

# On Actively-Secure Elementary MPC Reductions

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**Abstract.** We introduce the notion of *elementary MPC* reductions that allow us to securely compute a functionality  $f$  by making a single call to a constant-degree “non-cryptographic” functionality  $g$  without requiring any additional interaction. Roughly speaking, “non-cryptographic” means that  $g$  does not make use of cryptographic primitives, though the parties can locally call such primitives.

Classical MPC results yield such elementary reductions in various cases including the setting of passive security with full corruption threshold  $t < n$  (Yao, FOCS’86; Beaver, Micali, and Rogaway, STOC’90), the setting of full active security against a corrupted minority  $t < n/2$  (Damgård and Ishai, Crypto’05), and, for  $\text{NC}^1$  functionalities, even for the setting of full active (information-theoretic) security with full corruption threshold of  $t < n$  (Ishai and Kushilevitz, FOCS’00). This leaves open the existence of an elementary reduction that achieves full active security in the dishonest majority setting for all efficiently computable functions.

Our main result shows that such a reduction is unlikely to exist. Specifically, the existence of a computationally secure elementary reduction that makes black-box use of a PRG and achieves a very weak form of partial fairness (e.g., that holds only when the first party is not corrupted) would allow us to realize any efficiently-computable function by a *constant-round* protocol that achieves a non-trivial notion of information-theoretic passive security. The existence of the latter is a well-known 3-decade old open problem in information-theoretic cryptography (Beaver, Micali, and Rogaway, STOC’90).

On the positive side, we observe that this barrier can be bypassed under any of the following relaxations: (1) non-black-box use of a pseudo-random generator; (2) weaker security guarantees such as security with identifiable abort; or (3) an additional round of communication with the functionality  $g$ .

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## 1 Introduction

The design and analysis of secure multiparty computation (MPC) protocols crucially rely on the notion of *secure reductions*. For example, the classical completeness results of Yao [45] and Goldreich, Micali and Wigderson [25] can be interpreted as saying that the problem of securely computing a general  $n$ -party functionality  $f$  efficiently reduces to the problem of securely computing the elementary finite 2-party Oblivious Transfer (OT) functionality [41,21]. This paradigm of reducing a complicated  $f$  to a “simpler” randomized functionality  $g$  is especially useful when the reduction is *non-interactive*. That is, the parties compute  $f$  by making a non-interactive call to the  $n$ -party functionality  $g$  without any additional interaction. For example, Yao’s celebrated garbled circuit technique [45] can be viewed as a non-interactive passively-secure reduction from any 2-party functionality  $f$  to a functionality  $g$  that can be represented by a vector of constant-degree polynomials. Extensions to the multiparty setting and to the information-theoretic setting for  $\text{NC}^1$  functionalities were presented by Beaver, Micali and Rogaway [14] and by Ishai and Kushilevitz [34,35]. Overall for passively secure protocols, we have the following satisfying picture.

**Theorem 1 (Non-Interactive Passive Reductions [45,14,34,35]).** *Let  $f$  be an  $n$ -party functionality.*

- *If  $f$  is in  $\text{NC}^1$ , then there exists a non-interactive reduction from  $f$  to a constant-degree functionality  $g$ . The reduction preserves information-theoretic passive security against an adversary that corrupts up to  $n - 1$  parties.*
- *If  $f$  is efficiently computable (e.g., by a polynomial-size circuit family) and pseudorandom generators (PRG) exist, then there exists a non-interactive reduction from  $f$  to a constant-degree functionality  $g$ . The reduction preserves computational passive security against an adversary that corrupts up to  $n - 1$  parties.*

The above theorem and its many variants form the basis of all known general-purpose constant-round MPC protocols. Indeed, Theorem 1 non-interactively reduces the task of securely computing  $f$  to the task of securely computing a *constant-degree* function – a problem that can be solved within a constant number of rounds via standard protocols (e.g., [25,15,18]). Theorem 1 has also found, under the framework of randomized encoding (RE) [8], several surprising applications beyond MPC and even beyond cryptography. (See the surveys [33,4].)

*Elementary reductions.* One important feature of the above theorem is the fact that, even in the computational setting, the reduction makes a black-box use of the PRG and the functionality  $g$  is *completely independent* of the PRG. In more detail, a non-interactive reduction consists of a preprocessing phase where each party  $P_i$  applies some local preprocessing computation  $\text{pre}_i$  to its input  $x_i$  and its random tape  $r_i$ , and sends the result  $y_i = \text{pre}_i(x_i; r_i)$  to the  $g$ -oracle, which, in turn, computes a vector of outputs  $(v_1, \dots, v_n) = g(y_1, \dots, y_n)$  and delivers

$v_i$  to the  $i$ -th party. Each party then applies some local postprocessing function  $\text{post}_i$  to its local view, and generates the final the output  $z_i$  (See Figure 1). The computational non-interactive reduction of Theorem 1 is *elementary* in the following sense: The parties make only black-box calls to the PRG as part of  $\text{pre}_i$  and  $\text{post}_i$ , and the constant-degree functionality  $g$  is independent of the PRG and depends only on  $f$ .<sup>3</sup> We refer to such a reduction as *elementary* and point out that this feature and especially the fact that  $g$  is independent of the PRG, makes the reduction highly efficient (since one does not have to “garble” the PRG). Moreover, from a theoretical point of view, elementary reductions enable to base constant-round protocols on PRGs via fully black-box reductions which forms an important feasibility result.

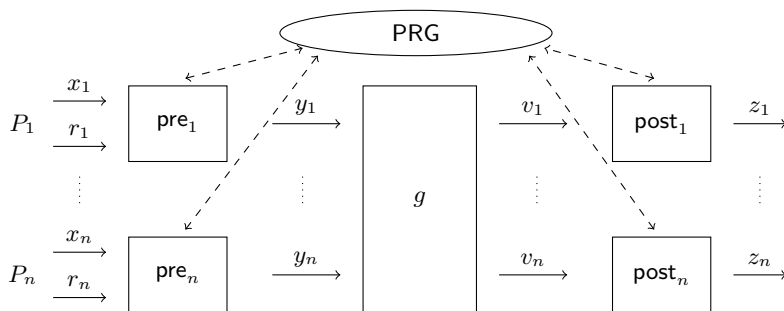


Fig. 1: Elementary non-interactive reduction (dotted arrows represent oracle queries).

*Actively-secure elementary reductions?* The status of elementary reductions in the active (aka malicious) setting, where parties may deviate from the protocol, is less clear. For  $\text{NC}^1$  functionalities, the information-theoretic part of Theorem 1 holds even in the active setting, and it provides an information-theoretic actively-secure reduction against an arbitrary coalition. In fact, the reduction preserves *fairness*, (namely, if one party receives its output then all parties do) and even *guaranteed output delivery* (i.e., honest parties are guaranteed to successfully complete the computation). That is, assuming an ideal realization of  $g$  with fairness (resp., guaranteed output delivery) against an adversary that actively corrupts a coalition  $T$ , we get a protocol for  $f$  with the same security guarantees. Adopting the perspective of Gordon et al. [28], the above result can be casted as a completeness result for fair secure computation of  $\text{NC}^1$  functionalities: The only resource that is needed in order to fairly compute an  $\text{NC}^1$  functionality is the ability to fairly compute a constant-degree functionality.

Unfortunately, no such result is known for the more general case of efficiently-computable functionalities (even for computational security), instead we only

<sup>3</sup> For the reader who is familiar with garbled circuits, we point out that  $g$  computes the “encrypted tables” of each gate which can be written as a degree-3 (multi-output function) over random mask bits, and pairs of the form  $(s, z)$  where  $s$  is a random seed that is chosen locally by some party and  $z = \text{PRG}(s)$  is pre-computed as part of the preprocessing phase.

have weaker results. In particular, assuming PRGs in  $\text{NC}^1$ , the work of [9] shows that every efficiently computable function  $f$ , non-interactively reduces to a constant-degree function  $g$  with fairness (and even guaranteed output delivery). However, the reduction is non-elementary since the function  $g$  depends (in a non-black-box way) on the code of the PRG. Elementary reductions that achieve weaker forms of security are implicit in the literature. This includes protocols that achieve guaranteed output delivery in the presence of *honest majority* [20], or dishonest-majority protocols that achieve (unfair) *security with abort* for single-receiver functionalities in the two-party setting [38] and in the multiparty setting [44,31]. This leaves open the following natural question:

*Is it possible to reduce every efficiently computable functionality to a constant-degree functionality via an elementary actively-secure reduction that preserves fairness, or even guaranteed output delivery, against arbitrary corruptions?*

### 1.1 Our Results

Our main result shows that it is unlikely to obtain an elementary fair reduction for general efficiently computable functions in the dishonest majority setting. Of course, we do not expect to obtain an unconditional negative result, since such a result would rule out the existence of information-theoretic elementary reductions for efficiently computable functions (a longstanding open problem in information-theoretic cryptography), and would imply complexity-theoretic groundbreaking results such as  $\text{P} \neq \text{NC}^1$ . Instead, we show that the existence of computationally-secure elementary fair reductions is essentially equivalent to the question of *information-theoretic* elementary reduction. That is, if  $f$  fairly-reduces to a non-cryptographic functionality  $g$  via a non-interactive reduction that makes a black-box use of a PRG, then these calls can be essentially removed. In fact, this holds even if the elementary reduction works only in the 2-party setting and only achieves fairness against an active adversary that only corrupts the second party (aka *partial fairness* [26]).<sup>4</sup> Furthermore, this result holds even if the PRG is modeled as a random oracle.

**Theorem 2.** *Suppose that every efficiently-computable 2-party functionality  $f$ , reduces to some constant-degree 2-party functionality  $g$  via an elementary reduction that makes black-box calls to a random oracle while providing partial fairness. Then, every efficiently-computable 2-party functionality  $f$  reduces to a constant-degree functionality  $g$  via a non-interactive reduction in the CRS model with inverse-polynomial average-case information-theoretic privacy against passive adversaries.*

The theorem’s hypothesis is, in a sense, minimal – if the parties are allowed to have an additional single round of interaction after calling  $g$  then one can achieve

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<sup>4</sup> Note that a multiparty fair elementary reduction implies a 2-party elementary fair reduction, which in turn implies a 2-party elementary reduction with partial fairness. Therefore if we rule out the latter, we also rule out the former.

partial fairness by using an elementary reduction that delivers an output to the second party (e.g., based on the appendix of [38]) and then ask the second party to deliver the outcome to the first party. Let us elaborate on this theorem’s implication. The notion of *inverse-polynomial average-case information-theoretic privacy* relaxes the standard notion of information-theoretic privacy by considering a scenario in which the honest party’s input is chosen at random (and the adversary’s input may be arbitrary) and by requiring only a fixed inverse polynomial simulation error as opposed to negligible.<sup>5</sup> In addition, the derived reduction is not completely non-interactive since the parties need an access to a common reference string (that can be removed at the expense of making the reduction non-uniform). These caveats can be removed under some circumstances (e.g., if the preprocessing algorithms make only random queries to the random-oracle which is the case in all existing constructions that employ a PRG – See Section 3).

