Cross-Examination

Claude Fluet* Thomas Lanzi‡

July 2022

Abstract

Two opposed parties seek to influence a decision maker. They invest in acquiring information and select what to disclose. The decision maker then adjudicates. We compare this setting with one allowing cross-examination. A cross-examiner tests the opponent in order to persuade the decision maker that the opponent did not disclose the whole truth. We show that the quality of decision-making deteriorates because both the threat and the potential benefits from cross-examination reduce incentives to investigate and because cross-examination too often makes the truth appear as falsehood.

Keywords: Bayesian persuasion, disclosure game, adversarial, partisan examination, procedural rules.

JEL: C72, D71, D82, D83, K41

*Université Laval, CRREP. Email: claude.fluet@fsa.ulaval.ca

†Université de Lorraine, BETA. Email: thomas.lanzi@univ-lorraine.fr

‡For helpful comments and suggestions, we thank Jesse Bull, Bertrand Crettez, Andrew Daughety, Jeffrey Ely, Tim Friehe, Bruce Kobayashi, Erik Talley, Navin Kartik, Kathryn Spier, Joshua Teitelbaum, and the participants of the 8th Annual Law and Economic Theory Conference 2018, the ASSET Conference 2021, and the Public Economic Theory Conference 2022. Financial support from SSHRC Canada is gratefully acknowledged (grant 435-2023-1671).

1 Introduction

Adversarial cross-examination is a key feature of the common law trial. More or less constrained forms are often also allowed in other institutions, e.g., industrial tribunals, disciplinary panels, commercial arbitration boards. How does the opportunity of cross-examination affect the acquisition of evidence by interested parties? How does it affect the quality of decision-making? We consider a persuasion game where the potential evidence consists of many pieces of hard information from which each party can select what to disclose. The decision maker then adjudicates. We compare this setting with a procedure permitting cross-examination, by which we mean raising issues about the other party's report. Cross-examination elicits information as to whether the opponent was misleading through withholding of evidence, enabling the decision maker to update her belief about the significance of a report.

We find that cross-examination reduces the quality of decision-making. Cross-examining the opponent or submitting countervailing evidence are substitutes, resulting in less incentives to gather information about the fact at issue. The quality of the decision maker's inferences then deteriorates because it also depends on the likelihood that a cross-examining party could have acquired relevant information. In addition, cross-examination has a chilling effect on the gathering of evidence by the party threatened by cross-examination. The possibility of manipulating information is reduced and there is the risk of erroneously appearing to be deceitful. Altogether, from the decision maker's standpoint, there is now too little gathering of evidence.

An example.— To illustrate, consider an individual filing a malpractice suit because of complications suffered following medical treatment. In Figure 1, complications always arise if treatment was inadequate (e.g., errors in diagnosis, mistakes in performance, and the like) irrespective of other potential factors. The frequency of inadequate treatments is known to be $p = 0.05$.[1] By contrast, with adequate treatment complications

[1] This is for the sake of our example. Danzon (1991) reports studies showing that a similar percentage of hospitalized patients suffered complications caused by health care management. See also Arlen (2013).

arise only with probability $\eta_{no} = 0.01$ if the patient has no particular risk factor and with probability $\eta_{rf} = 0.2$ if he does. The proportion of patients with the risk factor is $\gamma = 0.1$, so on average a proportion $\overline{\eta} := \gamma\eta_{rf} + (1-\gamma)\eta_{no} = 0.029$ experience complications even after adequate treatment.

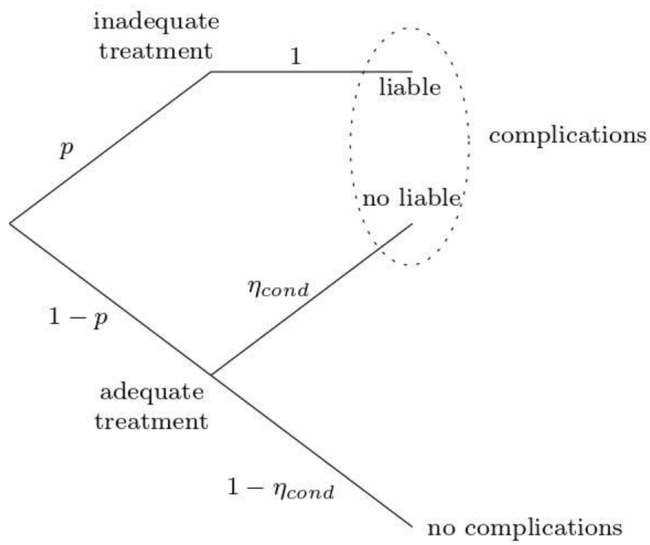

Fig. 1. Patient's prior condition *cond* is either rf denoting the presence of a risk factor or *no* for no risk factor.

By law, the plaintiff is entitled to damages if treatment was inadequate (the branch 'liable' in Figure 1). The quality of treatment is not directly observable but must be inferred. The legal rule is that the court must be convinced that complications are most likely due to inadequate treatment, i.e., a probability greater than one half. For a patient without the risk factor, the posterior probability is

$$\Pr(\text{inadequate} \,|\, \text{complications, no risk factor}) = \frac{p}{p + (1-p)\eta_{no}} = 0.84$$

For a patient with the risk factor, it is

$$\Pr(\text{inadequate} \,|\, \text{complications, risk factor}) = \frac{p}{p + (1-p)\eta_{rf}} = 0.21$$

Thus, a patient without the risk factor would win the suit, a patient with the risk factor would not.

However, although evidence about complications can always be provided, evidence about the plaintiff's prior condition does not always exist. With probability $\theta = 0.5$, some years back, the plaintiff faced events that necessitated check-ups. The relevant information from these check-ups is that they establish whether the plaintiff had or did not have the risk factor. There are therefore three possible types of plaintiffs: uninformed ones with no past record, informed ones with a record showing no risk factor, and informed ones with a record showing the risk factor. An informed plaintiff's strategy is to submit the good record and to withhold the bad one; uninformed ones submit nothing except for the evidence establishing complications. We add the possibility that the defendant may uncover the plaintiff's record from years back if he investigates, in which case the record (if it exists) is uncovered with probability $e = 0.8$. An informed defendant's strategy is then to submit the record if it shows the presence of the risk factor; otherwise the defendant is silent.

In our benchmark setting, the defendant investigates because this is worth the cost. The defendant prevails when he submits a record showing the risk factor; otherwise the plaintiff prevails, either because he submits a record showing no risk factor or because no record is submitted at all. The latter follows from the court's posterior probability

$$
\begin{aligned}
&\Pr(\text{ inadequate} \,|\, \text{complications, no record submitted })\\
&\quad = \frac{p[1-\theta+\theta\gamma(1-e)]}{p[1-\theta+\theta\gamma(1-e)]+(1-p)[(1-\theta)\overline{\eta}+\theta\gamma\eta_{rf}(1-e)]} = 0.62
\end{aligned}
$$

In this expression, the denominator is the joint probability of complications and of no record being submitted, taking account of the probabilities that the parties accessed a record and of their disclosure strategies. The first line of Table 1 shows the probability that the plaintiff prevails, conditional on complications, and the probability of judicial error, i.e., the defendant loses when treatment was adequate or the plaintiff loses when it was inadequate.[2]

[2] The details of the computations are given in the supplementary Appendix.

