collusion problem, and the traditional approach of optimizing within the class of collusion-proof mechanisms may again be useful. In this sense, the current paper complements the existing approach.

[40] This assumption may not be as restrictive as it may appear. Many forms of collusion involving coordinated participation is replicable by a collusive arrangement in our model. For instance, McAfee and McMillan (1992) consider collusion that sends only one selected bidder to the official auction. This is replicated by an arrangement that sends all bidders but have all of them (except possibly for one) bid a reserve price. The good can be then reallocated to the selected winner, if necessary.

[41]A few interesting papers have already employed an extensive form that permits agents to collude on their participation decisions. See Che and Kim (2005), Dequiedt (2004), Pavlov (2004), Quesada (2004) and Mookherjee and Tsumagari (2004).

[42]The logic is precisely the same as why "selling the firm to an agent" does not work in the traditional moral hazard model with a risk averse agent. Faure-Grimaud, et al. indeed shows the risk aversion can make collusion costly to deal with.

is often recognized, common knowledge required for Bayesian implementation is demanding. Relaxing this restriction will likely entail a real cost of preventing collusion. The exact nature of this cost and the method of minimizing it remain interesting open questions.

Appendix A: Proof of Lemma 1

We use the following theorem.

THEOREM OF THE ALTERNATIVE (FREDHOLM):[43] *For a matrix A and a vector a, the linear system $Ax = a$ has a solution x^* if and only if, for any vector λ, $\lambda A = \mathbf{0}$* implies *$\lambda a = 0$.*

Given this theorem, a solution to the system (12) exists if, for any (row) vectors $(\lambda_i^P, \lambda_i^B)_{i=1}^n$ and any (row) vector ξ,

$$\lambda_i^P P_i + \lambda_i^B B_i + \xi = \mathbf{0}, \forall i \quad \text{implies} \quad \sum_{i \in N} \lambda_i^P \cdot T_i + \sum_{i \in N} \lambda_i^B \cdot S_i + \xi \cdot [v - \Delta] = 0. \tag{23}$$

Note that λ_i^P, λ_i^B, and ξ are of sizes ℓ_i, $\ell_i(\ell_i - 1)$, and L, respectively

To prove (23), suppose $\lambda_i^P P_i - \lambda_i^B B_i + \xi = \mathbf{0}$ for all i, which implies

$$\lambda_i^P P_i + \lambda_i^B B_i = \lambda_j^P P_j + \lambda_j^B B_j = -\xi. \tag{24}$$

Let agents i and j be the ones satisfying Condition (PI$'$). The condition means that the space spanned by row vectors of P_i and B_i have only one dimensional vector space in common with the space spanned by row vectors of P_j and B_j. According to (24), ξ must belong to this one dimensional space. However, we have

$$e_1' P_1 = \cdots = e_n' P_n = \mu^{0\prime},$$

where e_i is the (column) vector of size ℓ_i whose elements are all 1's. Thus, it must be that for some scalar β, $\xi = \beta \mu^{0\prime}$. Then,

$$\begin{aligned} \sum_{i \in N} \lambda_i^P \cdot T_i &= \sum_{i \in N} \lambda_i^P P_i \cdot t_i = -\sum_{i \in N} [\lambda_i^B B_i + \xi] \cdot t_i = -\sum_{i \in N} \lambda_i^B \cdot S_i - \beta \sum_{i \in N} \mu^{0\prime} \cdot t_i \\ &= -\sum_{i \in N} \lambda_i^B \cdot S_i - \beta \sum_{i \in N} \mathbb{E}[t_i(\tilde{\theta})]. \end{aligned}$$

[43]See Carter (2001), p. 392, for instance.

