

# Bayesian Privacy\*

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March 30, 2020

## Abstract

Modern information technologies make it possible to store, analyze and trade unprecedented amounts of detailed information about individuals. This has led to public discussions on whether individuals' privacy should be better protected by restricting the amount or the precision of information that is collected by commercial institutions on their participants. We contribute to this discussion by proposing a Bayesian approach to measure loss of privacy in a mechanism. Specifically, we define the loss of privacy associated with a mechanism as the difference between the designer's prior and posterior beliefs about an agent's type, where this difference is calculated using Kullback-Leibler divergence, and where the change in beliefs is triggered by actions taken by the agent in the mechanism. We consider both ex-post (for every realized type, the maximal difference in beliefs cannot exceed some threshold  $\kappa$ ) and ex-ante (the expected difference in beliefs over all type realizations cannot exceed some threshold  $\kappa$ ) measures of privacy loss. Using these notions we study the properties of optimal privacy-constrained mechanisms and the relation between welfare/profits and privacy levels.

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\*We thank Benny Moldovanu and Doron Ravid for helpful conversations.

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# 1 Introduction

Modern information technologies make it possible to store, analyze and trade unprecedented amounts of detailed information about individuals. At the same time, the rapid growth of online markets has significantly increased the participation of individuals in decentralized pricing mechanisms that rely on personal information provided by the participants. Consequently, the organizers of these markets are able to gather vast amounts of data on individuals' characteristics such as their tastes and willingness-to-pay for products and services. These data are valuable to a variety of entities including commercial firms as well as political institutions. If leaked to these entities, this information may be used against the users' interests. In light of this, there has been a growing sentiment that governments should enact laws that regulate the ability of private entities to collect and use personal information. If the growing concerns for maintaining privacy were to lead to regulations that impose privacy constraints on pricing mechanisms, how would that affect the design of these mechanisms, and what is the trade-off between profits, welfare and privacy? This paper takes a step towards addressing these questions by proposing a Bayesian approach to the measurement of loss of privacy and applying this approach to the design of optimal mechanisms that are restricted in the amount/precision of private information that they can elicit from participants.

The cornerstone of our approach is the idea that loss of privacy is a *relative* notion: How much information is effectively extracted from an individual through his actions should be measured relative to what is already known about that individual. For example, if it is publicly known that some individual was convicted of some crime, then there is no loss of private information when that person voluntarily discloses his conviction. Similarly, how much privacy is lost when a reputed business manager (say, the CEO of a publicly traded firm) discloses his wealth should depend on existing public information (for example, about his annual income). In the context of private information that is gleaned through trade, a seller who operates in a particular zipcode may already know the wealth distribution of the residents in that zipcode. Similarly, if an individual who is already active on some platform (say, an online radio) decides to make a purchase on that platform, the information revealed from the purchase itself is in addition to the data that the platform has already collected prior to the purchase, such as that person's taste in music.

Taking the idea of relative privacy to mechanism design, we suppose that the designer already possesses some information about the participants in the form of a prior belief over their "types." He updates this belief as a result of the participants' interactions with the

mechanism, which reveal more information about them. For example, if the mechanism consists of a menu, then an individual’s choice of a particular menu item enables the designer to learn additional information about this person’s preferences. Consequently, the designer’s posterior belief about the participant’s type may be quite different from her prior belief. This suggests that the *difference* between the designer’s prior and posterior beliefs should serve as the basis for measuring the loss of privacy associated with a particular mechanism.

Building on this observation, we propose a Bayesian measure of relative privacy loss for mechanisms and apply it to screening mechanisms, which shut down the strategic interaction among different participants. Specifically, we consider the classic Mussa-Rosen set-up in which a monopolist seller faces increasing marginal cost for producing a higher quantity (or quality) of a product, and wishes to offer the optimal menu of quantity-price pairs to consumers with private willingness-to-pay per unit. The standard solution implies that, under a regularity condition, all consumer types that opt in perfectly reveal their private types. Hence, the optimal solution entails complete loss of privacy: The designer has a degenerate posterior belief on the type of each participant.

To study the design of mechanisms that preserve some level of privacy, we follow the information theory literature and propose to measure a mechanism’s inherent loss of privacy as the *maximal relative entropy* (i.e., the Kullback-Leibler divergence) between the seller’s posterior and prior beliefs. The posterior belief is derived from the “message” received in the mechanism, and the maximum KL divergence is computed across all messages (i.e., across all consumer types). We then augment the standard mechanism design problem by restricting attention to mechanisms with privacy loss at most  $\kappa$ . The parameter  $\kappa$ , which takes values between zero (full privacy) and infinity (no privacy), captures the strength of the privacy requirement. For any finite  $\kappa$ , our approach imposes an upper bound on the amount of new information that a designer may learn about any participant.

Before describing our results, we offer some discussion of this modeling framework. By imposing an exogenous privacy constraint, we take a “paternalistic” approach to privacy in the sense that we do not explicitly model consumers’ preferences over privacy (i.e., how consumers trade-off privacy, consumption and money), but rather assume that mechanisms are required to guarantee a certain level of privacy. This is motivated by research showing that most consumers are not fully aware of the implications of allowing commercial entities to record information about them. Indeed, many users make public postings on social media, log in to websites through their social media accounts and do not delete cookies (e.g., see Acquisti and Grossklags (2005), Barth and de Jong (2017) and

Kokolakis (2017)).<sup>1</sup> Our paternalistic approach is analogous to the one that is frequently taken in the design of commitment mechanisms, which try to help agents with self-control problems by limiting their choice sets even when there is no demand for such commitment devices on part of the agents.<sup>2</sup>

This perspective that a regulator imposes the exogenous privacy constraint motivates our choice of an information-theoretic measure of privacy loss. Our measure requires making no specific assumptions about the exact form of future interactions between the data holder and the agent. This reduced-form approach reflects our view that the continuation game is often unknown (especially to the regulator), making it impossible to predict how data collected today will be used in the future.<sup>3</sup>

Thus, a regulator may prefer the relative entropy measure, which is portable and applicable to any mechanism design setting regardless of the particular type space. The relative entropy measure also captures the idea that greater privacy loss means smaller uncertainty about a consumer’s characteristics after he takes an action. Although different functional forms can be used to measure the change in the seller’s beliefs, we choose KL divergence because of its popular usage and tractability. Nonetheless, our qualitative results are robust to a general class of belief divergences (see the discussion after Lemma 1, and Footnote 14).

Alternatively, our privacy constraint can be interpreted as imposing a budget for “securing” sensitive data. Under this interpretation, we view the designer’s prior belief as representing publicly available information. Messages that move the designer’s posterior further away from her prior disclose more private and perhaps more sensitive information about the agent. Storing more detailed information about the agent typically necessitates greater measures to ensure its security. Thus our proposed privacy measure captures in a stylized way that more precise information (relative to what is publicly known) is more costly to secure. This interpretation creates an interesting link between our approach

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<sup>1</sup>Even if consumers were to fully endogenize the consequences of disclosing their private information, it is often the case that individuals neglect the effects of sharing their information on *others*. For a discussion of the negative externalities and the “public bad” properties of loss of privacy, see e.g. Fairfield and Engel (2015) and Choi et al. (2019).

<sup>2</sup>Laibson (2018) calls it the commitment paradox and gives the following example: “College instructors adopt course policies that force students to focus on their coursework: pop quizzes, classroom attendance requirements, cold calling, graded problem sets, deadlines, classroom wifi blocking, and classroom laptop bans. In my experience, most students don’t welcome these paternalistic restrictions.”

<sup>3</sup>Oftentimes data that are collected for one purpose are used for a surprisingly different one. A notable example is the 2018 Cambridge Analytica political scandal in which it was revealed that Cambridge Analytica had harvested the personal data of millions of peoples’ Facebook profiles without their consent and used it for political advertising purposes.

to privacy and the literature on *rationaly inattentive sellers*. In both cases, the seller faces a cost of acquiring information that changes her belief. However, in the rational inattention literature, the seller can directly choose what information to acquire, whereas in our model she needs to incentivize another party to disclose that information to her.

Our main results highlight the following key properties of optimal privacy-preserving mechanisms. The optimal  $\kappa$ -constrained mechanism *partitions* the type space into finitely many intervals (whose number depends on  $\kappa$ ), such that consumers truthfully announce to which interval their type belongs. Thus, even though there is a continuum of types, and the privacy constraint allows for a continuum of noisy messages,<sup>4</sup> maximal profits are attained with only finitely many messages. When the production cost function and the type distribution satisfy some additional properties that we provide, any optimal  $\kappa$ -constrained mechanism consists of intervals that are *monotonically ordered* according to their mass from left to right, so that the gain from differentiating higher types either diminishes or increases.

The Bayesian measure of privacy loss has the advantage of admitting a welfare analysis of privacy restrictions, which to the best of our knowledge is absent in the literature. A priori, it is not clear whether stricter privacy requirements help or harm consumers since such requirements distort allocative efficiency. We show that when the marginal production cost is convex, buyer surplus is *maximized* at  $\kappa = 0$ , where every type receives the same quantity, and it is minimized at  $\kappa = \infty$ , where types are fully separated. However, we find that when costs are quadratic and the prior density function is decreasing in the type, total welfare is *minimized* at  $\kappa = 0$  (full privacy) and maximized at  $\kappa = \infty$  (no privacy). This result suggests that regulators may face a trade-off between consumer protection and trade efficiency.

To illustrate a complete characterization of the optimal privacy-preserving mechanism, we analyze the uniform-quadratic case where types are drawn from a uniform distribution and costs are quadratic. In this case, for any  $\kappa \in [\log(n), \log(n + 1))$ , the  $\kappa$ -optimal mechanism divides the type space into  $n$  equal intervals. Hence, when  $\kappa$  is in the interior of this interval, the privacy constraint is slack and profit is constant as  $\kappa$  increases within this interval.

A consumer's action or message can be thought of as a noisy signal that the designer observes about the consumer's type. Ex ante, there is a distribution over these signals induced by the prior type distribution and each type's optimizing behavior. An alternative, more permissive notion of privacy would require that *on average*, the reduction

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<sup>4</sup>E.g., when each type  $\theta$  reports  $\theta + \varepsilon$ , where  $\varepsilon$  is a continuous random variable.

in the designer’s uncertainty regarding the consumer should not exceed some threshold. More formally, one could impose that the *expected* relative entropy between the designer’s posterior and prior beliefs should be at most  $\kappa$ . This *ex-ante* notion of privacy, in contrast to the ex-post notion discussed previously, is lenient to events of high loss of privacy that occur with small probabilities. Thus, the designer can preserve privacy in a differential manner across consumer types, so long as on average a given level of privacy is maintained. This allows the designer to take advantage of the fact that some consumers’ private information may be more valuable than others, e.g., uncovering “high valuation types” may be more profitable than uncovering “low valuation types.”

We show that many of our findings continue to hold under the ex-ante notion of privacy. However, there are a number of major differences. First, even though it is again without loss to consider mechanisms that involve interval partitions, *existence* of an optimal mechanism is no longer straightforward. The difficulty arises since the ex-ante constraint, unlike our original ex-post version, allows for partitions with countably many intervals. Without a finite upper bound on the number of intervals, it is more challenging to use a compactness argument to prove existence. To show that an optimal mechanism indeed exists, we show that there can be at most one interval of arbitrarily small mass, i.e., at most one set of types about which the seller attains very precise information. This property restores compactness and settles the existence issue; it also implies that for  $\kappa$  small (near full privacy), the optimal ex-ante  $\kappa$ -constrained mechanism has exactly two intervals. Another distinction of the ex-ante constraint is that the resulting optimal mechanism always exhausts the privacy constraint. Consequently, the optimal mechanism in the uniform-quadratic case is different from the one derived for ex-post privacy: For  $\kappa \in (\log(n - 1), \log(n)]$ , there is exactly one “short” interval and  $n - 1$  “long” intervals of equal length; the lengths are uniquely determined by the binding privacy constraint, and the position of the “short” interval does not matter.

In the absence of a commonly-agreed-upon notion of privacy loss, our main contribution is to propose a Bayesian definition that builds upon a familiar concept from information theory, which has already been adopted by economists as a measure of the cost of information.<sup>5</sup> This privacy notion can be easily incorporated into the standard mechanism design framework, and has the advantage of allowing to quantify the effect of a marginal change in the privacy threshold on profits and welfare. As our results suggest, the proposed privacy notion also provides a rationale for using “simple/coarse” mechanisms with restricted message spaces.

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<sup>5</sup>Pomatto et al. (2019) provide an axiomatization of KL divergence as a measure of information cost.

We proceed as follows. In Section 2 we review the related literature. In Section 3 we introduce our ex-post Bayesian privacy notion, and in Section 4 we use this notion to analyze optimal privacy-constrained mechanisms in a monopolistic screening setting. Section 5 presents an alternative, ex-ante, Bayesian privacy measure and solves for the corresponding optimal mechanisms under this constraint. Section 6 concludes.

## 2 Related literature

As mentioned, our work is closely related to rational inattention (Sims (2003), Caplin and Dean (2015), Matějka and McKay (2015), Matějka (2016), Steiner et al. (2017), Caplin et al. (2019)). In that literature, an uninformed decision maker chooses the structure of a signal she wants to observe, subject to the information constraint that the signal can only contain a limited amount of information about the state (as measured by mutual information). Note that mutual information is equal to the expected KL divergence between the decision maker’s posterior and prior beliefs. Thus, the rational inattention approach connects to our mechanism designer’s problem under the ex-ante privacy constraint. The key difference is that in our setting, the “signal” observed is the agent’s message, which is bound by an additional incentive constraint. Studying the interaction between the information constraint and the incentive constraint is the main objective of our work.

The privacy constraint in our model entails that, *in equilibrium*, agents cannot communicate all their private information to the designer. Several papers have investigated a related question of optimal mechanism design with limited communication, by imposing *exogenous* restrictions on the cardinality of the action space available to agents. Notable examples are Green and Laffont (1987), Melumad et al. (1992), Blumrosen et al. (2007), Bergemann et al. (2012), Kos (2012) and Blumrosen and Feldman (2013). In a different setting, Mookherjee and Tsumagari (2014) study a dynamic mechanism design problem with costly communication and compare between centralized and decentralized production decisions. Van Zandt (2007), Fadel and Segal (2009) and Babaioff et al. (2013) study the interaction between communication capacity and incentive feasibility by quantifying the “cost of selfishness” – the amount of excess information (bits) that needs to be exchanged to implement a given social choice function, relative to the case in which agents honestly report their types. More generally, optimization problems over partitions have been considered in Alonso and Matouscheck (2008) and Frankel (2014), who study delegation, as well as in Crémer et al. (2007), who study language design within an organization.