Table 1
An example

	False positive rate under cross-examination	Probability[1] that plaintiff prevails	Probability[1] of judicial error
Equilibrium without cross-examination	--	0.876	0.283
Interim situation: cross-examination strategy A	0.124	0.782	0.283
Equilibrium with cross-examination: strategy B	0.623	0.533	0.355

[1]Conditional on complications

We now augment the defendant's toolbox by giving him the opportunity of cross-examining the plaintiff. This is useful when the plaintiff submitted no report and the defendant also did not. Two cross-examination strategies, A and B, are assumed to be available to the defendant, each one yielding two possible outcomes, *good* or *bad* from the plaintiff's point of view. The probabilities of these outcomes depend on the plaintiff's information status and the chosen strategy. For both strategies, the outcome is *bad* with probability $\beta = 1$ when the plaintiff is informed, i.e., when he concealed evidence. The outcome is *bad* with probability α when the plaintiff is uninformed (a 'false positive'). For strategy A, $\alpha = 0.12$; for strategy B, $\alpha = 0.62$. Because the *good* outcome perfectly reveals that the plaintiff is uninformed, the plaintiff then prevails. On the other hand, when the outcome of cross-examination is *bad*, the court's posterior belief is

$$\Pr(\text{ inadequate}\,|\,\text{complications, no record submitted, bad cross outcome })$$
$$= \frac{p[(1-\theta)\alpha + \theta\gamma(1-e)\beta]}{p[(1-\theta)\alpha + \theta\gamma(1-e)\beta] + (1-p)[(1-\theta)\overline{\eta}\alpha + \theta\gamma\eta_{rf}(1-e)\beta]}$$

The court observes the line of questioning and therefore knows what cross-examination strategy the defendant is following. It uses the appropriate α to update its belief.

Under strategy B, the court's posterior would equal 0.60, which would be of no use to the defendant. Strategy B is too noisy to influence the court's decision when no records are submitted. However, with strategy A, the court's posterior following the *bad* cross-examination outcome equals 0.5. The defendant then prevails because inefficient care is not more likely than not.[3] Therefore, the defendant chooses strategy A. The plaintiff now prevails only when he can submit a record showing no risk factor or when the outcome of cross-examination is *good*. The implications are shown in the second line of Table 1, referred to as the interim situation. The opportunity of cross-examination benefits the defendant because the plaintiff prevails less often, but this has no effect on the probability of judicial error. Compared to the situation without cross-examination, the error merely shifts from one kind (erroneously finding for the plaintiff) to the other kind (erroneously finding for the defendant).

However, the interim situation is not an equilibrium. Searching for the plaintiff's past records (which may not even exist) is costly. The defendant realizes that investigating is superfluous. It suffices to cross-examine the plaintiff. This always leads to the *bad* cross-examination outcome when the plaintiff withheld evidence, i.e., when an informed plaintiff did not submit the record because it was unfavorable. The defendant therefore switches to no investigation and relies solely on cross-examination to counter the plaintiff. Although the court does not observe the defendant's investigation effort, it will understand the defendant's incentives.

Setting $e = 0$ in the expression for the court's posterior and keeping the cross-examination strategy A, the court's posterior now equals 0.33. Thus, the defendant again prevails following the *bad* cross-examination outcome. But this also cannot be an equilibrium because the cross-examination strategy B now performs better from the defendant's point of view. With this strategy, given that the defendant is no longer expected to investigate, the court's posterior equals 0.5. Strategy B is preferred by the defendant because it does as well when the plaintiff is informed and much better when he is uninformed. At equilibrium, therefore, the defendant does not inves-

[3] This corresponds to the prosecutor's best Bayesian persuasion strategy in Kamenica and Gentzkov's (2011) motivating example.

tigate and he uses the cross-examination strategy B. The implications are shown in the third line of Table 1. The plaintiff prevails less often than when cross-examination is not allowed and the probability of judicial error is larger.

Context and related literature.— Strictly speaking, cross-examination is the interrogation of a witness called by the adverse party after the witness has testified. In a much quoted phrase, cross-examination "is beyond any doubt the greatest legal engine ever invented for the discovery of truth."(Wigmore, 1940, § 1367). However, cross-examination has also been criticized: "Wigmore's celebrated panegyric...is nothing more than an article of faith." (Langbein, 1985, p. 834). Most of the criticism focuses on cross-examination's potential for 'false positives'. Judge Frankel remarked that cross-examination is "like other potent weapons, equally lethal for heroes and villains" (Frankel, 1975, p. 1039); and that a skillful cross-examiner "will employ ancient and modern tricks to make a truthful witness look like a liar." (Frankel, 1980, p. 16). Indeed, a caveat shortly follows Wigmore's famous quotation: "A lawyer can do anything with cross-examination...He may...do more than he ought to do; he...may make the truth appear like falsehood."(Wigmore, 1940, § 1367).

Thus, there is a debate about the merits of cross-examination. Across different legal systems, we observe a wide variety of procedural rules governing examination, including nonpartisan examination and restrictions on the scope of cross-examination (see Weigend, 2010). In the US over recent years, a controversy developed about whether cross-examination should be allowed in Title IX hearings about sexual assault cases on college campuses. Opponents argued that adversarial cross-examination would deter reporting of sexual assaults, while proponents emphasized the right to due process for respondents. One proposal was to control cross-examination by requiring the accused party to submit cross-examining questions to a neutral examiner who would select the questions most likely to shed light on the case.[4]

[4] In 2011 the Obama administration substantially revised Title IX grievance procedures in order to encourage reporting. In 2020, the Trump administration issued its own Title IX guidance. The controversial new requirement concerned adversarial cross-examination. See Behre (2020) and Dowling (2021), and the many references therein.

In the legal literature, it has also been remarked that there is no theory – and little empirical evidence – about how cross-examination works.[5] We will interpret cross-examination in the general sense of actions that seek to lessen the weight of another party's report not by providing directly relevant countervailing evidence but by questioning the report's significance or interpretation. As a start, we follow the economic literature on disclosure games in assuming that evidence is hard information that can be concealed but cannot be falsified or forged (Grossman 1981, Milgrom 1981, Milgrom and Roberts 1986). Information can then be manipulated only when a party's information status is unobservable (Dye 1985, Shavell 1989). We integrate the possibility of cross-examination into such a framework.