Also,

$$\xi \cdot [v - \Delta] = \beta \mu^{0\prime} \cdot [v - \Delta] = \beta \mu^{0\prime} \cdot v - \beta \mathbb{E}[v(q(\tilde{\theta}))] + \beta \sum_{i \in N} \mathbb{E}[t_i(\tilde{\theta})] = \beta \sum_{i \in N} \mathbb{E}[t_i(\tilde{\theta})].$$

Therefore, we have

$$\sum_{i \in N} \lambda_i^P \cdot T_i + \sum_{i \in N} \lambda_i^B \cdot S_i + \xi \cdot [v - \Delta] = -\sum_{i \in N} \lambda_i^B \cdot S_i - \beta \sum_{i \in N} \mathbb{E}[t_i(\tilde{\theta})] + \sum_{i \in N} \lambda_i^B \cdot S_i + \beta \sum_{i} \mathbb{E}[t_i(\tilde{\theta})] = 0,$$

proving (23). ▌

Appendix B: Proof of Proposition 3

As stated in the text, our proof applies Theorem 1* of Maskin and Tirole (1992). This requires developing two welfare concepts. To this end, we define several notations. For each $\theta_i \in \Theta_i$, let $p_i^0(\theta_i)$ denote the probability that agent $i = 1, 2$ realizes that type. As before, $\mu := (p_1(\cdot), p_2(\cdot))$ denotes an arbitrary prior distribution of types and $\mu_i := p_i(\cdot)$ denotes the prior for agent $i = 1, 2$. We reserve $\mu^0 := (p_1^0(\cdot), p_2^0(\cdot))$ and $\mu_i^0 := p_i^0(\cdot)$ for true priors. Let

$$u_i^M(\tilde{\theta}_1, \tilde{\theta}_2 | \theta_1, \theta_2) := s_i(q(\tilde{\theta}_1, \tilde{\theta}_2), \theta_1, \theta_2) + t(\tilde{\theta}_1, \tilde{\theta}_2)$$

denote agent i's ex post payoff from mechanism $M = (q, t)$ when the agents have types (θ_1, θ_2) but report $(\tilde{\theta}_1, \tilde{\theta}_2)$. For each $\theta_1 \in \Theta_1$, we let $M_{\theta_1} := (q(\theta_1, \cdot), t(\theta_1, \cdot))$ denote a component of a menu corresponding to a report of type θ_1 by agent 1. Hence, we can write $M = \{M_{\theta_1}\}_{\theta_1 \in \Theta_1}$.

As before, we fix an arbitrary grand mechanism $M = (q, t)$ offered by the principal and consider a reallocational manipulation of M proposed by agent 1. We first define so called *interim efficiency.* A reallocational manipulation of M, $\check{M}$, is said to be *interim efficient (or IE*) relative to prior* $\hat{\mu}_1$ if, for some $(w(\theta_1))_{\theta_1 \in \Theta_1} \in \mathbb{R}_{++}^{|\Theta_1|}$, $\check{M}$ solves

$$[IE^*(\hat{\mu}_1; M)] \qquad \max_{\tilde{M} \in \mathcal{RM}_M} \sum_{\theta_1 \in \Theta_1} w(\theta_1) \left(\sum_{\theta_2 \in \Theta_2} p_2^0(\theta_2) u_1^{\tilde{M}}(\theta_1, \theta_2 | \theta_1, \theta_2) \right)$$

$$(IC^1) \qquad \sum_{\theta_2 \in \Theta_2} p_2^0(\theta_2) u_1^{\tilde{M}}(\theta_1, \theta_2 | \theta_1, \theta_2) \geq \sum_{\theta_2 \in \Theta_2} p_2^0(\theta_2) u_1^{\tilde{M}}(\theta_1', \theta_2 | \theta_1, \theta_2), \forall \theta_1, \theta_1' \in \Theta_1.$$

$$(IC^2(\hat{\mu}_1)) \qquad \sum_{\theta_1 \in \Theta_1} \hat{p}_1(\theta_1) u_2^{\tilde{M}}(\theta_1, \theta_2 | \theta_1, \theta_2) \geq \sum_{\theta_1 \in \Theta_1} \hat{p}_1(\theta_1) u_2^{\tilde{M}}(\theta_1, \theta_2' | \theta_1, \theta_2), \forall \theta_2, \theta_2' \in \Theta_2.$$

$$(IR_{\check{M}}{}^2(\hat{\mu}_1)) \qquad \sum_{\theta_1 \in \Theta_1} \hat{p}_1(\theta_1) u_2^{\tilde{M}}(\theta_1, \theta_2 | \theta_1, \theta_2) \geq \sum_{\theta_1 \in \Theta_1} \hat{p}_1(\theta_1) u_2^{\check{M}}(\theta_1, \theta_2 | \theta_1, \theta_2), \forall \theta_2 \in \Theta_2.$$