A number of papers have studied privacy in dynamic models, where the agent’s preferences for privacy is derived from how the designer can use the information against him in the future. Such models appear in Taylor (2004), Calzolari and Pavan (2006), Conitzer et al. (2012) among others. In contrast, our approach based on the divergence between prior and posterior beliefs is *reduced-form* and especially applicable to the question of regulation, where it is not a priori clear what the seller would/could do with the collected consumer data. Static models about privacy have been studied in Gradwohl (2018), who analyzes the problem of full implementation when agents prefer to protect their privacy, and in Gilboa-Freedman and Smorodinsky (2018), who axiomatize preferences over privacy.<sup>6</sup> Finally, in the two-sided market setting, Hidir and Vellodi (2018) and Ichihashi (2019) have considered letting the consumer directly communicate to the seller via cheap talk or Bayesian persuasion. In our model, however, the consumer reveals information about his private type by responding to the seller’s mechanism.

Turning to the computer science literature, our notion of privacy differs from the popular measure of “differential privacy.”<sup>7</sup> Introduced by Dwork et al. (2006), differential privacy roughly means that changing the data of a single individual (or of a single attribute of an individual) should have a negligible effect on computations done on the entire data. In the context of mechanism design, Pai and Roth (2013) show that this notion can be formalized as follows. Suppose there are  $n$  individuals, who each draws a private type from some set  $T$ . Define a mechanism  $M$  as a mapping from profiles of types  $t \in T^n$  to distributions over some set of outcomes  $X$ . Then  $M$  is  $\epsilon$ -*differentially private* if for all pairs of type profiles  $(t, t')$  that differ only in  $t_i$ , and for any payoff function  $u : X \rightarrow \mathbb{R}$ , it holds that

$$\mathbb{E}_{M(t)}u(x) \leq \exp(\epsilon) \cdot \mathbb{E}_{M(t')}u(x).$$

This definition implies that the message of a single player has a negligible effect on the outcome, such that any action is “almost” weakly dominant in the sense that it cannot affect a player’s payoff by a multiplicative factor of more than  $2\epsilon$ , regardless of the other players’ actions. In light of this, several studies in computer science have used

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<sup>6</sup>Also related is Ollár, Rostek and Yoon (2016), who analyze uniform pricing rules in markets with multiple traders facing Gaussian information structures. Their focus is on the information that traders may learn about each other from any feedback provided by the mechanism. They show that in their environment, privacy – in the sense that no trader learns anything about the other traders’ valuations – is necessary for truthful bidding.

<sup>7</sup>For more detailed surveys on privacy in computer science and economics, see Pai and Roth (2013), Heffetz and Ligett (2014) and Acquisti et al. (2016).



the above notion to design mechanisms where truth-telling is either almost or exactly weakly dominant; see, e.g., McSherry and Talwar (2007), Kearns et al. (2012), and Nissim et al. (2012). Other studies attempt to incorporate agents with privacy concerns into mechanism design, assuming an additive cost for loss of privacy that increases with the level of differential privacy (i.e., with the  $\epsilon$  above). Examples are Ghosh and Roth (2011), Ligett and Roth (2012), Fleischer and Lyu (2012).

What distinguishes our approach is that we measure privacy loss *relative* to a prior, whereas differential privacy is independent of the prior. Additionally, note that the differential privacy constraint is stated solely in terms of the (random) outcome distribution, sidestepping any action taken in the mechanism. This captures privacy loss from the perspective of an *outside observer*, but does not correspond to what the *mechanism designer* may learn through observing participants' choices. In this paper we focus on constraining the amount of information learned by the mechanism designer, and study a benchmark in which the designer cannot commit not to access the data received. Thus, we measure privacy loss using posterior beliefs that are derived from the messages sent, rather than the outcomes induced. In particular, the designer in our model *does not gain* from randomizing over allocations.

Another line of research in computer science deals with distortion and anonymization of databases and communication channels due to privacy concerns. This literature uses KL divergence to measure loss of privacy in a setting where a sender wants to send part of a dataset to a receiver in such a way that the receiver learns as little as possible about some other sensitive part of the data. The problem is formulated as finding the message that minimizes the KL divergence between the common prior on the sensitive data and the posterior, given the sender's message, subject to the constraint that the receiver attains some level of utility. Examples of works in this literature include Agrawal and Aggarwal (2001), Díaz et al. (2003), Rebollo-Monedero et al. (2010), Sankar et al. (2013) and Wang et al. (2016). However, these papers do not consider the strategic interaction between privacy, mechanism and agent behavior, as we do here.

### 3 Bayesian privacy

A single agent has a privately known type  $\theta \in \Theta$  and a type-dependent vNM utility function  $u : X \times \Theta \rightarrow \mathbb{R}$ , where  $X$  is the set of outcomes to be determined by a mechanism. The mechanism designer does not know the agent's type  $\theta$ , but has a prior belief about  $\theta$  represented by a probability measure  $F$  on  $\Theta$ , with strictly positive density  $f$  (with respect to a base Borel measure). The designer's payoff function is  $\pi : X \times \Theta \rightarrow \mathbb{R}$ .

To maximize expected payoff, the designer devises a mechanism  $\mathbb{M} = \langle M, g \rangle$ , where  $M$  is an arbitrary set of messages, and  $g : M \rightarrow X$  is a function that maps each message in  $M$  to an outcome  $x \in X$ . A strategy for the agent is a function  $\sigma : \Theta \rightarrow \Delta(M)$ . A strategy  $\sigma^*$  is said to be an equilibrium in the mechanism  $\mathbb{M}$  if each type  $\theta \in \Theta$  best responds to  $\mathbb{M}$ .

At the outset, the designer already has some information about the agent in the form of his prior belief  $F$ . Given a mechanism  $\mathbb{M}$  and an equilibrium  $\sigma^*$ , when the agent sends message  $m \in M$ , the designer updates her information to the posterior belief  $F(\cdot|m, \sigma^*)$ . This change of beliefs entails loss of privacy for the agent. For convenience, we define  $F(\cdot|m, \sigma^*) = F$  for any message  $m$  sent with zero probability by every type in  $\sigma^*$ .

We measure the loss of privacy entailed by a message  $m \in M$  in an equilibrium  $\sigma^*$  by the *relative entropy* between the posterior belief triggered by  $m$  and the prior belief: If the posterior measure  $F(\cdot|m, \sigma^*)$  has density  $f(\cdot|m, \sigma^*)$ , the relative entropy (or Kullback-Leibler Divergence) from  $F(\cdot|m, \sigma^*)$  to  $F$  is defined by:<sup>8</sup>

$$D_{KL}(F(\cdot|m, \sigma^*) || F) = \int_{\Theta} f(\theta|m, \sigma^*) \cdot \log \frac{f(\theta|m, \sigma^*)}{f(\theta)} d\theta. \quad (1)$$

If instead  $F(\cdot|m, \sigma^*)$  does not admit a density, we define  $D_{KL}(F(\cdot|m, \sigma^*) || F) = +\infty$  (when  $F(\cdot|m, \sigma^*)$  has an atom this definition preserves continuity). Throughout the paper, “log” represents the natural logarithm.

We define the *ex-post loss of privacy* associated with an equilibrium  $\sigma^*$  in a mechanism  $\mathbb{M}$  to be the *maximum* divergence between the possible posteriors and the prior:

**Definition 1** The ex-post loss of privacy in an equilibrium  $\sigma^*$  of a mechanism  $\mathbb{M}$  is given by:

$$I(\mathbb{M}, \sigma^*) = \sup_m [D_{KL}(F(\cdot|m, \sigma^*) || F)]$$

Thus, in equilibrium, the change in the designer’s beliefs is no more than  $I(\mathbb{M}, \sigma^*)$  regardless of the agent’s type. In the next section we study the problem of a designer who is restricted to use only mechanisms for which the above measure does not exceed some threshold.

Note that using relative entropy to quantify changes in beliefs does not bind our privacy measure to a particular metric over the set of types. To be specific, one could alternatively measure belief changes in a way that takes into account not only the relative

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<sup>8</sup>The relative entropy exhibits a number of key properties:  $D_{KL}(G||F) \geq 0$  for all  $G$  and  $F$  with equality if and only if  $G = F$ , and  $D_{KL}(G||F)$  is convex in both  $G$  and  $F$ . It is however not a metric due to the failure of symmetry and of the triangle inequality.

probabilities between prior and posterior beliefs, but also where these probabilities lie according to a certain distance function between types (such as the Euclidean metric). However, sticking to any particular metric might be misleading because how the collected data will be used in future interactions is often unknown at present. Furthermore, a metric-based measure is highly sensitive to the context. In some contexts, there is greater loss of privacy in knowing that the agent is either of two “far-away” types (according to the adopted metric) than knowing that he is one of two “close-by” types, while the opposite is true in other contexts. For example, in the context of body weight where distance between types is measured in pounds, there is greater loss of privacy in knowing that an individual is either extremely obese or extremely underweight (i.e., far-away types) than knowing that his weight is either 150 lbs or 160 lbs (close-by types). In contrast, in the context of geographic location where distance between types is measured in miles, there is greater loss of privacy in knowing that the agent’s residential address is one of two adjacent streets in Provo, Utah, than in knowing that his address is either a street in Los-Angeles or some street in New-York. Note that it is often not the collected data per se that matters for privacy considerations, but rather other variables that are correlated with the data. It is thus impossible to a priori choose one “right” metric that fits all possible relevant variables in all possible future scenarios. We instead choose to work with relative entropy, which is “metric-less” and applicable to any context.

Next, we apply our definition of privacy loss to the well-known problem of monopolistic screening.

## 4 Optimal privacy-constrained mechanisms

We consider the classic Mussa-Rosen (1978) set-up of monopolistic screening. A seller (she) wishes to sell some quantity/quality  $q \in \mathbb{R}^+$  to a buyer (he), in exchange for payment  $p \in \mathbb{R}$ . Thus, the set of outcomes  $X$  is the set of price and quantity pairs. The seller’s profit is given by:

$$\pi(p, q, \theta) = p - c(q)$$

where  $c(\cdot)$  is a twice-continuously differentiable cost function that satisfies  $c(0) = c'(0) = 0$  and  $c''(q) > 0$  for all  $q \geq 0$ .<sup>9</sup> The buyer’s type  $\theta \in [\underline{\theta}, \bar{\theta}]$  represents his willingness to pay per unit, which is unknown to the seller. If the buyer consumes  $q$  and pays  $p$ , his utility is

$$u(p, q, \theta) = q \cdot \theta - p$$

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<sup>9</sup>In this application the designer’s payoff function (i.e., profit) is independent of the agent’s type  $\theta$ .

We assume that the buyer’s virtual valuation,  $v(\theta) \equiv \theta - \frac{1-F(\theta)}{f(\theta)}$ , is increasing in  $\theta$  and satisfies  $v(\theta) \geq 0$ . To facilitate some technical arguments, we make the slightly stronger assumption that  $v$  is continuously differentiable and  $v' > 0$ .

Positive virtual valuation allows us to focus on the case in which the seller wants to include all buyer types, and the only question is what quantity and price should be offered to each buyer type. Nonetheless, some of our results extend to the case where  $v(\theta)$  is negative – in particular, the optimal privacy-constrained mechanism again partitions the type space into intervals (as we describe below in Proposition 1), even though the lowest interval may correspond to no sale.<sup>10</sup>

To sell the good the monopolist uses a mechanism  $\mathbb{M} = \langle M, p, q \rangle$ , where  $p : M \rightarrow \mathbb{R}^+$  and  $q : M \rightarrow \mathbb{R}^+$  are functions that map each message in  $M$  to an outcome: Given a message  $m \in M$ , the seller provides the quantity  $q(m)$  and charges the price  $p(m)$ .<sup>11</sup>

The seller’s expected profit in an equilibrium  $\sigma^*$  of a mechanism  $\mathbb{M}$  is given by:

$$\Pi(\mathbb{M}, \sigma^*) = \mathbb{E}_m [p(m) - c(q(m))]$$

where  $\mathbb{E}_m$  is evaluated according to the probability that each message  $m \in M$  is sent under the strategy  $\sigma^*$ .

Note that a priori we allow the buyer to randomize over messages that he finds indifferent. However, it will follow from our analysis (Lemma 1 below) that almost all buyer types *do not randomize* at the optimum.

In the absence of privacy constraints, an optimal (revenue maximizing) mechanism in this set-up is a direct revelation mechanism in which: (i) The buyer truthfully reports his type  $\theta$ , (ii) The produced quantity  $q(\theta)$  is determined such that  $c'(q(\theta)) = v(\theta)$ , and (iii) The requested price is  $p(\theta) = q(\theta)\theta - \int_{\underline{\theta}}^{\theta} q(x) dx$ .

In general, the privacy loss associated with a mechanism  $\mathbb{M}$  depends on the equilibrium  $\sigma^*$  that is played. However, in our monopolistic screening setting multiple equilibria only arise when a positive measure of buyer types are indifferent between two messages, which must then lead to the same quantity-price pair. As we discuss below, such messages are “wasteful” and without loss excluded from the optimal mechanism. Hence, to

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<sup>10</sup>The results in Proposition 2 and Proposition 3 also continue to hold, so long as we “exclude” the interval with no sale. Specifically, Proposition 2 would say the following: If  $c''' \geq 0$  and  $v(\theta)$  is strictly more concave than  $F(\theta)$ , then any  $\kappa$ -optimal mechanism consists of intervals ordered in increasing mass from left to right, except possibly for the lowest interval when its expected virtual valuation is negative (which corresponds to no sale). Similarly, Proposition 3 would say that in the uniform-quadratic case, any  $\kappa$ -optimal mechanism consists of intervals with equal lengths, except possibly for the lowest interval.

<sup>11</sup>The functions  $p(\cdot)$  and  $q(\cdot)$  correspond to the outcome function  $g(\cdot)$  in the previous section.

simplify the exposition, from now on we omit the reference to the equilibrium  $\sigma^*$  from the notation of privacy-loss. Thus,  $I(\mathbb{M})$  is the privacy loss entailed by the (essentially unique) equilibrium of  $\mathbb{M}$ .

## 4.1 The design problem

A regulator requires the seller to design a mechanism that does not exceed some privacy capacity  $\kappa > 0$ . The seller's problem can then be described as follows: Find a mechanism  $\mathbb{M} = \langle M, p, q \rangle$  and a strategy  $\sigma$  for the buyer that maximize the expected profit  $\Pi(\mathbb{M}) = \mathbb{E}_m [p(m) - c(q(m))]$  subject to three constraints:

1. *Incentive-compatibility* - given  $\mathbb{M}$ , the strategy  $\sigma$  is optimal for the buyer:

$$u(p(m), q(m), \theta) \geq u(p(m'), q(m'), \theta) \quad (\text{IC})$$

for all  $\theta \in \Theta$ , all  $m \in \text{supp}(\sigma(\theta))$  and all  $m' \in M$ ,

2. *Individual-rationality* - given  $\mathbb{M}$ , a buyer who follows  $\sigma$  is not worse off than if he did not participate in  $\mathbb{M}$ :

$$u(p(m), q(m), \theta) \geq 0 \quad (\text{IR})$$

for all  $\theta \in \Theta$  and all  $m \in \text{supp}(\sigma(\theta))$ ,

3. *Privacy constraint* -

$$I(\mathbb{M}) \leq \kappa. \quad (\text{P})$$

We refer to any mechanism that satisfies the above constraints as a  $\kappa$ -feasible mechanism.<sup>12</sup> Any mechanism that is profit-maximizing among all  $\kappa$ -feasible mechanisms is called a  $\kappa$ -optimal mechanism. Our objective is to derive key properties of this constrained-optimal mechanism. In particular, we are interested in addressing the following questions: What information does each buyer type disclose to the mechanism (Proposition 1)? Do some buyer types disclose more information than others (Proposition 2)? Is the privacy constraint even binding (Proposition 3 and ensuing discussion)?