Even with these minor caveats, the theorem’s implication is highly non-trivial since it implies constant-round information-theoretic MPC protocols that are far beyond the current state-of-the-art. For example, the implication of Theorem 2 allows us to compute every efficiently-computable two-party functionality using a constant-round protocol with inverse-polynomial average-case information-theoretic security in the OT-hybrid model. This, in turn, leads to a constant-round protocol for any efficiently-computable 3-party functionality with inverse-polynomial average-case information-theoretic security.<sup>6</sup> The existence of such protocols is a well-known 3-decade old open problem in information-theoretic cryptography that goes back to the seminal work of Beaver, Micali and Rogaway [14]. (See also the discussions in [36,33,43].) While the original question is typically formulated with respect to standard security, the relaxation to inverse-polynomial average-case security does not seem to make it more tractable.

We complement our main result with some positive results. First, we observe that any passively-secure elementary reduction can be compiled into an actively-secure non-interactive, yet non-elementary, reduction.

**Observation 1** *Suppose that the functionality  $f$  reduces to a constant degree functionality  $g$  via a non-interactive passively-secure reduction  $\Pi$ . Then,  $f$  reduces to a constant-degree functionality  $g'$  via a non-interactive actively-secure reduction  $\Pi'$  with guaranteed output delivery. Moreover, if  $\Pi$  is information-theoretically secure then so is  $\Pi'$ . The description of  $g'$  and  $\Pi'$  depends on the description of the preprocessing part of  $\Pi$ . Specifically, if  $\Pi$  makes use of a PRG in the preprocessing phase, then  $\Pi'$  and  $g'$  depend on the code of the PRG.*

This simple observation (whose proof is deferred to the full-version of this paper) shows that an elementary information-theoretic passively-secure reduction

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<sup>5</sup> This relaxation applies only to privacy, and correctness holds for arbitrary inputs except with negligible probability. Also, we can support an arbitrary inverse polynomial privacy error  $\alpha$ , at the expense of a  $\text{poly}(n)(1/\alpha)$  slow-down in the running-time of the protocol.

<sup>6</sup> Both results can be lifted to the active setting as well.

can be upgraded “for-free” to an information-theoretic actively-secure elementary reduction. Specifically, it can be used to upgrade the implication in Theorem 2 to the active setting (however the reduction still achieves only inverse polynomial average-case security).

Getting back to the computational setting, by combining Observation 1 with the passively-secure elementary reductions from Theorem 1, we derive the following corollary.

**Corollary 1.** *Assuming the existence of pseudorandom generators, every efficiently-computable functionality  $f$  reduces to a constant-degree functionality  $g$  via a non-interactive computationally-secure reduction with guaranteed output delivery against an active adversary. The reduction and the functionality  $g$  make a non-black-box use of the PRG.*

Previously, such a result was known only based on an  $\text{NC}^1$ -computable PRG [9] (or equivalently  $\text{NC}^1$ -computable one-way function; see [3, Chapter 5]). The combination of Theorems 2 and Corollary 1, provides another interesting example for a gap between a black-box use of a primitive and a non-Black-Box use of a primitive. (See Section 1.3 for further discussion.)

Finally, we ask what level of active security can be obtained via elementary reductions. It turns out that it is possible to obtain the following notion of *security with identifiable abort* [11]: Upon abort every honest party learns the identity of some corrupted party. (This additional feature provides several advantages – see [37] for a discussion.)

**Theorem 3.** *Every efficiently-computable functionality reduces to a constant-degree functionality via an elementary computationally-secure reduction that achieves active security with identifiable abort.*

This result can be extracted from the recent constant-round protocol of Baum et al. [13]. We provide a self-contained proof that highlights the main ingredients needed for elementary reductions. Our construction also has a minor advantage: It natively supports fairness at the expense of an additional round of interaction. That is, if the parties are allowed to interact with  $g$  twice (or, equivalently, replace  $g$  with two sequential calls to memoryless constant-degree functionalities  $g_1$  and  $g_2$ ) then full fairness can be obtained! (See Remarks 3 and 4.)

## 1.2 Technical Overview

Let us start by examining the computationally-secure passive elementary reductions from Theorem 1 and see why they fail to achieve active security.

*Attacking current protocols.* At a high-level, the garbled circuit technique non-interactively reduces the computation of the target functionality  $f$  to the computation of some form of a distributed encryption scheme. To make the reduction efficient for high-depth circuits, one has to use an encryption scheme whose keys are shorter than the message. The latter can be based on a PRG. Since the PRG should be employed locally, we ask each party  $P_i$  to compute, in the preprocessing phase, the PRG values on many random seeds  $(s_1, \dots, s_t)$  and send each of

these seeds,  $s_j$ , together with the outcome,  $\text{PRG}(s_j)$ , to the functionality  $g$ . The functionality  $g$  then combines these values together (via a low-degree operation) and outputs a bunch of ciphertexts for each gate of the circuit, together with some keys (seeds) for the input wires. In the postprocessing phase, each party  $P_i$  decodes the output of  $f$  by decrypting some of the ciphertexts (according to the computation path of the garbled circuit). As part of this decryption operation,  $P_i$  computes the PRG on seeds that were selected locally during the preprocessing phase by each of the participating parties. This structure ensures that this non-interactive reduction is indeed elementary: The functionality  $g$  is independent of the PRG, and the PRG is being invoked only locally and only in a black-box way.

Unfortunately, in the active setting, this independence can be exploited. An active adversary can send an invalid pair of the form  $(s, y \neq \text{PRG}(s))$ , and the functionality  $g$ , being “unaware” of the PRG, will not be able to detect such a cheating. As a result, honest parties are likely to get garbage values during the postprocessing phase and the decoding is likely to fail. Moreover, if the adversary knows an actual seed  $s'$  for which  $y = \text{PRG}(s')$ , then the adversary can, in principle, recover the correct value of  $f(x_1, \dots, x_n)$ , violating the fairness of the protocol. Our main theorem shows that this problem is not specific to the current instantiations of garbled circuits: Such an attack is inherent in the setting of elementary reductions and it can be avoided only if the PRG is not “really needed”.

*Attacking general protocols.* For simplicity let us focus on the two party case. We assume that the PRG is instantiated with a random oracle  $H$  and, for now, let us further assume that the parties invoke the oracle on randomly chosen seeds. Loosely speaking, we apply a variant of the above attack in which the second (corrupted) party samples a local independent random oracle  $G$  and uses this oracle in the preprocessing phase instead of using the publicly available oracle  $H$ . We argue that the reduction cannot detect such a cheating. Moreover, we note that the second party can still correctly recover the final outcome of the protocol. Indeed, except with negligible probability, the parties do not query the oracle on the same input, and so one can pretend that they honestly invoked the protocol on a new random oracle that is obtained by combining the oracles  $H$  and  $G$ . Both oracles are available for the second party and so she can use them in the postprocessing phase to correctly recover the output  $f(x_1, x_2)$ . Now if the protocol is indeed fair, then, intuitively, the first party should also be able to recover the output correctly (by accessing only  $H$  and without an access to the local oracle  $G$ ). Furthermore, it can be shown that even under this attack the honest party,  $P_1$ , learns nothing on the input of the corrupted party  $P_2$ .<sup>7</sup> Therefore, we get a modified protocol in which the preprocessing and

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<sup>7</sup> Both statements regarding the view of  $P_1$  (“fairness leads to correct output for  $P_1$ ” and “ $P_1$  learns nothing on  $P_2$ ’s input”) are not immediate. First, the formal simulation-based definition of fairness only ensures that  $P_1$  generates an output  $f(x_1, x'_2)$  with respect to some “effective input”  $x'_2$  of  $P_2$  and not necessarily with respect to the “real” input  $x_2$  that is given to  $P_2$ . This technicality is solved by

postprocessing computation of  $P_1$  depends only on  $H$ , the preprocessing part of  $P_2$  depends only on  $G$ , and its postprocessing computation depends on both  $G$  and  $H$ . We can therefore further modify the protocol by asking  $P_1$  (resp.,  $P_2$ ) to locally sample its own oracle  $H$  (resp.,  $G$ ), while removing the postprocessing phase of  $P_2$  and replacing it with an empty output. (Formally, we also change the functionality  $g$  so that it hands to  $P_2$  an empty value  $\perp$ .) This gives us an information-theoretic passively-secure non-interactive reduction that delivers an output only to the first party. We can easily fix this caveat and distribute an output to both parties, by running two copies of the reduction in parallel where  $P_1$  is the receiver in one copy and  $P_2$  is the receiver in the other copy. We can further make the reduction actively-secure by invoking Observation 1.

The above description is over-simplistic since we assumed that the parties call the PRG on uniform independent seeds. While this is a reasonable assumption (especially if the random oracle models a PRG), it can be removed via standard techniques. Specifically, the above argument holds as long as the calls to  $G$  and  $H$  in the preprocessing phase do not intersect. To avoid such an event, we identify “heavy” queries [12], and let  $P_2$  use its local oracle  $G$  only on non-heavy queries. This modification introduces several technicalities, which eventually allow us to obtain only inverse-polynomial average-case security. We can make sure that this problem does not affect the correctness of the protocol by adding to the functionality  $g$  a “detect-and-reveal” mechanism that identifies a “collision event” and releases, when such an event occurs, the private inputs of the parties. Thus, even when the event happens correctness remains unaffected. This additional mechanism increases the complexity of  $g$  to  $\text{NC}^1$ , and we can reduce its degree to a constant, by replacing the functionality with an  $\text{NC}^0$  information-theoretic randomized encoding.

*About the proofs of positive results.* As already mentioned, there are non-interactive reductions that preserve full active security (including guaranteed output delivery) either with information-theoretic security for  $\text{NC}^1$  functionalities [34,35] or with computational security for polynomial-size circuits assuming a non-black-box access a PRG in  $\text{NC}^1$  [9]. These results are based on constant-degree information-theoretic/computational randomized encodings which essentially correspond to extremely simple non-interactive reductions in which the parties do not apply any preprocessing computation. This feature is obtained by pushing all the computation to functionality  $g$ ; For  $\text{NC}^1$  functionalities this can be done by plugging an information-theoretic encryption scheme (e.g., one-time pad) into the garbled circuit construction, and in the computational setting, this is essentially done by relying on a PRG whose complexity is low enough so that it can be computed by  $g$ .