Next, a reallocational manipulation of M, $\tilde{M}^{RSW}(M)$, is said to be RSW^* *relative to* M if $\tilde{M}^{RSW}(M) = \bar{M}$, and, for each $\theta_1 \in \Theta_1$, there exists a mechanism $\{\bar{M}_{\theta_1}, \check{M}_{\theta_1'}\}_{\theta_1' \in \Theta_1 \setminus \{\theta_1\}}$ that solves

$$[RSW_{\theta_1}^*(M)] \qquad \max_{\tilde{M} \in \mathcal{RM}_M} \sum_{\theta_2 \in \Theta_2} p_2^0(\theta_2) u_1^{\tilde{M}}(\theta_1, \theta_2 | \theta_1, \theta_2)$$

subject to (IC^1),

$$(EPIC^2) \qquad u_2^{\tilde{M}}(\tilde{\theta}_1, \theta_2 | \tilde{\theta}_1, \theta_2) \geq u_2^{\tilde{M}}(\tilde{\theta}_1, \theta_2 | \tilde{\theta}_1, \theta_2'), \forall \tilde{\theta}_1 \in \Theta_1, \forall \theta_2, \theta_2' \in \Theta_2.$$

$$(EPIR_M^2) \qquad u_2^{\tilde{M}}(\tilde{\theta}_1, \theta_2 | \tilde{\theta}_1, \theta_2) \geq u_2^{M}(\tilde{\theta}_1, \theta_2 | \tilde{\theta}_1, \theta_2), \forall \tilde{\theta}_1 \in \Theta_1, \forall \theta_2 \in \Theta_2.$$

Theorem 1* of Maskin and Tirole (1992) proves that, if an RSW^* mechanism is IE^* relative to some positive prior, then any mechanism that satisfies (IC), (IR) and weakly Pareto-dominates the RSW^* for agent 1 is supported as an equilibrium of the game where agent 1 proposes a contract to agent 2. We apply this result to prove Proposition 3. By the hypothesis, there exists an ex post incentive compatible mechanism $M^* = (q^*, t^*)$ that implements V^* efficiently. We now construct mechanism $\bar{M} = (q^*, \bar{t})$, where

$$\bar{t}_2(\theta) := t_2^*(\theta) + \rho(\theta_1) - \mathbb{E}_{\tilde{\theta}_1}[\rho(\tilde{\theta}_1)], \tag{25}$$

where

$$\rho(\theta_1) := \mathbb{E}_{\tilde{\theta}_2} \left[v(q^*(\tilde{\theta}) - \sum_{i=1,2} t_i^*(\theta_1, \tilde{\theta}_2) \right],$$

and for agent 1,

$$\bar{t}_1(\theta) := -\bar{t}_2(\theta) + v(q^*(\theta)) - \mathbb{E}_{\tilde{\theta}_1}[\rho(\tilde{\theta}_1)]. \tag{26}$$

As can be seen from (26), the transfers sum up to a level that ensures an ex post constant payoff of $\mathbb{E}_{\tilde{\theta}_1}[\rho(\tilde{\theta}_1)] = V^*$ to the principal. Further, these transfers ensure the same interim payoffs for both agents and the same ex post incentive for agent 2, as t^*. Hence, $\bar{M}$ is RCP.

