Conflicts and Common Interests in Committees

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Abstract: Committees improve decisions by pooling independent information of members, but promote manipulation, obfuscation, and exaggeration of private information when members have conflicting preferences. When members' preferences differ, the report submitted by any individual can not allow perfect inference of his private information. Equilibrium outcomes transform continuous data into ordered ranks: voting procedures are the equilibrium methods that achieve consensus in committees. Voting necessarily coarsens the transmission of information among members, but is necessary to control strategic manipulations. Though impeded by conflicts, information sharing among committee members occurs nonetheless. Each member becomes more cautious in casting the crucial vote than when he alone makes the decision based on his own information. Increased quality of one member's information results in his casting the crucial vote more often. Committees make better decisions for at least one member than other modes of decision-making that do not depend on information sharing, such as taking turns or delegation. Committees are viable, though imperfect ways of making decisions when information is dispersed among members with conflicting interests.

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1. Introduction

Small-group decisions are ubiquitous for decisions under uncertainty. Judgment by a jury of one's peers, not by a single person, is the hallmark of the American criminal justice system. Committees recommend hiring and tenure decisions, are essential for project and investment undertakings in business firms, and are used for many administrative decisions in all organizations. Group evaluations bring different points of view to bear on an issue. They allow the pooling of information that is not otherwise available to a single decision-maker. But conflict among committee members limits the possibilities for information pooling. It is in the self interest of committee members to manipulate their evidence—to exaggerate favorable data that supports their preferred outcome, or conceal unfavorable data that works against it. This paper studies the tension between information aggregation and strategic manipulation of information in small committee decisions.

The value of aggregating diverse information among group members is an ancient idea. Condorcet (1785) proved that voting groups with diverse information make better decisions the larger the group size. The Condorcet Jury Theorem is an early application of the law of large numbers, and is further developed by Klevorick, Rothschild and Winship (1984). Only recently have economists and political scientists begun to study how strategic considerations reduce the aggregate value of information in real committees. Austen-Smith and Banks (1996) show that Condorcet's theorem requires that jurors vote non-strategically and "sincerely." They demonstrate that if votes are cast strategically, the theorem does not hold for some voting procedures such as unanimity. In a sense, strategic voting contaminates the scale economies inherent in large statistical samples.

The difficulty of eliciting private preferences for public goods in groups has been thoroughly studied (Gibbard, 1973; Satterthwaite, 1975). The subject of this paper is how small groups make decisions when diverse individual preferences are known to all, but when individuals possess private information that must be elicited in committee deliberations. Most research on this problem starts from Crawford and Sobel (1982), who analyze reporting games where a decision-maker elicits information from an expert with different preferences for the decision to be made (see also Green and Stokey, 1980). Holmstrom

(1983) studies a principal-agent setup where the principal can commit to delegating decision rights. The problem of eliciting private information from experts appears in a number of economic and political models: persuasion in debate (Milgrom and Roberts, 1986; Shin, 1994), agenda-setting in legislatures (Gilligan and Krehbiel, 1989; Austen-Smith 1990), and providing incentives for investment in expertise (Prendergast, 1993; Aghion and Tirole, 1997; Dewatripont and Tirole, 1999).

In committee decision-making, sharing of private information is essential. Our paper is closely related to papers by Austen-Smith and Banks (1996) and Feddersen and Pesendorfer (1996; 1997), who developed the pivotal voting argument in voting games with private information. We use a more natural and familiar information structure relevant for many economic decisions. In our model, set up in section 2, a committee must choose between two alternatives. Individual committee members are known to have partially conflicting interests in the decisions, and their information is private and non-verifiable. Committee members may disagree on which choice to be made given the evidence they have, but agree if the evidence is sufficiently strong in either direction. For example, in a recruitment committee evaluating a candidate, each member may be biased in favor if the candidate is in his own field, but each is willing to hire sufficiently high quality candidates regardless of field. Private information is an inherent problem in committee decision-making. In the recruitment example, information about candidate qualifications is dispersed in the committee because committee members have different perspectives or abilities to evaluate research in different fields. Since assessments are private, the committee decision can depend only on members' reports about their information, not on the actual information. Conflicting interests and private information give rise to strategic considerations in information sharing.

Information can not be fully shared among committee members under these circumstances. Section 3 shows how the likelihood principle is modified by self-interests of members. Although efficient decision-making requires that the decision be responsive to any small change in a member's data, such an outcome can not arise as an equilibrium outcome under any decision procedure. Continuous data of each committee member are partitioned and transformed into rank order information. Perfect inference of private information is impossible. Obfuscation is the rule rather than the exception in committees. The partitioning of continuous data into intervals can be interpreted as equilibrium outcomes of voting procedures. Voting is the equilibrium method of reaching decisions in committees. It coarsens the transmission of information among committee members, but is necessary to control strategic manipulations that arise from conflicts of interest.

In section 4, we analyze in detail the two-partition case. This amounts to the equilibrium of a simple voting procedure where each member votes "yes" or "no" depending on whether or not the strength of his private evidence exceeds a personal threshold. The voting equilibrium is suboptimal for two reasons: information is garbled, and the partition thresholds are chosen strategically rather than cooperatively. In the recruitment example, anticipating manipulation of evidence by fellow committee members, an individual "exaggerates" evidence that the candidate in his field produces high quality research by voting "yes" to his favored candidate even though he would have voted "no" with the same evidence were all information truthfully revealed. He lowers his own hiring bar because he knows that other members will raise theirs.

Incentives for manipulation and counter-manipulation generate a larger area of disagreement among members than is implied by their inherent conflicts in preferences. Still, exaggeration is limited, and information is aggregated by the committee, albeit imperfectly. The area of disagreement is bounded from above by the need for members to share their private information. We show that regardless of personal preferences, each committee member casts the decisive vote less frequently than if he were to make the decision based on his information only. Moreover, if some committee members are known to have more conclusive evidence, other members cast their deciding votes less frequently. Better informed members are decisive more often.

The tension between information manipulation and information sharing affects the welfare of committee members. For the committee as a whole, gains from sharing information outweigh distortions from information manipulation. When conflicts are small, all individual members benefit from information sharing. Regardless of the extent of conflicts, it is never Pareto improving to delegate to an individual member to make the decision based on his evidence only. The *ex ante* welfare of each individual committee member decreases as the preferences of fellow members diverge further away from his. When the preferences of his fellow members are sufficiently extreme, the benefits to an individual member from sharing information are outweighed by biases and distortions in the committee. He would be better off if he were to dictate the decision.

The voting model is used to analyze abstention in section 5. Although members always have incentives to influence the committee decision to advance their own interests, the gains from information sharing may be so large that it is in a member's self interest to abstain when his private information turns out to be relatively uninformative. We show that abstention improves the quality of committee decision. Voting with abstention is equivalent to a generalized voting procedure that allows each committee member to choose from three categories. In section 6 we study voting procedures with even more categories that generate equilibria with finer partitions of the private data. Finer partitions in turn allow for more efficient utilization of private information. However, conflicting interests among committee members impose an upper bound on how fine information partitioning can be. Great conflicts within the committee make fine partitions impossible.

2. A Model of Committee Decision-making

In the remainder of the paper, the problem of strategic information aggregation is discussed in the context of jury decision-making. The language of criminal trials facilitates the exposition. Jurors play no role in acquiring the information presented to them. They have different evidence due to differences in perspectives and capabilities in evaluating the information.

A verdict of "guilty" or "innocent" must be made by a jury of two persons, A and B. Member A's prior that the suspect is guilty is γ^a, and the personal costs of type I error (false conviction) and type II error (false acquittal) are λ_1^a and λ_2^a respectively. Let $k_1^a = \lambda_1^a(1-\gamma^a)$ and $k_2^a = \lambda_2^a\gamma^a$. The ratio $k^a = k_1^a/k_2^a$ represents the cost of false conviction relative to false acquittal. Member A also receives an observation (evidence) $Y^a = y^a$. The distribution of Y^a is continuous with density function $f_i^a(\cdot)$ if the suspect is innocent, or with density function $f_g^a(\cdot)$ if the suspect is guilty. Notation for member B is similar. We assume that Y^a and Y^b are independently distributed conditional on guilt or innocence. Conflicts in the committee exist as long as $k^a \neq k^b$, but members' interests are not directly opposed as long as k^a and k^b are strictly positive and finite. Both care about false conviction and false acquittal. There is no difference in this model between bias as manifested in γ and preference as manifested in λ; only their product matters.

If the vector of signals (y^a, y^b) is publicly observable, the optimal committee decision is a standard hypothesis testing problem that depends on the comparison of conditional expected loss under conviction or acquittal. Let α^a and α^b be relative Pareto weights for members A and B. Define $k_1 = \alpha^a k_1^a + \alpha^b k_1^b$, and $k_2 = \alpha^a k_2^a + \alpha^b k_2^b$. It can be shown[1] that conviction is optimal if and only if the likelihood ratio exceeds a threshold:

$$\frac{f_g^a(y^a)}{f_i^a(y^a)} \frac{f_g^b(y^b)}{f_i^b(y^b)} \geq \frac{k_1}{k_2}. \tag{2.1}$$

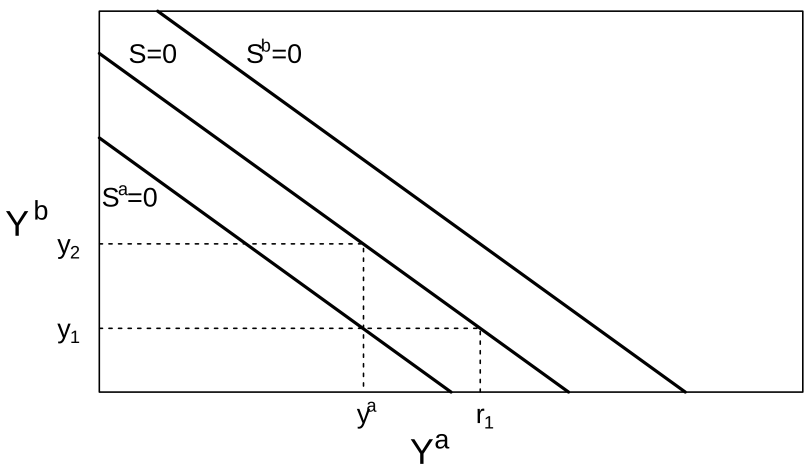
Throughout this paper, we assume that the likelihood ratio $f_g^j(\cdot)/f_i^j(\cdot)$ is strictly increasing for $j = a, b$. Then, the optimal decision rule is deterministic and strictly monotone in the evidence y^a and y^b. We represent the optimal rule by a strictly increasing "decision function" S, so that the decision is conviction if and only if $S(y^a, y^b) \geq 0$. The function S partitions the data space into two regions illustrated in Figure 1. Conviction occurs when the data lie above the $S = 0$ line, and acquittal occurs when the data lie below it.