In order to derive Observation 1, we note that instead of pushing the computation of the preprocessing part to  $g$ , it suffices to let  $g$  *verify* that the preprocessing of  $P_i$  was done properly and to replace  $P_i$ 's input to  $g$  with some default

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working with “authenticated functionalities”. Second, the standard MPC definition provides no guarantees on the privacy of a party  $P_2$  that deviates from the protocol. So the fact that  $P_1$  learns nothing requires concrete justification.



value if this condition fails. It is well known that such a verification procedure can be implemented via an  $\text{NC}^1$  functionality by asking each party to supply all the intermediate values of the preprocessing circuit, and by checking a list of degree-2 constraints, one for each gate. We can further replace this  $\text{NC}^1$  functionality with its constant-degree randomized encoding and derive Observation 1.

Finally, in order to obtain elementary reduction with identifiable abort (Theorem 3), we consider the garbled circuit construction and abstract the syntax of distributed encryption scheme that suffices for deriving elementary reduction. Roughly, despite being a symmetric-key cryptosystem, the key-generation algorithm (that will be run locally by each party) generates pairs of encryption/decryption keys, and is allowed to access a PRG. The encryption algorithm (which will be embedded inside  $g$ ) uses multiple encryption keys, one from each party, and some internal randomness, to encrypt a message. This algorithm should be in  $\text{NC}^1$  and should be PRG-independent. Finally, the decryption algorithm takes a ciphertext and decryption keys, and recovers the plaintext or outputs an error flag. This algorithm will be embedded in the postprocessing phase and is therefore allowed to call the PRG. We further require an expansion property, that is, the decryption keys should be shorter than the messages. We define different forms of robustness against malicious key-generation, and show how they affect the security of the resulting elementary reduction. While similar ideas have appeared implicitly in previous works (e.g., [14,20,13]), we believe that our formulation clarifies the necessary conditions that enable elementary reductions. We present a new instantiation of distributed encryption whose security suffices for “identifiable abort”, and for fairness given an additional round of interaction. The construction is based on information-theoretic MACs and secret-sharing based cut-and-choose ideas.

### 1.3 Discussion and other related works

*MPC reductions and Fairness.* There is a rich body of works studying fairness in MPC. (A summary of some central lower-bounds and upper-bounds can be found in [29] and in [27,40].) Most relevant to us is the work of Gordon et al. [28] on complete primitives for fairness. This work studies the ability to reduce fair protocols for general functionalities  $f$  to fair protocols for simpler functionalities  $g$  where “simplicity” is measured with respect to the input length of  $g$ . Our work complements this study by considering a different form of simplicity (low degree) and more restricted type of reductions (non-interactive).

*Elementary reductions to degree-2 functionalities.* Recent results regarding the exact round complexity of MPC, have motivated the study of the exact degree of the functionality  $g$  for which  $f$  reduces to. While the original randomized encoding tools achieve degree-3, the breakthrough results of [23,16] suggested that it may be possible to non-interactively reduce every efficiently-computable function to a degree-2 function. Indeed, such reductions were obtained explicitly in [6,7,10], and implicitly in [22,1,2], both for active and passive adversaries. For the honest majority setting, these reductions are elementary (with computational security for polynomial-size circuits and information-theoretic security for  $\text{NC}^1$

circuits) and, for the dishonest majority setting these reductions rely on a non-black-box use of oblivious transfer. The latter non-black-box dependency was shown to be necessary in [5] even if one is allowed to treat the oblivious transfer as a two-round functionality and allow the reduction to have two rounds of interaction.

*Other limits of random oracles in secure computation.* Haitner, Omri and Zarosim [30] and Mahmoody, Maji and Prabhakaran [39] showed that random oracles are essentially “useless” for secure 2-party computation of various functionalities. Specifically, they extended the Impagliazzo-Rudich separation [32] (and its tighter analysis given in [12]) and showed that, under mild conditions on the underlying functionality, any passively-secure protocol that makes use of a random oracle (RO) can be compiled into an information-theoretic protocol that does not depend on the random oracle. (In the active setting, the random oracle can be traded with an ideal commitment scheme.) While this result somewhat resembles our main theorem there are several important differences that suggest that our work captures a different limitation than the one captured in [30,39]. Details follow.

Firstly, the results of [30,39] work in the plain model while our results operate in a hybrid model in which the parties have access to a trusted party that implements a multiparty functionality. The power and usefulness of RO significantly changes in the presence of such a trusted party and one cannot easily transfer results from the plain model to the hybrid model. Indeed, our theorem is very sensitive to the exact notion of security that is being used and to the non-interactive nature of the reduction. In particular, Theorem 2 becomes incorrect if one allows an additional round of interaction or if one relaxes security to passive or even to security with abort as shown in Theorem 3. Secondly, from a technical point of view, our proof strongly exploits the fact that the functionality  $g$  is unaware of the structure of the PRG, together with the fairness properties of the protocol. These issues are unique to our setting and they do not appear in [30,39]. On the other hand, while the proofs of [30,39] tackle the challenging task of locally simulating the correlation that is induced in a RO-based interactive protocol, in our *non-interactive* setting this issue is handled easily based on simple machinery. (Specifically, we employ an extremely degenerate version of heavy-query learners. See Section 3.) Finally, and perhaps most importantly, we know that a non-black-box access to PRGs *does help* in our setting, and it can be used to bypass the negative result (i.e., to obtain computationally-secure fair non-interactive reductions as shown in Corollary 1). No similar result is known in the plain model.

Taking a more general perspective, our work provides an interesting example for a cryptographic task for which (1) we cannot rule out the existence of an information-theoretic solution; (2) we can show that a black-box use of a given primitive is useless; but (3) a non-black-box use of the primitive allows us to solve the problem. While we are aware of examples in which (1) and (2) hold (e.g., [30,39]), and examples where (2) and (3) hold (most closely to our work,

the impossibility of elementary reductions to oblivious transfer [5]), the current combination of (1)–(3) seems rather unique to our setting.

## 2 Elementary Reductions

In this section, we formalize the notion of elementary reductions. At a high level, an elementary reduction from an  $n$ -input functionality  $f$  to another  $n$ -input, constant degree, non-cryptographic functionality  $g$ , is a non-interactive reduction that yields a non-interactive secure MPC protocol realizing  $f$ , where the parties make a single query to a trusted implementation of  $g$ . We refer to such protocols as elementary  $g$ -oracle protocols. We start by formally defining the syntax of such protocols. A pictorial representation of an elementary  $g$ -oracle protocol appears in Figure 1.

**Definition 1 (Non-interactive  $g$ -oracle Protocol).** *A non-interactive  $g$ -oracle protocol is an  $n$ -party MPC protocol in the  $g$ -hybrid model that makes a single non-interactive call to the functionality  $g$ . Such a protocol is defined by a tuple of PPT algorithms  $(\text{pre}_1, \dots, \text{pre}_n, \text{post}_1, \dots, \text{post}_n)$ , where the parties make a single call to the  $n$ -input ideal functionality  $g$  as follows:*

1. **Pre-processing:** Each party  $P_i$  (for  $i \in [n]$ ) runs the pre-processing algorithm  $\text{pre}_i$  on its input  $x_i$  and randomness  $r_i$  to obtain  $y_i$ .
2.  **$g$ -oracle:** Each party  $P_i$  (for  $i \in [n]$ ) invokes functionality  $g$  using its pre-processed input  $y_i$ . The functionality returns output  $v_i$  to party  $P_i$ .
3. **Post-processing:** Each party  $P_i$  (for  $i \in [n]$ ) finally runs the post-processing algorithm  $\text{post}_i$  on the output  $v_i$  received from  $g$  to obtain the final output  $z_i$ .

*The protocol is elementary if the preprocessing and postprocessing algorithms make only black-box calls to a PRG and  $g$  is a constant-degree functionality (i.e., each of its outputs can be written as a constant degree polynomial over the binary field) whose description is independent of the PRG.*

The security of  $g$ -oracle Protocol is defined by following the standard real/ideal paradigm using the standard extension to the hybrid model (see, for example, [24, Chapter 7] and [17]), and can be instantiated with different variants of security (e.g., computational/information-theoretic, passive/active, guaranteed-output-delivery/fairness/security-with-abort/security-with-identifiable abort). We postpone the exact specification to the technical sections.

*Remark 1 (Non-Interactive Reductions and Randomized Encoding).* Given a non-interactive  $g$ -oracle protocol for  $f$  and a randomized encoding  $\hat{g}(y; \rho)$  of  $g(y)$ , one can always obtain a non-interactive  $g'$ -oracle protocol where  $g'(y, \rho_1, \dots, \rho_n) := \hat{g}(x; \sum_i \rho_i)$ , the original preprocessing functions are extended by letting each party send a random string  $\rho_i$  to the functionality  $g'$  (in addition to the original  $(y_i, r_i)$  parts) and the postprocessing algorithm is extended with the RE decoder. This transformation preserves all the types of security that are

considered in this paper (including information-theoretic security), and does not rely on computational assumptions/tools. Since  $\text{NC}^1$  functionalities can be encoded by constant-degree functionalities [35] or even by  $\text{NC}^0$  functionalities [8], we can freely move from a liberal definition of elementary protocols in which  $g$  is allowed to be an  $\text{NC}^1$  (possibly randomized) functionality, to a more restricted definition in which  $g$  should be a constant-degree deterministic functionality or even an  $\text{NC}^0$  functionality.

### 3 Lower Bound for Elementary Reduction with Fairness

#### 3.1 The Set-up

In this section, we focus for simplicity on two-party functionalities  $f : X_1 \times X_2 \rightarrow Z_1 \times Z_2$  where  $f_i : X_1 \times X_2 \rightarrow Z_i$  denote the restriction of  $f$  to its  $i$ -th output. Let  $\mathcal{H}$  be a probability distributions over functions from  $\mathcal{D}$  to  $\mathcal{R}$ . An elementary non-interactive reduction  $\Pi$  from  $f$  to a two-party functionality  $g : Y_1 \times Y_2 \rightarrow V_1 \times V_2$  in the  $\mathcal{H}$  model consists of four oracle aided algorithms  $(\text{pre}_1, \text{post}_1, \text{pre}_2, \text{post}_2)$  which are sometimes grouped as  $P_1 = (\text{pre}_1, \text{post}_1)$  and  $P_2 = (\text{pre}_2, \text{post}_2)$ . Formally, all the above objects are parameterized by a security parameter  $\lambda$ , and they are required to be computationally-efficient with respect to this parameter. For simplicity (and without loss of generality), we assume that the  $f_\lambda$  is defined over  $\{0, 1\}^\lambda \times \{0, 1\}^\lambda$  and so we can think of the input length as the security parameter (which will be kept implicit most of the time). For concreteness, we also think of the domain  $\mathcal{D}_\lambda$  and range  $\mathcal{R}_\lambda$  of  $\mathcal{H}_\lambda$  as  $\{0, 1\}^\lambda$ . (Though, our results are insensitive to this choice, and any domain and range can be used as long as there exists a  $\text{poly}(\lambda)$ -time algorithm that uniformly samples a an element from these sets.)