Suppose the principal offers $\bar{M}$. By construction, $\bar{M}$ is ex post incentive compatible for agent 2. This means that $\bar{M}$ satisfies the constraints of $[RSW^*_{\theta_1}(\bar{M})]$ for each $\theta_1 \in \Theta_1$. Hence, each type θ_1 of agent 1 can guarantee interim payoff of $U_i^{\bar{M}}(\theta_1)$ by offering $\bar{M}$, i.e., the null side contract, implying that the payoff for each type of agent 1 from an RSW^* mechanism relative to $\bar{M}$ must be at least that of $\bar{M}$. At the same time, the RSW^* mechanism relative to $\bar{M}$ must be a reallocational manipulation of $\bar{M}$, so it gives V^* to the principal (by design of $\bar{t}$), and it must satisfy (IC) and (IR),[44] so it must be noncollusive optimal. Since $\bar{M}$ has the same allocation rule as M^*, $\bar{M}$ must also implement V^* efficiently. Then, the RSW^* payoff for each type of agent 1 must equal that of $\bar{M}$. Or else, there must be an reallocational manipulation of $\bar{M}$ that gives strictly higher payoff to some type of agent 1 and no lower payoff to all other types of agent 1 and all types of agent 2 (since it must satisfy $(EPIR^2_{\bar{M}})$) than $\bar{M}$. Since $\bar{M}$ is RCP, this implies there exists a mechanism that implements V^* but generates higher total surplus than $\bar{M}$, which contradicts the fact that $\bar{M}$ efficiently implements V^*. We thus conclude that $\bar{M}$ is RSW^* relative to $\bar{M}$.

Next, we prove that $\bar{M}$ is interim efficient relative to some positive prior. To this end, consider another program:

$$[IE^0] \qquad \max_{\tilde{M}\in\mathcal{RM}_{\bar{M}}} \sum_{\theta_1\in\Theta_1} p_1^0(\theta_1)\left(\sum_{\theta_2\in\Theta_2} p_2^0(\theta_2) u_1^{\tilde{M}}(\theta_1,\theta_2|\theta_1,\theta_2)\right)$$

subject to

$$(IC^1),\ (IC^2(\mu_1^0)),\ (IR^1),\ \text{and}\ (IR^2_{\bar{M}}(\mu_1^0)).$$

We claim that $\bar{M}$ solves $[IE^0]$. First, since $\bar{M}$ is noncollusive optimal and RCP, any reallocational manipulation of $\bar{M}$ guarantees V^* to the principal. If there exists a mechanism $\tilde{M} \in \mathcal{RM}_{\bar{M}}$ that solves $[IE^0]$ and yields agent 1 a higher (ex ante) payoff than $\bar{M}$, then $\tilde{M}$ is feasible and Pareto-dominates $\bar{M}$ since the former yields agent 2 no less payoff than the latter (due to a constraint in $[IE^0]$) and yields the principal V^* (since $\bar{M}$ is RCP), which contradicts that $\bar{M}$ efficiently implements V^*. Thus, $\bar{M}$ must solve $[IE^0]$. Let $\lambda(\theta_1) \geq 0$ denote the Lagrangean multiplier associated with individual rationality of agent 1's type

[44]That the RSW^* mechanism satisfies (IC^1) can be checked easily and is established in Proposition 1 of Maskin and Tirole (1992). That it satisfies (IC^2) follows from $(EPIC^2)$, which is required for $[RSW^*_{\theta_1}(\bar{M})]$. For each $\theta_1 \in \Theta_1$, a solution to $[RSW^*_{\theta_1}(\bar{M})]$ must satisfy (IR) since it satisfies $(EPIR^2_{\bar{M}})$, and we conclude that it must give at least the payoff of $U_1^{\bar{M}}(\theta_1) \geq \overline{U}_1(\theta_1)$ to agent 1 with type $\theta_1 \in \Theta_1$.

$\theta_1 \in \Theta_1$ at the solution. Then, $[IE^0]$ can be rewritten:

$$\max_{\tilde{M}\in\mathcal{RM}_{\bar{M}}} \sum_{\theta_1\in\Theta_1} (p_1^0(\theta_1) + \lambda(\theta_1)) \left(\sum_{\theta_2\in\Theta_2} p_2^0(\theta_2) u_1^{\tilde{M}}(\theta_1, \theta_2 | \theta_1, \theta_2) \right)$$

subject to

$$(IC^1),\ (IC^2(\mu_1^0)),\ \text{and}\ (IR_{\bar{M}}^2(\mu^0)),$$

from which it follows that $\bar{M}$ solves $[IE^*(\mu_1^0; \bar{M})]$ for $w_1(\theta_1) := p_1^0(\theta_1) + \lambda(\theta_1)$, $\theta_1 \in \Theta_1$. We thus conclude that $\bar{M}$ is IE^* relative to the true prior μ_1^0, which is positive.