## 4.2 Interval mechanisms

Note that in standard mechanism design the monopolist maximizes her expected profit subject only to the incentive-compatibility and individual-rationality constraints. Under

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<sup>12</sup>How relevant the value of  $\kappa$  is for feasibility depends on the prior, as does the KL divergence measure.

our assumptions on the virtual valuation, the optimal mechanism in this case perfectly screens every buyer type, and each of the posterior beliefs is a degenerate distribution with a single atom on the buyer’s exact type. The loss of privacy entailed by such a mechanism is infinite according to our definition, and is therefore infeasible for any finite  $\kappa$ . This means that in a  $\kappa$ -optimal mechanism the monopolist obtains only a noisy signal about the buyer’s type. Our first result establishes that this noise has a particular structure, which can be interpreted as a *coarse revelation principle*: There is no loss of generality in focusing on mechanisms that partition the type space into intervals and each type reports the interval he belongs to.

**Lemma 1** *For any  $\kappa$ -feasible mechanism, there exists another  $\kappa$ -feasible mechanism  $\mathbb{M} = \langle M, p, q \rangle$  with the same profit level, such that  $M$  consists of intervals that partition  $[\underline{\theta}, \bar{\theta}]$ , and each type  $\theta \in \Theta$  reports the message  $m \in M$  for which  $\theta \in m$ .*

For future reference, we call such mechanisms as described in the lemma “interval mechanisms.”

The intuition for this result is as follows (see the appendix for the formal proof). First, messages that lead to the same quantity-price pair can be combined without affecting the outcome of the mechanism. Due to convexity of the relative entropy function, this also relaxes the privacy constraint. We can thus without loss assume that different messages in the mechanism are strictly ranked by the quantity levels they are mapped into. Next, we argue that the set of types selecting the same message in equilibrium must form an interval; this is because buyer preference is single crossing in the type and quantity served. Finally, any two of these intervals do not intersect each other except at the boundary, since the indifference condition holds for at most one type. The lemma then follows.<sup>13</sup>

We highlight that our model *does allow* the buyer to mix over different messages, in case he is indifferent. But Lemma 1 shows that buyer randomization *does not happen* in the optimal mechanism. This result stands in contrast to the rational inattention literature, where entropy-based constraints often lead to stochastic, non-partitional signals. The distinction arises because in our setting, stochastic “signals” (i.e., messages) are constrained by the buyer’s indifference condition and turn out to be costly for the seller.

It is also worth noting that the above argument only uses the convexity of KL divergence, so that combining “redundant” messages decreases the maximum relative entropy between prior and posterior beliefs. Because of this, Lemma 1 would continue to hold

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<sup>13</sup>The same argument and result hold even if the designer’s objective is to maximize a weighted sum of profit and consumer surplus.

if the privacy measure were an arbitrary convex function of the distribution of posterior beliefs (as often assumed in the literature on costly information acquisition).

Specializing to the case of KL divergence, we next derive the privacy loss of any interval mechanism. Note that when the seller sees a message  $m = [\theta', \theta'']$  in equilibrium, her posterior density updates to  $f(\theta | m) = \frac{f(\theta)}{F(\theta'') - F(\theta')}$  for  $\theta \in [\theta', \theta'']$ , and  $f(\theta | m) = 0$  otherwise. The relative entropy between this posterior belief and the prior is computed as

$$\int_{\theta'}^{\theta''} f(\theta | m) \log \frac{f(\theta | m)}{f(\theta)} d\theta = -\log [F(\theta'') - F(\theta')]. \quad (2)$$

Since the ex-post privacy constraint requires this to be at most  $\kappa$ , we derive the following result:

**Lemma 2** *An interval mechanism is  $\kappa$ -feasible if and only if each of the intervals has mass (according to the prior  $F$ ) at least  $e^{-\kappa}$ .<sup>14</sup>*

Assuming now that the intervals in  $M$  are  $m_1 = [\theta_0, \theta_1], m_2 = [\theta_1, \theta_2], \dots, m_n = [\theta_{n-1}, \theta_n]$ , with  $\underline{\theta} = \theta_0 < \theta_1 < \dots < \theta_n = \bar{\theta}$ . Given the number  $n$  and cutoffs  $\theta_1, \dots, \theta_{n-1}$ , we can derive the optimal quantity and price that a  $\kappa$ -optimal mechanism assigns to each message. Specifically, note that the expected profit for the seller from employing this interval mechanism is given by:<sup>15</sup>

$$\Pi(\mathbb{M}) = \sum_{i=1}^n \left[ q(m_i) \int_{\theta_{i-1}}^{\theta_i} v(\theta) f(\theta) d\theta - c(q(m_i)) \cdot [F(\theta_i) - F(\theta_{i-1})] \right], \quad (3)$$

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<sup>14</sup>Essentially the same result holds if KL divergence is replaced by a more general divergence of the form  $\int_{\theta} \phi\left(\frac{f(\theta|m)}{f(\theta)}\right) dF(\theta)$  for some convex function  $\phi$ , with KL being the special case of  $\phi(x) = x \log x$ . Indeed, Lemma 2 would state that in any  $\kappa$ -feasible interval mechanism, each interval has mass at least  $l$ , where  $l$  is defined such that  $l \cdot \phi\left(\frac{1}{l}\right) = \kappa$ . Since this lower bound on interval mass is the only feasibility constraint (for the ex-post privacy model), our subsequent results also generalize to this class of divergences so long as  $\kappa$  is suitably scaled according to  $\phi$ .

<sup>15</sup>To see this, recall that in every mechanism that satisfies (local) IC and binds IR at the lowest type, the seller's profit is given by  $\Pi(\mathbb{M}) = \int_{\underline{\theta}}^{\bar{\theta}} \left[ \tilde{q}(\theta) \theta - \int_{\underline{\theta}}^{\theta} \tilde{q}(x) dx - c(\tilde{q}(\theta)) \right] f(\theta) d\theta$ , where  $\tilde{q}(\theta)$  is the quantity provided to type  $\theta$ . The first term in the integrand is the social surplus generated by selling quantity  $\tilde{q}(\theta)$  to type  $\theta$ , the second term is the minimal information rent that is left with type  $\theta$  in every IC mechanism, and the third term is the cost of producing  $\tilde{q}(\theta)$ . The seller is the residual claimant of welfare. Equation (3) is obtained from this formula using integration by parts.

where  $v(\theta)$  is the virtual valuation of type  $\theta$ . Therefore, the quantity that maximizes the expected profit while maintaining IC and IR is uniquely determined by:<sup>16</sup>

$$c'(q(m_i)) = \mathbb{E}_F[v(x) \mid x \in [\theta_{i-1}, \theta_i]] \quad \text{for any } m_i = [\theta_{i-1}, \theta_i] \in M. \quad (4)$$

The standard envelope condition (derived from local IC) for buyer surplus also pins down the requested price:

$$p(m_i) = q(m_i) \cdot \theta_{i-1} - \sum_{j=0}^{i-1} (\theta_j - \theta_{j-1}) \cdot q(m_j) \quad \text{for any } m_i = [\theta_{i-1}, \theta_i] \in M. \quad (5)$$

It follows that the assignment of types to quantity-price pairs in any  $\kappa$ -optimal mechanism is completely determined by the interval partition. To save notation, we will write  $q_i$  and  $p_i$  in place of  $q(m_i)$  and  $p(m_i)$  whenever the partition is fixed by the context.

Summarizing the above discussion, we have reduced the problem to finding the profit-maximizing interval partition subject to each interval having mass at least  $e^{-\kappa}$ , where profit follows from Equations (3) and (4).

### 4.3 Characterization

With the above preliminary analysis, we can show that a  $\kappa$ -optimal (interval) mechanism exists. Indeed, by Lemma 1, it is sufficient to show there exists a profit-maximizing interval partition. For this we apply a compactness argument. Consider the following metric on the space of finite partitions: If  $M$  consists of cutoffs  $\{\theta_1, \dots, \theta_{n-1}\}$  and  $M'$  consists of cutoffs  $\{\theta'_1, \dots, \theta'_{m-1}\}$ , then define  $d(M, M')$  to be the smallest  $\delta \geq 0$  such that for each  $\theta_i$  there exists  $\theta'_j$  within  $\delta$  distance from it, and vice versa. It is straightforward to check this is indeed a metric, and that the resulting quantities  $q_i$  and profit  $\Pi(M)$  are continuous with respect to this metric.

When the number of cutoffs is bounded above by  $e^\kappa$  (as ensured by Lemma 2), the space of partitions is compact in the topology induced by this metric. Thus, if we consider any sequence of feasible partitions that approximates the supremum profit, there exists a convergence subsequence. The limit partition is also feasible under the ex-post privacy constraint, and by continuity it must achieve the supremum profit. Hence we have found an optimal interval mechanism.

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<sup>16</sup>Since  $c$  is strictly convex and  $c'(0) = 0$ , the first order condition (4) uniquely determines the value of the optimal  $q(m_i)$ . The fact that virtual valuation is increasing ensures that higher types receive higher quantity in equilibrium, and thus local IC implies global IC.



**Proposition 1** *There exists a  $\kappa$ -optimal mechanism  $\mathbb{M} = \langle M, p, q \rangle$ , such that  $M$  consists of intervals (each with mass  $\geq e^{-\kappa}$ ) that partition  $[\underline{\theta}, \bar{\theta}]$ , and each type  $\theta \in \Theta$  reports the interval to which it belongs. The number of intervals in the optimal partition is bounded above by  $e^\kappa$  and bounded below by  $\frac{e^\kappa}{2}$ .*

The bounds on the optimal number of intervals provide a direct sense of how the privacy requirement constrains the screening ability. The upper bound of  $e^\kappa$  follows from the fact that each feasible interval has mass at least  $e^{-\kappa}$ . The lower bound of  $\frac{e^\kappa}{2}$  holds because each interval in the *optimal* partition has mass *at most*  $2e^{-\kappa}$ ; otherwise it could be split into two sub-intervals both with mass exceeding  $e^{-\kappa}$ . By Lemma 2, the resulting partition would be feasible, and Lemma 4 in the appendix shows that this split would increase the seller's profit.

An immediate corollary of Proposition 1 is the following:

**Corollary 1** *For  $0 < \kappa < \log(2)$ , any  $\kappa$ -optimal interval mechanism involves perfect pooling. For  $\log(2) \leq \kappa < \log(3)$ , any  $\kappa$ -optimal interval mechanism consists of exactly two intervals.*

The first part follows from observing that for a very small  $\kappa$ , the number of intervals is at most  $e^\kappa < 2$ , hence, only a single interval can be accommodated. As for the second part,  $\kappa \in [\log(2), \log(3))$  means there can be at most two intervals. Moreover, by Lemma 4 in the appendix, the seller always benefits from having more information in the form of dividing an interval into two sub-intervals (so long as the resulting partition is still feasible). In particular, any feasible two-interval partition leads to higher profit compared to the trivial partition, leading to the above result.

In general, it is difficult to fully characterize the optimal number  $n$  of intervals and their cutoffs for an arbitrary distribution  $F$  and cost function  $c$ , without imposing additional structure on these primitives. Our next result provides a step toward that characterization by showing that under certain conditions on  $F$  and  $c$ , the optimal mechanism has the property that the precision of information that the designer collects is *monotonic* in the agent's type: i.e., she either knows more about lower types or knows more about higher types.

To present this result we introduce the function  $G(x) = F^{-1}(x) \cdot (x - 1)$  for all  $x \in [0, 1]$ . Observe that  $G(F(\theta)) = \theta(F(\theta) - 1)$ , whose derivative with respect to  $\theta$  is  $v(\theta)f(\theta)$ . Hence, by the chain rule,  $G'(F(\theta)) = v(\theta)$ . We say that  $v(\theta)$  is *strictly more concave (convex)* than  $F(\theta)$  if  $G'(x)$  is strictly concave (convex) in  $x$ .

**Proposition 2** *Suppose that the cost function  $c(\cdot)$  has non-negative third derivative, and that the virtual valuation  $v(\theta)$  is strictly more concave than  $F(\theta)$ . Then any  $\kappa$ -optimal mechanism consists of intervals that are ordered in increasing mass from left to right; that is,  $F(\theta_{i+1}) - F(\theta_i) \geq F(\theta_i) - F(\theta_{i-1})$  for all  $i \in \{1, \dots, n-1\}$ . Symmetrically, the intervals in the optimal mechanism would be ordered in decreasing mass if  $c''' \leq 0$  and  $v(\theta)$  is strictly more convex than  $F(\theta)$ .*

We mention that a sufficient condition for  $v(\theta)$  to be more concave than  $F(\theta)$  is that the prior density function  $f(\theta)$  is increasing and log-concave; in fact,  $F(\theta)$  would be convex and  $v(\theta)$  concave.<sup>17</sup> For example, this is satisfied when  $F(\theta) = \theta^r - s$  with  $\underline{\theta} = s^{\frac{1}{r}}$  and  $\bar{\theta} = (s+1)^{\frac{1}{r}}$ , where  $r$  and  $s$  are parameters satisfying  $r > 1$  and  $s > \frac{1}{r}$  (the latter ensuring that virtual valuations are positive).

The intuition for Proposition 2 is as follows. From  $c'(q_i) = \mathbb{E}_F[v(x) \mid x \in [\theta_{i-1}, \theta_i]]$ , we see that the second derivative  $c''$  measures the extra production cost incurred when the seller divides an interval into two sub-intervals and adjusts quantity/price accordingly. So  $c''' > 0$  means that the seller faces greater production cost in trying to screen the higher types. On the other hand, observe that the derivative of the virtual valuation captures the revenue gain when dividing an interval into two.<sup>18</sup> Thus  $v(\theta)$  being more concave  $F$  implies that the seller benefits less from differentiating high types. Both effects combine to yield intervals that are optimally ordered in increasing mass.