Our basic set-up is similar to Shin's (1998) analysis of the adversarial procedure but with the following features. First, we consider situations where the parties' information is endogenous, as in Kim (2014) or Kartik et al. (2017). Secondly, the information acquired by a party may consist of several pieces (Dewatripont and Tirole, 1999; Demougin and Fluet, 2008; or Bull and Watson, 2019). The two features together allow for equilibria where both parties invest in acquiring information. Moreover, when a party submits evidence, the decision maker may remain uncertain whether the party disclosed the whole truth. This allows for actions, referred to as cross-examination, that generates information, possibly noisy, about the eventual withholding of evidence. Cross-examination is modeled as a 'publicly observable experiment' in the spirit of the Bayesian persuasion literature (Kamenica and Gentzkow, 2011; Kamenica, 2019; Bergemann and Morris, 2019). The cross-examiner subjects the cross-examined to a testing process in order to persuade the decision maker that the cross-examined concealed unfavorable evidence. The test is designed to maximize the probability that the cross-examined will fail the test, subject to Bayesian plausibility.

The paper develops as follows. Section 2 describes the basic set-up. Section 3 analyzes the procedure without the opportunity of cross-examination,

[5] See Sanchirico (2009) and Wigmore himself: "What is the theory of [cross-examination's] efficiency?...Upon this we commonly reflect but little." (ibid, § 1368). See also Lempert: "[T]he likely effectiveness of cross-examination in getting at the truth is seldom examined – numerous court opinions and commentaries rely on Wigmore's conclusion...rather than on empirical evidence." (Lempert, 1998, p. 345).

which serves as benchmark, and then with cross-examination; next, we derive the implications. Section 4 concludes. Proofs are in the Appendix.

2 Model

An arbitrator A must settle an issue over which two parties have diametrically opposed interests. The parties are referred to as the plaintiff P and the defendant D. We use this terminology because one party will bear the burden of proof, which in a trial is usually assigned to the plaintiff. The issue or true fact is $\omega \in \{\omega_0, \omega_1\}$. The parties and the arbitrator share the same prior probability p that the true fact is ω_1. The arbitrator's decision is $d \in \{0, 1\}$ where 0 is favored by the defendant and 1 is favored by the plaintiff. The arbitrator wants her decision to match the true fact. Her payoff is $u_A(d, \omega) = 1$ if $d = i$ when $\omega = \omega_i$, where $i \in \{0, 1\}$, and $u_A(d, \omega) = 0$ otherwise. The parties only care about the arbitrator's decision. The plaintiff's payoff from the arbitrator's decision is d, the defendant's payoff is $-d$.

Investigation.— There is uncertainty about the potential pool of information, e.g., related facts, documents, expert opinions or witnesses. With probability $\theta \in (0, 1)$, the evidence that could be brought forward contains two pieces of hard information, denoted x and y with realizations in $\{x_0, x_1\}$ and $\{y_0, y_1\}$ respectively. With probability $1 - \theta$, the evidence consists of the single piece x. For instance, some document is known to exist but there is uncertainty about the existence of yet another relevant document; or it is known that there was a witness of some event pertaining to the issue but there is uncertainty about the existence of a second witness.[6] We let m denote the state where the evidence consists of the two pieces x and y; s is the state where the evidence consists of the single piece x (the mnemonic is m for *m*ultiple and s for *s*ingle). That there are two possible states of the evidence is common knowledge.

Searching for the evidence is costly and not always successful. Party $j \in \{P, D\}$ uncovers the evidence with probability e_j at a cost $C(e_j)$, an increasing and strictly convex function with $C(0) = C'(0) = 0$ and $C'(1) \geq 1$.

[6] In the example, x is the evidence showing the occurrence of *complications* or *no complications*, while y is a record showing a *risk factor* or *no risk factor*.

The inequality ensures that, given the stakes normalized to plus or minus one, a party will never want to obtain the evidence for sure.[7] When the state of the evidence is m, a successful party uncovers (x, y); otherwise, a successful party uncovers only x. Given the investment in gathering evidence, the parties' net payoffs are

$$u_P = d - C(e_P), \quad u_D = -d - C(e_D).$$

How the evidence relates to the true fact is as follows. $P(x, y, \omega)$ is the joint probability of the true fact and of the evidence when the state of the evidence is m. We also use P for marginal or conditional distributions derived from $P(x, y, \omega)$. For instance, the prior is $P(\omega_1) = p$. Applying Bayes' rule, posteriors about the true fact are

$$P(\omega_i \mid x, y) = \frac{P(x, y, w_i)}{P(x, y, \omega_1) + P(x, y, \omega_0)} \qquad i = 0, 1.$$

When the state of the evidence is s, the joint density of x and ω is $P(x, \omega)$, so that x has the same meaning irrespective of the state of the evidence.

We make assumptions ensuring the existence of equilibria where the plaintiff bears the burden of proof and where both parties have an incentive to search for the evidence.

Assumption 1: $p \leq \frac{1}{2}$ and $P(\omega_1 \mid x_1) > \frac{1}{2} > P(\omega_1 \mid x_1, y_0)$.

By itself, x_1 makes ω_1 more likely than not, while y_0 overturns the posterior based on x_1 alone. Assumption 1 is easily seen to imply $P(\omega_1 \mid x_0) < \frac{1}{2} < P(\omega_1 \mid x_1, y_1)$.

Communication and adjudication.— Investigation is followed by a communication phase in which the parties may report to the arbitrator. Reports are denoted by r_j, $j \in \{P, D\}$. If party j was unsuccessful in obtaining the evidence, its submission is by force the empty report $r_j = \emptyset$. If the party was successful and the state of the evidence is s, its report belongs to the

[7] In our motivating example, the plaintiff always had access to the potential evidence, i.e., $e_P = 1$, whereas the defendant's investigation effort was $e = e_D \in \{0, 0.8\}$. Here we assume that both parties need to investigate and that investigation efforts are continuous variables.

set $\{\emptyset, (x, \emptyset)\}$ where $\emptyset$ means that the party submits nothing and $(x, \emptyset)$ that it reports only x. If the party was successful and the state of the evidence is m, its report belongs to the set $\{\emptyset, (x, \emptyset), (\emptyset, y), (x, y)\}$. Thus, when a party reports nothing, the arbitrator does not know whether the party was truly unsuccessful or whether it chose not to submit evidence. When a party reports $(x, \emptyset)$, the arbitrator does not know whether the party could also have submitted y. When a party reports $(\emptyset, y)$, however, the state of the evidence is revealed and the arbitrator knows that the party could have submitted x as well.

The arbitrator's updated beliefs will depend on both parties' reports. We write $\mu(r_P, r_D)$ for the arbitrator's belief that the true fact is ω_1. Similarly, her adjudication strategy is $d(r_P, r_D) \in \{0, 1\}$. The sequentially rational decision is $d = 1$ if her belief $\mu > \frac{1}{2}$ and $d = 0$ if $\mu < \frac{1}{2}$. When $\mu = \frac{1}{2}$, she is indifferent. As tie-breaker, we impose that she then finds for the defendant, i.e., the plaintiff prevails only if the arbitrator believes that ω_1 is more likely than not.