Theorem 1* of Maskin and Tirole (1992) then implies that, given the grand mechanism $\bar{M}$, the null side contract is supported as a PBE of the collusion game proposed by agent 1, supported by the "passive belief" that the status quo $\bar{M}$ will be truthfully implemented, following (an out-of-equilibrium) rejection of the collusion offer.[45] ▮

Appendix C: Proof of Proposition 4

The equilibrium strategies, given grand mechanism M^*, are described as follows: Agent 1 proposes the null side contract, and the contract is accepted by all other agents, whereafter each agent reports truthfully in M^*. If agent 1 offers a non-null contract, then each agent best responds to the following off-the-equilibrium belief: (1) Following agent 1's devation, each agent $i \neq 1$ believes that agent 1 is of such a type that would benefit strictly from deviation, and that any other agent, agent $j(\neq 1, i)$, will accept the deviation offer if he is of such a type that would be (weakly) better off from accepting it. (2) Following a rejection of any side contract proposed by agent 1, each agent holds the passive belief and reports truthfully when playing M^*, so M^* is truthfully implemented.

We show that there is no profitable deviation for agent 1. Suppose to the contrary that a positive measure of types of agent 1 is better off deviating to propose a non-null side contract. For the deviation to be profitable, it must be accepted by a positive measure of other agents' types that get weakly better off by doing so, given the specified belief following that deviation. Let $\overline{\Theta}_1$ denote the set of agent 1's types that are deviating,

[45] Formally, Maskin and Tirole treat the status quo mechanism as "exogenous." But the status quo outcome in some applications of theirs, such as contract renegotiation, is a result of some endogenous play much like in our context. A similar restriction of "passive" beliefs will be required to support the claimed equilibrium in those circumstances.

and let $\overline{\Theta}_i$ with $i \neq 1$ denote the set of agent i's types that are accepting the deviation. Let $\overline{\Theta} := \prod_{i \in N} \overline{\Theta}_i$, and define $\overline{\Theta}_{-i}$ and $\overline{\Theta}_{-i-j}$ as usual. Also, let $\tilde{M} = (\tilde{q}, \tilde{t}) \in \mathcal{RM}_{M^*}$ denote the mechanism/outcome being implemented via the deviation side contract. Let $\bar{u}_i^M(\theta) := s_i(q(\theta), \theta) + t_i(\theta)$ denote the ex post payoff arising from outcome $M = (q, t)$.

For the deviation to be profitable for agent 1 with type $\theta_1 \in \overline{\Theta}_1$, we must have

$$\mathbb{E}\left[\bar{u}_1^{\tilde{M}}(\tilde{\theta}) 1_{\{\tilde{\theta}_{-1} \in \overline{\Theta}_{-1}\}} + \bar{u}_1^{M^*}(\tilde{\theta}) 1_{\{\tilde{\theta}_{-1} \notin \overline{\Theta}_{-1}\}} \middle| \tilde{\theta}_1 = \theta_1\right] > \mathbb{E}\left[\bar{u}_1^{M^*}(\tilde{\theta}) \middle| \tilde{\theta}_1 = \theta_1\right]. \tag{27}$$

To understand the second term of the LHS, note that the deviation is rejected if $\tilde{\theta}_{-1} \notin \overline{\Theta}_{-1}$ and, given the belief in (2), M^* is truthfully implemented whenever a rejection occurs. Rewrite (27) as

$$\mathbb{E}\left[\bar{u}_1^{\tilde{M}}(\tilde{\theta}) 1_{\{\tilde{\theta}_{-1} \in \overline{\Theta}_{-1}\}} \middle| \tilde{\theta}_1 = \theta_1\right] > \mathbb{E}\left[\bar{u}_1^{M^*}(\tilde{\theta}) 1_{\{\tilde{\theta}_{-1} \in \overline{\Theta}_{-1}\}} \middle| \tilde{\theta}_1 = \theta_1\right].$$