We assume that when the parties are honest the outputs generated by the reduction are correct except with negligible error. The reduction should also achieve passive security against an adversary that corrupts the first party (aka *privacy*) and a weak form of partial fairness against an active adversary that corrupts the second party. We formalize these notions below for general protocols in the  $\mathcal{H}$ -model. (These definitions will be applied to MPC reductions, and specifically, to non-interactive  $g$ -oracle protocols.)

*Passive security in the  $\mathcal{H}$  model.* Following the standard convention, when working with respect to random oracles we assume that adversaries are computationally unbounded but make a polynomially-bounded number of queries to the oracle (see, e.g., [30,39,5]). We also introduce an average-case version of privacy.

**Definition 2 (privacy and AVG-privacy).** *A protocol  $\Pi$  in the  $\mathcal{H}$ -hybrid model realizes  $f$  with  $\alpha$ -privacy against party  $i$  if there exists an efficient randomized simulator  $\text{Sim}(x_i, z_i)$  whose output consists of a view  $w$  and a stateful randomized oracle  $H$  such that for every computationally-unbounded distinguisher  $\mathcal{A}$  that makes at most  $\text{poly}(\lambda)$  queries to its oracle and for every  $\lambda$ -bit*

inputs  $(x_1, x_2)$  it holds that

$$\Delta_{\mathcal{A}, \Pi, i}(x_1, x_2) := \left| \Pr_{H \leftarrow \mathcal{H}_\lambda} [\mathcal{A}^H(x_1, x_2, \text{view}_{\Pi, P_i}^H(x_1, x_2)) = 1] - \Pr_{(w, H) \leftarrow \mathcal{S} \text{Sim}(x_i, f_i(x_1, x_2))} [\mathcal{A}^H(x_1, x_2, w) = 1] \right|,$$

is upper-bounded by  $\alpha(\lambda)$ , where  $\text{view}_{\Pi, P_i}^H(x_1, x_2)$  denotes the view of  $P_i$  in an execution of  $\Pi^H(x_1, x_2)$  with fresh randomness for both parties and oracle  $H$ . If  $\alpha$  is negligible, we say that  $\Pi$  is IND-private against party  $i$ .

We say that the protocol is  $\alpha$ -AVG-private against the first party if for every computationally-unbounded distinguisher  $\mathcal{A}$  that makes at most  $\text{poly}(\lambda)$  queries to its oracle and for every  $\lambda$ -bit input  $x_1$ , it holds that

$$\mathbb{E}_{x_2} [\Delta_{\mathcal{A}, \Pi, 1}(x_1, x_2)] \leq \alpha(\lambda).$$

The notion of  $\alpha$ -AVG-privacy against the second party is defined analogously, i.e., for every  $x_2$ , we require that  $\mathbb{E}_{x_1} [\Delta_{\mathcal{A}, \Pi, 2}(x_1, x_2)] \leq \alpha(\lambda)$ .

We mention that our proof goes through even if one uses a slightly weaker definition in which the oracle queries of the distinguisher  $\mathcal{A}$  may depend only on the input of the corrupted party. We prefer the current definition due to its simplicity.

The *random oracle* model corresponds to the case where  $\mathcal{H}$  is distributed uniformly over all functions from  $\mathcal{D}_\lambda$  to  $\mathcal{R}_\lambda$ . Also, observe that the notion of information-theoretic IND-privacy in the *standard model* can be derived from the above definition by instantiating  $\mathcal{H}$  with some fixed simple function (like the all zero function or the identity function.)

*Fairness against  $P_2$ .* Following Goldwasser and Lindell [26], we require *fairness* against an active adversary that corrupts only the *second party* (aka *partial fairness*).<sup>8</sup> Roughly speaking, this means that when  $P_1$  is honest, complete fairness is essentially achieved (i.e., either all parties abort or all parties receive correct outputs). But when  $P_1$  is actively corrupt, fairness may be violated. In fact, unlike the notion of partial fairness from [26], we make no requirement at all in this case (i.e., an actively corrupted  $P_1$  can learn the input of  $P_2$ ). Again, this makes the result stronger.

**Definition 3 (Fairness against  $P_2$ ).** A protocol  $\Pi$  in the  $\mathcal{H}$ -hybrid model realizes  $f$  with fairness against an adversary that corrupts  $P_2$  if for every computationally-unbounded distinguisher  $\mathcal{A}$  that makes at most  $\text{poly}(\lambda)$  queries to its oracle, there exists a simulator  $\text{Sim}$  whose running-time is polynomial in the running time of  $\mathcal{A}$ , such that for every pair of inputs  $x_1, x_2 \in \{0, 1\}^\lambda$  the distributions  $\text{Ideal}_{f, \text{Sim}}(x_1, x_2)$  and  $\text{Real}_{\Pi, \mathcal{A}}^H(x_1, x_2)$ , where  $H \leftarrow \mathcal{H}_\lambda$  cannot be

<sup>8</sup> As mentioned in the introduction, unlike full fairness which is impossible in the plain model without honest majority [19], partial fairness can be achieved (using multiple rounds) in the plain model assuming the existence of OT.

distinguished by any computationally-unbounded distinguisher  $D$  with advantage better than negligible.

As usual, the random variable  $\text{Real}_{\Pi, \mathcal{A}}^H(x_1, x_2)$  corresponds to the joint outputs of  $P_1$  and the  $\mathcal{A}$  (who corrupts  $P_2$ ) in the execution of  $\Pi$  over the inputs  $x_1$  and  $x_2$  and with respect to the oracle  $H$ . The random variable  $\text{Ideal}_{f, \text{Sim}}(x_1, x_2) = (z_1, z_2)$  corresponds to the joint outputs of the first party and  $\text{Sim}$  in an ideal-world execution in which the parties access to an  $f$ -oracle that either computes  $f$  or sends an abort symbol to both parties (depending on the choice of the simulator). That is,  $\text{Sim}(x_2)$  computes some  $x'_2 \in X_2 \cup \{\perp\}$  and sends it to  $f$ . If  $x'_2 = \perp$  the functionality sets the output  $z_1$  of  $P_1$  to  $\perp$  and returns  $z'_2 = \perp$  to the simulator, and if  $x'_2 \neq \perp$  the functionality returns  $z_1 = f_1(x_1, x'_2)$  and  $z'_2 = f_2(x_1, x'_2)$ . The simulator terminates with the output  $z_2$  which is computed based on  $z'_2$  and its internal state.

*Remark 2 (weak fairness).* We remark that for our purposes, it suffices to assume that fairness holds only for *computationally-bounded* adversary  $\mathcal{A}$  and even if the corresponding simulator is allowed to be computationally unbounded. Even more importantly, we only need to consider the following specific (computationally-bounded) distinguisher  $D$  that given a pair  $(z_1, z_2)$  (supposedly sampled from  $\text{Ideal}_{f, \text{Sim}}^H(x_1, x_2)$  or from  $\text{Real}_{\Pi, \mathcal{A}}^H(x_1, x_2)$ ) outputs 1 if

$$z_1 \neq f_1(x_1, x_2) \wedge z_2 = f_2(x_1, x_2).$$

Equivalently, one can think of a game (that can be played both in the ideal world and real world) in which the adversary  $\mathcal{A}(x_2)$  (resp., simulator  $\text{Sim}(x_2)$ ) wins when interacting with  $P_1(x_1)$ , if she outputs the “right” value  $f_2(x_1, x_2)$  while the honest party  $P_1$  errs and outputs some  $z_1 \neq f_1(x_1, x_2)$ . We say that a protocol achieves weak-fairness against  $P_2$  if for any such adversary  $\mathcal{A}$ , there exists an ideal-world simulator  $\text{Sim}$  such that for every  $x_1, x_2$ , the winning probability in the real execution is upper-bounded by the winning probability in the ideal execution (plus some negligible quantity).

Weak fairness is implied by fairness, and it can be viewed as an extension of the correctness property of the protocol. (Indeed, if, for example, the honest party outputs the “right” value, we do not care whether an active adversary gets to learn the honest party’s input.)

*Authenticated functionality.* Fairness will be mostly useful when it is applied to so-called authenticated functionalities. Formally, given an arbitrary 2-party functionality  $f_1(x_1, x_2)$  that delivers an output only to  $P_1$ , we define a 2-party functionality  $f((x_1, k), x_2)$  that delivers  $f_1(x_1, x_2)$  to  $P_1$  and delivers  $\text{MAC}_k(x_2)$  to  $P_2$  where  $k$  is a  $\lambda$ -bit key for a one-time information-theoretic secure message authentication-code MAC. We refer to  $f$  as the  $P_1$ -authenticated version of  $f_1$ .

### 3.2 Main Results

We can now state our key theorem whose proof will be deferred to the following subsections. In the following, we say that a reduction  $\Pi$  in the random-oracle

model makes *input-independent queries* if the calls to the oracle  $H$  that a party  $P_i$  makes are statistically-independent of its input  $x_i$ . We say that the reduction makes uniform queries if, in addition, each query to  $H$  in the preprocessing phase is sampled uniformly and independently of all the other queries. Known elementary reductions (that make use of PRG's) satisfy these additional properties.

**Theorem 4.** *Let  $f$  be the  $P_1$ -authenticated version of some functionality  $f_1$ . Assume the existence of an elementary non-interactive reduction  $\Pi$  from  $f$  to a constant-degree two-party functionality  $g : Y_1 \times Y_2 \rightarrow V_1 \times V_2$  in the random-oracle model that achieves privacy against  $P_1$  and weak fairness against  $P_2$ . Then, for every inverse polynomial  $\alpha(\lambda)$ , there exists an efficient two-round reduction  $\Sigma$  from  $f_1$  to an  $\text{NC}^1$  functionality  $g'$  with the following properties.*

1. (*Syntax*) *At the first round  $P_1$  sends a message to  $P_2$  that consists of random coins. Then, both parties make a call to  $g'$  (who delivers output only to  $P_1$ ) and then  $P_1$  applies some postprocessing computation and terminates with an output. (The other party terminates with an empty output.)*
2. (*Correctness*) *For every input  $x_1, x_2$  the output of  $P_1$  is  $f_1(x_1, x_2)$  except with negligible probability.*
3. (*Privacy against  $P_2$* ) *The reduction achieves information-theoretic privacy against the second party.*
4. (*AVG-privacy against  $P_1$* ) *The reduction achieves information-theoretic  $\alpha$ -AVG-privacy against the first party. Moreover, if the original reduction  $\Pi$  makes only input-independent queries then the reduction  $\Sigma$  is  $O(\alpha)$ -private, and if the reduction makes uniform queries then  $\Sigma$  is private (with negligible privacy error).<sup>9</sup>*

Since the first message sent from  $P_1$  to  $P_2$  in  $\Sigma$  consists of only random coins, we can think of  $\Sigma$  as a non-interactive reduction in a CRS model where the parties get an access to a shared random string. (For passively-secure protocols, the CRS model is equivalent to a two-round model in which the first message contains random coins.)