## 4.4 Uniform-quadratic case

To give a complete and detailed characterization of an optimal  $\kappa$ -constrained mechanism, we need to select a specification of the distribution of types and of the cost function. Although such a characterization is only a particular example, it is still insightful as it gives a vivid illustration of the properties of optimal mechanism that we derived in the previous subsection. One specification that admits an elegant analytical characterization is the “uniform-quadratic” case, where  $F$  is uniform and  $c$  is quadratic. Since in this case  $c''' = 0$  and  $v(\theta)$  is *as convex as*  $F(\theta)$  (both are linear in  $\theta$ ), the results in Proposition 2 suggest that the ordering of intervals does not matter for profit. As we show below, this property enables us to focus on the lengths of the intervals and obtain a full characterization of the optimal partition in this special case.

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<sup>17</sup>We have  $v''(\theta) = \left(\frac{f'(\theta)}{f(\theta)}\right)' \cdot \frac{1-F(\theta)}{f(\theta)} - \frac{f'(\theta)}{f(\theta)} \cdot \left(1 + \frac{f'(\theta)(1-F(\theta))}{f(\theta)^2}\right) < 0$ .

<sup>18</sup>This can be understood by considering the extreme case: When the virtual valuation  $v(\theta)$  is constant, it is (unconstrained) optimal to offer the same quantity to every buyer type, and there is no gain from creating sub-intervals.

**Proposition 3** *Suppose  $F \sim U[\underline{\theta}, \bar{\theta}]$  with  $\bar{\theta} \geq 2\underline{\theta}$  (so that  $v(\underline{\theta}) \geq 0$ ), and  $c(q) = \frac{q^2}{2}$ . Then, given any positive integer  $N$  and any  $\kappa \in [\log(N), \log(N + 1))$ , the  $\kappa$ -optimal mechanism divides the type space into  $N$  equal intervals.*

To prove this result, we show that maximizing profit in the uniform-quadratic case is equivalent to minimizing the *cubic sum* of the lengths of the intervals. Subject to the feasibility constraint that these lengths are at least  $e^{-\kappa}$ , we argue that an equal division (into as many intervals as can be accommodated) is optimal.

We highlight that the optimal mechanism in this case is locally the same as  $\kappa$  increases. Thus, for  $\kappa$  in the interior of the interval  $(\log(N), \log(N + 1))$ , the optimal mechanism entails a privacy loss of  $\log(N)$  which is strictly less than  $\kappa$ . It follows that the ex-post privacy constraint is often slack. This is one of the challenges in obtaining a full characterization of the optimal mechanism more generally.

## 4.5 Welfare analysis

Varying the privacy capacity of a mechanism affects the seller's profit, the buyer surplus and the total welfare. In this section we analyze how  $\kappa$  changes these quantities. Throughout this section we assume  $F$  has monotone hazard rate, that is  $\frac{f(\theta)}{1-F(\theta)}$  increases in  $\theta$ . This property implies that the virtual valuation  $v(\theta)$  is increasing.

Because higher  $\kappa$  relaxes the privacy constraint (P) in the seller's problem, it is immediate to notice that the expected profit  $\Pi$  is weakly increasing in  $\kappa$ .

**Corollary 2** *Profit from a  $\kappa$ -optimal mechanism is increasing in  $\kappa$ .*

As the uniform-quadratic case shows, this monotonicity is not always strict. However, we do know that profit is maximized at  $\kappa = \infty$ , when the monopolist is allowed to fully separate all buyer types. Profit is minimized at  $\kappa = 0$ , with full privacy.<sup>19</sup>

On the other hand, one may expect that buyer surplus is higher when the privacy constraint is tighter. However, this is not obvious because privacy may hurt allocative efficiency so much that it actually damages the buyer's payoff. As far as we are aware, there is no general finding in the literature regarding how buyer surplus varies with the interval partition.

We consider a weaker problem of which privacy level maximizes/minimizes buyer surplus. Under an assumption on the production cost function, we show that the buyer

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<sup>19</sup>In fact, profit is strictly maximized/minimized at the extreme  $\kappa$ , because profit strictly increases when an interval is divided into two sub-intervals (and quantities/prices are adjusted accordingly). This is proved in Lemma 4 in the appendix.

is necessarily worse-off when the seller obtains finer information about her in the form of dividing an interval into two. As a result we obtain:

**Proposition 4** *Suppose the cost function  $c$  satisfies  $c''' \geq 0$ . Then buyer surplus from a  $\kappa$ -optimal mechanism is maximized at  $\kappa = 0$ , where every type receives the same quantity, and it is minimized at  $\kappa = \infty$ , where types are fully separated.*

Finally, a regulator might be interested in finding the level of  $\kappa$  that maximizes total welfare. The answer turns out to be more subtle, as the following partial characterization suggests:

**Proposition 5** *Assume quadratic costs  $c(q) = \frac{q^2}{2}$ . If the density  $f(\theta)$  increases in  $\theta$ , then total welfare is maximized at  $\kappa = 0$  and minimized at  $\kappa = \infty$ . Conversely, if  $f(\theta)$  decreases in  $\theta$ , then total welfare is minimized at  $\kappa = 0$  and maximized at  $\kappa = \infty$ .*

As a corollary, it is interesting to note that in the uniform-quadratic case, total welfare in the  $\kappa$ -optimal mechanism is independent of the privacy capacity  $\kappa$ .

## 5 Ex-ante Bayesian privacy

So far we have analyzed an ex-post notion of privacy loss. Under this criterion, the monopolist cannot learn too much about *any* buyer type. In this section we explore an alternative, less stringent, notion of privacy, requiring the designer not to learn too much about the buyer type *on average*. Formally, we weaken the ex-post privacy constraint  $I(\mathbb{M}) \leq \kappa$  to its ex-ante version:

**Definition 2** The ex-ante loss of privacy entailed by mechanism  $\mathbb{M} = \langle M, p, q \rangle$  is given by

$$I^{ea}(\mathbb{M}) = \mathbb{E}_m [D_{KL}(F(\cdot|m) \parallel F)]$$

where  $\mathbb{E}_m$  is evaluated according to the probability that each message  $m \in M$  is sent in an equilibrium of  $\mathbb{M}$ .<sup>20</sup>

That is, we impose an upper bound on the average change in the seller's beliefs, as measured by relative entropy. Given  $\kappa > 0$ , we say a mechanism is *ex-ante  $\kappa$ -feasible* if  $I^{ea}(\mathbb{M}) \leq \kappa$ . It is *ex-ante  $\kappa$ -optimal* if it is profit-maximizing among all mechanisms  $\mathbb{M}$  that satisfy IC, IR and the ex-ante privacy constraint.

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<sup>20</sup>In calculating  $I^{ea}(\mathbb{M})$  we adopt the convention that  $0 \cdot \infty = 0$ , and therefore  $I^{ea}(\mathbb{M})$  can still be finite if there is a measure-zero set of messages (sent in equilibrium) that induce posterior distributions  $F(\cdot|m)$  whose divergence from the prior  $F$  is infinite. But if the set of such messages has positive measure, then  $I^{ea}(\mathbb{M}) = +\infty$  according to our definition.

## 5.1 Existence

To begin the analysis, we can use essentially the same argument to show that Lemma 1 also holds under the ex-ante criterion. Thus it is without loss to consider interval mechanisms. Using Equation (2), we can compute the ex-ante loss of privacy entailed by a (finite) interval mechanism to be:

$$I^{ea}(\mathbb{M}) = \sum_{i=1}^n - [F(\theta_i) - F(\theta_{i-1})] \cdot \log [F(\theta_i) - F(\theta_{i-1})] = H(g_M), \quad (6)$$

where  $g_M(m_i) = F(\theta_i) - F(\theta_{i-1})$  is a discrete distribution over the elements of  $M$  induced by the prior, and  $H(\cdot)$  is the Shannon entropy function. At this moment we cannot rule out the possibility that there are countably many intervals. In that case, the discrete distribution  $g_M$  is defined in the same way, and we again have  $I^{ea}(\mathbb{M}) = H(g_M)$ .

This discussion suggests that under the ex-ante privacy constraint, the profit maximization problem reduces to finding an interval partition  $M$  subject to  $H(g_M) \leq \kappa$  that maximizes the profit in Equation (3) with quantities given by (4).

However, existence of an optimal mechanism is not straightforward in this case. The reason is that the feasibility constraint  $H(g_M) \leq \kappa$  allows for countably many intervals, which lose compactness (unlike with the ex-post constraint). We settle the existence issue in the following result:

**Proposition 6** *There exists an ex-ante  $\kappa$ -optimal mechanism  $\mathbb{M} = \langle M, p, q \rangle$ , such that  $M$  consists of finitely many intervals that partition  $[\underline{\theta}, \bar{\theta}]$ , and each type  $\theta \in \Theta$  reports the interval to which it belongs.<sup>21</sup>*

We provide a sketch of the proof here, leaving further details to the appendix. Consider a sequence of ex-ante  $\kappa$ -feasible interval mechanisms  $\mathbb{M}_j = \langle M_j, p_j, q_j \rangle$  such that  $\Pi(\mathbb{M}_j)$  converges to the supremum profit  $\Pi^*$  across feasible mechanisms. We will replace each mechanism  $\mathbb{M}_j$  by another feasible interval mechanism  $\tilde{\mathbb{M}}_j = \langle \tilde{M}_j, \tilde{p}_j, \tilde{q}_j \rangle$ , such that the new message set  $\tilde{M}_j$  consists of at most  $N$  intervals, where  $N$  is a constant that depends only on  $F$  and  $\kappa$ . This upper bound  $N$  restores compactness and allows us to find a subsequence of the partitions  $\{\tilde{M}_j\}$  that converges to some limit partition  $\tilde{M}_\infty$ , under the metric defined in Section 4.3. By continuity,  $\tilde{M}_\infty$  is also a feasible

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<sup>21</sup>It is instructive to compare this result to an analogous result in the rational inattention literature. Matějka (2016) shows that a rationally inattentive seller would charge only finitely many prices even though there is a continuum of states. The argument used to prove that result relies on properties of Hermite polynomials. In contrast, the proof in our environment is simpler and only makes use of the tradeoff between privacy and profit when merging/dividing intervals.

mechanism, and it achieves the limit profit along the convergent subsequence. Therefore, if we could carry out the replacement in such a way that  $\Pi(\tilde{\mathbb{M}}_j) \geq \Pi(\mathbb{M}_j)$ , then  $\Pi(\tilde{M}_\infty) \geq \limsup_j \Pi(\tilde{M}_j) = \Pi^*$  and  $\tilde{M}_\infty$  would be ex-ante  $\kappa$ -optimal.

It remains to find the appropriate replacements  $\tilde{\mathbb{M}}_j$ . As discussed, starting from any mechanism  $\mathbb{M}_j$ , merging two adjacent intervals in  $M_j$  into a single interval (and adjusting the quantities/prices accordingly) strictly decreases the profit. However, by doing so the seller is able to save on the ex-ante privacy measure, which enables him to divide any other interval in  $M_j$  into two sub-intervals, increasing the profit. The key argument, then, is to *compare the profit gain in the latter step to the profit loss in the former*. We show that whenever two adjacent intervals are both of mass smaller than some constant  $\epsilon$ , they can be combined to create enough slackness in the privacy constraint; and if the slackness is used to break another (big) interval into two, the seller achieves a net profit gain. Intuitively, this profit comparison holds because the entropy function severely punishes against precise knowledge about any small set of types. So when the seller combines two “small” intervals into a single one, the saved privacy measure is significant relative to the reduction in profit.

By repeatedly combining adjacent “small” intervals, we are able to transform  $\mathbb{M}_j$  into a mechanism  $\tilde{\mathbb{M}}_j$  with weakly higher profit, and with no adjacent intervals both having mass  $< \epsilon$ . The upshot is that  $\tilde{M}_j$  has at most  $N := \frac{2}{\epsilon} + 1$  intervals, completing the proof.<sup>22</sup>

## 5.2 Properties of optimal ex-ante constrained mechanisms

In contrast to the ex-post problem, the ex-ante privacy constraint always binds at the optimal mechanism. Moreover, unlike Lemma 2, the number of intervals now admits a *lower bound* of  $e^\kappa$ .

**Proposition 7** *The privacy constraint is exhausted in any ex-ante  $\kappa$ -optimal mechanism  $\mathbb{M}$ ; that is,  $I^{ea}(\mathbb{M}) = \kappa$ . Moreover, any optimal mechanism involves at least  $e^\kappa$  intervals.*

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<sup>22</sup>To be fully rigorous, in the proof we first find a replacement with finitely many intervals. This can be done because for any limit point  $M_j$  (more precisely, the bounds of intervals in  $M_j$ ) may have, the seller incurs little profit loss if she combines all the small intervals near this limit point. Such loss is covered by the net profit gain in merging two small intervals and dividing a long one. Once we have a finite  $M_j$  to begin with, we still need to guarantee that the process of “combining small intervals” will come to an end. We do this by combining two pairs of adjacent small intervals at once and breaking a big interval into two. There is still net profit gain, and in addition the total number of intervals strictly decreases. The final  $\tilde{M}_j$  involves at most one pair of adjacent small intervals, so its size is again bounded uniformly across  $j$ .

The first part holds because the seller always benefits from dividing an interval into two. By choosing one of the sub-intervals to be “small,” the *average* privacy constraint is still satisfied. The second part is a result of the first part, Equation (6) and the following well-known estimate of the Shannon entropy (applied to  $g_M$ ):

**(Cover and Thomas, Theorem 2.6.4)** *If a discrete random variable  $X$  takes  $n$  values, then its Shannon entropy satisfies  $H(X) \leq \log(n)$ , with equality if and only if  $X$  has a uniform distribution.*

On the other hand, we show that when the ex-ante privacy constraint is stringent, two messages are sufficient to implement the optimal mechanism. This complements the previous Corollary 1.

**Proposition 8** *There exists  $\underline{\kappa} > 0$  such that any ex-ante  $\kappa$ -optimal interval mechanism consists of exactly two intervals.*

We prove the result via a lemma stating that there can be at most one interval with arbitrarily small mass. Thus, even though the average privacy constraint allows the seller to learn almost perfectly about sets of small types, the optimal solution involves at most one such set. In the above proof sketch for Proposition 6, we have already discussed why having two adjacent “small” intervals is suboptimal. The next lemma additionally rules out the presence of two “small” intervals that are non-adjacent.

**Lemma 3** *For every  $k > 0$ , there exists  $\epsilon > 0$  such that any ex-ante  $\kappa$ -optimal interval mechanism with  $\kappa \leq k$  has at most one interval with mass  $< \epsilon$ .*

Finally, Proposition 2, which gives sufficient conditions for the optimality of intervals that are increasing/decreasing in mass, continues to hold under the ex-ante privacy measure. This is because the proof of Proposition 2 is based on evaluating whether profit increases or decreases when two adjacent intervals are “switched.” Since switching does not affect the amount of privacy loss under both the ex-post and ex-ante measures, this argument extends without change.

The welfare results Proposition 4 and Proposition 5 also generalize to the current setting, since their proofs only involve welfare comparison when combining two adjacent intervals. Whether we adopt the ex-post or ex-ante privacy measure, the coarsest interval partition corresponds to  $\kappa = 0$ , and the finest partition to  $\kappa = \infty$ . These levels of privacy requirement thus maximize/minimize buyer surplus and/or total welfare.