As will become clear, the pivotal belief is the one following the reports $r_P = (x_1, \emptyset)$ and $r_D = \emptyset$. When the plaintiff uncovers (x_1, y_0), he will want to conceal y_0. The pair of reports $r_P = (x_1, \emptyset)$ and $r_D = \emptyset$ then arises because the defendant was unsuccessful in his search for evidence (otherwise he would have submitted y_0). However, although the plaintiff may want to manipulate the evidence by disclosing only x_1, he will not be credible if the probability that there are two pieces of evidence is sufficiently large. Let

$$k_P := P(x_1, \omega_1) - P(x_1, \omega_0),\; k_D := P(x_1, y_0, \omega_0) - P(x_1, y_0, \omega_1) \qquad (1)$$

and note that both k_P and k_D are positive per Assumption 1. The next assumption will allow for the possibility of manipulating information.

Assumption 2: $\theta < k_P/(k_P + k_D)$.

Finally, we want the arbitrator to rule in the defendant's favor when no evidence is submitted by either party. Her belief will then generally differ from the prior p because it depends on her conjecture on how likely it is that the parties uncovered evidence that they did not disclose. Our third assumption will ensure that $\mu(\emptyset, \emptyset) \leq \frac{1}{2}$, meaning that the plaintiff bears the burden of proof.

ASSUMPTION 3: $P(x_1, y_1) \geq (2\theta - 1)P(x_1, y_0)$.

The condition is satisfied if $P(x_1, y_1) \geq P(x_1, y_0)$ as in our motivating example or if $\theta \leq \frac{1}{2}$, which was also the case. To give another example, suppose that x and y are independent conditionally on the true fact, with $P(x_i \mid \omega_i) = q > \frac{1}{2}$ and $P(y_i \mid \omega_i) = h > \frac{1}{2}$. Then $P(x_1, y_1) > P(x_1, y_0)$. If $q > 1 - p \geq \frac{1}{2}$ and h is sufficiently larger than q, then Assumption 1 is also satisfied.

The intuition for Assumption 3 is that a plaintiff bearing the burden of proof has at least as much incentives to acquire evidence as the defendant. When no evidence is disclosed, and given the prior, the plaintiff will therefore be at least as likely to have engaged in strategic non-disclosure, which justifies ruling against him.

The foregoing is sufficient to describe a procedure without the opportunity of cross-examination, which we take as benchmark. The time line is then as follows. First, Nature chooses the true fact, whether the evidence consists of one or two pieces, and the realizations of the pieces of evidence, all of which remains unobservable at this stage. Next, the parties simultaneously choose their investigation efforts, e_P and e_D respectively, and Nature chooses whether they access the evidence or not, all of which is private information.[8] At the third stage, the parties simultaneously submit their reports r_P and r_D. At the last stage, the arbitrator observes the reports, updates her beliefs, and adjudicates. The solution concept is perfect Bayesian equilibrium.

Cross-Examination.— When cross-examination is allowed, an additional stage is inserted between disclosure and adjudication. A party submitting evidence can now be questioned by the adverse party. Cross-examination yields information that differs from the direct evidence discussed so far because it relates not to the true fact as such but to the possibility that a party manipulated his report. The cross-examiner seeks to elicit whether the party knows more than he reported, for instance another relevant doc-

[8] The parties would have less incentives to acquire evidence if their investigation effort were observable by the arbitrator. See Henry (2009) and Wong and Yang (2018).

ument was uncovered but not submitted.[9] In the adjudication phase, the arbitrator's beliefs will now depend on the parties' reports and on the outcome of cross-examination.

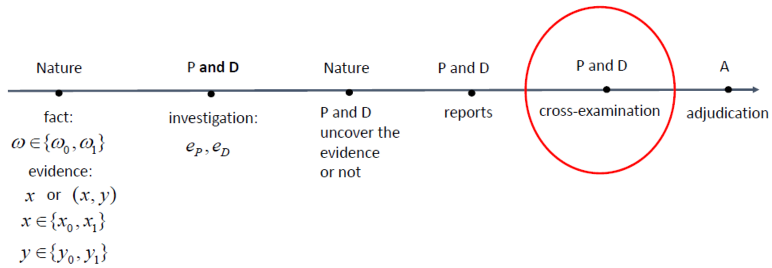

Fig. 2. Time line

In our setting, cross-examination will serve a purpose only following the reports $r_P = (x_1, \emptyset)$ and $r_D = \emptyset$. If the arbitrator can then be persuaded that the plaintiff concealed evidence, the defendant will have prevailed because the concealed evidence must have disfavored the plaintiff. We model cross-examination as a test to which the plaintiff is subjected by the defendant (or his counsel). The test unfolds publicly, so that the arbitrator can draw the appropriate inferences. For instance, following a string of so-called leading questions which can only be answered with yes or no, the cross-examined may be led to contradict himself or the outcome may at least suggest contradiction.

It suffices to represent the outcome as a binary signal correlated with the plaintiff's information status. The cross-examination test yields the signal $\chi \in \{b, g\}$ with conditional probabilities

$$\beta := \Pr(\chi = b \mid m) \text{ and } \alpha := \Pr(\chi = b \mid s). \tag{2}$$

β is the probability of outcome b conditional on concealment of evidence by the plaintiff, i.e., when the state of the evidence is m; α is the probability of the same outcome when the plaintiff did not conceal evidence. The defendant's cross-examination strategy is the pair (α, β) and is observed by

[9] We assume that there is no penalty for withholding evidence. For instance, legal advice is routinely about the selection of information to disclose to a tribunal (Kaplow and Shavell, 1989).

the arbitrator. Figure 2 summarizes the time-line. The circle is the added cross-examination stage.

3 Analysis

Equilibria may differ in inessential ways with respect to disclosure decisions. We consider a profile of strategies consistent with both the cases where cross-examination is or is not allowed. In this profile, the plaintiff is proactive because he is the party bearing the burden of proof. He always submits a priori favorable evidence and suppresses a priori unfavorable evidence, where 'a priori' refers to raw posteriors as given by P. By contrast, the defendant has a minimum disclosure strategy. He only submits 'overpowering' evidence, if he can.