By repeating the reduction twice (while replacing the roles of  $P_1$  and  $P_2$ ) we can make sure that both parties receive an output. Moreover, we can reduce the complexity of  $g'$  from  $\text{NC}^1$  to an  $\text{NC}^0$  functionality (following Remark 1), and derive Theorem 2. Furthermore, by exploiting the fact that  $\text{NC}^0$  functionalities can be evaluated by making a single round of parallel calls to an ideal OT-functionality with passive information-theoretic privacy (using a variant of Yao's protocol), we get the following corollary.

**Corollary 2.** *Suppose that every efficiently-computable two-party functionality  $f$  can be reduced to some constant-degree two-party functionality in the random-oracle model via an elementary reduction that achieves privacy against  $P_1$  and weak fairness against  $P_2$ .*

<sup>9</sup> In fact, it suffices to assume that only the preprocessing algorithm of  $P_2$  makes input-independent/uniform queries.

Then, every such functionality can be computed in the CRS model by making only parallel calls to Oblivious-Transfer with information-theoretic  $O(\alpha)$ -AVG-privacy for any a-priory given inverse polynomial  $\alpha$ . Furthermore, if the hypothesis holds with respect to reductions that make input-independent queries then the resulting protocol is  $O(\alpha)$ -private, and if the hypothesis holds with respect to uniform queries then the resulting protocol is private (with negligible privacy error).

We note that the above yields an efficient constant-round multiparty protocol for  $n \geq 3$  in the plain model with passive  $O(\alpha)$ -AVG-privacy against any single party. Indeed, consider, wlog, the single-output functionality  $f(x_1, \dots, x_n)$  that delivers its output to  $P_1$ . Then each party  $i$  shares its input  $x_i$  via 2-out-of-2 secret-sharing and hands one share  $r_i$  to  $P_1$  and another share  $x'_i = r_i \oplus x_i$  to  $P_2$ . Then,  $P_1$  and  $P_2$  run the OT-based protocol (promised by Corollary 2) for the two-party functionality  $f'((r_1, \dots, r_n), (x'_1, \dots, x'_n))$  where the OT-channel is being replaced by a constant-round protocol (e.g., BGW) for computing the degree-2 OT functionality.

*Notation.* The following notation will be extensively used throughout the proof of Theorem 4. For a pair of oracles  $G, H : \mathcal{D} \rightarrow \mathcal{R}$  and a set  $S \subset \mathcal{D}$ , we define the oracle  $G[S] \cup H$  to be the oracle that given  $q$  returns  $G(q)$  if  $q \in S$  and otherwise, returns  $H(q)$ . For an oracle-aided algorithm  $A(x; r)$  with input  $x$  and randomness  $r$  we let  $Q(A^H(x; r))$  denote the tuple of queries that  $A(x; r)$  makes to  $H$ . When  $r$  is omitted,  $Q(A^H(x))$  denotes the random variable that contains all the queries that  $A$  makes when executed with  $x$ ,  $H$  and a uniformly chosen  $r$ .

### 3.3 Tools: Finding Heavy queries

To prove Theorem 4, we will need the following simple lemma that can be viewed as a (very) degenerate version of the Barak-Mahmoody [12] heavy-query learner.

**Lemma 1.** *Let  $A$  be a randomized input-less oracle-aided algorithm that makes at most  $T$  queries to a random oracle  $H : \mathcal{D} \rightarrow \mathcal{R}$  and runs in time  $t$ . Then, there exists an oracle-aided randomized “heavy-query finder” algorithm  $F_A^H(\epsilon, \delta)$  with the following properties:*

1. (efficiency)  $F_A^H(\epsilon, \delta)$  runs in time  $\text{poly}(1/\epsilon, \log(1/\delta), t)$  and makes at most  $\text{poly}(T, 1/\epsilon, \log(1/\delta))$  queries to its oracle  $H$ . The output of  $F_A^H(\epsilon, \delta)$ , denoted by  $Q_h$ , is the list of queries that  $F$  issued to its oracle  $H$ .
2. (Hitting heavy queries) For every fixing of the oracle  $H$ , with probability  $1 - \delta$  over the internal coins of  $F$  the output  $Q_h$  of  $F_A^H(\epsilon, \delta)$  satisfies the following

$$\forall w \notin Q_h, \quad \Pr_{r_A, G}[w \in Q(A^{H[Q_h] \cup G}(r_A))] \leq \epsilon, \quad (1)$$

where  $r_A$  denotes the random tape of  $A$ .

That is, in a random execution of  $A$  in which queries that belong to  $Q_h$  are answered by  $H$  and other queries are answered by an independent random oracle  $G$ , every string  $w \notin Q_h$  will be hit by a query of  $A$  with probability at most  $\epsilon$ .



*Proof.* Let us assume without loss of generality that  $A$  never makes the same query twice. For  $i \in [T]$ , we let  $A_i$  denote a modified version of the algorithm  $A$  which is halted after  $i$  queries. (Thus  $A_T = A$ .) The algorithm  $F$  proceeds as follows.

1. Take  $\epsilon' = \epsilon/T$  and let  $\ell = O((1/\epsilon') \log(T/(\delta \cdot \epsilon)))$ , and initializes an empty list  $Q_h$ .
2. For  $i = 1$  to  $T$  do:
  - (a) Sample  $\ell$  random inputs,  $r^1, \dots, r^\ell$  for  $A$ , use “lazy sampling” to sample  $\ell$  random oracles  $G^1, \dots, G^\ell$  and invoke  $\ell$  executions  $A_i(r^1), \dots, A_i(r^\ell)$  where the first  $i - 1$  queries of the  $j$ -th instance are answered according to  $H[Q_h] \cup G^j$ .
  - (b) Given the  $i$ -th tuple of queries  $(q^1, \dots, q^\ell)$  (hereafter referred to as the  $i$ -queries) we mark every string  $w$  that appears in at least  $\epsilon'/2$  locations as “heavy” and add it to  $Q_h$ .

For  $i \in [T]$  let  $Q_h[i]$  denote the set  $Q_h$  at the end of the  $i$ -th iteration and let  $Q_h[0]$  denote the empty set. Call  $Q_h[i]$  *good* if (1) holds wrt to  $Q_h[i]$ , the algorithm  $A_i$ , and the error parameter  $\epsilon_i = i \cdot \epsilon/T$ . Since  $Q_h[0]$  is trivially good, it suffices to show that for every  $i \in [T]$ ,

$$\Pr[Q_h[i] \text{ is good} \mid Q_h[i-1] \text{ is good}] \geq 1 - \delta/T,$$

and conclude, via a union-bound, that  $Q_h = Q_T$  is good with probability  $1 - \delta$ , as required.

Fix some  $i$ , and condition on  $Q_h[i-1]$  being good. We prove a lower-bound on the probability that  $Q_h[i]$  is good. Call a string  $w \notin Q_h[i-1]$  *heavy* if  $\Pr[q_i = w] > \epsilon'$ , where  $q_i$  is the random variable that represents the  $i$ -th query of  $A$  in a random execution where all the queries in  $Q_h[i-1]$  are answered by  $H$  and all other queries are answered by a random oracle  $G$ . (So the probability is taken over the randomness of  $A$  and the randomness of  $G$ .) Such a heavy query is expected to appear in at least  $\epsilon'$ -fraction of the  $i$ -queries, and therefore, by a Chernoff bound, a fixed heavy string  $w$  will be marked and added to  $Q_h[i]$  except with probability of  $\exp(-\Omega(\epsilon'\ell))$ . Since there are at most  $1/\epsilon'$  heavy strings, we conclude that, except we probability  $\exp(-\Omega(\epsilon'\ell))/\epsilon' \leq \delta/T$ , *all* heavy strings are added to  $Q_h[i]$ . In this case,  $Q_h[i]$  is indeed good, since the probability (over  $r_A$  and  $G$ ) that some  $w \notin Q_h[i]$  is being queried by  $A^{H[Q_h] \cup G}(r_A)$  is at most  $\epsilon_{i-1} + \epsilon' = (i-1)\epsilon/T + \epsilon/T = \epsilon_i$ , as required.  $\square$

### 3.4 Proof of Theorem 4

Let  $\Pi = (P_1 = (\text{pre}_1, \text{post}_1), P_2 = (\text{pre}_2, \text{post}_2))$  be an elementary non-interactive reduction from  $f$  to  $g(y_1, y_2) = (v_1, v_2)$  in the random-oracle model. Let  $T = T(\lambda)$  be an upper-bound on the number of queries that are made by both  $P_1$  and  $P_2$ . For an inverse polynomial parameter  $\alpha := \alpha(\lambda)$  set  $\epsilon = \alpha/(2T)$  and  $\delta = \alpha/2$ , and let  $F = F_{\text{pre}_2}(\epsilon, \delta)$  denote the heavy-query finder applied to  $\text{pre}_2$ , viewed as a randomized algorithm. (That is, we concatenate the input  $x_2$  of  $\text{pre}_2$  to its random tape  $r_1$ .) Observe that the running time of  $F$  is  $\text{poly}(\lambda)$ .

Recall that  $f$  denotes the  $P_1$ -authenticated version of  $f_1$ . Accordingly, the input of  $P_1$  consists of a pair  $(x_1, k)$  where  $k$  is a MAC-key. Throughout this section, we assume that  $P_1$  chooses  $k$  at random. Most of the time we will keep  $k$  implicit as part of the random tape  $r_1$  of  $P_1$ . That is, we let  $r_1 = (k, r'_1)$  where  $r'_1$  denotes the random tape of  $P_1$  that is consumed during the execution of the protocol.

**An intermediate protocol  $\Pi_1$  and the no-collision event** We consider the following modified reduction  $\Pi_1 = (P_1, P'_2)$  in which the second party gets an access to the standard random oracle  $H$  and an additional private random oracle  $G$ . (Jumping ahead, the oracle  $G$  will be sampled locally by the second party via lazy sampling.) Specifically, the party  $P'_2$  acts as follows:

- (preprocessing step) First  $P'_2$  calls the heavy-query finder  $F^H$  with randomness  $r_F$ , and gets a list of queries  $Q_h$ . Then  $P'_2$  invokes  $\text{pre}_2(x_2; r_2)$  with the oracle  $H[Q_h] \cup G$  where  $G$  is a private oracle defined by coins  $r_G$ ; That is, all the queries that are issued to the RO are answered by using the private oracle  $G$  unless they belong to  $Q_h$ .
- (postprocessing phase)  $P'_2$  first generates the list  $L$  of all queries that were issued to  $G$  in the preprocessing step. Next,  $P'_2$  invokes  $\text{post}_2(v_2; r_2)$  with the oracle  $G[L] \cup H$ . That is, whenever a query  $q$  is issued to the random oracle, she answers the query with  $G(q)$  if  $q \in L$ , and answers it with  $H(q)$  otherwise.