If Y^a and Y^b have the same conditional distributions, then for many special distributions (such as the normal), the mean of the signals is a sufficient statistic. In such cases the optimal decision rule (2.1) takes the linear form, convict if and only if $y^a + y^b \geq \delta$, where δ is a function of the preference and distribution parameters and represents the "standard of proof." More generally, take logarithms of (2.1) and denote the value of the log likelihood ratios by ρ^a and ρ^b. The optimal rule can be expressed in terms of a linear aggregation of the evidence, namely, convict if and only if $\rho^a + \rho^b \geq \log(k_1/k_2)$. One can think of the "evidence" as the value of the log likelihood ratio instead of the value of the observation itself. In fact, the log likelihood ratio summarizes all the evidence pertinent to the two

[1] See, for example, DeGroot (1970). This optimal decision rule is a special case of the Neyman-Pearson lemma.

Figure 1

Optimal decision rules and information manipulation



hypotheses, guilt versus innocence. Under conditional independence, linear aggregation of the log likelihood ratios is always the optimal decision rule.[2]

The above characterization of the optimal decision rule applies to individual decision-making as well. In particular, if member A has access to both Y^a and Y^b, then his optimal decision rule is to convict if and only if

$$\frac{f_g^a(y^a)}{f_i^a(y^a)} \frac{f_g^b(y^b)}{f_i^b(y^b)} \geq \frac{k_1^a}{k_2^a}. \tag{2.2}$$

Under our assumption of monotone likelihood ratios, the personal optimal decision rule for each member is also deterministic and strictly increasing in y^a and y^b, but the partitions are different when the two members have conflicting interests ($k_1^a/k_2^a \neq k_1^b/k_2^b$). If the decision function S^j ($j = a, b$) represents member j's personal optimal decision rule, then there is no intersection between $S^a(y^a, y^b) = 0$ and $S^b(y^a, y^b) = 0$ in the data space. Figure 1 illustrates the case where member A has a lower standard of conviction than B ($k^a < k^b$). The region between $S^a = 0$ and $S^b = 0$ is the disagreement zone: for the same data (y^a, y^b) in the region, A prefers conviction and B prefers acquittal. The size of the

[2] This result holds whether or not Y^a and Y^b have the same conditional distributions. See, for example, Edwards (1992).

region measures how much the two members differ in preference and prior. The difference between the members' personal optimal decision rules is the source of their incentives to misrepresent their own evidence and attempt to tilt the committee decision to their own preferences when signals are not publicly observed.

3. Manipulation Leads to Garbling

3.1. Incentives to garble in a reporting game

Committee decisions only can be made on the basis of members' reports of their private information. Consider the reporting game where the two members report r^a and r^b simultaneously after learning their private evidence y^a and y^b, and the decision is made according to the Pareto-weighted optimal decision rule convict if and only if $S(r^a, r^b) \geq 0$. We want to establish that truthful reporting is not an equilibrium strategy as long as the two members differ in preferences or prior. Since $k^a \neq k^b$, regardless of the Pareto weights there is at least one member, say A, whose personal optimal decision function S^a differs from the committee decision function S. Suppose B always reports his observation y^b truthfully. Member A does not know the value of B's observation when he submits his report and treats Y^b as a random variable. If A submits report r^a, the suspect is convicted if the realization y^b is such that $S(r^a, y^b) \geq 0$. But conditional on $Y^a = y^a$, the optimal personal standard of conviction for A is whenever y^b satisfies $S^a(y^a, y^b) \geq 0$. Since S differs from S^a, reporting $r^a = y^a$ is not optimal for member A.[3]

Figure 1 illustrates the optimal report for member A conditional on his evidence y^a. Since $k^a < k^b$, member A is biased toward conviction relative to the committee decision function S. Conditional on y^a, the Pareto-optimal outcome convicts if $y^b \geq y_2$, but A prefers to convict if $y^b \geq y_1$. If B reports his signal truthfully, member A achieves his personal optimal lower standard of conviction by reporting r_1.

[3] Note that this argument does not depend on whether or not S is strictly monotone over the whole support of the evidence. As long as it is strictly monotone in the neighborhood of y^a, reporting y^a truthfully is not optimal for A if B reports truthfully all the time.

The above result can be generalized. As long as the decision rule from reports to decisions is deterministic and strictly monotone like the optimal rule represented by S, truth-telling is not an equilibrium. Further, there exists no manipulation equilibrium where members use invertible reporting strategies that would allow perfect inference of their private data. To see this point, suppose that the decision rule is convict if and only if $T(r^a, r^b) \geq 0$, where T is strictly increasing in each argument, and suppose that there exists a reporting equilibrium where each member j manipulates his information y^j with an invertible function R^j. Without loss of generality, assume that R^a and R^b are strictly increasing. Then, reporting truthfully ($r^a = y^a$ and $r^b = y^b$) is an equilibrium of the reporting game with the decision function $\tau(y^a, y^b) = T(R^a(y^a), R^b(y^b))$. Since $T(\cdot,\cdot)$ is strictly increasing in each argument, and $R^a(y^a)$ and $R^b(y^b)$ are strictly increasing functions, $\tau(\cdot,\cdot)$ is strictly increasing in each argument. As long as the two members differ in preference or prior, for any point (y^a, y^b) in the data space, there is incentive for at least one member, say A, to lie if the other member reports the truth. The reason is that A's personal optimal decision rule convict if and only if $S^a(y^a, y^b) \geq 0$ differs from the outcome convict if and only if $\tau(y^a, y^b) \geq 0$ if he reports the truth. Therefore, (R^a, R^b) can not be an equilibrium under the decision function T, a contradiction. We summarize the finding in the following proposition.

Proposition 3.1. *Given any deterministic and strictly monotone decision rule, there is no equilibrium of the reporting game where members use invertible reporting strategies.*

With little modification, the above result extends to committees with more than two members. Efficient information sharing requires that the committee decision be responsive to small changes in any member's data, but when information is private, incentives for manipulation arise if the committee decision rule is responsive to small changes in members' reports. Since invertible strategies allow people to infer the actual observation from the report, the non-existence of equilibrium with invertible strategies in a reporting game proves incentives to garble private information in committee decision-making. Indeed, since our argument depends only on the local characteristics of the reporting strategies, there exists no equilibrium with partially invertible strategies (i.e. reporting functions

$R(\cdot)$ that are invertible for some interval in the support of the evidence). Garbling occurs almost everywhere.

There are two ways of garbling private data: adding noise to the observation in the report or partitioning data into intervals. Both types of strategies are non-invertible and prevent perfect inference of data. However, mixed strategies can not be used in equilibrium given any deterministic and strictly monotone decision rule. The reason is that given any equilibrium reporting strategy of B, member A does not know the value of B's observation when he submits his report and treats B's report r^b as a random variable. Since the decision rule is strictly monotone, given any signal y^a, member A can not be indifferent between two reports with different values. Because intentionally adding noise to the signal requires indifference among different outcomes, mixed strategies are not equilibrium strategies. Partitions are the only candidates for equilibrium reporting strategies in a reporting game with a deterministic and strictly monotone decision rule. Equilibria with partition strategies will be established starting from section 4.

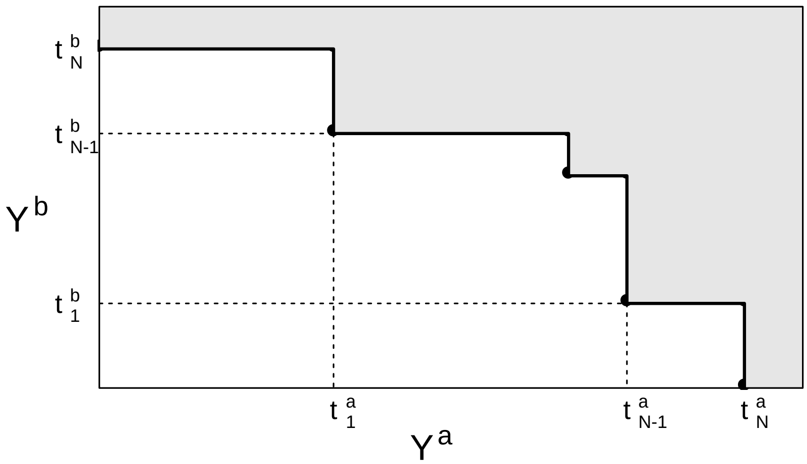
3.2. Partitioning private data is the only possible outcome

Proposition 3.1 can be strengthened from a mechanism design perspective. A limitation of the proposition is that it derives partitioning of private data under a particular decision-making procedure, where each member is free to report any signal and a deterministic and strictly monotone decision rule maps the reports to the decisions. We will see in this sub-section that in fact partitioning of private data is the only possible deterministic outcome regardless of the decision procedure adopted by the committee. But in order to understand what happens in equilibrium under different ways of making decisions, we need to restate the proposition in a way that is independent of the particular information-reporting game. This requires side-stepping the game and the equilibrium strategy by directly examining how the private data are transformed into decisions in the data space.

Formally, a "decision mechanism" in our setup consists of a "report space" for each player that defines all the reports he can choose, and a "committee rule" that maps a vector of reports to a decision. Since the report spaces and the committee rule can be arbitrary, the concept of decision mechanism captures all possible ways for the committee to make a

Figure 2

A partition outcome



decision. An example of a decision mechanism is the reporting game considered in section 3.1. It is a "direct decision mechanism," because the report space for each member is the statistical support of his signal. One can easily imagine "indirect mechanisms" where reports are not restricted to the support of the signals. For example, a voting procedure is an indirect mechanism because the report space for each member consists of two votes, yes and no. Whether direct or indirect, if a decision-making mechanism has an equilibrium, then the equilibrium defines an "outcome," a mapping from the data space to the decision that is a combination of the equilibrium strategies and the committee rule.

The outcome of efficient sharing of information, as represented in formula by (2.1), is deterministic and strictly monotone. A deterministic outcome divides data space into the conviction and acquittal regions. A deterministic and strictly monotone outcome has a boundary that is a strictly decreasing function in the data space, such as $S = 0$ in Figure 1. The other possibility is a deterministic but weakly monotone outcome, represented by a boundary that is a decreasing step function, as in Figure 2. Such an outcome can be called a "partition" outcome, which is defined by an equal number of thresholds for the two members. Continuous data of each member are partitioned by the thresholds into intervals, and the committee decision depends only on which interval each member's private data belong to. Small changes in a member's data no longer matter as in the outcome of efficient information aggregation. Using the revelation principle (Gibbard, 1973; Dasgupta, Hammond and Maskin, 1979; Myerson, 1979; Harris and Townsend, 1981), we can restate Proposition 3.1 as the following.