Specifically, when the state of the evidence is s, an informed plaintiff's report is $r_P = \emptyset$ if $x = x_0$ and $r_P = (x_1, \emptyset)$ if $x = x_1$. When the state of the evidence is m, an informed plaintiff's report is

$$r_P = \begin{cases} (x, y) \text{ if } P(\omega_1 \mid x, y) > \frac{1}{2} \\ (x_1, \emptyset) \text{ if the evidence is } (x_1, y_0) \\ \emptyset \text{ otherwise} \end{cases} \tag{3}$$

When the state of the evidence is s, an informed defendant always reports nothing. When the state of the evidence is m, he reports

$$r_D = \begin{cases} (x, y) \text{ if } P(\omega_1 \mid x, y) \leq \frac{1}{2} \\ \emptyset \text{ otherwise} \end{cases} \tag{4}$$

Note that (4) implies that the defendant submits the evidence when he uncovers (x_1, y_0).

A strategy such as the plaintiff's is referred to as a 'sanitization strategy' in Shin (1994); see also Shin (1998) and Kartik et al. (2017). In their setting, each party can only access a single piece of evidence which is either disclosed whole or not at all. In our case, the evidence may come in one or two pieces. Disclosing only one piece reveals that the party was successful in uncovering the evidence but may create suspicion that the other piece has been withheld, subjecting the party to the risk of adverse inferences or of cross-examination when the procedure allows it.[10] The defendant's strategy of only submitting favorable evidence with two pieces of information avoids this risk.

3.1 No Cross-Examination

Some pairs of reports will not arise on the equilibrium path. The arbitrator's beliefs are then obtained as the limit of completely mixed strategies where the parties play out-of-equilibrium moves with some small probability. Beliefs off the equilibrium path then yield the same decisions as would the raw posteriors.

As noted, the critical belief is the one associated with $r_P = (x_1, \emptyset)$ and $r_D = \emptyset$. This pair of reports cannot arise when the state of the evidence is m and the defendant also uncovered the evidence. If $y = y_1$, the plaintiff would have reported it; if $y = y_0$, the defendant would have reported it. However, these reports may arise if the state of the evidence is s or if it is m and the defendant was unsuccessful. The arbitrator weighs the two possibilities. Her skepticism vis-à-vis the plaintiff depends on her conjecture of the defendant's investigation effort. To make this explicit, we write the arbitrator's belief as $\mu((x_1, \emptyset), \emptyset; e_D)$ where e_D is the arbitrator's conjecture about the defendant's effort.

Given the disclosure strategies, and applying Bayes' rule, the arbitrator believes that the fact ω_1 has probability

$$\mu((x_1, \emptyset), \emptyset; e_D) = \frac{(1-\theta)P(x_1, \omega_1) + \theta P(x_1, y_0, \omega_1)(1 - e_D)}{\sum_i \{(1-\theta)P(x_1, \omega_i) + \theta P(x_1, y_0, \omega_i)(1 - e_D)\}} \tag{5}$$

Recalling the definitions of k_P and k_D in (1), the following is immediate.

Observation 1: $\mu((x_1, \emptyset), \emptyset; e_D) > \frac{1}{2}$ is equivalent to

$$k_P(1-\theta) > k_D\theta(1 - e_D) \tag{6}$$

Note that, per Assumption 2, the inequality (6) always holds.

Another observation is that, given the pair of reports $r_P = (x_1, \emptyset)$ and $r_D = \emptyset$, the arbitrator's skepticism vis-à-vis the plaintiff is decreasing in

[10] To borrow from Bull and Watson (2019), a party's disclosure conveys information through the report's *face value* and as a signal of the party's private information.

her conjecture e_D. When the defendant does not submit counterevidence, a greater investigation effort on his part makes it more likely that there is only a single piece of evidence. Formally, the arbitrator's belief that the state of the evidence is m, equivalently that the plaintiff concealed evidence, is

$$\nu(e_D) = \frac{\theta P(y_0 \mid x_1)(1 - e_D)}{(1 - \theta) + \theta P(y_0 \mid x_1)(1 - e_D)} \tag{7}$$

We summarize the implications as follows.

Lemma 1 *At the information set defined by the reports $r_P = (x_1, \emptyset)$ and $r_D = \emptyset$, the arbitrator believes that ω_1 has probability*

$$\mu((x_1, \emptyset), \emptyset; e_D) = [1 - \nu(e_D)]P(\omega_1 \mid x_1) + \nu(e_D)P(\omega_1 \mid x_1, y_0) \tag{8}$$

where e_D is her conjecture about the defendant's investigation effort and $\nu(e_D)$ is her belief that the plaintiff concealed unfavorable evidence; $\nu(e_D)$ is decreasing in e_D.

Equilibrium.— From the foregoing, the arbitrator finds for the plaintiff if the evidence submitted reduces to x_1 or if it is (x_1, y_1). There may be other possibilities because Assumption 1 does not fully constrain the posteriors when $x = x_0$.[11] Let S be the set of pairs (x, y) such that $P(\omega_1 \mid x, y) > \frac{1}{2}$. At the investigation stage, the parties' expected payoffs are then

$$\overline{u}_P = e_P W - C(e_P), \quad \overline{u}_D = -\, e_P W - C(e_D), \tag{9}$$

where

$$W := (1 - \theta)P(x_1) + \theta \left[\sum_{(x,y) \in S} P(x, y) + P(x_1, y_0)(1 - e_D) \right] \tag{10}$$

is the plaintiff's expected gain (or probability of prevailing) conditional on having access to the evidence.

[11] The assumption implies only that $P(\omega_1 \mid x_0, y_0)$ and $P(\omega_1 \mid x_0, y_1)$ cannot both be above $\frac{1}{2}$.

In (9), e_D is the plaintiff's conjecture about the defendant's investment; e_P is the defendant's conjecture about the plaintiff's investment. At equilibrium, the conjectures are correct and solve the system of first-order conditions:

$$\begin{aligned} C'(e_P) &= (1-\theta)P(x_1) + \theta\left[\sum_{(x,y)\in S} P(x,y) + P(x_1,y_0)(1-e_D)\right] && (11) \\ C'(e_D) &= e_P\theta P(x_1,y_0) && (12) \end{aligned}$$

We denote the (unique) solution by e_P^{nc} and e_D^{nc} where nc stands for 'no cross-examination'.

Proposition 1 (No Cross-Examination) *In the unique equilibrium with the plaintiff bearing the burden of proof, the plaintiff prevails with the report* $r_P = (x_1, \emptyset)$ *when the defendant does not provide counterevidence. The parties' investigation efforts satisfy* $e_P^{nc} > e_D^{nc} > 0$.

Both parties actively search for the evidence and both may simultaneously participate at the communication stage. This follows from the assumption that there are potentially multiple pieces of evidence.[12]

3.2 Cross-Examination

A party submitting evidence can now be cross-examined by the opponent. As noted, this can serve a purpose only when the plaintiff reports $(x_1, \emptyset)$ and the defendant is unable to provide counterevidence.