Our main goal is to show that  $P_1$  is likely to output the correct value. This will follow from a sequence of claim, but first it will be useful to define some “good” event under which correctness holds. (This event will also serves us in the following sections.)

*The good “no-collision” event  $E$ .* Informally, the “no collision” event happens if in the preprocessing phase  $P_1$  does not query any point that is sent in the preprocessing phase of  $P'_2$  to  $G$ . Formally, let  $Q_G$  denote the list of oracle queries that the preprocessing phase of  $P'_2$  sends to  $G$  when it is invoked with input  $x_2, r_2$  and  $r_F$  and with the oracles  $H$  and  $G$ , and let  $Q_1 = Q(\text{pre}_1^H(x_1; r_1))$  denote the list of oracle queries that  $P_1$  sends to  $H$  when it is invoked with inputs  $x_1, r_1$  and oracle  $H$ , we define the “no-collision” event to be

$$E := Q_1 \text{ and } Q_G \text{ are disjoint.}$$

Observe that  $E$  depends on the values  $(H, x_1, r_1, x_2, r_2, r_F, G)$ . The following claim follows from the properties of the algorithm  $F$ .

**Claim 5 (Collisions are rare).** *For every  $H, x_1$  and  $r_1$ , we have  $\Pr_{x_2, r_2, G, r_F}[\neg E] \leq \alpha$ .*

We defer the proof of this Claim to the full version of this paper.

Let  $\beta(x_1, x_2) := \Pr_{H, G, r_1, r_2, r_F}[\neg E(H, x_1, r_1, x_2, r_2, r_F, G)]$ . By Claim 5, for every  $x_1$ , the expectation  $\mathbb{E}_{x_2}[\beta(x_1, x_2)]$  is at most  $\alpha$ . If the reduction makes input-independent queries or uniform queries, a stronger bound can be easily derived.

**Claim 6.** *If  $\text{pre}_2$  makes input-independent queries (resp., uniform queries) then for every  $x_1, x_2$ , it holds that  $\beta(x_1, x_2)$  is upper-bounded by  $\alpha$  (resp., by a negligible function in  $\lambda$ ).*

We defer the proof of this Claim to the full version of this paper.

**Correctness of  $\Pi_1$**  We move on and show that, conditioned on  $E$ , the party  $P'_2$  is likely to output the “correct” value. Let  $\text{out}_{P_1, P'_2}^H(x_1, x_2; (r_1, r_2, r_F, G)) = (z'_1, z'_2)$  denote the outputs of  $P_1$  and  $P'_2$  on inputs  $(x_1, x_2)$ , oracle  $H$ , and random tapes  $r_1, r_2$  and  $r_F$  and local oracle  $G$ .

**Claim 7 ( $P'_2$  is typically correct).** *For every inputs  $x_1, x_2$ , consider the output distribution  $\text{out}_{P_1, P'_2}^H(x_1, x_2; (r_1, r_2, r_F, G)) = (z'_1, z'_2)$  induced by randomly chosen  $r_1 = (k, r'_1), r_2, r_F$  and  $H, G$ . Then,*

$$\Pr[z'_2 \neq f_2((x_1, k), x_2) | E] \leq \text{neg}(\lambda). \quad (2)$$

We remark that the claim actually holds over a worst-case choice of  $k$  (though we will not need this property). We defer the proof of this Claim to the full version of this paper.

By using partial fairness (and the security of the MAC), we will show that  $P_1$  is likely to output the correct value whenever  $P_2$  does it. Formally, we prove the following claim.

**Claim 8 ( $P_1$  is correct when  $P'_2$  is correct).** *For every input  $x_1$  and  $x_2$ ,*

$$\Pr_{H, r_1, r_2, r_F, G}[z'_1 \neq f_1(x_1, x_2) \wedge z'_2 = f_2((x_1, k), x_2)] \leq \text{neg}(\lambda), \quad (3)$$

where  $\text{out}_{P_1, P'_2}^{H, G}(x_1, x_2; (r_F, r_1, r_2)) = (z'_1, z'_2)$  and  $r_1 = (k, r'_1)$ .

We defer the proof of this Claim to the full version of this paper. By combining all three claims we derive the following lemma.

**Lemma 2 ( $P_1$  is typically correct).** *For every input  $x_1$  and  $x_2$ ,*

$$\Pr_{r_1=(r'_1, k), r_2, r_F, G, H}[z'_1 \neq f_1(x_1, x_2) | E] \leq \text{neg}(\lambda) \quad (4)$$

where  $\text{out}_{P_1, P'_2}^{H, G}(x_1, x_2; (r_F, r_1, r_2)) = (z'_1, z'_2)$ .

*Proof.* The LHS is upper-bounded by

$$\Pr_{H, r_1, r_2, r_F, G}[z'_1 \neq f_1(x_1, x_2) \wedge z'_2 = f_2((x_1, k), x_2) | E] + \Pr_{H, r_1, r_2, r_F, G}[z'_2 \neq f_2((x_1, k), x_2) | E].$$

By Claims 5 and (8), the first summand is negligible, and by Claim 7 the second summand is also negligible.  $\square$

**Privacy of  $\Pi_1$**  Our next goal is to show that  $\Pi_1$  preserves privacy against a passive adversary that corrupts the first party  $P_1$ . Recall that the view of  $P_1$  (both in  $\Pi$  and in  $\Pi_1$ ) consists of the following values: the input  $x_1$ , the random tape  $r_1$ , a list of the preprocessing queries  $Q_1$  and a list of all the oracle responses  $R_1$ , the value  $v_1$  given to the first party by the functionality  $g$ , and a list  $S_1$  of queries that are performed in the postprocessing step and the list of the corresponding oracle answers  $T_1$ .

We relate the  $P_1$ -privacy of  $\Pi_1$  to the  $P_1$ -privacy of  $\Pi$  by showing that the view in both experiments is statistically close. In fact, it will be useful to prove this even when  $P_1$  gets to see the randomness  $r_F$  used by  $P'_2$  for sampling  $Q_h$ . Let us refer to this modified protocol as  $\Pi_2$ . (E.g., think of  $r_F$  as being taken from a shared random tape.)

**Claim 9.** *There exists an efficient randomized oracle-aided procedure  $\rho^{(\cdot)}(\cdot)$  that takes a  $P_1$ -view  $w$  under  $\Pi$  and outputs a  $P_1$ -view  $w'$  under  $\Pi_2$  and lazy-samples an oracle  $H$  such that the following holds. For every  $(x_1, x_2)$  the distribution of*

$$(H, w') = \rho^V(\text{view}_{\Pi, P_1}^V(x_1, x_2; r_1, r_2)) \quad \text{where } V, r_1, r_2 \text{ are uniform,}$$

is  $O(\beta(x_1, x_2))$ -statistically close to

$$(H, \text{view}_{\Pi_2, P_1}^H(x_1, x_2; r_1, r_2, r_F, G)) \quad \text{where } H, r_1, r_2, r_F, G \text{ are uniform.}$$

Recall that  $\beta(x_1, x_2) := \Pr_{H, G, r_1, r_2, r_F}[\neg E(H, x_1, r_1, x_2, r_2, r_F, G)]$ .

*Proof.* Given  $w = (x_1, r_1, Q_1, R_1, v_1, S_1, T_1)$  (supposedly a  $P_1$ -view under  $\Pi$ ) and an oracle  $V$ , the mapping  $\rho$  does the following:

- Sample a random tape  $r_F$  for  $F$ , let  $Q_h = F^V(r_F)$ , and let  $H$  be a fresh random oracle that is consistent with  $V$  on the queries  $Q_1 \cup Q_h$ .
- Invoke  $\text{post}_1^H(v_1; r_1)$  with the oracle  $H$  and collect all the queries and their answers in the lists  $(S'_1, T'_1)$ .
- Output  $w' = (x_1, r_1, r_F, Q_1, R_1, v_1, S'_1, T'_1)$ .

Fix  $x_1$  and  $x_2$  and let  $w$  be a random view of  $P_1$  that corresponds to the experiment  $\Pi^V(x_1, r_1, x_2, r_2)$  with randomly chosen tapes  $r_1$  and  $r_2$  and random oracle  $V$ . We will show that  $w'$  is statistically-close to  $\text{view}_{\Pi_2, P_1}^H(x_1, x_2; r_1, r_2, G)$  where the oracle  $G$  is defined as follows.

For every fixing of  $x_2, r_2$  and  $r_F$ , let us denote by  $L$  the list of queries that  $P'_2$  sends to its “local” oracle when its global oracle is set to  $V$  and its local oracle is also set to  $V$ . Formally,  $L = Q_2 \setminus Q_h$  where  $Q_h = F^V(r_F)$  and  $Q_2 = Q(\text{pre}_2^V(x_2; r_2))$ . Then, the oracle  $G$  is defined to be  $V[L] \cup U$  where  $U$  is a fresh oracle.

Let  $\beta = \beta(x_1, x_2)$ . We begin by showing that the joint distribution

$$(H, G) \text{ is } 3\beta\text{-close to uniform.} \quad (*)$$

Since  $E$  happens with probability  $1 - \beta$ , it suffices to show that the conditional distribution  $((H, G)|E)$  is  $\beta$ -close to uniform. Next, note that under  $E$  the oracles

$G$  and  $H$  are statistically independent (since  $G$  and  $H$  are based on disjoint entries of  $V$ ), and therefore it suffices to show that  $(G|E)$  is  $\beta$ -close to uniform and that  $(H|E)$  is  $\beta$ -close to uniform. Indeed, without conditioning, the marginal distribution of  $G$  (resp.,  $H$ ) is uniform and so the conditional distribution deviates from uniform by at most  $\Pr[-E] = \beta$ , and  $(*)$  follows.