PROPOSITION 3.2. *Partition outcomes are the only possible deterministic equilibrium outcomes of any decision mechanism.*

The revelation principle states that any outcome of a mechanism can be replicated by a truth-telling equilibrium of a direct mechanism. If there exists an equilibrium outcome of some mechanism that is strictly monotone and deterministic, then there is a truth-telling equilibrium of a direct mechanism that yields the same outcome. Since the outcome is strictly monotone and deterministic, the decision function of the direct mechanism is strictly monotone and deterministic. But we already know from Proposition 3.1 that truth-telling can not be an equilibrium given such a decision mechanism, a contradiction. This contradiction proves that no deterministic equilibrium outcome of any mechanism exists that is strictly monotone.[4]

Proposition 3.2 thus derives partitioning of private data as the only possible deterministic equilibrium outcome under any decision procedure, including the reporting game with a deterministic and strictly monotone decision function considered in Proposition 3.1. Partitioning data is a particular form of garbling that restricts information in a natural way and prevents full revelation of private evidence. Information aggregation in the committee occurs in a garbled form. What matters to the committee decision is which interval each member's private data belong to. Note that for each member the intervals are ranked by the resulting probabilities of conviction. These intervals can be interpreted as categories in a voting procedure, and the outcome represented by the decreasing step function in Figure 2 gives the voting rule that determines how two categories are mapped

[4] A similar argument establishes that a deterministic equilibrium outcome of any mechanism must be weakly increasing in the sense that a stronger signal for guilt results in a weakly greater probability of conviction. This is what we have assumed in the discussions. However, random outcomes cannot excluded as candidates for equilibrium outcomes. Consider the following decision mechanism. Each member chooses conviction or acquittal. If they agree, that choice is carried out. If they disagree, they flip a coin with even odds to decide. One can show that this mechanism has a random outcome with threshold reporting strategies.

into a decision. For example, Figure 2 represents the case of a voting procedure with N categories and with a unilateral conviction rule: the committee decision is conviction if any member's private data fall into the category with the strongest signals of guilt, regardless of the data received by the other member. Detailed examples of voting procedures will be presented from the next section, where we construct partition as equilibrium outcomes and show that any partition outcome corresponds to the equilibrium outcome of a voting procedure. Proposition 3.2 thus gives a strong sense that we derive voting with categories as a necessary method to achieve consensus in committee decision-making.

The result that manipulation arising from conflicting interests leads to information garbling is related to Crawford and Sobel's (1982) work on cheap talk games. As in their model, it is not possible to verify the private information of any committee member. But we study the problem of strategic information aggregation instead of signaling. In a committee decision-making environment, reports submitted by members are fed into a committee decision rule, and reports of other committee members can not be simply dismissed as cheap talk by any member. Other differences between our model and that of Crawford and Sobel are that decisions in our model are discrete instead of continuous, and that committee members do not always disagree on which choice to make.

4. Voting as Equilibrium Garbling

4.1. Characterization of the two-partition equilibria

In this section, we prove that there are decision procedures such that two-partition outcomes are equilibrium outcomes, and provide comparative statics studies of equilibrium strategic manipulations of private information. A two-partition outcome is defined by a pair of thresholds. There are two possibilities, depending on whether the acquittal region or the conviction region is convex. The first one corresponds to "unilateral conviction" and the second to "unilateral acquittal." In unilateral conviction, the outcome is conviction whenever at least one member receives a signal above his threshold. With unilateral acquittal, the outcome is conviction unless each member's signal exceeds his threshold.

Characterizing a two-partition equilibrium outcome amounts to finding a pair of thresholds. Define the thresholds (t^a_*, t^b_*) according to

$$\begin{aligned} \frac{f^a_g(t^a_*)}{f^a_i(t^a_*)} \frac{F^b_g(t^b_*)}{F^b_i(t^b_*)} &= k^a, \\ \frac{f^b_g(t^b_*)}{f^b_i(t^b_*)} \frac{F^a_g(t^a_*)}{F^a_i(t^a_*)} &= k^b. \end{aligned} \tag{4.1}$$

Similarly, define the thresholds (t^a_{**}, t^b_{**}) according to

$$\begin{aligned} \frac{f^a_g(t^a_{**})}{f^a_i(t^a_{**})} \frac{1 - F^b_g(t^b_{**})}{1 - F^b_i(t^b_{**})} &= k^a, \\ \frac{f^b_g(t^b_{**})}{f^b_i(t^b_{**})} \frac{1 - F^a_g(t^a_{**})}{1 - F^a_i(t^a_{**})} &= k^b. \end{aligned} \tag{4.2}$$

Proposition 4.1. *Unilateral conviction with thresholds defined by (4.1) and unilateral acquittal with thresholds defined by (4.2) are equilibrium outcomes.*

Proof. Consider only unilateral conviction; the case of unilateral acquittal is similar. We construct a truth-telling equilibrium of a direct mechanism with unilateral conviction as the equilibrium outcome. Consider the direct mechanism where members report what their signals are and the decision is reached by a partition of reports: convict if either A's report r^a exceeds t^a_* or B's report r^b exceeds t^b_* and acquittal otherwise. Based on the observation $Y^a = y^a$, member A's posterior on the probability that the suspect is guilty is $\eta\gamma^a f^a_g(y^a)$, and the probability that the suspect is innocent is $\eta(1-\gamma^a)f^a_i(y^a)$, where the normalizing factor η equals the reciprocal of $\gamma^a f^a_g(y^a) + (1-\gamma^a)f^a_i(y^a)$. By submitting a report $r^a \geq t^*_a$, member A ensures conviction. His expected cost (from false conviction) is $\eta k^a_1 f^a_i(y^a)$. If he submits report $r^a < t^*_a$ instead, the verdict depends on member B's report. From A's point of view, the suspect will be wrongly convicted with probability $1 - F^b_i(t^b_*)$, and wrongly acquitted with probability $F^b_g(t^b_*)$. Member A's total expected loss from the two types of errors is then $\eta k^a_1 f^a_i(y^a)[1 - F^b_i(t^b_*)] + \eta k^a_2 f^a_g(y^a) F^b_g(t^b_*)$. Comparing the costs of the two reports shows that submitting a report $r^a \geq t^*_a$ is preferred to submitting a report $r^a < t^*_a$ if and only if

$$\frac{f^a_g(y^a)}{f^a_i(y^a)} \frac{F^b_g(t^b_*)}{F^b_i(t^b_*)} \geq k^a. \tag{4.3}$$

By the definition of the thresholds t_*^a and t_*^b and the monotone likelihood ratio property, reporting $r^a \geq t_a^*$ is better than reporting $r^a < t_a^*$ if and only if $y^a \geq t_*^a$. Furthermore, since A's report affects the outcome only when it changes from above the threshold to below or vice versa, truth-telling is optimal for A. The argument for B is symmetric. *Q.E.D.*

The equilibrium conditions in the reporting game can be understood in terms of a "pivotal voting" argument (Austen-Smith and Banks, 1996; Feddersen and Pesendorfer, 1997). Stated in our framework, strategic reporting requires that each member choose his report as if it were pivotal. With unilateral conviction, member A's report is pivotal if and only if member B's signal is below his threshold t_*^b. The likelihood ratio for the event that $Y^a = y^a$ and $Y^b < t_*^b$ is given by the left-hand-side of (4.3). The optimal decision rule for A is to ensure conviction if and only if this likelihood ratio is greater than or equal to k^a, as required by pivotal reporting. An alternative way to see why pivotal reporting is optimal is to consider how members choose the threshold rule before observing the signal. Anticipating that B uses a reporting rule with threshold t_*^b, member A chooses his threshold t^a to minimize the expected loss $k_1^a(1 - F_i^a(t^a)F_i^b(t_*^b)) + k_2^a F_g^a(t^a)F_g^b(t_*^b)$. In the above expression, member A's choice of threshold t^a affects his expected loss only when $Y^b < t_*^b$. The first order condition for an optimal threshold t^a is precisely (4.1).

An implication of the pivotal voting argument in our model is that a sequential voting procedure, where individuals in a committee express their positions one by one, has the same equilibrium as the simultaneous voting model considered here.[5] Suppose that member A votes first and adopts a two-partition strategy: convict if and only if $y^a \geq t^a$. With unilateral conviction, if A votes for conviction, there is no decision for B to make. If A votes for acquittal, then B knows that $Y^b = y^b$ and $y^a < t^a$. His expected loss is $\eta k_1^b f_i^b(y^b)F_i^a(t^a)$ if he votes to convict and $\eta k_2^b f_g^b(y^b)F_g^a(t^a)$ if he votes to acquit, where η is a normalizing factor. Member B therefore votes to convict if and only if $y^b \geq t^b$, where t^b satisfies (4.1). Now, if A votes to acquit, he expects member B to adopt a two-partition strategy with the

[5] Dekel and Piccione (1999) reach the same conclusion in a different setup.

threshold determined by (4.1). But the decision problem of A as a first-mover is exactly the same as the problem he faces when the two members vote simultaneously.[6]

As usual, the equilibrium outcomes of unilateral conviction or unilateral acquittal can be achieved by a number of mechanisms. The proof of Proposition 4.1 gives a direct mechanism that generates the outcomes in a truth-telling equilibrium, through a weakly monotone decision function that mimics the step functions illustrated in Figure 2. Note that truth-telling is an equilibrium because unlike the decision rules considered in Proposition 3.1, the decision rule constructed here is not responsive to small changes in the reports. In fact, committee members are indifferent among all reports that lie in the same interval as the data (below or above the personal threshold defined in (4.1) and (4.2)), so they might as well tell the truth. Weak monotonicity of the decision function limits the room for data manipulation to lying about which interval the private data are in. But anticipating that the other member chooses the interval honestly, each member has incentives to do the same because picking the wrong interval is too costly.

A more natural mechanism that achieves the same equilibrium outcomes is the one considered in Proposition 3.1, where the two members submit reports on what they observe, and the decision rule is to convict if and only if $T(r^a, r^b) \geq 0$, where T is an arbitrary strictly increasing function. Proposition 3.1 shows that there is no equilibrium with invertible reporting strategies. Now we prove that there exists an equilibrium with categorical and non-invertible reports. Suppose that r_1^j is the maximum admissible report and r_0^j is the minimum admissible report for each member j ($j = a, b$). For T to be a meaningful decision function, we must have $T(r_1^a, r_1^b) \geq 0$ and $T(r_0^a, r_0^b) < 0$. Then either $T(r_1^a, r_0^b) \geq 0$ or $T(r_1^a, r_0^b) < 0$. In the first case, the assumption that T is increasing implies that $T(r_0^a, r_1^b) \geq 0$.[7] This case is precisely unilateral conviction: given the decision

[6] The equivalence between sequential and simultaneous voting requires that the first mover be unable to commit to a threshold rule. This is a reasonable assumption in our setup because the strategy in the voting game is not observable even when the reports are sequentially submitted. Since the value of the signal is not public by assumption, any attempt to commit to a certain strategy is not verifiable. Thus, member A can not manipulate member B's threshold rule, even though B's threshold depends on A's threshold through equation (4.1).