We first characterize the conditions under which cross-examination is effective in the sense that it can turn the tables in favor of the defendant. Before cross-examination takes place, the arbitrator's belief that the plaintiff concealed evidence is $\nu(e_D)$ as defined in the preceding section. Her updated belief after cross-examination is denoted $\nu(e_D, \chi)$, as it will depend on the outcome of cross-examination. Accordingly, her belief that the true fact is ω_1 is then

$$\mu((x_1,\emptyset),\emptyset,\chi;e_D) = [1-\nu(e_D,\chi)]P(\omega_1 \mid x_1) + \nu(e_D,\chi)P(\omega_1 \mid x_1,y_0)$$

[12] This contrasts, for instance, with Shin (1998) or Kim (2014).

When the outcome of cross-examination is $\chi = b$, then

$$\nu(e_D, b) = \frac{\theta P(y_0 \mid x_1)(1 - e_D)\beta}{(1-\theta)\alpha + \theta P(y_0 \mid x_1)(1 - e_D)\beta}$$

which yields the following.

OBSERVATION 2: $\mu((x_1, \emptyset), \emptyset, b; e_D) \leq \frac{1}{2}$ is equivalent to

$$\alpha k_P(1-\theta) \leq \beta k_D \theta (1 - e_D) \tag{13}$$

The cross-examination test, as defined by (α, β), is effective only when condition (13) is satisfied. $\chi = b$ is then the bad outcome from the plaintiff's point of view, with α and β as the false and true positive rates respectively. Because of the inequality in Observation 1, condition (13) requires the true positive rate to be sufficiently greater than the false positive rate.[13]

Equilibrium.— Recall that the pair of reports $r_P = (x_1, \emptyset)$ and $r_D = \emptyset$ can be reached in two circumstances: (i) the defendant did not access the evidence; or (ii) the defendant accessed the evidence and the state of the evidence is s, implying that the plaintiff did not in fact withhold evidence. The cross-examiner (i.e., the defendant or his counsel) knows the circumstances. Thus, the cross-examiner may be of two types, either (i) uninformed; or (ii) informed where this means that he knows that the evidence reduces to the single piece disclosed by the plaintiff.

This raises the possibility that a cross-examination strategy could reveal the cross-examiner' information status. In a related framework with an informed persuader, Perez-Richet (2014) shows that one can confine attention to pooling equilibria. In the present context, these are equilibria where both the informed and uninformed cross-examiner choose the same cross-examination test.[14] Perez-Richet also shows that plausible refinements select the 'high type' optimal persuasion strategy. The high type here is the uninformed cross-examiner because an informed one does not want his type

[13] Obviously, the outcome $\chi = g$ then yields $\mu((x_1, \emptyset), \emptyset, b; e_D) > \frac{1}{2}$. This is equivalent to $(1-\alpha)k_P(1-\theta) > (1-\beta)k_D\theta(1-e_D)$, which follows from (6) and (13).

[14] The pooling result does not necessarily obtain when the sender's payoff is a continuous function of the receiver's ex post beliefs; see Hedlund (2017).

to be revealed. This would reveal that the plaintiff did not suppress evidence, thereby defeating the purpose of cross-examination. We therefore consider the cross-examination strategy that an uninformed cross-examiner would choose.[15]

The uninformed cross-examiner's belief that the state of the evidence is m, i.e., that the plaintiff concealed evidence, is

$$\nu_D = \frac{\theta P(y_0 \mid x_1)}{(1-\theta) + \theta P(y_0 \mid x_1)}$$

Cross-examination is designed to maximize the probability that the plaintiff fails the test. We assume a perfectly skillful cross-examiner: he can choose any α and β in the unit interval, but will of course want to satisfy the inference constraint (13). Thus, the cross-examination test solves

$$\max_{(\alpha,\beta)\in[0,1]^2} (1-\nu_D)\alpha + \nu_D\beta \quad \text{s.t.} \quad \alpha k_P(1-\theta) \leq \beta k_D \theta(1-e_D)$$

The solution, expressed in terms of the arbitrator's conjecture e_D, is

$$\alpha = \frac{k_D\theta(1-e_D)}{k_P(1-\theta)}, \quad \beta = 1 \tag{14}$$

Next, we turn to the investigation stage. The parties expect the plaintiff to fail cross-examination with probability α when the plaintiff does not conceal evidence, and with probability β when he does. Therefore, conditional on uncovering the evidence, the probability that the plaintiff prevails is now

$$\begin{aligned} W &= (1-\theta)P(x_1)(1-\alpha) \\ &\quad +\theta\left[\sum_{(x,y)\in S} P(x,y) + P(x_1,y_0)(1-e_D)(1-\beta)\right] \end{aligned} \tag{15}$$

With the parties' payoffs defined as in (9), their investigation efforts solve

[15] As it turns out, an informed cross-examiner will be perfectly happy with the same strategy.

the system of first-order conditions:

$$\begin{aligned} C'(e_P) &= (1-\theta)P(x_1)(1-\alpha) \\ &\quad +\theta\left[\sum_{(x,y)\in S} P(x,y) + P(x_1,y_0)(1-e_D)(1-\beta)\right] \end{aligned} \tag{16}$$

$$C'(e_D) = e_P\theta(1-\beta)P(x_1,y_0). \tag{17}$$

Solving the system defined by (14) and (16)-(17) yields the equilibrium investigation efforts e_P^{cr} and e_D^{cr}, where *cr* stands for cross-examination, together with the equilibrium cross-examination strategy.

Proposition 2 (Cross-Examination) *The parties' investigation efforts satisfy* $e_P^{cr} < e_P^{nc}$ *and* $e_D^{cr} = 0$. *The defendant's cross-examination strategy is* $\alpha = k_D\theta/k_P(1-\theta)$ *and* $\beta = 1$.

The defendant no longer investigates because investigation is costly and cross-examination is a perfect substitute in countering a deceitful opponent. The plaintiff investigates less because investigation is less profitable. He fails the cross-examination when he attempts to manipulate the evidence and he may fail the test even when he is truthful.

3.3 Quality of Decision Making

The arbitrator's expected utility is the probability of correct adjudication

$$\begin{aligned} \overline{u}_A &= p\Pr(d=1 \mid \omega_1) + (1-p)\Pr(d=0 \mid \omega_0) \\ &= 1-p+[\Pr(d=1,\omega_1) - \Pr(d=1,\omega_0)] \end{aligned} \tag{18}$$

where $\Pr(d \mid \omega)$ is the probability of decision d at equilibrium, conditional on the true fact being ω, and $\Pr(d,\omega)$ is the joint probability. Different procedures, depending on whether cross-examination is or is not allowed, differ in the quality of decision-making through the expression in brackets.

The decision $d=1$ can only arise when the plaintiff uncovers the evidence and then when he submits $(x,y) \in S$ or x_1, provided in the latter case that no counterevidence is submitted or the plaintiff does not fail cross-examination. We first give a general formulation of (18) in terms of the parties' investigation efforts and an effective cross-examination strategy.