### 5.3 Uniform-quadratic case revisited

Recall that in the uniform-quadratic case, the solution under the *ex-post* constraint divides the type space evenly. Since this solution does not always exhaust the (ex-ante or ex-post) privacy constraint, we know from Proposition 7 that profit is not maximized under the ex-ante constraint. Indeed, the optimal mechanism under the ex-ante privacy constraint differs from the optimal mechanism under the ex-post constraint. Moreover, it has novel implications regarding the trade-off between privacy and profit, which does not arise under the ex-post constraint. In light of this, we revisit the uniform-quadratic example to further illustrate the difference between the two privacy notions.

**Proposition 9** *Suppose  $F \sim U[\underline{\theta}, \bar{\theta}]$  with  $\bar{\theta} \geq 2\underline{\theta}$ , and  $c(q) = \frac{q^2}{2}$ . Then, given any positive integer  $N > 1$  and any  $\kappa \in (\log(N-1), \log(N)]$ , the ex-ante  $\kappa$ -optimal mechanism divides the type space into  $N$  intervals.*

*Specifically,  $N - 1$  of these intervals have the same lengths  $\ell_b$ , while the last interval has weakly smaller length  $\ell_s$ . These two lengths are uniquely determined by the total length  $\bar{\theta} - \underline{\theta}$  and the binding privacy constraint:*

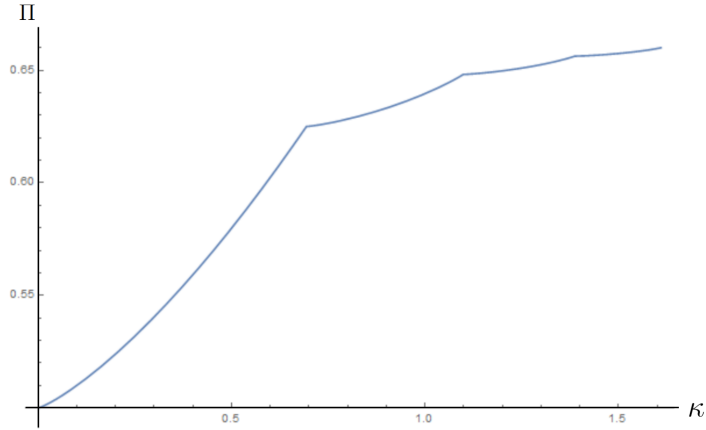
$$\begin{aligned} \bar{\theta} - \underline{\theta} &= \ell_s + (N - 1) \ell_b \\ \kappa &= -\frac{\ell_s}{(\bar{\theta} - \underline{\theta})} \log \frac{\ell_s}{(\bar{\theta} - \underline{\theta})} - (N - 1) \cdot \frac{\ell_b}{(\bar{\theta} - \underline{\theta})} \log \frac{\ell_b}{(\bar{\theta} - \underline{\theta})} \end{aligned}$$

*The optimal interval partition is unique up to reordering of the intervals.*

The proof consists of three steps. First, we show that the expected profit (and privacy measure) only depends on the lengths of the intervals in the partition, and not on the ordering of these intervals. Next, we argue that the first- and second-order conditions for the constrained maximization problem can only be satisfied if the intervals have at most two lengths, with exactly one interval having shorter length. Lastly, we determine the optimal *number* of intervals from the binding privacy constraint.

The structure of this optimal mechanism has an interesting implication for the trade-off between privacy and profit. For  $\underline{\theta} = 1$  and  $\bar{\theta} = 2$  in the uniform-quadratic case, Figure 1 depicts the expected profit of the monopolist in the ex-ante  $\kappa$ -optimal mechanism as a function of  $\kappa$ .





**Figure 1.** The privacy-profit frontier in the uniform-quadratic case

The kinks in Figure 1 represent values of  $\kappa$  where the number of intervals in the  $\kappa$ -optimal mechanism increases. Between kink points the number of intervals remains fixed but the intervals change. Notice that while there are *diminishing* returns to loss of privacy when the number of intervals increase, there are *increasing* returns to loss of privacy when  $\kappa$  increases but the number of intervals remains fixed (that is, the curve between kink points is convex). This means that when we introduce a new (small) interval, the initial change in expected profit is small relative to the loss of privacy; intuitively, the ex-ante privacy measure punishes against precise information about a small set of types. But as we continue to lower privacy, expected profit rises at an increasing rate until a new interval is added.

We mention that the qualitative features of the privacy-profit frontier are robust to small changes in the prior distribution (away from uniform). This is because the set of ex-ante  $\kappa$ -optimal mechanisms, when viewed as a correspondence from the distribution  $F$  to the space of interval partitions, is upper-hemicontinuous.<sup>23</sup>

## 6 Concluding remarks

This paper proposed a Bayesian approach to incorporating privacy constraints into mechanism design. The underlying idea is that the designer *already* has some prior information about the participants, and the loss of privacy induced by a mechanism should be

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<sup>23</sup>This follows from the Maximum Theorem, since the seller solves a constrained optimization problem in which profit is continuous in the interval partition (with respect to the metric defined in Section 4.3), and the constraint  $H(g_M) \leq \kappa$  is both upper- and lower-hemicontinuous.

measured as the *difference* between this prior information and the updated information that can be inferred from the agents' interaction with the mechanism. This entails an additional constraint - on top of the standard incentive-compatibility and individual-rationality constraints - that needs to be satisfied by a mechanism: The difference between the prior and posterior information must be below some threshold.

We illustrate this approach by using relative entropy to compute the difference between the prior and posterior beliefs and applying this measure to a canonical monopolistic screening problem. We show the implications of imposing the privacy constraint at the ex-post stage (i.e., for every realized consumer type, the loss of privacy must be below some bound), and at the ex-ante stage (i.e., the loss of privacy is bounded when averaging over possible type realizations). We also demonstrate how our framework can be helpful in understanding the effect of privacy constraints on consumer and seller welfare.

Our approach opens the door to many interesting questions about mechanism design and privacy. First, how does our analysis extend to an environment with multiple agents? In our online appendix we derive the optimal symmetric mechanism under ex-post privacy for uniformly distributed types. This leaves open the question of designing optimal privacy-preserving auctions when asymmetric treatment of bidders is allowed. Second, since we follow the standard Bayesian approach to mechanism design, we inherit its assumption that the prior distribution is commonly known. How should a regulator elicit the prior beliefs of the mechanism designer in practice? We hope that future research will provide answers to these and related questions.

# A Proofs for the main model

## A.1 Preliminaries

We define two auxiliary functions. First, we define  $\phi(x)$  as the inverse of  $c'$ , i.e.,  $c'(\phi(x)) = x$  for all  $x \geq 0$ . Convexity of the cost function and  $c'(0) = 0$  ensures that  $\phi$  is uniquely defined and increasing. In fact, by the chain rule we have

$$\phi'(x) = \frac{1}{c''(\phi(x))}.$$

Since  $c''(q)$  is positive and continuous for  $q \geq 0$ , we deduce that  $c''(\phi(x))$  is bounded above and away from zero for  $x \in [v(\underline{\theta}), v(\bar{\theta})]$ .

Next, we define the function  $h(x)$  as follows:

$$h(x) = \phi(x) \cdot x - c(\phi(x))$$

The first derivative of  $h(x)$  is given by:

$$h'(x) = \phi'(x) \cdot x + \phi(x) - c'(\phi(x)) \cdot \phi'(x) = \phi'(x) \cdot x + \phi(x) - x \cdot \phi'(x) = \phi(x)$$

Thus the second derivative  $h''$  is bounded above and away from zero for  $x \in [v(\underline{\theta}), v(\bar{\theta})]$ .

The following lemma provides an estimate of the seller's profit gain when an interval is divided into two sub-intervals. It will be used in subsequent proofs.

**Lemma 4** *There exists a positive constant  $\eta$  depending on  $F$  and  $c(\cdot)$ , such that for any triple of cutoffs  $a < b < c$ , the profit gain  $\Delta$  incurred when dividing a single interval  $[a, c]$  into two sub-intervals  $[a, b]$  and  $[b, c]$  (and adjusting quantities/prices accordingly) satisfies*

$$\eta \leq \frac{\Delta}{(F(b) - F(a))(F(c) - F(b))(F(c) - F(a))} \leq \frac{1}{\eta}.$$

Note from Equations (3) and (4) that  $\Delta$  only depends on  $a, b, c$  and is independent of the remaining cutoffs.

**Proof:** Let  $\mathbb{E}v(m_i)$  denote  $\mathbb{E}_F[v(\theta) \mid \theta \in [\theta_{i-1}, \theta_i]]$ . Then the profit of mechanism  $\mathbb{M} = \langle M, p, q \rangle$  as given by Equations (3) and (4) can be rewritten as

$$\Pi(\mathbb{M}) = \sum_i h(\mathbb{E}v(m_i)) \cdot [F(\theta_i) - F(\theta_{i-1})]$$

When an interval  $[a, c]$  is divided into  $[a, b]$  and  $[b, c]$ , the profit gain is therefore

$$\begin{aligned} \Delta = & h(\mathbb{E}[v(\theta) \mid a \leq \theta \leq b]) \cdot [F(b) - F(a)] + h(\mathbb{E}[v(\theta) \mid b \leq \theta \leq c]) \cdot [F(c) - F(b)] \\ & - h(\mathbb{E}[v(\theta) \mid a \leq \theta \leq c]) \cdot [F(c) - F(a)]. \end{aligned} \tag{7}$$

For notational convenience, let  $v_1 = \mathbb{E}[v(\theta) \mid a \leq \theta \leq b]$ ,  $v_2 = \mathbb{E}[v(\theta) \mid b \leq \theta \leq c]$  and  $v = \mathbb{E}[v(\theta) \mid a \leq \theta \leq c]$ . Observe that  $v_1 < v < v_2$  and

$$v_1 \cdot [F(b) - F(a)] + v_2 \cdot [F(c) - F(b)] = \int_a^b v(\theta) f(\theta) d\theta + \int_b^c v(\theta) f(\theta) d\theta = v \cdot [F(c) - F(a)]. \tag{8}$$

Thus from Equation (7) and the strict convexity of  $h$ , it is clear that  $\Delta > 0$ .

To obtain a sharper estimate as required by the lemma, we apply second-order Taylor expansion to write

$$\begin{aligned} h(v_1) &= h(v) + (v_1 - v)h'(v) + \frac{(v_1 - v)^2}{2}h''(\xi) \\ h(v_2) &= h(v) + (v_2 - v)h'(v) + \frac{(v_2 - v)^2}{2}h''(\zeta) \end{aligned}$$

for some  $\xi \in (v_1, v)$  and  $\zeta \in (v, v_2)$ . Plugging these into Equation (7) and using (8), we have

$$\begin{aligned} \Delta &= h(v_1) \cdot [F(b) - F(a)] + h(v_2) \cdot [F(c) - F(b)] - h(v) \cdot [F(c) - F(a)] \\ &= \frac{(v_1 - v)^2}{2}h''(\xi) \cdot [F(b) - F(a)] + \frac{(v_2 - v)^2}{2}h''(\zeta) \cdot [F(c) - F(b)]. \end{aligned}$$

Recall that  $h''$  is bounded above and away from zero, and  $F(b) - F(a)$  is on the same order as  $b - a$  (since the density  $f$  is bounded above and away from zero). Thus the lemma would follow once we show that  $v - v_1$  is on the same order as  $c - b$  (and similarly  $v_2 - v$  is on the same order as  $b - a$ ).

Indeed, we can rewrite Equation (8) as  $(v_2 - v_1) \cdot [F(c) - F(b)] = (v - v_1) \cdot [F(c) - F(a)]$ . Thus it remains to show  $v_2 - v_1$  is on the same order as  $c - a$ . Note that

$$v_2 - v(b) = \frac{\int_b^c [v(\theta) - v(b)] f(\theta) d\theta}{F(c) - F(b)} = \frac{\int_b^c \int_b^\theta v'(y) f(\theta) dy d\theta}{F(c) - F(b)}.$$

As  $v'(y)f(\theta)$  is bounded above and away from zero, the numerator above is on the same order as  $\int_b^c \int_b^\theta 1 dy d\theta = \frac{(c-b)^2}{2}$ . So  $v_2 - v(b)$  is on the same order as  $c - b$ . Similarly

$v(b) - v_1$  is on the same order as  $b - a$ . This proves that  $v_2 - v_1$  is on the same order as  $c - a$ , and hence the lemma.

## A.2 Proof of Lemma 1

We will show that any mechanism  $\mathbb{M} = \langle M, p, q \rangle$  that satisfies  $I(\mathbb{M}) = \kappa$ , for some finite  $\kappa > 0$ , can be transformed into an interval mechanism in a way that does not change the expected profit of the monopolist, and weakly decreases the loss of privacy.

Given  $\mathbb{M} = \langle M, p, q \rangle$  and a best-response strategy  $\sigma(\cdot)$  for the agent under  $\mathbb{M}$ , we first drop duplicate messages: We say that message  $m'$  is a duplicate of message  $m$  if  $p(m) = p(m')$  and  $q(m) = q(m')$ . Clearly, if  $m'$  is a duplicate of  $m$ , then removing  $m'$  from  $M$  and adjusting  $\sigma$  such that all types who sent  $m'$  would now send  $m$ , does not change the seller's expected profit. Moreover, the posterior belief given the message  $m$  in the new mechanism is an average of the posterior beliefs given the messages  $m$  and  $m'$  in the original mechanism. Due to the convexity of the divergence function  $D_{KL}(F(\cdot|m) || F)$  in its first argument, the entailed loss of privacy  $I(\mathbb{M})$  is decreased. *This is true under both the ex-post and ex-ante measures of privacy.*<sup>24</sup>

Next, denote by  $\mu(m)$  the set of all types who report the message  $m \in M$  with positive probability under  $\sigma$ :

$$\mu(m) = \{\theta \in \Theta \mid m \in \text{supp}(\sigma(\theta))\}$$

Since the agent's preference satisfies increasing differences in  $(\theta, q)$ , the set  $\mu(m)$  is either an interval or a singleton.<sup>25</sup> However, since  $\kappa$  is finite, there can be only a zero-measure

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<sup>24</sup>Given  $\sigma$  and  $F$ , denote by  $\Pr(m \mid \sigma, F)$  and  $\Pr(m' \mid \sigma, F)$  the probabilities that messages  $m$  and  $m'$  are reported under  $\sigma$ , respectively. Then the convexity of  $D_{KL}(F(\cdot|m) || F)$  in its first argument implies that:

$$\begin{aligned} & \Pr(m \mid \sigma, F) \cdot D_{KL}(F(\cdot|m) || F) + \Pr(m' \mid \sigma, F) \cdot D_{KL}(F(\cdot|m') || F) \\ & \geq [\Pr(m \mid \sigma, F) + \Pr(m' \mid \sigma, F)] \cdot \left[ D_{KL} \left( \frac{\Pr(m \mid \sigma, F) \cdot F(\cdot|m) + \Pr(m' \mid \sigma, F) \cdot F(\cdot|m')}{\Pr(m \mid \sigma, F) + \Pr(m' \mid \sigma, F)} \parallel F \right) \right] \end{aligned}$$

where  $\frac{\Pr(m \mid \sigma, F) \cdot F(\cdot|m) + \Pr(m' \mid \sigma, F) \cdot F(\cdot|m')}{\Pr(m \mid \sigma, F) + \Pr(m' \mid \sigma, F)}$  is the posterior belief that is induced when all the types who sent  $m'$  in equilibrium would now send  $m$ .