[7] Otherwise, the committee decision would depend on A's evidence only: regardless of member B's report, conviction ensues if A submits report r_1^a because $T(r_1^a, r_0^b) \geq 0$ and $T(r_1^a, \cdot)$ is increasing, and acquittal ensues if A reports r_0^a because $T(r_0^a, r_1^b) < 0$ and $T(r_0^a, \cdot)$ is increasing.

function T, it is an equilibrium that member A reports r_1^a if $y^a \geq t_a^*$ and r_0^a if $y^a < t_a^*$ and B reports r_1^b if $y^b \geq t_b^*$ and r_0^b if $y^b < t_b^*$. Similarly, in the other case, $T(r_1^a, r_0^b) < 0$ implies $T(r_0^a, r_1^b) < 0$. Then the following strategy profile is an equilibrium that yields unilateral acquittal as the outcome: member A reports r_1^a if $y^a \geq t_a^{**}$ and r_0^a if $y^a < t_a^{**}$ and B reports r_1^b if $y^b \geq t_b^{**}$ and r_0^b if $y^b < t_b^{**}$.[8] Note that for any given decision function $T(r^a, r^b)$, typically there are many other values of the reports $(r_0^a, r_1^a, r_0^b, r_1^b)$ that support the same equilibrium of threshold reporting strategies. The numerical values of reports have to be coordinated by the committee members.

Under the decision mechanisms described above, in equilibrium each member submits only two reports, depending on how his data compares with his threshold, much like voting. A voting procedure is an indirect decision mechanism, as members choose between the two votes "conviction" and "acquittal," instead of submitting a report about what they observe. With two committee members, there are two possible voting procedures: either one conviction vote is sufficient for conviction, or two votes are required. It is clear that the first voting procedure yields unilateral conviction (with thresholds defined by 4.1) as the equilibrium outcome, and the second procedure yields the unilateral acquittal outcome (with thresholds defined by 4.2).

A voting procedure is appealing as a decision-making mechanism. Unlike the direct mechanism described in the proof of Proposition 4.1, the same voting procedure can be implemented independently of the equilibrium thresholds. This robustness feature of a voting procedure is important in any real-life committee, as the preference parameters and hence the equilibrium thresholds vary according to the composition of the committee and other circumstances. A voting procedure is also robust with respect to uncertainty in the preferences and biases of fellow committee members, as the uncertainty does not affect derivation of equilibrium as long as it can be represented by probability distributions. Moreover, implementation of a voting procedure does not require coordination in

[8] Perhaps an example with an explicit decision function is helpful to illustrate this point. Suppose that the committee decision function is $T(r^a, r^b) = r^a + r^b - \delta$ where δ is some standard of proof. If reports are restricted to $[0, 1]$ (to avoid uninteresting indeterminacies that may arise when members submit unbounded reports), a meaningful standard of proof δ is positive but not greater than 2, and $r_1^j = 1$ and $r_0^j = 0$. Then, unilateral conviction is an equilibrium outcome when $0 < \delta \leq 1$, and unilateral acquittal is an equilibrium outcome when $1 < \delta \leq 2$.

choosing reports by committee members, as discussed in the previous paragraph. As seen in later sections, a strictly monotone decision rule typically has equilibrium outcomes with more than two categories. Further coordination by committee members is necessary for the decision mechanism to yield a particular outcome. A voting procedure solves the coordination problem through an agreement, prior to receiving private data, on the set of admissible reports and on the mapping from reports to decisions. The simple voting procedures discussed in this section involves only a choice between yes and no votes and a specification of either unilateral conviction or unilateral acquittal. A more general one can involve choosing from more than two categories, such as "strongly recommended," "recommended," and "not recommended," and an agreement on how the choices made by committee members are mapped into a decision. Examples of such generalized voting procedures will be discussed in sections 5 and 6.

Information aggregation with discontinuous data and strategic voting is analyzed in a series of interesting papers by Austen-Smith and Banks (1996) and Feddersen and Pesendorfer (1996; 1997; 1998). In their model, private signals are binary, a feature that limits their analysis of information manipulation to mixed strategies. Our model differs in several respects.[9] By using a richer information structure with continuously distributed private signals, we are able to study a richer set of information manipulation in committee decision-making. Instead of the mixed-strategy equilibria of Feddersen and Pesendorfer, we characterize the partition equilibria, which will allow us to consider in detail obfuscation, exaggeration, and abstention as distinctive forms of evidence manipulation. More importantly, we do not impose voting as the collective decision procedure. We start with an information aggregation procedure that is optimal in the absence of strategic manipulation and derive voting as equilibrium garbling. In the following analysis of the two-partition equilibrium, we go beyond the pivotal voting argument of Feddersen and Pesendorfer, which is valid regardless of whether or not the preferences of members coincide. We emphasize the role of conflicting interests in committee decision-making.

[9] Duggan and Martinelli (1999) uses a setup similar to ours to extend the results of Feddersen and Pesendorfer on the Condorcet Jury Theorem. They only characterize the two-partition equilibrium outcome, assuming common preferences among members. But common preferences lead to truth-telling equilibrium with perfect information aggregation, as shown above.

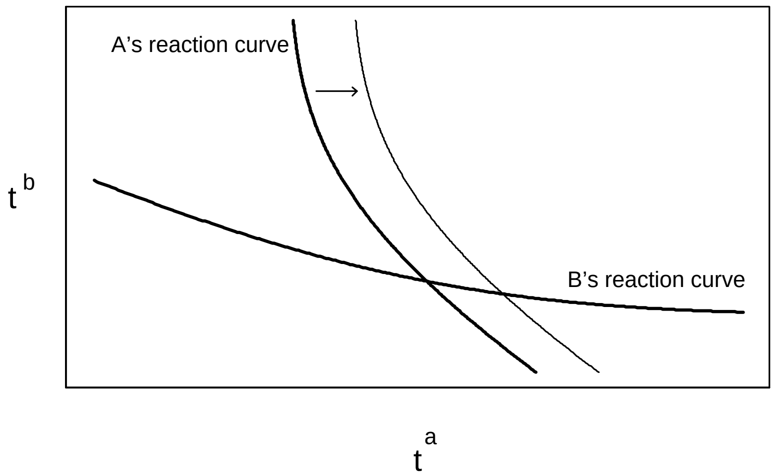
4.2. Uniqueness and stability of equilibrium

For the rest of this section, we use the voting procedures as the underlying game. The two procedures are referred to as the case of unilateral conviction and the case of unilateral acquittal. For unilateral conviction, equations (4.1) define "reaction functions," and the equilibrium is an intersection of the two curves in the (t^a, t^b) plane. For $j = a, b$, denote $l^j(\cdot) = f_g^j(\cdot)/f_i^j(\cdot)$, and $L_*^j(\cdot) = F_g^j(\cdot)/F_i^j(\cdot)$. By the monotone likelihood ratio property that l^j is an increasing function, $L_*^j(\cdot)$ is also increasing. Thus, the two reaction functions are downward sloping in the (t^a, t^b) plane. Existence of an intersection of two functions can be guaranteed under appropriate boundary conditions on the likelihood ratios. For example, suppose that for each $j = a, b$ the support of Y^j is a finite interval $[\underline{y}^j, \overline{y}^j]$. Then, if $l^a(\underline{y}^a)L_*^b(\overline{y}^b) \leq k^a$ and $l^a(\overline{y}^a)L_*^b(\underline{y}^b) \geq k^a$, then A's reaction function is well-defined on $[\underline{y}^a, \overline{y}^a]$ for any $t^b \in [\underline{y}^b, \overline{y}^b]$. A symmetric set of conditions guarantees that B's reaction function is well-defined. The Brouwer fixed-point theorem can be applied to the equations (4.1) to show that an equilibrium exists. If the support of Y^j is infinite, existence of equilibrium can be guaranteed if one can find finite intervals on which the above boundary conditions are satisfied. For example, if Y^j is normally distributed, such intervals can always be found and an equilibrium always exists.

A sufficient condition for a unique intersection of the two reaction functions is that one reaction function is steeper than the other one whenever the two intersect. This condition is satisfied if $l^j(\cdot)/L_*^j(\cdot)$ is monotone. Uniqueness of equilibrium is necessary for analysis of equilibrium properties. If in addition $l^j(\cdot)/L_*^j(\cdot)$ is increasing, then the equilibrium is globally "stable" in a pseudo-dynamic sense that starting from any initial values the trajectory of the two thresholds converges to the intersection of the reaction curves. A sufficient condition for stability is that member A's reaction function is steeper than that of member B. Direct calculations verify that this is true if $l^j(\cdot)/L_*^j(\cdot)$ is increasing. As is the case for many static games, stability in the pseudo-dynamic sense is required to avoid perverse comparative statics (Dixit 1986). Figure 3 depicts the reaction functions for the case where conditional on guilt or innocence Y^a and Y^b are normally distributed. This case satisfies the increasing condition on $l^j(\cdot)/L_*^j(\cdot)$.

Figure 3

Reaction functions in the two-partition equilibrium



The case of unilateral acquittal is analogous. Define $L^j_{**}(\cdot) = [1 - F^j_g(\cdot)]/[1 - F^j_i(\cdot)]$. The monotone likelihood ratio property also implies that $L^j_{**}(\cdot)$ is an increasing function. As in the first case, the assumption that $l^j(\cdot)/L^j_{**}(\cdot)$ is increasing is sufficient to ensure that equilibrium is unique and stable. For example, if Y^j is normally distributed conditional on guilt or innocence, then both l^j/L^j_* and l^j/L^j_{**} are monotonically increasing.

4.3. Information manipulation and information sharing

This sub-section presents a few comparative statics results for the voting game that illustrate the tension between information manipulation and information sharing. With unilateral conviction, equations (4.1) imply that if Y^a and Y^b have the same conditional distributions, then $k^a > k^b$ implies $t^a_* > t^b_*$. That is, if member A is more biased toward acquittal than member B, the equilibrium threshold for conviction is higher for member A than that for member B. For the same observation value $Y^a = Y^b = y$, member A votes to acquit while member B votes to convict if $y \in (t^b_*, t^a_*)$. Therefore $|t^a_* - t^b_*|$ can be thought of as the "area of disagreement" between the two members.

That l^j/L^j_* is increasing implies that $dt^a_*/dk^a > 0$ and $dt^b_*/dk^a < 0$. Thus, the area of disagreement increases as conflict of interests, $|k^a - k^b|$, increases. As member A becomes more biased toward acquittal and his standard for conviction increases, member B counters by lowering his own standard, which induces A to increase t_*^a further. The increase in the equilibrium threshold t_*^a can be decomposed into two parts: the increase due to shift of A's reaction function, and the increase along A's reaction function due to decrease in B's threshold. See Figure 3. The second part shows that the area of disagreement in committee decision-making is larger than that implied by inherent conflicts in preferences, due to the strategic manipulation and counter-manipulation of reporting thresholds. In this sense conflicts tend to exaggerate favorable evidence. When member A is more biased toward acquittal than member B, member A raises his threshold not only because of the concern for false conviction, but also to balance member B's opposite tendency to convict. Member A votes to acquit more often than in the absence of information manipulation by B.