Lemma 2 *The probability of correct adjudication is* $\overline{u}_A = 1-p+e_P\Lambda$ *where*

$$\Lambda = \theta\Delta + [k_P(1-\theta)(1-\alpha) - k_D\theta(1-e_D)(1-\beta)] \tag{19}$$

and

$$\Delta = \sum_{(x,y)\in S} [P(x,y,\omega_1) - P(x,y,\omega_0)]$$

If the parties never communicated evidence, the arbitrator would always find for the defendant, so the probability of correct adjudication would then be $1-p \geq \frac{1}{2}$. The term $e_P\Lambda$ is the value added by the investigation and communication phases. We will refer to Λ as the value of communication because it is the increase in the probability of a correct decision conditional on the plaintiff's uncovering of the evidence. The value of communication depends on the evidence potentially submitted by the plaintiff, the counterevidence that the defendant could submit and the information potentially provided by cross-examination.

When cross-examination is not allowed, substituting the equilibrium investigation efforts in (19) and setting α and β to zero, the value of communication is

$$\Lambda^{nc} = \theta\Delta + k_P(1-\theta) - k_D\theta(1-e_D^{nc}) \tag{20}$$

When cross-examination is allowed, substituting in (19) from the equilibrium values of Proposition 2, the value of communication is

$$\Lambda^{cr} = \theta\Delta + k_P(1-\theta) - k_D\theta \tag{21}$$

Proposition 3 *When cross-examination is allowed, the quality of decision making deteriorates : (i) the plaintiff investigates less,* $e_P^{cr} < e_P^{nc}$*, and is therefore less likely to come forward with evidence; (ii) the value of communication is reduced,* $\Lambda^{cr} < \Lambda^{nc}$*, because the defendant does not investigates,* $e_D^{cr} = 0$.

The opportunity of cross-examination reduces the quality of decision-making for two reasons. First, communication is less likely to be triggered. Secondly, communication is less informative. The second effect depends on the defendant's investigation effort and on the equilibrium cross-examination strategy.

To disentangle the effects, it is useful to consider cases where the plaintiff's or the defendant's probability of uncovering the evidence are exogenously given. Suppose both are exogenous with $e_P = e_P^{nc}$ and $e_D = e_D^{nc}$. When cross-examination is not allowed, the setting then reduces to a pure communication game; the equilibrium disclosure strategies are the same as before. Without cross-examination, the value of communication is therefore $\Lambda = \Lambda^{nc}$ as defined above. If e_P is endogenous, it solves (11) with $e_D = e_D^{nc}$ taken as exogenous; hence, $e_P = e_P^{nc}$ at equilibrium. Similarly, if e_D is endogenous, it solves (12) with $e_P = e_P^{nc}$ taken as exogenous; hence, $e_D = e_D^{nc}$ at equilibrium. Therefore, the quality of decision making is the same in all of these cases and equals

$$\overline{u}_A = 1 - p + e_P^{nc}\Lambda^{nc} \tag{22}$$

This is no longer true when cross-examination is allowed. We consider in turn the three cases above.

(i) Exogenous $e_P = e_P^{nc}$ *and* $e_D = e_D^{nc}$

The defendant produces the counterevidence when he can. Otherwise, he cross-examines the plaintiff. From (14), the defendant's sequentially optimal cross-examination strategy is defined by $\beta = 1$ and α equal to

$$\alpha' := \frac{k_D\theta(1 - e_D^{nc})}{k_P(1 - \theta)}$$

Substituting in (19) then yields $\Lambda = \Lambda^{nc}$. Thus, the quality of decision making is unchanged and remains the same as in (22). A deceitful plaintiff always fails cross-examination but there are also erroneous decisions against an honest plaintiff. The two effects cancel out on average in terms of the quality of decision making.

(ii) Exogenous $e_D = e_D^{nc}$

The equilibrium cross-examination strategy remains as in (i), i.e., $\alpha = \alpha'$ and $\beta = 1$. However, comparing (11) and (16), the plaintiff investigates less because his expected gain is smaller. Thus, the equilibrium $e_P < e_P^{nc}$ and the quality of decision making is less than in (22).

(iii) Exogenous $e_P = e_P^{nc}$

The arbitrator now expects the defendant's investigation effort to be $e_D^{cr} = 0$, which is correct at equilibrium. From (14), the defendant's sequentially optimal cross-examination strategy is therefore $\beta = 1$ and α equal to

$$\alpha'' := \frac{k_D \theta}{k_P(1-\theta)} > \alpha'$$

Substituting in (19) then yields $\Lambda = \Lambda^{cr} < \Lambda^{nc}$. The quality of decision making is again less than in (22) but for a different reason. The arbitrator is now more skeptical vis-à-vis the plaintiff than in (ii) because the defendant is less likely to have accessed the evidence. Following the reports $r_P = (x_1, \emptyset)$ and $r_D = \emptyset$ and prior to cross-examination, the arbitrator now assigns probability $\nu(e_D^{cr}) > \nu(e_D^{nc})$ to the possibility that the plaintiff concealed evidence. Because of the arbitrator's greater skepticism, the defendant can use a more aggressive examination strategy, $\alpha'' > \alpha'$. This generates a less informative signal $\chi \in \{b, g\}$, hence the decrease in the value of communication.

4 Concluding Remarks

Posner (1999, p. 1543) remarks that: "A principal social value of the right of cross-examination is deterrent: the threat of cross-examination deters some witnesses from testifying at all and others from giving false or misleading evidence." We studied a situation where cross-examination does indeed reduce the probability of testimony. However, given a sophisticated Bayesian decision maker, decision making deteriorates because cross-examination deters too much, both with respect to the party facing the threat of cross-examination and the one who stands to benefit from it.

We assumed a circumscribed pool of hard evidence pertaining to the fact at issue. The parties have relatively little discretion in this respect. They choose how much to invest in gathering the evidence and what portion they will report. By contrast, a cross-examiner has complete latitude in framing the test to which the opponent will be subjected. Being a partisan, the cross-examiner seeks to persuade that the opponent's report is deceitful. It sufficed to raises just enough doubt that the report does not contain the whole truth.

The assumption of a perfectly skillful cross-examiner may seem too strong. In practice, how much information can be extracted through cross-examination will depend on the cross-examiner's ingenuity and on the complexities of the situation. However, the assumption of perfect skillfulness does not drive our results. In the supplementary Appendix, we consider the case where the set of possible cross-examination strategies is constrained: the feasible pairs of false and true positives belong to a concave subset of the unit square. The results are then essentially the same as previously, except that the party benefitting from the opportunity of cross-examination will generally also investigate, although less than when cross-examination is not allowed. It follows that the value of communication is again reduced when cross-examination is allowed, for the same reasons as in the preceding section.