This inequality precisely says that ex-ante privacy loss is decreased. It further implies that the relative entropy induced by the new message  $m$  is no greater than the maximum of the relative entropies induced by the two old messages  $m$  and  $m'$ . Hence ex-post privacy loss is also decreased.

<sup>25</sup>Formally, if  $\theta' \in \mu(m)$  and  $\theta'' \in \mu(m)$  for some  $m \in M$ , then  $\theta \in \mu(m)$  for all  $\theta \in [\theta', \theta'']$ . To see this, observe that  $\theta' \in \mu(m)$  implies  $q(m)\theta' - p(m) \geq q(m')\theta' - p(m')$  for every message  $m'$ . Similarly  $q(m)\theta'' - p(m) \geq q(m')\theta'' - p(m')$ . Since any  $\theta \in (\theta', \theta'')$  is a convex combination of  $\theta'$  and  $\theta''$ , the

subset of messages  $m \in M$  for which  $\mu(m)$  is a singleton.<sup>26</sup> We can therefore drop these messages from  $M$ , and pick a new best response for each type whose message was dropped. Since the behavior of only a zero-measure set of types was affected, the expected profit  $\Pi(\mathbb{M})$  and the entailed loss of privacy  $I(\mathbb{M})$  are both unchanged.

Henceforth we may assume that  $\mu(m)$  is an interval for each  $m$ . Since there are no duplicates, for every pair of messages  $m$  and  $m'$  the intersection  $\mu(m) \cap \mu(m')$  is either empty or a singleton (in other words, almost all types do not randomize between messages as part of their best-response).

To complete the transformation of  $\mathbb{M}$  into an interval mechanism we now use a standard revelation argument: replace every message  $m \in M$  with the corresponding interval  $\mu(m)$ , and adjust the function  $p$  (resp.  $q$ ) such that whenever the agent reports the interval  $\mu(m)$  in the “transformed” mechanism he would get the price (resp. quantity) that he would have got if he reported the message  $m$  in the “original” mechanism. The elements in the transformed message set are pairwise disjoint intervals whose union is  $\Theta$ , and therefore they constitute a partition of  $\Theta$ . IC, IR, privacy loss and profit are maintained under this transformation, which proves the lemma. ■

### A.3 Proof of Proposition 1

Given Lemma 1 and Lemma 2, it only remains to prove the bounds on the optimal number of intervals. This follows from the argument given in the main text, after Proposition 1.

### A.4 Proof of Proposition 2

We focus on the case where  $c''' \geq 0$  and  $v(\theta)$  is strictly less convex than  $F(\theta)$ . The proof strategy is to show that whenever an interval has more mass than its adjacent interval on the right, these two intervals can be “switched” to increase profit. That is, we consider changing the two intervals  $[\theta_{t-1}, \theta_t]$  and  $[\theta_t, \theta_{t+1}]$  into two new intervals  $[\theta_{t-1}, \tilde{\theta}_t]$  and  $[\tilde{\theta}_t, \theta_{t+1}]$ , where  $\tilde{\theta}_t$  is defined by  $F(\tilde{\theta}_t) - F(\theta_{t-1}) = F(\theta_{t+1}) - F(\theta_t)$ . By the assumption that the (original) left interval has greater mass, we have  $\tilde{\theta}_t < \theta_t$ .

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above two inequalities lead to  $q(m)\theta - p(m) \geq q(m')\theta - p(m')$ . Thus  $m$  is a best-response of type  $\theta$ . It is in fact a *strict* best-response because the last inequality is strict whenever  $m' \neq m$ ; otherwise  $q(m)\theta' - p(m) = q(m')\theta' - p(m')$  and  $q(m)\theta'' - p(m) = q(m')\theta'' - p(m')$  hold simultaneously, showing that  $m'$  is a redundant copy of  $m$ . Hence for any  $\theta$  strictly in between  $\theta'$  and  $\theta''$ ,  $\sigma(\theta)$  puts probability 1 on sending the message  $m$ .

<sup>26</sup>When  $\mu(m)$  is a singleton, the message  $m$  is sent by exactly one type, and therefore  $m$  reveals this type in equilibrium.

Let  $u, w, \tilde{u}, \tilde{w}$  denote the expected virtual valuation on the four intervals  $[\theta_{t-1}, \theta_t]$ ,  $[\theta_t, \theta_{t+1}]$ ,  $[\theta_{t-1}, \tilde{\theta}_t]$ ,  $[\tilde{\theta}_t, \theta_{t+1}]$  respectively. Then, as in the proof of Lemma 4, the profit increase due to switching the two intervals is given by

$$\Delta = (h(\tilde{w}) - h(u)) \cdot [F(\theta_t) - F(\theta_{t-1})] - (h(w) - h(\tilde{u})) \cdot [F(\theta_{t+1}) - F(\theta_t)].$$

Observe that  $(\tilde{w} - u) \cdot [F(\theta_t) - F(\theta_{t-1})] = (w - \tilde{u}) \cdot [F(\theta_{t+1}) - F(\theta_t)]$ .<sup>27</sup> So to show  $\Delta$  is positive we just need to show

$$\frac{h(\tilde{w}) - h(u)}{\tilde{w} - u} > \frac{h(w) - h(\tilde{u})}{w - \tilde{u}}.$$

We claim that the above inequality follows from  $\tilde{w} + u > w + \tilde{u}$ , which we will prove later. Indeed, as  $h$  is strictly convex, the RHS of this inequality increases in  $w$ . So it suffices to prove the weak version of the inequality assuming  $\tilde{w} + u = w + \tilde{u}$ . For that we rewrite it as  $(w - \tilde{u}) \cdot \int_u^{\tilde{w}} h'(y) dy \geq (\tilde{w} - u) \cdot \int_{\tilde{u}}^w h'(y) dy$ , which is in turn equivalent to

$$(w - \tilde{w} + u - \tilde{u}) \cdot \int_u^{\tilde{w}} h'(y) dy \geq (\tilde{w} - u) \cdot \left[ \int_{\tilde{u}}^u h'(y) dy + \int_{\tilde{w}}^w h'(y) dy \right].$$

Since we assume  $u - \tilde{u} = w - \tilde{w}$  (and  $\tilde{w} > u$ ), this last inequality holds whenever  $h'$  is a concave function. Recall that  $h'(y) = \phi(y)$  and  $\phi'(y) = \frac{1}{c'(\phi(y))}$ . So we have  $h''(y) = \frac{1}{c''(\phi(y))}$ , which is indeed decreasing in  $y$  because  $c''' > 0$ .

To complete the proof, it remains to verify that  $\tilde{w} + u > w + \tilde{u}$ . Recall that  $G(x) = F^{-1}(x) \cdot (x - 1)$  for all  $x \in [0, 1]$ , such that  $G(F(\theta)) = \theta(F(\theta) - 1)$ , whose derivative is  $v(\theta)f(\theta)$ . Thus the expected virtual valuation  $\tilde{w} = \mathbb{E}[v(\theta) \mid \tilde{\theta}_t \leq \theta \leq \theta_{t+1}]$  can be written as

$$\tilde{w} = \frac{\int_{\tilde{\theta}_t}^{\theta_{t+1}} v(\theta)f(\theta)d\theta}{F(\theta_{t+1}) - F(\tilde{\theta}_t)} = \frac{G(F(\theta_{t+1})) - G(F(\tilde{\theta}_t))}{F(\theta_{t+1}) - F(\tilde{\theta}_t)}.$$

For notational convenience, we let  $a = F(\theta_{t-1}), b = F(\theta_t), c = F(\theta_{t+1})$  with  $a < b < c$  and  $b > \frac{a+c}{2}$ . Then  $F(\tilde{\theta}_t) = a + c - b < b$  and we have  $\tilde{w} = \frac{G(c) - G(a+c-b)}{b-a}$ . With similar computations for  $u, w, \tilde{u}$ , we only need to prove

$$\frac{G(c) - G(a+c-b) + G(b) - G(a)}{b-a} > \frac{G(c) - G(b) + G(a+c-b) - G(a)}{c-b}.$$

---

<sup>27</sup>Both are equal to  $\int_{\theta_t}^{\theta_{t+1}} v(\theta)f(\theta)d\theta - \int_{\theta_{t-1}}^{\tilde{\theta}_t} v(\theta)f(\theta)d\theta$ .

This is equivalent to

$$2(c-b) \cdot \int_{a+c-b}^b G'(x)dx > (a+c-2b) \cdot \left[ \int_a^{a+c-b} G'(x)dx + \int_b^c G'(x)dx \right],$$

which holds so long as  $G'$  is a strictly concave function. This is indeed the case because  $G'(F(\theta)) = v(\theta)$ , which is less convex than  $F(\theta)$ . The proposition follows. ■

## A.5 Proof of Proposition 3

The following lemma gives a simple formula for the profit in the uniform-quadratic case.

**Lemma 5** *In the uniform-quadratic case, the profit from any interval partition with cutoffs  $\underline{\theta} = \theta_0 < \theta_1, \dots, \theta_{n-1} < \theta_n = \bar{\theta}$  is*

$$\Pi = \left( \frac{1}{6} (\bar{\theta} - \underline{\theta})^2 + \frac{1}{2} \underline{\theta}^2 - \frac{1}{6(\bar{\theta} - \underline{\theta})} \sum_{i=1}^n (\theta_i - \theta_{i-1})^3 \right),$$

which depends only on the lengths  $\{\theta_i - \theta_{i-1}\}_{i=1}^n$ .

Proof: When the agent's type is uniformly distributed over  $[\underline{\theta}, \bar{\theta}]$ , the virtual value of type  $\theta$  is given by  $v(\theta) = 2\theta - \bar{\theta}$ , and the optimal quantity for any interval  $[\theta_{i-1}, \theta_i]$ , as determined by Equation (4), is  $\theta_i = \theta_i + \theta_{i-1} - \bar{\theta}$ .

The profit as given by Equation (3) is:

$$\begin{aligned} \Pi(\omega) &= \sum_{i=1}^n (\theta_i + \theta_{i-1} - \bar{\theta}) \cdot \int_{\theta_{i-1}}^{\theta_i} (2x - \bar{\theta}) \frac{1}{\bar{\theta} - \underline{\theta}} dx - \frac{(\theta_i + \theta_{i-1} - \bar{\theta})^2}{2} \frac{\theta_i - \theta_{i-1}}{\bar{\theta} - \underline{\theta}} \\ &= \frac{1}{2(\bar{\theta} - \underline{\theta})} \left( \sum_{i=1}^n (\theta_i - \theta_{i-1}) (\theta_i + \theta_{i-1})^2 - 2 \sum_{i=1}^n (\theta_i^2 - \theta_{i-1}^2) \cdot \bar{\theta} + \sum_{i=1}^n (\theta_i - \theta_{i-1}) \cdot \bar{\theta}^2 \right). \end{aligned}$$

The three terms in the parentheses above can be simplified as follows:  $\sum_{i=1}^n (\theta_i - \theta_{i-1}) = (\bar{\theta} - \underline{\theta})$ ,  $\sum_{i=1}^n (\theta_i^2 - \theta_{i-1}^2) = (\bar{\theta}^2 - \underline{\theta}^2)$ , and  $\sum_{i=1}^n (\theta_i - \theta_{i-1}) (\theta_i + \theta_{i-1})^2 = \frac{4}{3} (\bar{\theta}^3 - \underline{\theta}^3) - \frac{1}{3} \sum_{i=1}^n (\theta_i - \theta_{i-1})^3$ .<sup>28</sup> Plugging the three expressions back, we obtain the lemma. ■

Back to the proposition, when  $\kappa \in [\log(N), \log(N+1))$ , we have  $e^\kappa < N+1$ . So by Lemma 2, any feasible interval mechanism has at most  $N$  intervals. Now by Lemma 5, among interval partitions with at most  $N$  intervals, maximizing profit is equivalent

<sup>28</sup>To simplify the third term we used the identity  $(x-y)(x+y)^2 = \frac{4}{3}(x^3 - y^3) - \frac{1}{3}(x-y)^3$ .



to minimizing  $\sum_{i=1}^N x_i^3$ , where  $x_i = \theta_i - \theta_{i-1}$  is the length of the interval  $m_i$  (which can be zero if less than  $N$  intervals are used). Subject to  $x_i \geq 0$  and the total length  $\sum_{i=1}^N x_i = \bar{\theta} - \underline{\theta}$ , the cubic sum  $\sum_{i=1}^N x_i^3$  is clearly minimized when the intervals have equal lengths. Hence, the equal partition maximizes profit among all partitions with at most  $N$  intervals, even ignoring the feasibility constraint. Since it is  $\kappa$ -feasible, it must then be the ex-post  $\kappa$ -optimal mechanism. ■

## A.6 Proof of Proposition 4

By the envelope theorem, the interim expected utility of a buyer with type  $\hat{\theta}$  is given by  $\int_{\theta \leq \hat{\theta}} q(\theta) d\theta$ . Thus ex-ante buyer surplus can be computed as

$$\int \int_{\theta \leq \hat{\theta}} q(\theta) d\theta dF(\hat{\theta}) = \int q(\theta)(1 - F(\theta)) d\theta. \quad (9)$$

In what follows, we consider the effect of combining two adjacent intervals in a mechanism into a single interval. Specifically, let  $\theta_{j-1}, \theta_j, \theta_{j+1}$  be three adjacent cutoffs in a constrained-optimal mechanism (for any  $\kappa$ ). Write  $v_j = \mathbb{E}[v(x) \mid x \in [\theta_{j-1}, \theta_j]]$ ,  $v_{j+1} = \mathbb{E}[v(x) \mid x \in [\theta_j, \theta_{j+1}]]$ , and  $v = \mathbb{E}[v(x) \mid x \in [\theta_{j-1}, \theta_{j+1}]]$ . Then the corresponding optimal quantities for these intervals are  $q_j = \phi(v_j)$ ,  $q_{j+1} = \phi(v_{j+1})$  and  $q = \phi(v)$ . Thus, the change in buyer surplus when “eliminating” the cutoff  $\theta_j$  is

$$\begin{aligned} \Delta &:= q \cdot \int_{\theta_{j-1}}^{\theta_{j+1}} (1 - F(\theta)) d\theta - q_j \cdot \int_{\theta_{j-1}}^{\theta_j} (1 - F(\theta)) d\theta - q_{j+1} \cdot \int_{\theta_j}^{\theta_{j+1}} (1 - F(\theta)) d\theta \\ &= (q - q_j) \cdot \int_{\theta_{j-1}}^{\theta_j} (1 - F(\theta)) d\theta - (q_{j+1} - q) \cdot \int_{\theta_j}^{\theta_{j+1}} (1 - F(\theta)) d\theta. \end{aligned}$$