Although conflicts cause evidence manipulation, incentives to exaggerate favorable evidence are balanced in equilibrium by incentives to share information. Comparing the equilibrium with how each member would make the decision based on his own private information shows how the committee members share their information. If member j ($j = a, b$) makes the decision alone, the optimal decision rule convicts if and only if own evidence y^j exceeds a threshold $\hat{t}^j$ that satisfies:

$$\frac{f_g^j(\hat{t}^j)}{f_i^j(\hat{t}^j)} = k^j. \tag{4.4}$$

Comparing (4.4) to the equilibrium condition (4.1), since $L_*^j(\cdot) < 1$, $\hat{t}^j$ is lower than t_*^j. When member j observes evidence y^j between $\hat{t}^j$ and t_*^j, he votes to acquit even though he would have chosen conviction if he were the only decision-maker. Member j thus utilizes the information of the other member by casting the decisive vote for conviction less frequently. Note that this is true independent of member j's preferences. Even if member j is biased toward conviction, the need to utilize the fellow member's information still makes him more "conservative" towards conviction. In the case of unilateral acquittal, the decisive vote is acquittal instead of conviction: each member utilizes the information of the other member by voting for acquittal less frequently than if the decision were made on the basis of own information.

Incentives to share information under conflicting interests can also be examined by considering how voting behavior changes when the signal received by one member, say B, becomes more discriminating. If evidence is public information, increased quality of B's signal would call for a greater weight attached to it in the decision rule. When evidence is private, changes in weights can be easily undone by information manipulation. Information sharing occurs, in a garbled form, through changes in the equilibrium thresholds. Formally, borrowing from the concept of statistical power, we say that a signal is more discriminating than another if it results in a lower probability of type I error, holding fixed the probability of type II error. Consider a modification of the structure of information available to the members. Member A still observes Y^a. Member B observes Y^b with probability $1-\pi$, and observes the true state of guilt or innocence with probability π. An increase in π improves the power of the signal available to member B. The event that B votes acquittal has a likelihood ratio L_*^b, where

$$L_*^b = \frac{(1-\pi)F_g^b(t_*^b)}{\pi + (1-\pi)F_i^b(t_*^b)}.$$

The numerator of L_*^b is the probability of committing a type II error by member B, and the denominator is one minus the probability of his committing a type I error. Since L_*^b is decreasing in π, a higher value of π corresponds to more discriminating evidence. In Figure 3, an increase in π causes A's reaction function to shift to the right. The effect is the same as an increase in A's bias toward acquittal: t_*^a increases and t_*^b decreases. The interpretation is straightforward. Voting to convict decides the verdict regardless of the value of the other member's signal. Voting to acquit, on the other hand, defers the decision to the other member. When member B gains access to more discriminating evidence, member A takes advantage of the improved information by raising t_*^a and deferring the decision to member B. This is achieved by raising the conviction threshold t_*^a.

The analysis is symmetric for the case of unilateral acquittal. Given the modified information structure,

$$L_{**}^b = \frac{\pi + (1-\pi)(1-F_g^b(t_{**}^b))}{(1-\pi)(1-F_i^b(t_{**}^b))}.$$

An increase in π increases L_{**}^b, so t_{**}^a falls and t_{**}^b rises. Voting to acquit decides the final outcome of the case. Member A avoids submitting a decisive vote in order to take advantage of the more discriminating evidence from member B. He therefore lowers t_{**}^a and votes for acquittal less often. Even if member A is biased toward acquittal, the need to utilize the fellow member's superior information still makes him more conservative towards casting the decisive vote.

4.4. Conflicts and welfare

Conflicts reduce the *ex ante* welfare of members. There is a close relation between the extent of divergence in preferences, $|k^a - k^b|$, and expected losses in the voting game. With unilateral conviction, equilibrium expected loss to member A is given by

$$\mathrm{E}[C^a(Y^a, Y^b)] = k_1^a(1 - F_i^a(t_*^a)F_i^b(t_*^b)) + k_2^a F_g^a(t_*^a)F_g^b(t_*^b).$$

Differentiating with respect to k^b and using the equilibrium condition (4.1) for member A,

$$\frac{d\mathrm{E}[C^a(Y^a, Y^b)]}{dk^b} = [-k_1^a f_i^b(t_*^b)F_i^a(t_*^a) + k_2^a f_g^b(t_*^b)F_g^a(t_*^a)]\frac{dt_*^b}{dk^b}. \tag{4.5}$$

Since $dt_*^b/dk^b > 0$ when l^j/L_*^j is increasing, $d\mathrm{E}[C^a(Y^a, Y^b)]/dk^b$ has the same sign as $k^b - k^a$. For example, if $k^b > k^a$, a further increase in k^b raises member A's expected loss in the equilibrium.

Conflicts reduce welfare because strategic manipulation becomes more important. A committee with less cooperation uses information less efficiently and welfare in the voting game is lower than in a full information equilibrium. Equation (4.5) shows that $d\mathrm{E}[C^a(Y^a, Y^b)]/dk^b$ has the same sign as $k^b - k^a$, and similarly $d\mathrm{E}[C^b(Y^a, Y^b)]/dk^a$ has the same sign as $k^a - k^b$. If $k^a = k^b$ there is no conflict of interest in the committee, and equilibrium threshold choices minimize the expected loss for both members. If $k^a < k^b$, raising the equilibrium threshold for member A and lowering it for member B will reduce the expected loss for both members, because the first order gain will outweigh the second order loss. If we define "cooperative decision-making" as choosing thresholds to minimize a weighted sum of expected loss for the two members, then conflicts in preferences generate incentives to deviate from cooperative decision-making. Starting from the cooperative solution, if member A is more concerned with false acquittal than member B is, A will lower his threshold for conviction, which induces B to raise his threshold in order to balance A's bias for conviction. In equilibrium, both members are made worse off.

4.5. Do-it-yourself, delegation, and taking turns

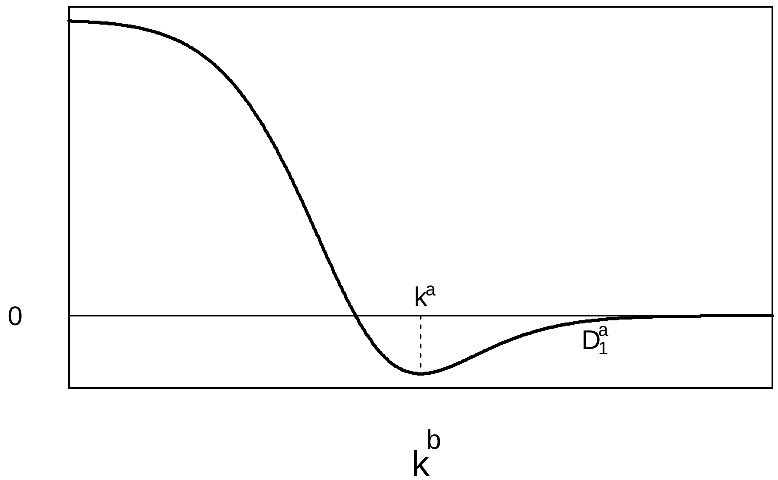
Since conflicting preferences lead to strategic manipulation in voting and welfare loss for both members, will the gains from information sharing in a committee be sufficient to outweigh the losses from strategic voting? The answer is clearly "yes" when conflicts are small. Even though votes are manipulated, aggregation produces better outcomes than alternatives that do not aggregate private information. We will show that in some sense gains from information sharing always dominate losses from information manipulation regardless of the extent of conflicts.

Let $\mathrm{E}[C^a(Y^a)]$ denote member A's unconditional expected loss when he alone makes the decision based on his own information. Then $\mathrm{E}[C^a(Y^a)] = k_1^a(1 - F_i^a(\hat{t}^a)) + k_2^a F_g^a(\hat{t}^a)$, where the optimal threshold $\hat{t}^a$ satisfies condition (4.4). Consider the difference $D_1^a = \mathrm{E}[C^a(Y^a, Y^b)] - \mathrm{E}[C^a(Y^a)]$ as a function of k^b. We showed that $d\mathrm{E}[C^a(Y^a, Y^b)]/dk^b < 0$ for $k^b < k^a$ and $d\mathrm{E}[C^a(Y^a, Y^b)]/dk^b > 0$ for $k^b > k^a$. Since $\mathrm{E}[C^a(Y^a)]$ is independent of k^b, the difference D_1^a decreases for $k^b < k^a$ and then increases for $k^b > k^a$, reaching a minimum at $k^b = k^a$. In the limiting case when k^b approaches infinity, member B always votes acquittal and lets member A make the decision. Therefore, $D_1^a = 0$. At the other limit, when k^b approaches zero, member B ensures conviction by himself. Member A's expected loss is then simply k_1^a, and the difference D_1^a is given by $k_1^a F_i^a(\hat{t}^a) - k_2^a F_g^a(\hat{t}^a)$. By the definition of $\hat{t}^a$, we have $k_1^a f_i^a(y^a) > k_2^a f_g^a(y^a)$ for all $y^a < \hat{t}^a$. Integrating over the range $y^a \le \hat{t}^a$ then establishes that $D_1^a > 0$. Figure 4 shows D_1^a as a function of k^b. From A's point of view, do-it-yourself decision-making is preferred to committee decision-making only if k^b is sufficiently smaller than k^a. Note that D_1^a is negative at $k^b = k^a$. With no conflict of preferences, committee decision-making dominates do-it-yourself decision-making because more information is better. Indeed, if conflicts are not so great, committee decisions are better for both members.

Let $\mathrm{E}[C^b(Y^a)]$ denote member B's unconditional expected loss when member A alone makes the decision based on his private information. Clearly, if Y^a and Y^b have identical conditional distributions, $\mathrm{E}[C^b(Y^b)] \le \mathrm{E}[C^b(Y^a)]$. That is, each member always prefers deciding by himself to letting the other member make the decision. Let $D_2^b(k^b)$ be the

Figure 4

Welfare comparison: do-it-yourself versus committee



difference between the expected loss to member B under committee decision-making and his expected loss if he delegates the decision to A. Then, for all k^a,

$$D_2^b = D_1^b + \mathrm{E}[C^b(Y^b)] - \mathrm{E}[C^b(Y^a)] \leq D_1^b.$$

From Figure 4 (interchanging the roles for A and B), a necessary (but not sufficient) condition for D_2^b to be positive is that $k^a < k^b$.

The above analysis implies that mutually agreed delegation can not occur. For member B to prefer delegating to A, D_2^b must be positive. For member A to accept the delegation, D_1^a must be positive. A necessary condition for the former is that $k^a < k^b$, and a necessary condition for the latter is $k^b < k^a$. These two conditions are incompatible. The intuition of this result is clear from its derivation. For the delegation of decision-making to A to be agreeable to both members, the benefits of using B's information in committee decision-making must be small to both A and B. Since conviction can be ensured unilaterally, the benefits are small to B only if A is more biased toward conviction, and the benefits are small to A only if B is more biased toward conviction. Thus, if delegating decision-making to A is acceptable to A, it will not be so to B.