It may be remarked that the chilling effect on the plaintiff's incentives to investigate bears a similarity with the effect of mandatory disclosure. It is well known that reducing the scope of manipulating information may be detrimental to the quality of decision-making when information is costly (Matthews and Postlewaite, 1985; Farrell, 1086; Shavell, 1994; Schweizer, 2017). There is then a trade-off between the agent's incentives to acquire information and the quality of communication conditional on the information acquired. Our results differ because, owing to the adversarial context, the transfer of information depends on the likelihood that both parties are informed, including the cross-examiner. Moreover, rather than mandatory disclosure as such, we deal with the involuntary transmission of information strategically distorted through partisan persuasion.

Finally, in our setting only one party found it useful to cross-examine the opponent. This followed mechanically from the simplifying assumption that the potential evidence consists of at most two pieces of information. The party with the burden of proof then sometimes submitted incomplete evidence, which the other party attempted to rebut by disclosing countervailing evidence or through cross-examination. Should that party itself disclose evidence, its report may also be misleading if the potential evidence consists of more than two pieces. By relaxing the assumption on the structure of evidence, the analysis can be extended to bilateral cross-examination.

Appendix

Proof of Lemma 1. Multiplying the numerator and denominator in (7) by $P(x_1)$,

$$\begin{aligned}\nu(e_D) &= \frac{\theta P(x_1,y_0)(1-e_D)}{(1-\theta)P(x_1)+\theta P(x_1,y_0)(1-e_D)} \\ &= \frac{\sum_i \theta P(x_1,y_0,\omega_i)(1-e_D)}{\sum_i\{(1-\theta)P(x_1,\omega_i)+\theta P(x_1,y_0,\omega_i)(1-e_D)\}}\end{aligned}$$

Using (5), it follows that

$$\begin{aligned}&\mu((x_1,\emptyset),\emptyset;e_D) = \\ &\left(\frac{\sum_i(1-\theta)P(x_1,\omega_i)}{\sum_i\{(1-\theta)P(x_1,\omega_i)+\theta P(x_1,y_0,\omega_i)(1-e_D)\}}\right)\left(\frac{P(x_1,\omega_1)}{\sum_i P(x_1,\omega_i)}\right) \\ &+\left(\frac{\sum_i \theta P(x_1,y_0,\omega_i)(1-e_D)}{\sum_i\{(1-\theta)P(x_1,\omega_i)+\theta P(x_1,y_0,\omega_i)(1-e_D)\}}\right)\left(\frac{P(x_1,y_0,\omega_1)}{\sum_i P(x_1,y_0,\omega_i)}\right)\end{aligned}$$

which is the same as (8).■

Proof of Proposition 1. We first show that $e_P^{nc} > e_D^{nc} > 0$ and then show that this implies $\mu(\emptyset,\emptyset) < \frac{1}{2}$.

(i) $e_P^{nc} > e_D^{nc} > 0$

The solution to (11) and (12) is clearly unique and both e_P^{nc} and e_D^{nc} are positive because $C'(0) = 0$. Given $C'' > 0$, the claim that $e_P^{nc} > e_D^{nc}$ is equivalent to $C'(e_P^{nc}) > C'(e_D^{nc})$ and therefore, using (11) and (12), to

$$(1-\theta)P(x_1)+\theta\left[\sum_{(x,y)\in S} P(x,y)+P(x_1,y_0)(1-e_D^{nc})\right] > e_P^{nc}\theta P(x_1,y_0).$$

The left-hand side is decreasing in e_D^{nc} and the right-hand side increasing in e_P^{nc}, so it suffices that the inequality holds at $e_P^{nc} = e_D^{nc} = 1$, i.e.,

$$(1-\theta)P(x_1) + \theta\left[\sum_{(x,y)\in S} P(x,y) - P(x_1,y_0)\right] > 0. \tag{23}$$

By Assumption 1, $(x_1, y_1) \in S$ so that (23) is satisfied if

$$(1-\theta)P(x_1) + \theta\left[P(x_1,y_1) - P(x_1,y_0)\right] > 0$$

equivalently if

$$(1-\theta)[P(x_1,y_0) + P(x_1,y_1)] + \theta\left[P(x_1,y_1) - P(x_1,y_0)\right] > 0$$

which is equivalent to Assumption 3.

(ii) $\mu(\emptyset,\emptyset) < \frac{1}{2}$

Applying Bayes' rule,

$$\mu(\emptyset,\emptyset) = \frac{p\Pr(r_P = \emptyset, r_D = \emptyset \mid \omega_1)}{\Pr(r_P = \emptyset, r_D = \emptyset)}$$

so that $\mu(\emptyset,\emptyset) < \frac{1}{2}$ if

$$\frac{\Pr(r_P = \emptyset, r_D = \emptyset \mid \omega_0)}{\Pr(r_P = \emptyset, r_D = \emptyset \mid \omega_1)} > \frac{p}{1-p}. \tag{24}$$

Because $p \le \frac{1}{2}$, the inequality (24) holds if it does for $p = \frac{1}{2}$, equivalently if

$$\xi := \Pr(r_P = \emptyset, r_D = \emptyset \mid \omega_0) - \Pr(r_P = \emptyset, r_D = \emptyset \mid \omega_1) > 0.$$

Given the disclosure strategies, and letting $\overline{S}$ be the complement of S,

$$\begin{aligned}
&\Pr(\ r_P = \emptyset, r_D = \emptyset \mid \omega_i\ ) = \\
&(1-\theta)\{1 - e_P + P(\ x_0 \mid \omega_i\ )e_P\} + \theta(1-e_D) \sum_{(x,y)\in\overline{S}\setminus(x_1,y_0)} P(\ x,y \mid \omega_i\ ) \\
&\qquad + \theta(1-e_P)(1-e_D)P(\ x_1,y_0 \mid \omega_i\ ) + \theta(1-e_P) \sum_{(x,y)\in S} P(\ x,y \mid \omega_i\ )
\end{aligned}$$

This yields

$$\begin{aligned}\xi &= e_P\{(1-\theta)[P(x_1 \mid \omega_1)-P(x_1 \mid \omega_0)]-\theta[P(x_1,y_0 \mid \omega_0)-P(x_1,y_0 \mid \omega_1)](1-e_D)\} \\ &\quad +\theta(e_P-e_D)\sum_{(x,y)\in S}[P(\ x,y \mid \omega_1\ )-P(\ x,y \mid \omega_0\ )]\end{aligned}$$

The expression in the curly brackets is positive (recall Observation 1); the expression on the second line is also positive because $e_P > e_D$ as shown above.■

Proof of Proposition 2. That $e_P^{cr} < e_P^{nc}$ follows from the first-order conditions (11) and (16). The rest of the argument is in the text.■

Proof of Lemma 2. For given e_P, e_D, α, and β, the marginal probability of decision $d = 1$ is $e_P W$ where W is as defined in (15). Rewriting (15) with the conditional probabilities in (18) yields (19).■

Proof of Proposition 3. The result follows from the definition of $\overline{u}_A$ in Lemma 2 and the argument in the text.■

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