We will show  $\Delta \geq 0$ . Indeed, observe that

$$v(F(\theta_{j+1}) - F(\theta_{j-1})) = \int_{\theta_{j-1}}^{\theta_{j+1}} v(\theta) d\theta = v_j(F(\theta_j) - F(\theta_{j-1})) + v_{j+1}(F(\theta_{j+1}) - F(\theta_j)).$$

So  $(v - v_j)(F(\theta_j) - F(\theta_{j-1})) = (v_{j+1} - v)(F(\theta_{j+1}) - F(\theta_j))$ . Hence,

$$\frac{q - q_j}{q_{j+1} - q} = \frac{\phi(v) - \phi(v_j)}{\phi(v_{j+1}) - \phi(v)} \geq \frac{v - v_j}{v_{j+1} - v} = \frac{F(\theta_{j+1}) - F(\theta_j)}{F(\theta_j) - F(\theta_{j-1})} \geq \frac{\int_{\theta_j}^{\theta_{j+1}} (1 - F(\theta)) d\theta}{\int_{\theta_{j-1}}^{\theta_j} (1 - F(\theta)) d\theta}, \quad (10)$$

which precisely means that  $\Delta \geq 0$ . In the above, the first inequality holds because  $\phi$  is concave (as its inverse function  $c'$  is assumed to be convex). The last inequality holds

because it can be rewritten as

$$\frac{\int_{\theta_{j-1}}^{\theta_j} (1 - F(\theta)) d\theta}{F(\theta_j) - F(\theta_{j-1})} \geq \frac{\int_{\theta_j}^{\theta_{j+1}} (1 - F(\theta)) d\theta}{F(\theta_{j+1}) - F(\theta_j)},$$

where the LHS is  $\frac{\int_{\theta_{j-1}}^{\theta_j} (1 - F(\theta)) d\theta}{\int_{\theta_{j-1}}^{\theta_j} f(\theta) d\theta} \geq \frac{1 - F(\theta_j)}{f(\theta_j)}$  by the assumption that  $\frac{1 - F(\theta)}{f(\theta)}$  is decreasing, and similarly the RHS is at most  $\frac{1 - F(\theta_j)}{f(\theta_j)}$ . This completes the proof that  $\Delta \geq 0$ .

Now, starting from any mechanism, repeatedly combining adjacent intervals eventually leads to the fully pooling mechanism, which yields weakly higher buyer surplus. Thus  $\kappa = 0$  maximizes buyer surplus. Similarly  $\kappa = \infty$  minimizes buyer surplus. ■

## A.7 Proof of Proposition 5

With quadratic costs, total welfare contributed by a buyer of type  $\theta$  is  $\theta q(\theta) - (q(\theta))^2/2$ . Thus ex-ante total welfare is  $\int q(\theta) \cdot \left(\theta - \frac{q(\theta)}{2}\right) f(\theta) d\theta$ . Note that on each interval  $[\theta_{i-1}, \theta_i]$ ,  $q(\theta)$  is constant and equal to the expected virtual valuation on this interval. Thus, ex-ante total welfare can be equivalently written as

$$\int q(\theta) \cdot \left(\theta - \frac{v(\theta)}{2}\right) f(\theta) d\theta. \quad (11)$$

Compared with the above Equation (9) for buyer surplus, the difference here is that the function  $\left(\theta - \frac{v(\theta)}{2}\right) f(\theta)$  takes the place of  $1 - F(\theta)$ .

Note that  $f(\theta)$  is increasing implies that  $\theta - \frac{v(\theta)}{2}$  is decreasing, since its derivative is  $-\frac{(1 - F(\theta))f'(\theta)}{2f(\theta)^2}$ . Thus we can repeat the above argument to show that combining two intervals increases total welfare, which must be maximized at  $\kappa = 0$  and minimized at  $\kappa = \infty$ . This proves the first half of the proposition.

As for the second half, we can apply a symmetric argument: If  $f(\theta)$  is decreasing, then  $\theta - \frac{v(\theta)}{2}$  is increasing. This implies that combining two intervals would decrease total welfare, since the last inequality in Equation (10) would be reversed (and the first inequality would hold equal thanks to quadratic costs). Therefore total welfare would be minimized with a single interval, and maximized with full screening. ■

## B Proofs for the ex-ante measure

### B.1 Proof of Proposition 6

We expand on the proof sketch outlined in the main text. As discussed, the key is to find a replacement  $\tilde{\mathbb{M}}$  for any mechanism  $\mathbb{M}$  such that profit is not decreased, and the number of intervals in  $\tilde{M}$  is bounded.

**Step 1. Find a “big” interval.** Set  $l = e^{-\kappa}$ . We first show that any ex-ante  $\kappa$ -feasible interval mechanism contains a “big” interval with mass  $\geq l$  (according to  $F$ ). Indeed, from Equation (6) we have

$$I(\mathbb{M}) = \sum_i -[F(\theta_i) - F(\theta_{i-1})] \cdot \log [F(\theta_i) - F(\theta_{i-1})] \leq \kappa.$$

Since  $\sum_i [F(\theta_i) - F(\theta_{i-1})] = 1$ , there exists some  $i$  s.t.  $-\log [F(\theta_i) - F(\theta_{i-1})] \leq \kappa$ . In other words, the interval  $m_i$  has mass at least  $e^{-\kappa}$ .

Fixing this choice of  $l$ , we define  $\epsilon$  to be a small positive constant as given by Lemma 6 below. Starting from  $\mathbb{M}$ , we will now look for the replacement  $\tilde{\mathbb{M}}$ .

**Step 2. From countable to finite.** We first find a replacement  $\hat{\mathbb{M}}$  with at least as much profit and only *finitely* many intervals. Suppose  $p$  is an accumulation point of the cutoffs in  $\mathbb{M}$ . Then on the left of  $p$  we can order the intervals in  $M$  from left to right as  $m_1, m_2, \dots$ , with  $m_i$  converging to  $p$ . In particular, the mass of  $m_i$  converges to zero, and we can find some  $m_s$  and  $m_{s+1}$  both with mass  $< \epsilon$ . Applying Lemma 6 below, we can merge the intervals  $m_s$  and  $m_{s+1}$  and divide the “big” interval into two sub-intervals, in such a way that the (ex-ante) privacy measure is unchanged and profit is strictly increased. The achieved profit gain is sufficient to cover the loss from additionally combining all the (countably many) intervals  $m_t, m_{t+1}, \dots$ , so long as we choose  $t$  to be sufficiently large. As this last step also relaxes the privacy constraint, we obtain a replacement mechanism in which  $p$  is no longer an accumulation point of intervals on its left. Doing the same exercise for intervals on the right of  $p$  yields a mechanism in which  $p$  is not an accumulation point.

In fact, we can achieve this replacement with some extra properties. Note that whenever an accumulation point  $p$  exists, the “big” interval must have mass strictly greater than  $l = e^{-\kappa}$ ; otherwise the privacy constraint requires every interval in  $M$  to have mass exactly  $l$ , a contradiction. Thus by choosing  $m_s$  and  $m_{s+1}$  to have sufficiently small mass, we can ensure that when they are merged and the “big” interval is divided into two sub-intervals, *the bigger sub-interval still has mass  $> l$* . In other words, we can perform the

replacement in such a way that the *same big interval* is sequentially divided (each time creating a small sub-interval on the left and a big one on the right). The benefit is that as we get rid of the accumulation points in  $\mathbb{M}$  one by one (which may be countably many), we obtain a sequence of replacement mechanisms that become finer in the original “big” interval in  $\mathbb{M}$  and more coarse everywhere else. This sequence converges, and the limit mechanism has at most one accumulation point in the “big” interval.<sup>29</sup> By merging and dividing once more, we arrive at  $\hat{\mathbb{M}}$  with finitely many intervals and weakly higher profit than  $\mathbb{M}$ .

**Step 3. From finite to bounded.** We now demonstrate how to replace the finite mechanism  $\hat{\mathbb{M}}$  with yet another mechanism  $\tilde{\mathbb{M}}$  with higher profit and at most  $N := \frac{2}{\epsilon} + 4$  intervals. Starting from  $\hat{\mathbb{M}}$ , if there are *two pairs* of adjacent intervals (i.e., 4 distinct ones) all with mass  $< \epsilon$ , then we combine both pairs at the same time and used the privacy measure saved from one of the mergers to divide the “big” interval into two sub-intervals. The privacy constraint is relaxed, and by Lemma 6 below, total profit is increased if we choose the merger that induces greater profit loss.

Hence whenever  $\hat{\mathbb{M}}$  contains two pairs of adjacent “small” intervals, it can be replaced with a mechanism  $\hat{\mathbb{M}}^{(1)}$  with higher profit and *one less interval in total*. The latter property ensures that when iterating this process, we will eventually reach a mechanism  $\tilde{\mathbb{M}}$  in which at most one pair of adjacent intervals both have mass  $< \epsilon$ . Excluding this pair and the two intervals next to them, at least half of the remaining intervals have mass  $\geq \epsilon$ . So the total number of intervals in  $\tilde{\mathbb{M}}$  is bounded by  $N = \frac{2}{\epsilon} + 4$ . ■

**Lemma 6** *Given  $l > 0$ , there exists  $\epsilon \in (0, l)$  with the following property. If any interval mechanism  $\mathbb{M}$  has two adjacent small intervals both of mass  $< \epsilon$  as well as a big interval of mass  $\geq l$ , then when merging the two small intervals and using the saved ex-ante privacy measure to divide the big interval into two sub-intervals, the profit gain in the latter step is at least twice as big as the profit loss in the former step.*

**Proof:** Suppose there are two adjacent intervals with mass  $x, y < \epsilon$ ; assume without loss that  $x \leq y$ . If we combine them into a single interval, the profit loss is on the order of  $xy(x + y)$  by Lemma 4. Meanwhile, Equation (6) implies that the amount of privacy measure saved is

$$\alpha = (x + y) \log(x + y) - x \log x - y \log y = x \log\left(1 + \frac{y}{x}\right) + y \log\left(1 + \frac{x}{y}\right). \quad (12)$$

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<sup>29</sup>If we do not divide the same big interval repeatedly, then it is possible that new accumulation points arise in the iterative process. That would complicate the argument.

By assumption, there exists another interval of mass  $L \geq l$ . We use the saved privacy measure to break this interval into two: That is, we look for a sub-interval of mass  $\delta \in (0, \frac{L}{2})$  such that the total privacy measure is restored. This requires

$$L \log L - (L - \delta) \log(L - \delta) - \delta \log \delta = \alpha.$$

From this we obtain<sup>30</sup>

$$\delta \cdot |\log \delta| \geq \frac{\alpha}{2}. \quad (13)$$

We claim that (12) and (13) together imply  $\delta \geq x\sqrt{x+y}$  (whenever  $x \leq y < \epsilon$ ). For this it suffices to show that

$$x\sqrt{x+y} \cdot \log\left(\frac{1}{x\sqrt{x+y}}\right) < \frac{x \log(1 + \frac{y}{x})}{2} < \frac{\alpha}{2}.$$

Rearranging, the above inequality is equivalent to

$$\frac{1}{x\sqrt{x+y}} < \left(1 + \frac{y}{x}\right)^{\frac{1}{2\sqrt{x+y}}}.$$

For small  $x, y$ , the exponent  $\frac{1}{2\sqrt{x+y}}$  is at least 4. So by binomial expansion, the RHS above has size at least

$$\left(\frac{1}{4}\right)^4 \cdot \left(\frac{y}{x}\right)^4 \geq \left(\frac{1}{8\sqrt{x+y}}\right)^4 \cdot \frac{y}{x} = \frac{y}{4096x(x+y)^2} \geq \frac{1}{8192x(x+y)}.$$

This is indeed greater than the LHS, which was  $\frac{1}{x\sqrt{x+y}}$ .

Hence we have shown that when using the saved capacity to divide the big interval into two sub-intervals, the smaller sub-interval has mass  $\delta \geq x\sqrt{x+y}$ . By Lemma 4, the resulting profit gain is on the order of  $\delta(L - \delta)L \geq \frac{L^2\delta}{2}$ . Since  $L \geq l$  which is given, this profit gain is at least on the order of  $\delta \geq x\sqrt{x+y}$ . This profit gain exceeds the initial profit loss (which is about  $xy(x+y)$ ) due to combining two small intervals, completing the proof.

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<sup>30</sup>By the Mean Value Theorem,  $L \log L - (L - \delta) \log(L - \delta) = \delta(1 + \log \zeta)$  for some  $\zeta \in (L - \delta, L)$ . So  $\delta(1 + \log \frac{\zeta}{\delta}) = \alpha$ . Since  $\zeta \geq \frac{L}{2} \geq \delta$ , this implies

$$\delta \leq \alpha = x \log\left(1 + \frac{y}{x}\right) + y \log\left(1 + \frac{x}{y}\right) \leq x \cdot \frac{y}{x} + y \cdot \frac{x}{y} = x + y \leq \frac{1}{e}.$$

Thus we further have  $1 + \log \zeta \leq 1 \leq -\log \delta$ . From  $\delta(1 + \log \frac{\zeta}{\delta}) = \alpha$  we then deduce  $\delta \cdot |\log \delta| \geq \frac{\alpha}{2}$ .

## B.2 Proof of Proposition 7

The argument is already sketched in the main text, after Proposition 7. In particular, Lemma 4 ensures that the seller strictly benefits from dividing any interval into two sub-intervals.

## B.3 Proof of Proposition 8

We argue that Proposition 8 follows from Lemma 3, which we prove below. Indeed, that lemma implies the existence of some  $\epsilon > 0$  such that any ex-ante  $\kappa$ -optimal interval mechanism with  $\kappa \leq 1$  contains at most one interval with mass  $< \epsilon$ . For this  $\epsilon$ , define  $\underline{\kappa} = -\epsilon \log \epsilon$ . Then in any  $\kappa$ -optimal mechanism with  $\kappa \leq \underline{\kappa} < 1$ , Equation (6) and feasibility implies

$$\sum_i -[F(\theta_i) - F(\theta_{i-1})] \cdot \log [F(\theta_i) - F(\theta_{i-1})] \leq \kappa \leq -\epsilon \log \epsilon.$$

In particular,  $[F(\theta_i) - F(\theta_{i-1})] \cdot \log [F(\theta_i) - F(\theta_{i-1})] > \epsilon \log \epsilon$  holds for every interval. Note that the function  $x \log x$  is decreasing for  $x \in [0, \frac{1}{e}]$  and increasing for  $x \in [\frac{1}{e}, 1]$ . Thus the preceding inequality implies either  $F(\theta_i) - F(\theta_{i-1}) < \epsilon$ , or  $F(\theta_i) - F(\theta_{i-1}) > \frac{1}{2}$ .