We can also show that it is never a Pareto improvement for the two members to dissolve the committee and make decisions by taking turns. Let $D_3^a = (D_1^a + D_2^a)/2$ be the difference in member A's expected loss from committee decision-making and his expected loss from taking turns. Since $k^b < k^a$ is a necessary condition both for $D_1^a \geq 0$ and for $D_2^a \geq 0$, it is also a necessary condition for $D_3^a \geq 0$. On the other hand, for member B to prefer taking turns to committee decision-making (i.e., $D_3^b \geq 0$), a necessary condition is $k^b > k^a$. It follows that at least one party will object to dissolving the committee and making decisions by taking turns instead.[10]

Welfare comparisons between committee decision-making and delegation or taking turns, do not change if acquittal instead of conviction is reached unilaterally. With unilateral acquittal, the decisive vote is acquittal. For the delegation of decision-making to B to be agreeable to both members, the benefits of using A's information in committee decision-making must be small to both A and B. Since acquittal can be ensured unilaterally, the benefits are small to A only if B is more biased toward acquittal, but the benefits are small to B only if A is more biased toward acquittal. Delegation or taking turns can not Pareto dominate committee decision-making because for at least one member, the gains from information sharing outweigh the loss from information manipulation.

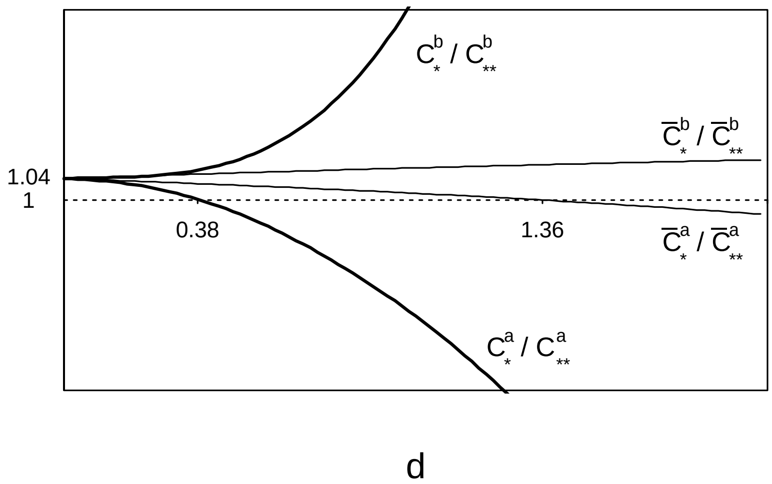
4.6. Voting procedures and voting behavior

In a two-partition equilibrium, there are essentially just two decision procedures for a committee of two members, unilateral conviction and unilateral acquittal. It might seem that requiring two votes for conviction instead of one vote is a more "stringent" standard of proof. But this is only true when members cast their votes without regard to the voting procedure. Since each member cares only about the final verdict rather than his own vote, he votes to convict less cautiously when unanimity is required, knowing that the other member may have information that will lead to a vote against conviction. On the other hand, if one vote is sufficient for a guilty verdict, each member is more cautious in casting a vote to convict, knowing that such a vote would have a decisive effect regardless of the other member's information. More precisely, the monotone likelihood ratio property

[10] The conclusion that it is never Pareto optimal to make decisions by taking turns may not hold when individual members must bear the cost of gathering their own information. The reason is that information is a public good in committee decision-making, and is under-provided due to the free-rider problem. For implications of the free-rider problem for committee decision-making, see Li (1999).

Figure 5

Conflicts and personal preference over decision procedures



implies that for each $j = a, b$, $L^j_*(\cdot) \leq 1$ and $L^j_{**}(\cdot) \geq 1$. It then follows from Proposition 4.1 that $t^j_* \geq t^j_{**}$. Thus, both members set a lower standard of conviction when the decision procedure is changed from unilateral conviction to unilateral acquittal.[11] This aspect of comparison of decision procedures illustrates the common interests in sharing information in committee decision-making.

The extent of conflicts in the committee affects members' preference over decision procedures. When the two members have identical interests, they agree on which decision procedure should be used in committee decision-making. By continuity, small differences in preference do not generate disagreement about the *ex ante* choice of decision procedure. However, as conflicts increase in the committee, strategic manipulations of information amplify the differences in personal preference over decision procedures. For a numerical example, let $F_i \sim N(0,1)$ and $F_g \sim N(1,1)$ be the common distribution functions, conditional on innocence and on guilt. Then, if the common preference k exceeds 1 so that both members are relatively biased toward acquittal, unilateral acquittal is preferred to unilateral conviction. Now, consider how an individual member's preference over the decision

[11] This comparison of decision procedures complements the works of Sah and Stiglitz (1986; 1988), who consider committees without the strategic manipulations that arise from conflicting interests.

procedure changes in the following comparative statics exercise. Let $k_1^a = k - d$, $k_1^b = k + d$, and $k_2^a = k_2^b = 1$. As d increases from 0 to k, k^a decreases and k^b increases. To examine the role of equilibrium manipulations of information, define a "cooperative" threshold $\bar{t}_*$ under unilateral conviction that satisfies $l(\bar{t}_*)L_*(\bar{t}_*) = k$. By construction, $\bar{t}_*$ minimizes the equally-weighted sum of expected cost to the two members under unilateral conviction, regardless of the extent of conflicts d. Similarly, define $\bar{t}_{**}$ under unilateral acquittal that satisfies $l(\bar{t}_{**})L_{**}(\bar{t}_{**}) = k$. Figure 5 illustrates how each member j's preference changes with d, by plotting the ratio of his expected cost under unilateral conviction to the cost under unilateral acquittal. With "cooperative" thresholds, member B's preference for unilateral acquittal becomes stronger as he becomes more biased toward acquittal (i.e., $\bar{C}_*^b/\bar{C}_{**}^b$ increases with d). Member A initially shares B's preference, as shown by $\bar{C}_*^a/\bar{C}_{**}^a$, but switches his preference to unilateral conviction as he becomes more concerned with false acquittal. In the numerical example shown (where $k = 2$), this happens around $d = 1.36$. In contrast, equilibrium manipulations of information arising from increasing conflicts between A and B in the non-cooperative game imply a larger difference in personal preference over decision procedure. Figure 5 also plots the ratio of each member j's equilibrium expected cost C_*^j under unilateral conviction to the cost C_{**}^j under unilateral acquittal. As with cooperative decision-making, the difference between C_*^b/C_{**}^b and C_*^a/C_{**}^a becomes greater as d increases, but the divergence goes much faster. Member A switches his preferred procedure from unilateral acquittal to unilateral conviction around $d = 0.38$, but would prefer unilateral acquittal if standards were set cooperatively.

5. Abstention

In our voting game studied in the previous section, abstention is not allowed. This assumption may appear innocuous. In the case of unilateral conviction, for example, allowing members to abstain from voting after observing their evidence will not change behavior because abstention is equivalent to voting for acquittal. However, if abstention is allowed, members take the abstention of others into account and equilibrium thresholds change. In this model abstention improves the quality of decision-making.

We need to specify what happens when both members decide to abstain. The simplest way is to specify a "default decision" when both abstain. If the default is acquittal, abstaining is still equivalent to voting for acquittal and therefore has no effect on the equilibrium. But suppose the default is conviction. Then a vote to acquit by A results in conviction only if B votes to convict, while abstention by A results in conviction when B either votes to convict or abstains. Since abstention is more likely to result in conviction than a vote for acquittal, we expect equilibrium strategies to involve two thresholds, $t_1^j < t_2^j$, such that a member strategy is

$$R^j(y^j) = \begin{cases} \text{"convict"}, & \text{if } y^j \geq t_2^j \\ \text{"abstain"}, & \text{if } t_2^j > y^j \geq t_1^j \\ \text{"acquit"}, & \text{if } y^j < t_1^j. \end{cases}$$

Using similar reasoning as in the proof of Proposition 4.1, we can establish that the thresholds for member A satisfy:

$$\begin{aligned} \frac{f_g^a(t_1^a)}{f_i^a(t_1^a)} \frac{F_g^b(t_2^b) - F_g^b(t_1^b)}{F_i^b(t_2^b) - F_i^b(t_1^b)} &= k^a, \\ \frac{f_g^a(t_2^a)}{f_i^a(t_2^a)} \frac{F_g^b(t_1^b)}{F_i^b(t_1^b)} &= k^a; \end{aligned} \tag{5.1}$$

and a symmetric pair of equations holds for B. The term $(F_g^b(t_2^b) - F_g^b(t_1^b))/(F_i^b(t_2^b) - F_i^b(t_1^b))$ in the first equation of (5.1) is the likelihood that B abstains. In that case, A can guarantee acquittal only if he votes to acquit. The term $F_g^b(t_1^b)/F_i^b(t_1^b)$ in the second equation is the likelihood that B votes to acquit. In that case, A can guarantee acquittal if he abstains. The monotone likelihood ratio condition implies that $(F_g^j(t_2^j) - F_g^j(t_1^j))/(F_i^j(t_2^j) - F_i^j(t_1^j)) > f_g^j(t_1^j)/f_i^j(t_1^j)$ and $F_g^j(t_1^j)/F_i^j(t_1^j) < f_g^j(t_1^j)/f_i^j(t_1^j)$. Then, if $t_2^b > t_1^b$, (5.1) implies that $t_2^a > t_1^a$, and vice versa. Thus, the thresholds $(t_1^a, t_2^a, t_1^b, t_2^b)$ defined by (5.1) form a Nash equilibrium of the voting game.

The outcome of the above Nash equilibrium of the voting game with abstention can be replicated by the decision mechanism discussed earlier in section 3. Showing that this is the case illustrates the point that typically a number of partition equilibria exist for an arbitrarily given decision mechanism. Recall that each member j chooses between two reports r_0^j and r_1^j, and the decision is made according to some strictly increasing decision function $T(r^a, r^b)$. In the case of unilateral conviction, the two reports r_0^j and r_1^j for each member j satisfy the property that $T(r_1^a, r_0^b) \geq 0$, $T(r_0^a, r_1^b) \geq 0$, and $T(r_0^a, r_0^b) < 0$. We can find a report $\bar{r}^a \in (r_0^a, r_1^a)$ for member A such that $T(\bar{r}^a, r_0^b) < 0$. Since $T(\bar{r}^a, r_1^b) > T(r_0^a, r_1^b) \geq 0$, there is a report $\bar{r}^b \in (r_0^b, r_1^b)$ for member B such that $T(\bar{r}^a, \bar{r}^b) \geq 0$ and $T(r_0^a, \bar{r}^b) < 0$. The three reports $r_0^j < \bar{r}^j < r_1^j$ for each member j, together with the decision function $T(r^a, r^b)$, then implement the voting equilibrium outcome with conviction as the default decision when both abstain.

Comparing the thresholds in the equilibrium with abstention with the equilibrium thresholds without abstention shows that allowing abstention makes committee members more "careful" in casting their votes. Formally, for each $j = a, b$, $t_2^j > t_*^j > t_1^j$ (the proof is in the appendix). If the evidence is not very strong either way, a member chooses to abstain. Standards of evidence for voting to convict or to acquit are raised so that the probability of voting either way is reduced for both members. We expect that efficiency in information sharing improves as a result.

Proposition 5.1. *Expected loss under the three-partition equilibrium is lower than expected loss under the two-partition equilibrium for each committee member.*

Proof. See the appendix. *Q.E.D.*

With no conflict of preferences, abstention can not improve the quality of committee decision, because valuable evidence is thrown away. However, when preferences conflict, allowing abstention reduces harmful strategic manipulations in the committee. Moreover, abstention allows each member to adopt a reporting strategy involving three categories instead of two. Finer partition of information further improves the welfare of the committee.