From now on, fix the random tapes  $r_1, r_2, r_F$  and the oracles  $V, H$  and  $G$ . We begin by showing that the response that the oracle  $g$  sends to  $P_1$  in an execution of  $\Pi_2^H(x_1, x_2; r_1, r_2, r_F, G)$  is equal to  $v_1$ . Indeed, the values  $(x_1, r_1, Q_1, R_1)$  in the execution of  $\Pi^V(x_1, r_1, x_2, r_2)$  are identical to the ones that are computed in the execution  $\Pi_2^H(x_1, r_1, x_2, r_2, r_F, G)$ . (Since  $Q_1 = Q(\text{pre}_1^V(x_1; r_1)) = Q(\text{pre}_1^H(x_1; r_1))$  and  $R_1 = V(Q_1) = H(Q_1)$ .) Consequently, in both experiments,  $P_1$  sends the same message  $y_1$  to the oracle  $g$ . Furthermore, in both experiments,  $P_2$  sends the same message  $y_2$  to the oracle  $g$  since  $y_2 = \text{pre}_2^V(x_2; r_2) = \text{pre}_2^{H[Q_1] \cup G}(x_2; r_2)$ . We conclude that the ideal functionality  $g$  is applied to the same input in both experiments and therefore, conditioned on the above, the message,  $v_1$ , that is being delivered by  $g$  to  $P_1$  is distributed identically in both experiments. Finally, the postprocessing queries  $S'_1$  and their answers  $T'_1$  are generated in both experiments by applying the deterministic procedure  $\text{post}_1^H(v_1; r_1)$ .  $\square$

We can now prove the following lemma.

**Lemma 3 ( $P_1$ -privacy).** *There exists a simulator against a passive  $P_1$  adversary such that for every  $(x_1, x_2)$  the statistical deviation of the simulator from the real distribution, as defined in Definition (2), is upper-bounded by  $O(\beta(x_1, x_2)) + \text{neg}(\lambda)$ .*

Consequently, by Claim 5 the protocol  $\Pi_2$  is  $O(\alpha)$ -AVG-private against the first party. Moreover, by Claim 6, if  $\text{pre}_2$  makes input-independent queries then the protocol is  $O(\alpha)$ -private, and if  $\text{pre}_2$  makes uniform queries then  $\Pi_1$  is private (with negligible privacy error).

*Proof.* Given an input/output pair  $(x_1, z_1)$  for  $P_1$ , we define a  $P_1$ -simulator  $\text{Sim}_2(x_1, z_1)$  for  $\Pi_2$  as follows. Call the  $P_1$ -simulator  $\text{Sim}(x_1, z_1)$  of  $\Pi$  and generate a view  $w = (x_1, r_1, Q_1, R_1, v_1, S_1, T_1)$  together with a simulated random oracle  $V$ . Generate a view  $w'$  of the new protocol together with an oracle  $H$ , by calling the procedure  $\rho^V(w)$  promised in Claim 9.

We show that for every  $(x_1, x_2)$ , the simulated view deviates from the real view by  $O(\beta(x_1, x_2)) + \text{neg}(\lambda)$ . Indeed, fix an oracle-aided distinguisher  $D^H$  that distinguishes with advantage  $\Delta$  between the  $\Pi_2$ -simulated view,  $\text{Sim}_2(x_1, z_1)$ , to the real view  $\text{view}_{\Pi_2, P_1}^H(x_1, x_2)$  where  $H$  (and the local random tapes) are random. We construct a distinguisher  $D'$  against  $\Pi$  as follows: Given  $w$  and an oracle access to  $V$ , compute  $\rho^V(w) = (H, w')$  and output  $D^H(w')$ .

By definition, it holds that

$$\Pr_{(V, w) \leftarrow \text{Sim}(x_1, z_1)} [D'^V(w) = 1] = \Pr_{(H, w') \leftarrow \text{Sim}_2(x_1, z_1)} [D^H(w') = 1].$$

Also, by Claim 9,

$$|\Pr[D^V(\text{view}_{\Pi, P_1}^V(x_1, x_2)) = 1] - \Pr[D^H(\text{view}_{\Pi_2, P_1}^H(x_1, x_2)) = 1]| \leq 3\beta(x_1, x_2).$$

By the privacy of  $\Pi_1$ , we conclude that  $\Delta + 3\beta(x_1, x_2) \leq \text{neg}(\lambda)$  and the lemma follows.  $\square$

**Deriving Theorem 4** We can now remove the random oracle and derive Theorem 4. Let  $g'$  denote a modified version of  $g$  whose input, in addition to  $(y_1, y_2)$ , consists of the query list  $Q_1$  that the first party issued to  $H$  in the preprocessing phase, and the list  $L$  that the second party in  $\Pi_2$  issued to its local oracle during the preprocessing stage. In addition, the functionality takes the private input  $x_2$  from the second party. The functionality  $g'$  checks if there is a collision between the lists  $Q_1$  and  $L$  (i.e., if  $\neg E$  happens) and if this is the case it sends a flag  $e = 0$  together with  $x_2$  to the first party. Otherwise, it computes  $g(y_1, y_2) = (v_1, v_2)$ , sends  $v_1$  to the first party with the flag  $e = 1$ . In any case,  $g'$  delivers a  $\perp$  to the second party.

Consider the following reduction  $\Sigma$  from  $f_1$  to  $g'$ .

1. The first party lazy samples a random oracle  $H$  and samples random tapes  $r_F$  and  $r_1$ . She computes  $Q_h = F^H(r_F)$  and sends to the second party the list of query/response pairs  $(q, H(q))_{q \in Q_h}$ . (Note that it suffices to send  $r_F$  and all the  $H$ -answers that are provided to  $F^H(r_F)$  and therefore the first message consists of a sequence of random coins.)
2. The two parties generate  $g$ -queries  $(y_1, y_2)$  like in  $\Pi_1$ . Namely, the first party computes  $y_1 = \text{pre}_1^H(x_1; r_1)$  and the second party computes  $y_2 = \text{pre}_2^{H[Q_h] \cup G}(x_2; r_2)$  where  $r_2$  is a fresh random tape and  $G$  is a private oracle that is sampled locally. The parties call  $g'$  with the inputs  $(y_1, Q_1 = Q(\text{pre}_1^H(x_1; r_1)))$  for the first party and the inputs  $y_2, x_2$  and  $L = Q(\text{pre}_2^{H[Q_h] \cup G}(x_2; r_2)) \setminus Q_h$  for the second party.
3. In the postprocessing phase, the first party checks the received flag  $e$ . If  $e = 1$  it retrieves the value  $v_1$  from the oracle  $g'$  and outputs  $\text{post}_1^H(v_1; r_1)$ . Otherwise, it retrieves the value  $x_2$  and outputs  $f_1(x_1, x_2)$ . In any case, the second party aborts with an empty output.

The syntax of  $\Sigma$  satisfies the syntax promised in Theorem 4 (item 1). Indeed, to see that  $g'$  can be implemented in  $\text{NC}^1$ , we observe that each pair of strings  $(q_1, q_2)$  in  $Q_1 \times Q_G$  are of bit length  $\ell = \text{poly}(\lambda)$  and so we can check if  $q_1 = q_2$  by an  $O(\ell)$ -size circuit of depth  $\log(\ell) + O(1)$ . Since the number of pairs in  $|Q_1 \times Q_G|$  is polynomial in  $\lambda$ , we can check all pairs in parallel and aggregate the result via an “OR-tree”. Overall we can detect if  $E$  happens by an  $\text{NC}^1$  circuit, and combine it with the original  $\text{NC}^1$  circuit of  $g$  (promised by the fact that it is a constant-degree functionality).

Also, the only value that  $P_2$  receives is  $(q, H(q))_{q \in Q_h}$  which is distributed independently of  $P_1$ 's input. Therefore, the protocol is private against the second party. To analyze privacy against the first party, observe that, for every  $x_1, x_2$  and oracle  $H$ , conditioned on the event  $E$ , the view of  $P_1$  in  $\Sigma$  is distributed

identically to its view under  $\Pi_2$ . Hence, by Lemma 3, there exists a simulator that on  $(x_1, x_2)$  has a statistical deviation of  $O(\beta(x_1, x_2)) + \text{negl}(n)(\lambda)$ . Consequently, by Claim 5 the protocol  $\Sigma$  is  $O(\alpha)$ -AVG-private against the first party. Moreover, by Claim 6, if  $\text{pre}_2$  makes input-independent queries then the protocol is  $O(\alpha)$ -private, and if  $\text{pre}_2$  makes uniform queries then  $\Sigma$  is private (with negligible privacy error).

As for correctness, observe that, conditioned on  $E$ , the output distribution of  $\Sigma(x_1, x_2)$  is identical to the output distribution of  $\Pi_1^H(x_1, x_2)$ . Therefore, Lemma 2 guarantees correctness under  $E$  (except with negligible error probability). When  $E$  does not happen, correctness holds trivially since  $x_2$  is being revealed.

## 4 Distributed Encryption

### 4.1 Definition

In this section, we define a new notion of a multi-party symmetric-key encryption scheme, which we call a *distributed encryption scheme*. In this primitive, each party samples a key independent of the other parties, and the message is simultaneously encrypted under each party’s key. Although this is a symmetric-key primitive, we refer to the keys used in the encryption algorithm as the “encryption” keys and the ones used in the decryption algorithm are referred to as the “decryption” keys. This will allow us to define the encryption algorithm in a way that is independent of the underlying cryptographic primitive (e.g., a PRG), without giving-up on the benefits of computational-security; Notably, it will be crucial to have decryption keys whose bit-length is shorter than the message’s length. We define different forms of privacy and correctness properties which hold as long as the adversary runs in polynomial-time (in the security parameter  $\lambda$ ) and corrupts at most  $t(n)$  out of the  $n(\lambda)$  parties. We refer to  $t = t(n)$  as the corruption threshold.

**Definition 4 (Distributed Encryption: Syntax).** A distributed encryption scheme is defined by a triple of PPT algorithms  $(\text{KeyGen}, \text{Enc}, \text{Dec})$  as follows:

- $\text{KeyGen}(1^\lambda, 1^n, 1^\ell) \rightarrow (\text{ek}, \text{dk})$ : On input the security parameter  $\lambda$ , the number of parties  $n = n(\lambda)$  and the bit-length of the messages  $\ell$ , the randomized key generation algorithm outputs a decryption key  $\text{dk}$  and an encryption key  $\text{ek}$ . The length of  $\text{dk}$  is required to be  $p(\lambda)$  for some fixed polynomial  $p$  that is independent of  $n$  and  $\ell$ .
- $\text{Enc}(1^\lambda, 1^n, 1^\ell, m, \text{ek}_1, \dots, \text{ek}_n) \rightarrow \text{ct}$ : On input the security parameter  $\lambda$ , a message  $m \in \{0, 1\}^\ell$  and a set of encryption keys  $\text{ek}_1, \dots, \text{ek}_n$ , the randomized encryption algorithm outputs a ciphertext  $\text{ct}$ .
- $\text{Dec}(\text{ct}, \text{dk}_1, \dots, \text{dk}_n) \rightarrow (b, m, \text{bad})$ : Given a ciphertext  $\text{ct}$  and a set of decryption keys  $(\text{dk}_1, \dots, \text{dk}_n)$  as inputs, the decryption algorithm outputs a validity bit  $b \in \{0, 1\}$ , the message  $m \in \{0, 1\}^\ell \cup \{\perp\}$  and a set  $\text{bad} \subset [n]$ .