In words, each interval in  $M$  has mass either less than  $\epsilon$  or greater than  $\frac{1}{2}$ . By definition of  $\epsilon$ , there is at most one interval with mass  $< \epsilon$ . It is also clear that at most one interval can have mass  $> \frac{1}{2}$ . Hence any ex-ante  $\kappa$ -optimal interval mechanism with  $\kappa \leq \underline{\kappa}$  consists of at most two intervals. Since the ex-ante privacy constraint is exhausted, exactly two intervals are employed. ■

## B.4 Proof of Lemma 3

In the proof of Proposition 6, we showed that in any ex-ante  $\kappa$ -feasible mechanism there is a “big” interval of mass at least  $e^{-\kappa} \geq e^{-k}$ . So by Lemma 6, there cannot be two adjacent intervals both with mass  $< \epsilon$  (for some small  $\epsilon$ ).

It remains to deal with the situation where two small intervals are not adjacent. The proof strategy is to move one of these intervals to be next to the other, and to show that the profit change is at most on the order of  $xy$ , where  $x, y$  are the mass of these small intervals. Once this is shown, we can repeat the argument in the proof of Lemma 6, merging the now adjacent small intervals and dividing the big interval. As computed in that proof, the profit gain in the last step is on the order of  $x\sqrt{x+y}$ , which exceeds any profit loss incurred earlier. This would complete the proof.

To be more specific, suppose the two small intervals are  $[\theta_{i-1}, \theta_i]$  and  $[\theta_j, \theta_{j+1}]$ , for some  $i < j$ . Set  $x = F(\theta_i) - F(\theta_{i-1})$  and  $y = F(\theta_{j+1}) - F(\theta_j)$ . Consider *moving the small interval on the left toward the right while maintaining its mass*: We can do this sequentially by replacing  $\theta_i$  with  $\tilde{\theta}_i = F^{-1}(F(\theta_{i+1}) - x)$ , then replacing  $\theta_{i+1}$  with  $\tilde{\theta}_{i+1} = F^{-1}(F(\theta_{i+2}) - x)$ , so on and so forth until  $\tilde{\theta}_{j-1} = F^{-1}(F(\theta_j) - x)$  and the two small intervals become adjacent. This process preserves the ex-ante privacy measure, and it remains to estimate the profit change.

Note that in each step, the two intervals  $[\tilde{\theta}_{t-1}, \theta_t]$  and  $[\theta_t, \theta_{t+1}]$  are changed into two new intervals  $[\tilde{\theta}_{t-1}, \tilde{\theta}_t]$  and  $[\tilde{\theta}_t, \theta_{t+1}]$ . Thus, as in the proof of Proposition 2, the profit increase is given by

$$\begin{aligned} \Delta_t = & h(\tilde{u}) \cdot [F(\tilde{\theta}_t) - F(\tilde{\theta}_{t-1})] + h(\tilde{w}) \cdot [F(\theta_{t+1}) - F(\tilde{\theta}_t)] \\ & - h(u) \cdot [F(\theta_t) - F(\tilde{\theta}_{t-1})] - h(w) \cdot [F(\theta_{t+1}) - F(\theta_t)] \end{aligned} \quad (14)$$

where  $u, w, \tilde{u}, \tilde{w}$  represent the expected virtual valuation on the intervals  $[\tilde{\theta}_{t-1}, \theta_t]$ ,  $[\theta_t, \theta_{t+1}]$ ,  $[\tilde{\theta}_{t-1}, \tilde{\theta}_t]$ ,  $[\tilde{\theta}_t, \theta_{t+1}]$  respectively.

We first consider the difference  $h(\tilde{w}) \cdot [F(\theta_{t+1}) - F(\tilde{\theta}_t)] - h(u) \cdot [F(\theta_t) - F(\tilde{\theta}_{t-1})]$ . By construction,  $F(\theta_{t+1}) - F(\tilde{\theta}_t) = F(\theta_t) - F(\tilde{\theta}_{t-1}) = x$ , so this difference simplifies to  $(h(\tilde{w}) - h(u)) \cdot x$ . Moreover, as we showed in the proof of Lemma 4,

$$u = \mathbb{E}[v(\theta) \mid \tilde{\theta}_{t-1} \leq \theta \leq \theta_t] = v(\theta_t) + O(\theta_t - \tilde{\theta}_{t-1}) = v(\theta_t) + O(F(\theta_t) - F(\tilde{\theta}_{t-1})) = v(\theta_t) + O(x)$$

where “ $O(\cdot)$ ” is the standard big O notation with implied constants depending on the distribution and cost function. Thus  $h(u) = h(v(\theta_t)) + O(x)$  and similarly  $h(\tilde{w}) = h(v(\theta_{t+1})) + O(x)$ . It follows that

$$h(\tilde{w}) \cdot [F(\theta_{t+1}) - F(\tilde{\theta}_t)] - h(u) \cdot [F(\theta_t) - F(\tilde{\theta}_{t-1})] = [h(v(\theta_{t+1})) - h(v(\theta_t))] \cdot x + O(x^2).$$

Next we consider the other difference  $h(\tilde{u}) \cdot [F(\tilde{\theta}_t) - F(\tilde{\theta}_{t-1})] - h(w) \cdot [F(\theta_{t+1}) - F(\theta_t)]$  in Equation (14). It simplifies to  $(h(\tilde{u}) - h(w)) \cdot [F(\theta_{t+1}) - F(\theta_t)]$ . Moreover,

$$\begin{aligned} \tilde{u} &= \frac{\int_{\tilde{\theta}_{t-1}}^{\tilde{\theta}_t} v(\theta) f(\theta) d\theta}{F(\tilde{\theta}_t) - F(\tilde{\theta}_{t-1})} = \frac{\int_{\tilde{\theta}_{t-1}}^{\tilde{\theta}_t} v(\theta) f(\theta) d\theta}{F(\theta_{t+1}) - F(\theta_t)} = w + \frac{\int_{\tilde{\theta}_{t-1}}^{\theta_t} v(\theta) f(\theta) d\theta - \int_{\tilde{\theta}_t}^{\theta_{t+1}} v(\theta) f(\theta) d\theta}{F(\theta_{t+1}) - F(\theta_t)} \\ &= w + \frac{[v(\theta_t) - v(\theta_{t+1})] \cdot x}{F(\theta_{t+1}) - F(\theta_t)} + \frac{\int_{\tilde{\theta}_{t-1}}^{\theta_t} [(v(\theta) - v(\theta_t))] \cdot f(\theta) d\theta - \int_{\tilde{\theta}_t}^{\theta_{t+1}} [v(\theta) - v(\theta_{t+1})] \cdot f(\theta) d\theta}{F(\theta_{t+1}) - F(\theta_t)} \end{aligned}$$

$$= w + \frac{[v(\theta_t) - v(\theta_{t+1})] \cdot x}{F(\theta_{t+1}) - F(\theta_t)} + O(x^2),$$

where the last step holds because for each  $\theta \in [\tilde{\theta}_{t-1}, \theta_t]$ , the difference between  $[(v(\theta) - v(\theta_t)) \cdot f(\theta)]$  and  $[(v(\theta + \theta_{t+1} - \theta_t) - v(\theta_{t+1})) \cdot f(\theta + \theta_{t+1} - \theta_t)]$  is at most on the order of  $(\theta_t - \theta) \cdot (\theta_{t+1} - \theta_t) = O(x) \cdot [F(\theta_{t+1}) - F(\theta_t)]$ . Thus  $h(\tilde{u}) = h(w) + h'(w) \cdot \frac{[v(\theta_t) - v(\theta_{t+1})] \cdot x}{F(\theta_{t+1}) - F(\theta_t)} + O(x^2)$ . It follows that

$$h(\tilde{u}) \cdot [F(\tilde{\theta}_t) - F(\tilde{\theta}_{t-1})] - h(w) \cdot [F(\theta_{t+1}) - F(\theta_t)] = h'(w) \cdot [v(\theta_t) - v(\theta_{t+1})] \cdot x + O(x^2)$$

Taken together, we have estimated the RHS of Equation (14), so that

$$\Delta_t = \{h(v(\theta_{t+1})) - h(v(\theta_t)) - [v(\theta_{t+1}) - v(\theta_t)] \cdot h'(\mathbb{E}[v(\theta) \mid \theta \in [\theta_t, \theta_{t+1}]])\} \cdot x + O(x^2).$$

Summing across  $t \in \{i, \dots, j-1\}$ , we obtain that when moving the small interval on the left to be adjacent to the one on the right, the total profit change is<sup>31</sup>

$$\Delta_{LR} = O(x^2) + \sum_{t=i}^{j-1} \{h(v(\theta_{t+1})) - h(v(\theta_t)) - [v(\theta_{t+1}) - v(\theta_t)] \cdot h'(\mathbb{E}[v(\theta) \mid \theta \in [\theta_t, \theta_{t+1}]])\} \cdot x.$$

If we instead move the small interval on the right to be adjacent to the one on the left, then total profit change is similarly computed as

$$\Delta_{RL} = O(y^2) - \sum_{t=i}^{j-1} \{h(v(\theta_{t+1})) - h(v(\theta_t)) - [v(\theta_{t+1}) - v(\theta_t)] \cdot h'(\mathbb{E}[v(\theta) \mid \theta \in [\theta_t, \theta_{t+1}]])\} \cdot y.$$

Note the minus sign in front of the second term; this is because when moving from the right to the left, the ordering of the subscripts need to be reversed.

Now observe that if we compute the weighted sum  $y \cdot \Delta_{LR} + x \cdot \Delta_{RL}$ , then the second term is cancelled out. This yields

$$y \cdot \Delta_{LR} + x \cdot \Delta_{RL} = O(x^2 y + y^2 x).$$

Therefore  $\Delta_{LR}$  and  $\Delta_{RL}$  cannot both be very negative. To be concrete we may without loss assume  $\Delta_{LR} \geq -O(xy)$ . Then in moving the small interval on the left to the right, the initial profit loss (if any) is small relative to the profit gain provided in Lemma 6. This again contradicts optimality, and hence there cannot even be two small intervals that are non-adjacent. ■

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<sup>31</sup>There are  $j-i$  terms of order at most  $x^2$ , and since  $j-i$  is bounded by the total number of intervals which in turn is bounded by Lemma 6, their sum is still  $O(x^2)$ .



## B.5 Proof of Proposition 9

We will show that in any profit-maximizing partition with exactly  $n$  intervals, all but one of the intervals have the same lengths and the last interval has weakly smaller length. To see how this claim implies the result, suppose  $\kappa \in (\log(N - 1), \log(N)]$ . By Proposition 7, the number of intervals in the optimal solution satisfies  $n \geq e^\kappa > N - 1$ . Thus  $n \geq N$ . Moreover, if  $n > N$ , then at least  $N$  intervals would have the same lengths. It would follow that *each* of the intervals in the optimal partition has *mass* smaller than  $\frac{1}{N}$ , which is at most  $e^{-\kappa}$ . This would contradict feasibility, i.e., Equation (6). Hence, with the preceding claim, we will know that the optimal partition involves exactly  $N$  intervals. The two lengths are then uniquely determined, as described in the Proposition. Finally, the ordering of the intervals does not matter for either the privacy measure or for profit, thanks to Lemma 5.

It remains to prove the above claim that characterizes the lengths of the optimal intervals. For an interval partition, let  $x_i = \frac{\theta_i - \theta_{i-1}}{\theta - \underline{\theta}}$  denote the probability mass of the  $i$ -th interval. In what follows we will work with the probability masses  $\{x_i\}$  instead of the cutoffs  $\{\theta_i\}$ . By Lemma 5 and Equation (6), seller's profit maximization problem under the ex-ante privacy constraint can be rewritten as the following constrained minimization problem:  $\min \sum_{i=1}^n x_i^3$  subject to  $x_i \geq 0$ ,  $\sum_{i=1}^n x_i = 1$ , and  $\sum_{i=1}^n x_i \log x_i \leq -\kappa$ . For a fixed  $n$ , the Lagrangian is given by:

$$\mathcal{L}(\alpha, \beta, \{x_i\}_{i=1}^n) = \sum_{i=1}^n x_i^3 + \alpha(1 - \sum_{i=1}^n x_i) - \beta(\sum_{i=1}^n x_i \log x_i + \kappa).$$

Thus, whenever each  $x_i$  is strictly positive and  $\{x_i\}$  is a local constrained minimizer, the first order conditions imply

$$3x_i^2 - \beta \log x_i = \alpha + \beta \quad \text{for all } 1 \leq i \leq n. \quad (15)$$

If  $\beta \leq 0$ , then the function  $3x^2 - \beta \log x$  is monotonically increasing. Thus every  $x_i$  is the same, which completes the proof. Otherwise assume  $\beta > 0$ . In this case the derivative of the function  $3x^2 - \beta \log x$  is  $6x - \frac{\beta}{x}$ , which is monotonically increasing and crosses 0 at  $\hat{x} = \sqrt{\frac{\beta}{6}}$ . Thus, the function  $3x^2 - \beta \log x$  decreases on  $[0, \hat{x}]$  and increases on  $[\hat{x}, \infty)$ . Equation (15) yields that  $x_i$  can take at most two values  $\underline{x}$  and  $\bar{x}$ , with  $\underline{x} < \hat{x} < \bar{x}$ .

Below we analyze the second order conditions to show that at most one  $x_i$  can be equal to  $\underline{x}$ . Suppose for the sake of contradiction that in the optimal solution  $\beta > 0$  and  $x_1 = x_2 = \underline{x}$ . Let  $g(x) = (\sum_{i=1}^n x_i, \sum_{i=1}^n x_i \log x_i)' \in \mathbb{R}^2$  denote the constraint values. Then its Jacobian  $D_g(x)$  is the  $2 \times n$  matrix whose first row is all 1s and whose second

row is  $(1 + \log x_1, \dots, 1 + \log x_n)$ . Consider  $v = (1, -1, 0, \dots, 0)' \in \mathbb{R}^n$ . Then clearly  $v$  belongs to the null space of  $D_g(x)$ .

The second derivative of the Lagrangian  $\mathcal{L}(\alpha, \beta, x)$  with respect to (the vector)  $x$  is the diagonal matrix  $H = \text{diag}(6x_1 - \frac{\beta}{x_1}, \dots, 6x_n - \frac{\beta}{x_n})$ . It is easy to see that

$$v' H v = 6x_1 - \frac{\beta}{x_1} + 6x_2 - \frac{\beta}{x_2} = 2 \left( 6\underline{x} - \frac{\beta}{\underline{x}} \right),$$

which is negative because  $\underline{x} < \hat{x}$ . But this fails the second derivative test for constrained local minima; see, e.g., Simon and Blume (1994), page 468. Hence the proof is complete.

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