6. More Categories

If the option to abstain increases the effective number of categories in the information-reporting game from two to three, are there other equilibrium outcomes that support finer partitioning of information? The answer is yes, but differences in preferences limit how fine partitions can be.

Fix any integer $N \geq 1$. For expositional convenience, we first look at the decision mechanism considered in Proposition 3.1. See Figure 2 for a graphical illustration. Recall that each member submits a report about his signal and the decision rule is to convict if and only if $T(r^a, r^b) \geq 0$, where T is strictly increasing. We construct an equilibrium where each member j ($j = a, b$) uses a $(N+1)$-partition strategy, with reports $r^j_0 < r^j_1 < \ldots < r^j_N$, such that for each $n = 0, \ldots, N$, r^j_n is reported if $y^j \in [t^j_n, t^j_{n+1})$, where $t^j_1, \ldots, t^j_N$ are the N thresholds ($t^j_0 = \underline{y}^j$ and $t^j_{N+1} = \overline{y}^j$ are defined as the lower and upper bound of the support of Y^j.) The reports $r^j_0, \ldots, r^j_N$ satisfy the property (and a symmetric one by interchanging the roles of a and b) that for each $n = 0, 1, \ldots, N$, $T(r^a_{N-n}, r^b_n) \geq 0$ and $T(r^a_{N-n-1}, r^b_n) < 0$. This is a "pivotal" condition for the reports. Unlike the equilibrium with two-partition strategies, each member can convey the strength of his evidence by choosing different reports. A report r^b_n by member B results in conviction only when member A chooses a report at least as large as r^a_{N-n}. We consider the case of unilateral conviction by assuming $T(r^a_N, r^b_0) \geq 0$ and $T(r^a_0, r^b_N) \geq 0$: submitting a report r^j_N ensures conviction regardless of the report of the other member.

Existence of the reports that satisfy the pivotal condition can be shown by induction, similar to how we show abstention can be implemented by adding another report for each committee member. Moreover, if member A adopts the above reporting strategy with the $N+1$ reports $r^a_0, \ldots, r^a_N$, member B has no incentives to use reports other than $r^b_0, \ldots, r^b_N$. For example, any report $r^b \in (r^b_n, r^b_{n+1})$ such that $T(r^a_{N-n-1}, r^b) < 0$ is the same as r^b_n (because both result in conviction if and only if $r^a \geq r^a_{N-n}$), and any $r^b \in (r^b_n, r^b_{n+1})$ such that $T(r^a_{N-n-1}, r^b) \geq 0$ is the same as r^b_{n+1}. As in the two-partition case, many sets of reports satisfy the pivotal conditions for an $(N+1)$-partition equilibrium, but they all lead to the same equilibrium.

For illustration, suppose that the decision rule is conviction if and only if the sum of reports is at least 7. Consider a reporting strategy profile where each member submits an integer-valued report of 1 to 10. Submitting any report of 7 or above will ensure conviction unilaterally and is strategically equivalent. Each member has 7 strategically distinct reports. A report of, say, 4 leads to conviction if and only if the other member submits a report at least as large as 3. Furthermore, given that the other member chooses only among integers from 1 to 10, there is no incentive for each member to choose reports other than these 10 numbers. This decision procedure thus induces a 7-partition outcome. If the committee convicts whenever the sum of reports is at least 15, then submitting any report of 4 or below will ensure acquittal unilaterally. This induces another 7-partition outcome corresponding to the case of unilateral acquittal.

The above example makes another important point. If the report of each member is restricted to an integer-valued score of 1 to 10, then we have a "generalized voting procedure." Choosing a score can be thought of as choosing a category. A generalized voting procedure is an indirect decision mechanism because the choice of reports by members is restricted and the choice is not directly related to the signals they receive. However, as long as the generalized voting procedure specifies the outcome for each pair of chosen categories according to the step function in Figure 2, it induces the same 7-partition outcome as the original decision mechanism. In general, any outcome of the $(N+1)$-partition equilibrium we construct for the decision mechanism with decision function T can be replicated by a generalized voting procedure. This kind of procedure is sometimes observed in committee decision-making. An example is the point system used in sports such as figure skating and gymnastics, and in advisory reports such as recommendation letters. As in the case of voting procedures, one advantage of a generalized voting procedure over the decision mechanism with a strictly increasing function T is that the former avoids coordination problems that arise from having many partition equilibria and from having many reports consistent with each equilibrium outcome.

Deriving conditions for the $(N+1)$-partition equilibrium is a straightforward extension of the proof of Proposition 4.1. A pivotal voting argument is also available. By construction, for each $n = 1, \ldots, N$, a choice between r^a_{n-1} and r^a_n for member A is pivotal only if member B reports r^b_{N-n}: if A reports r^a_{n-1} there is acquittal, and if he reports r^a_n there is conviction. Member A therefore makes the choice between the two reports conditional on his evidence $Y^a = y^a$ and on B's report $r^b = r^b_{N-n}$ (that is, $y^b \in [t^b_{N-n}, t^b_{N-n+1})$). The expected loss to A from choosing R^a_n is $\eta k^a_1 f^a_i(y^a)(F^b_i(t^b_{N-n+1}) - F^b_i(t^b_{N-n}))$, and from choosing r^a_{n-1} is $\eta k^a_2 f^a_g(y^a)(F^b_g(t^b_{N-n+1}) - F^b_g(t^b_{N-n}))$, where η is a normalization factor under Bayesian updating, and the terms in the brackets are the probability that B's evidence lies in the interval that allows A to be pivotal. Thus, reporting r^a_n instead of r^a_{n-1} is optimal if and only if $y^a \geq t^a_n$ where the threshold t^a_n satisfies

$$\frac{f^a_g(t^a_n)}{f^a_i(t^a_n)} \frac{F^b_g(t^b_{N-n+1}) - F^b_g(t^b_{N-n})}{F^b_i(t^b_{N-n+1}) - F^b_i(t^b_{N-n})} = k^a. \tag{6.1}$$

By the monotone likelihood ratio property, $[F^j_g(u) - F^j_g(v)]/[F^j_i(u) - F^j_i(v)]$ is increasing in both u and v for all $u > v$.[12] Since the above argument holds for $n = 1, \ldots, N$, the thresholds defined by equations (6.1) satisfy $t^a_1 < \ldots < t^a_N$. Thus, the pivotal voting argument proves that if member B uses a reporting strategy with thresholds $t^b_1 < \ldots < t^b_N$, the strategy defined by (6.1) is optimal for member A.

To conclude, the thresholds for an equilibrium with a $(N+1)$-partition strategies are described by the N equations in (6.1), plus a symmetric set of N equations for member B. The conditions (4.1) for the two-partition equilibrium and conditions (5.1) for the three-partition one are special cases of (6.1). If members have identical preferences, partitions can get finer and finer as N increases. The solution converges to that implied by the Neyman-Pearson lemma, and full information revelation occurs. However, conflicts in preferences and prior place an upper bound on how fine partitions can be in equilibrium.

PROPOSITION 6.1. *If $k^a \neq k^b$, then for any interval $[y^j_{\min}, y^j_{\max}]$ in the support of Y^j there is an $\epsilon > 0$, such that for any equilibrium thresholds $t^j_n, t^j_{n-1} \in [y^j_{\min}, y^j_{\max}]$, $t^j_n - t^j_{n-1} > \epsilon$.*

PROOF. See the appendix. *Q.E.D.*

The proof of Proposition 6.1 essentially states that in a partition equilibrium, any two adjacent thresholds of a member are located outside the area between the personal optimal decision functions S^a and S^b in Figure 1. If the two members have a greater difference in preferences, the decision functions are further apart, and the lower bound on the distance between adjacent thresholds for each member becomes larger. Thus, the upper

[12] The derivative of this ratio with respect to u has the same sign as $f^j_g(u)[F^j_i(u) - F^j_i(v)] - f^j_i(u)[F^j_g(u) - F^j_g(v)]$. By the monotone likelihood ratio property, $f^j_g(u)f^j_i(y) \geq f^j_i(u)f^j_g(y)$ for all $y \leq u$. Integrating over y from v to u gives $f^j_g(u)[F^j_i(u) - F^j_i(v)] \geq f^j_i(u)[F^j_g(u) - F^j_g(v)]$. Monotonicity in v can be proved in a similar manner.

bound on the fineness of equilibrium partitions for a given interval depends negatively on the difference in preferences, $|k^a - k^b|$. Great conflicts within the committee make fine partitions impossible.

7. Conclusion

Committee members' incentives to manipulate private information to tilt decisions toward their personally preferred outcome imply that information can not be efficiently aggregated by committees. Perhaps this is the basis for the old joke: "Ques. How do committees make decisions? Ans. Badly." Nonetheless, committees are used to make many business and other decisions. We have illuminated some of the reasons for their continued use and survival. True, self interest and strategic considerations make information pooling in committees imperfect, but that is relative to some unattainable ideal. Garbled information still leads to better decisions for all members together than if one of them acted as "dictator" and made the decision without benefit of other, albeit strategically manipulated, information. Decisions are better in the sense that not all members would prefer ex ante to dissolve the committee and randomly select a dictator among them to make less informed decisions.

The reason is that viable committees must share some common goals, even though individual members might weigh outcomes somewhat differently. All members certainly want to gain the statistical advantages of information sharing. What makes the process work is that the committee rules and procedures are themselves chosen to temper and control strategic misrepresentations and filter the data, given self-interested behavior. Procedures are adopted that coarsen the reporting of information and put a natural limit on feasible manipulations. They control conflict in an acceptable way. The greater the differences of a priori opinion among members, the coarser the rules must be to control conflict. The quality of committee decisions necessarily declines with the degree of conflict. Yet poor as committee decisions might be when conflicts are reasonably large, they still might be better than what one person could achieve for the combined interests of the group as a whole from unilateral, and less-informed, decisions.

The two-partition voting mechanism studied in detail here is a very clear analytical representation of these ideas. In the statistical decision problem from which it is constructed, all sample information is perfectly aggregated into a "score." Minimizing the loss function sets a critical score. If the sample score exceeds the threshold, the committee makes one decision, and if it falls short of the threshold another decision is picked. Voting in a committee is a cruder kind of scoring system, but a scoring system nonetheless. Each person in the committee sets his own critical standard endogenously. The object is placed into one category or another by the committee depending on the proportion of members whose sample information places it above or below their own strategically determined personal thresholds.

Classifications that would be chosen by a hypothetical perfect aggregation scheme can not occur in a committee. This inefficiency can not be eliminated unless there is no conflict. Personal thresholds are chosen to "undo" the presumed biases of other members, but not by enough to completely nullify the information of others. For instance, members defer to those who have more informed sample information—members who have greater expertise and who are drawing their data out of probability distributions with greater precision—in the sense that the better informed members are decisive more often.