Taking expectations across all types in $\overline{\Theta}_1$, we obtain

$$\mathbb{E}\left[\bar{u}_1^{\tilde{M}}(\tilde{\theta}) 1_{\{\tilde{\theta} \in \overline{\Theta}\}}\right] > \mathbb{E}\left[\bar{u}_1^{M^*}(\tilde{\theta}) 1_{\{\tilde{\theta} \in \overline{\Theta}\}}\right]. \tag{28}$$

For agent $i \neq 1$ with type $\theta_i \in \overline{\Theta}_i$ to accept the side contract, we must have[46]

$$\mathbb{E}\left[\bar{u}_i^{\tilde{M}}(\tilde{\theta}) 1_{\{\tilde{\theta}_{-i} \in \overline{\Theta}_{-i}\}} + \bar{u}_i^{M^*}(\tilde{\theta}) 1_{\{\tilde{\theta}_1 \in \overline{\Theta}_1, \tilde{\theta}_{-1-i} \notin \overline{\Theta}_{-1-i}\}} \middle| \tilde{\theta}_i = \theta_i\right] \geq \mathbb{E}\left[\bar{u}_i^{M^*}(\tilde{\theta}) 1_{\{\tilde{\theta}_1 \in \overline{\Theta}_1\}} \middle| \tilde{\theta}_i = \theta_i\right],$$

which can be rewritten as

$$\mathbb{E}\left[\bar{u}_i^{\tilde{M}}(\tilde{\theta}) 1_{\{\tilde{\theta}_{-i} \in \overline{\Theta}_{-i}\}} \middle| \tilde{\theta}_i = \theta_i\right] \geq \mathbb{E}\left[\bar{u}_i^{M^*}(\tilde{\theta}) 1_{\{\tilde{\theta}_{-i} \in \overline{\Theta}_{-i}\}} \middle| \tilde{\theta}_i = \theta_i\right].$$

Taking expectations across all types in $\overline{\Theta}_i$ yields

$$\mathbb{E}\left[\bar{u}_i^{\tilde{M}}(\tilde{\theta}) 1_{\{\tilde{\theta} \in \overline{\Theta}\}}\right] \geq \mathbb{E}\left[\bar{u}_i^{M^*}(\tilde{\theta}) 1_{\{\tilde{\theta} \in \overline{\Theta}\}}\right]. \tag{29}$$

Summing (28) and (29) across all agents, we obtain

$$\mathbb{E}\left[\sum_{i \in N} \bar{u}_i^{\tilde{M}}(\tilde{\theta}) 1_{\{\tilde{\theta} \in \overline{\Theta}\}}\right] > \mathbb{E}\left[\sum_{i \in N} \bar{u}_i^{M^*}(\tilde{\theta}) 1_{\{\tilde{\theta} \in \overline{\Theta}\}}\right],$$

which implies that

$$\mathbb{E}_{\tilde{\theta}}\left[\left(v(\tilde{q}(\tilde{\theta})) + \sum_{i \in N} s_i(\tilde{q}(\tilde{\theta}), \tilde{\theta})\right) 1_{\{\tilde{\theta} \in \overline{\Theta}\}}\right] > \mathbb{E}_{\tilde{\theta}}\left[\left(v(q^*(\tilde{\theta})) + \sum_{i \in N} s_i(q^*(\tilde{\theta}), \tilde{\theta})\right) 1_{\{\tilde{\theta} \in \overline{\Theta}\}}\right],$$

since M^* satisfies (6) (or (11)), and $\tilde{M} \in \mathcal{RM}_{M^*}$. This contradicts (22). ▌

[46] This inequality can be explained in a similar way to (27). Here, the RHS and the second term of the LHS follow from the fact that agent i's belief in (1) is correct about what types of agent 1 would make the deviation offer and what types of each agent $j \neq 1, i$ would accept or reject it.

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