While there are few general analytical results on how voting plurality— simple majority, super-majority, or unanimity—affects the quality of committee decisions, the analysis illuminates some of the economic considerations involved in these debates. It is interesting that though requiring unanimity for conviction makes each member decisive for conviction, self-interest makes them less cautious in voting to convict because others are more likely to have information against conviction. On the other hand, requiring unanimity for acquittal makes voters more cautious in voting for conviction. These are precisely the reasons why Condorcet's Theorem fails when strategic considerations play a role in voting (Austin-Smith and Banks, 1996; Feddersen and Pesendorfer, 1998). Strictly speaking in our model, each issue coming before the committee would have an optimal plurality. We have chosen not to pursue this line because our model is not sufficiently well structured for that kind of analysis. Committee rules are chosen to achieve a certain kind of durability to a broad variety of issues that come before it. But the nature of preferences, voting rules, incentives to collect information (Li, 1999), the presentation of arguments and rhetoric in committee deliberations (Posner, 1998; Dewatripont and Tirole, 1999), and intertemporal vote trading for ongoing committees are all likely to be important for understanding the choice of committee rules. This model is too crude to incorporate such things.

In conclusion, voting is often said to be an inferior decision mechanism because it does not allow the intensity of one's preferences to be expressed in the final tally. And so it is for purely private decisions in which information and tastes of others are not directly germane. But in group decisions where social gains arise from the pooling information, the intensity of differences in preferences and opinion leads to discordance among group members that causes trouble. Voting procedures bound the expression of intensity and discordance among voters and lead to better informed group decisions. Perhaps this is the main lesson in this paper.

Appendix

A.1. Proof of Proposition 5.1

First, we show by contradiction that $t_2^j > t_*^j > t_1^j$ for each $j = a, b$. Suppose $t_*^a \geq t_2^a$. Then, using the second equation in (5.1) and the first equation in (4.1), we have $t_1^b \geq t_*^b$. From the monotonicity of $l^j(\cdot)/L_*^j(\cdot)$, we get

$$\frac{l^b(t_1^b)}{L_*^b(t_1^b)} \frac{l^a(t_*^a)}{L_*^a(t_*^a)} \geq \frac{l^b(t_*^b)}{l^b(t_*^b)} \frac{l^a(t_2^a)}{L_*^a(t_2^a)}.$$

Cross multiplying and using (4.1) and (5.1) again, we get $l^b(t_1^b)L_*^a(t_2^a) \geq k^b$. The condition for the threshold t_1^b is described by the equation

$$l^b(t_1^b)\frac{F_g^a(t_2^a) - F_g^a(t_1^a)}{F_i^a(t_2^a) - F_i^a(t_1^a)} = k^b.$$

Thus, $L_*^a(t_2^a) \geq [F_g^a(t_2^a) - F_g^a(t_1^a)]/[F_i^a(t_2^a) - F_i^a(t_1^a)]$, which contradicts the monotone likelihood ratio property. Now, suppose $t_*^a \leq t_1^a$. In the equilibrium without abstention, $l^b(t_*^b)L_*^a(t_*^a) = k^b$. In the equilibrium with abstention, $l^b(t_2^b)L_*^a(t_1^a) = k^b$. These two conditions imply that $t_*^b \geq t_2^b$. We can then follow the same method as before to derive a contradiction.

To prove Proposition 5.1, consider a Cournot tatonnement process that begins with the two-partition equilibrium without abstention and converges towards the three-partition equilibrium with abstention. Note that any two-partition strategy can be viewed as a three-partition strategy by adding an additional threshold for each member appropriately. For $j = a, b$, let $\underline{y}^j$ and $\overline{y}^j$ be the lower and the upper bound of the support Y^j. If $z_1^a = \underline{y}^a$ and $z_2^a = t_*^a$ are member A's two thresholds, and $z_1^b = t_*^b$ and $z_2^b = \overline{y}^b$ are B's two thresholds, the voting outcome is the same as the two-partition equilibrium defined by (4.1). In each iteration of the Cournot tatonnement, the new thresholds are chosen as best responses to the previous thresholds. The proof proceeds in two steps. Step 1 shows that the two-partition equilibrium converges monotonically to the three-partition equilibrium in a Cournot tatonnement process. Step 2 shows that expected loss for each member falls in each iteration of the tatonnement.

Step 1: The equilibrium conditions for the thresholds of member A specified in (5.1) can be used to define the reaction functions $z_1^a = g_1(z_1^b)$ and $z_2^a = g_2(z_1^b, z_2^b)$. The reaction functions for member B can be specified analogously. Note that all the reaction functions are strictly decreasing in their arguments. If we define $x = (z_1^a, z_2^a, -z_1^b - z_2^b)$ and let $h : \mathbb{R}^4 \to \mathbb{R}^4$ be the reaction function in the redefined variables, then $h(x)$ is monotonic increasing in x. The Cournot tatonnement is specified by the process $x(t) = h(x(t-1))$. The initial thresholds are specified near the two-partition equilibrium, $x(0) = (\underline{y}^a, t_*^a + \epsilon, -t_*^b, -\overline{y}^b)$, where $\epsilon > 0$ is arbitrarily small. An induction argument establishes that $x(t)$ increases monotonically. Suppose $x(t) \geq x(t-1)$. Then, because the reaction function $h(\cdot)$ is monotonic,

$$x(t+1) = h(x(t)) \geq h(x(t-1)) = x(t).$$

Furthermore, using the conditions for the two-partition equilibrium, it can be verified that $x(1) = h(x(0)) \geq x(0)$, and the induction argument is complete. A bounded and monotonic sequence converges to a limit point $\hat{x}$. By the continuity of the payoff functions, this point must also be an equilibrium point, $\hat{x} = h(\hat{x})$. To see this, note that $C^j(x^j(t), x^{-j}(t-1)) \leq C^j(x^j, x^{-j}(t-1))$ for all x^j $(j = a, b)$ because $x(t)$ is the best response to $x(t-1)$. Since C^j is continuous in x^j and $x(t) \to \hat{x}$, we have $C^j(\hat{x}^j, \hat{x}^{-j}) \leq C^j(x^j, \hat{x}^{-j})$ for all x^j. Therefore $\hat{x}$ is indeed a three-partition equilibrium point.

Step 2: Let the expected loss to member j be

$$\begin{aligned} C(z^a, z^b, k^j) =& k^j[1 - F_i^a(z_2^a) + (F_i^a(z_2^a) - F_i^a(z_1^a))(1 - F_i^b(z_1^b)) + F_i^a(z_2^b))] \\ &+ [(F_g^a(z_2^a) - F_g^a(z_1^a))F_g^b(z_1^b) + F_g^a(z_1^a)F_g^b(z_g^b)]. \end{aligned}$$

Without loss of generality, assume $k^a \geq k^b$. The change in cost for member A between two successive iterations is

$$\begin{aligned} &C(z^a(t+1), z^b(t+1), k^a) - C(z^a(t), z^b(t), k^a) \\ \leq& \mathbf{D}_{z^a} C(z^a(t+1), z^b(t+1), k^a)(z^a(t+1) - z^a(t)) \\ &+ \mathbf{D}_{z^b} C(z^a(t), z^b(t+1), k^a)(z^b(t+1) - z^b(t)), \end{aligned}$$

where $\mathbf{D}_{z^a} C$ and $\mathbf{D}_{z^b} C$ are the gradient vectors of C with respect to z^a and z^b. The inequality above follows from the convexity of the cost function. Because convergence is monotonic, we have $z^a(t+2) \geq z^a(t+1)$. Convexity of the cost function in z^a and the fact that $z^a(t+2)$ is a best response to $z^b(t+1)$ then imply

$$\mathbf{D}_{z^a} C(z^a(t+1), z^b(t+1), k^a) \leq \mathbf{D}_{z^a} C(z^a(t+2), z^b(t+1), k^a) = 0.$$

Furthermore, since $\mathbf{D}_{z^b} C$ is decreasing in k, and since $k^a \leq k^b$, we have

$$\mathbf{D}_{z^b} C(z^a(t), z^b(t+1), k^a) \geq \mathbf{D}_{z^b} C(z^a(t), z^b(t+1), k^b) = 0.$$

Finally, the monotonicity of the convergence process implies that $z^a(t+1) - z^a(t) \geq 0$ and $z^b(t+1) - z^b(t) \leq 0$. Thus the change in cost for member A is negative.

For member B, we follow a different decomposition to get

$$\begin{aligned} & C(z^a(t+1), z^b(t+1), k^b) - C(z^a(t), z^b(t), k^b) \\ \leq & \mathbf{D}_{z^b} C(z^a(t+1), z^b(t+1), k^b)(z^b(t+1) - z^b(t)) \\ & + \mathbf{D}_{z^a} C(z^a(t+1), z^b(t), k^b)(z^a(t+1) - z^a(t)). \end{aligned}$$

Because convergence is monotonic, we have $z^b(t+2) \leq z^b(t+1)$. Convexity of the cost function in z^b and the fact that $z^b(t+2)$ is a best response to $z^a(t+1)$ then imply

$$\mathbf{D}_{z^b} C(z^a(t+1), z^b(t+1), k^a) \geq \mathbf{D}_{z^a} C(z^a(t+1), z^b(t+2), k^a) = 0.$$

Furthermore, since $\mathbf{D}_{z^a} C$ is decreasing in k, and since $k^a \leq k^b$, we have

$$\mathbf{D}_{z^a} C(z^a(t+1), z^b(t), k^b) \leq \mathbf{D}_{z^a} C(z^a(t+1), z^b(t), k^a) = 0.$$

Finally, since $z^a(t+1) - z^a(t) \geq 0$ and $z^b(t+1) - z^b(t) \leq 0$, the change in cost for member B is also negative. *Q.E.D.*

A.2. Proof of Proposition 6.1

The monotone likelihood ratio property implies that, for all $u > v$,

$$l^j(u) > (F_g^j(u) - F_g^j(v))/(F_i^j(u) - F_i^j(v)) > l^j(v),$$

where $l^j(\cdot) = f_g^j(\cdot)/f_i^j(\cdot)$. From this result and from the equilibrium conditions for t_{n-1}^a and for t_{N+1-n}^b, we have $l^a(t_{n-1}^a) l^b(t_{N+1-n}^b) < k^a$, and $l^b(t_{N+1-n}^b) l^a(t_n^a) > k^b$. Adding these inequalities: $l^b(t_{N+1-n}^b) l^{a\prime}(\zeta)(t_n^a - t_{n-1}^a) > k^b - k^a$, where ζ is between t_n^a and t_{n-1}^a. Similar manipulations using the equations for t_n^a and for t_{N+1-n}^b yield $l^b(t_{N+1-n}^b) l^{a\prime}(\zeta)(t_n^a - t_{n-1}^a) > k^a - k^b$. Therefore

$$t_n^a - t_{n-1}^a > \frac{|k^a - k^b|}{l^b(t_{N+1-n}^b) l^{a\prime}(\zeta)}.$$

If $t_n^a - t_{n-1}^a \leq \epsilon$, then since ϵ can be arbitrarily small and since $l^b(\cdot)$ and $l^{a\prime}(\cdot)$ are both bounded over any fixed interval, the above inequality contradicts $k^a \neq k^b$. *Q.E.D.*

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