Our syntax for the encryption algorithm is somewhat degenerate since  $\ell$  and  $n$  can be extracted from  $m$  and  $\text{ek}_1, \dots, \text{ek}_n$ . We therefore typically omit these

parameters except for special cases where wish to emphasize the restriction of Enc to concrete lengths.

We now proceed to define three properties of a distributed encryption scheme: *privacy*, *security with abort*, *security with identifiable abort*.

*Privacy.* An adversary who is allowed to choose a subset of the encryption keys, should not be able distinguish between encryptions of any two messages of its choice.

**Definition 5 ( $t(n)$ -Privacy).** *A distributed encryption scheme is said to have one-time  $t(n)$ -privacy (where  $t(n) < n(\lambda)$ ) if every n.u PPT adversary  $\mathcal{A}$  cannot win the following game with more than  $\frac{1}{2} + \mu(\lambda)$  probability where  $\mu$  is some negligible function:*

- $\mathcal{A}(1^\lambda)$  selects the following values and sends them to the challenger: parameters  $1^n$  and  $1^\ell$ , a pair of messages  $m_0, m_1 \in \{0, 1\}^\ell$ , a  $t(n)$ -subset  $\mathcal{I} \subset [n(\lambda)]$ , and a tuple of arbitrary encryption keys  $\{\text{ek}_i\}_{i \in \mathcal{I}}$  for the corrupted parties.
- The challenger samples keys for the remaining parties, i.e., for each  $i \in [n(\lambda)] \setminus \mathcal{I}$ ,  $(\text{ek}_i, \text{dk}_i) \leftarrow \text{KeyGen}(1^\lambda, 1^n, 1^\ell)$  and samples a bit  $b \leftarrow_{\$} \{0, 1\}$  uniformly at random. It then computes  $\text{ct} \leftarrow \text{Enc}(1^\lambda, m_b, \text{ek}_1, \dots, \text{ek}_n)$  and sends  $\text{ct}$  to  $\mathcal{A}$ .
- The adversary responds with a bit  $b'$  and wins if  $b' = b$ .

*Security with Abort.* In addition to privacy, we require different flavors of correctness which hold even against active adversaries that corrupt the keys. Our first variant requires security-with-abort. Formally,

**Definition 6 ( $t(n)$ -Security with Abort).** *A distributed encryption scheme is said to have one-time  $t(n)$ -security with abort (where  $t(n) < n(\lambda)$ ) if it satisfies  $t(n)$ -privacy and satisfies the following additional property (referred to as  $t(n)$ -detection). There exists an efficiently computable randomized predicate  $P$  that outputs “pass” (1) or “abort” (0), such that for every polynomials  $n = n(\lambda)$ ,  $\ell = \ell(\lambda)$ , every  $t(n)$ -subset  $\mathcal{I} \subset [n]$ , every message  $m \in \{0, 1\}^\ell$  and every tuple of corrupted keys  $\{\text{ek}_i, \text{dk}_i\}_{i \in \mathcal{I}}$ , the following random variables are  $\text{negl}(\lambda)$ -close in statistical distance:  $(\text{ct}, \text{Dec}(\text{ct}, \text{dk}_1, \dots, \text{dk}_n))$  and  $(\text{ct}, m')$ , where*

$$(\text{ek}_i, \text{dk}_i) \leftarrow \text{KeyGen}(1^\lambda, 1^n, 1^\ell) \quad \forall i \in [n] \setminus \mathcal{I}, \text{ct} \leftarrow \text{Enc}(1^\lambda, m, \text{ek}_1, \dots, \text{ek}_n),$$

and

$$\begin{cases} m' = (1, m, \emptyset), & \text{if } 1 \leftarrow P((\text{ek}_i, \text{dk}_i)_{i \in [n]}) \\ m' = (0, \perp, \emptyset), & \text{if } 0 \leftarrow P((\text{ek}_i, \text{dk}_i)_{i \in [n]}). \end{cases}$$

Note that the adversary wins if it can make the decryption algorithm err (output a value different than  $m$  or  $\perp$ ). Moreover, the above definition implies that the event of aborting cannot depend on the message  $m$  (since the predicate  $P$  should simulate it without knowing  $m$ .) Finally, note that our notion of detection is information-theoretic. (We do not define a computational variant of this notion, since all our constructions are information-theoretic anyway.)

We construct a distributed encryption scheme satisfying  $(n-1)$ -security with abort based on message-authentication codes in Section 4.2.



*Security with Identifiable Abort.* In the following we strengthen our requirement so that when abort happens a bad party is identified.

**Definition 7 ( $t(n)$ -Security with Identifiable Abort).** *A distributed encryption scheme is said to have one-time  $t(n)$ -security with identifiable abort (where  $t(n) < n(\lambda)$ ) if it has  $t(n)$ -privacy and satisfies the following additional property (referred to as  $t(n)$ -identification) for every polynomials  $n = n(\lambda)$  and  $\ell = \ell(\lambda)$ . There exists an efficiently computable randomized predicate  $P$  that takes a vector of keys  $(ek_i, dk_i)_{i \in [n]}$  and outputs a pair  $(a, \text{bad})$  where  $a \in \{0, 1\}$  is a validity bit (“pass” or “abort”) and  $\text{bad} \subset [n]$  is (supposedly) a subset of corrupted parties. The predicate should satisfy  $t(n)$ -detection and, in addition, for any  $t(n)$ -subset  $\mathcal{I} \subset [n]$  of the parties and any vector of keys  $(ek_i, dk_i)_{i \in [n]}$  where  $(ek_i, dk_i)_{i \in \mathcal{I}}$  may be chosen arbitrarily and  $(ek_i, dk_i)_{i \in [n] \setminus \mathcal{I}}$  are sampled independently from  $\text{KeyGen}(1^\lambda, 1^n, 1^\ell)$ , if  $P((ek_i, dk_i)_{i \in [n]})$  outputs “abort” then, except with negligible probability, its second output  $\text{bad}$  satisfies  $\text{bad} \subset \mathcal{I}$ .*

In Section 4.3 we show how to upgrade any distributed encryption scheme satisfying  $(n - 1)$ -security with abort into an  $(n - 1)$ -secure scheme with identifiable abort.

## 4.2 Distributed Encryption Satisfying Security with Abort

In this section we present our construction of a distributed encryption scheme that satisfies  $(n - 1)$ -security with abort. The construction naturally follows the MAC-and-Encrypt paradigm while exploiting the internal randomness of the encryption algorithm for the use of MAC.

**Theorem 10.** *Assuming the existence of a pseudo-random generator, there exists a distributed encryption scheme that satisfies  $(n - 1)$ -security with abort. Moreover, the key-generation and decryption algorithms make a black-box use of the PRG and the encryption algorithm is independent of the PRG and is in  $\text{NC}^1$  whenever  $n$  and  $\ell$  are polynomial in  $\lambda$ .<sup>10</sup>*

*Information-theoretic MAC.* For the proof of the theorem, we will need to employ an information theoretic one-time secure MAC scheme  $(M.\text{KeyGen}, \text{MAC})$  where  $M.\text{KeyGen}(1^\ell, 1^\lambda)$  samples a key  $\text{mk}$  such that  $\text{MAC}_{\text{mk}} : \{0, 1\}^\ell \rightarrow \{0, 1\}^\lambda$  is pair-wise independent hash function. That is, for every pair of inputs  $x \neq y \in \{0, 1\}^\ell$ , for  $\text{mk} \leftarrow M.\text{KeyGen}(1^\ell, 1^\lambda)$ , the random variable  $(\text{MAC}_{\text{mk}}(x), \text{MAC}_{\text{mk}}(y))$  is uniform over  $\{0, 1\}^\lambda \times \{0, 1\}^\lambda$ . In standard implementation (e.g., using Toeplitz-based affine transformation) the key-length is of size  $\ell + 2\lambda$ , and both  $(M.\text{KeyGen}, \text{MAC})$  can be computed by an  $\text{NC}^1$  circuit of size polynomial in  $\ell$  and  $\lambda$ .

**Lemma 4.** *The construction in Figure 2 satisfies  $(n - 1)$ -security with abort.*

We defer the proof of this Lemma to the full version of this paper.

<sup>10</sup> More precisely, for every fixed polynomials  $n(\lambda)$  and  $\ell(\lambda)$ , the encryption algorithm, viewed as an infinite sequence of functions  $\{\text{Enc}_\lambda\}_{\lambda \in \mathbb{N}}$  that is parameterized solely by  $\lambda$ , can be realized by a poly-time uniform  $\text{NC}^1$  circuit family. This notion of efficiency, that will be also used in the next subsection, suffices for our needs.

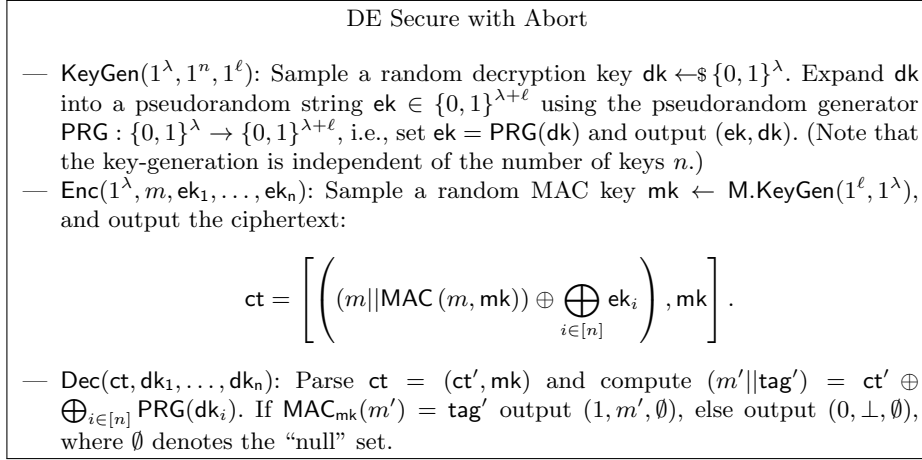


Fig. 2: A distributed encryption scheme that satisfies  $(n - 1)$ -security with abort

### 4.3 Distributed Encryption Satisfying Security with Identifiable Abort

**Theorem 11.** *Assuming the existence of a distributed encryption scheme  $(\overline{\text{KeyGen}}, \overline{\text{Enc}}, \overline{\text{Dec}})$  that satisfies one-time  $(n - 1)$ -security with abort there exists a distributed encryption scheme that satisfies  $(n - 1)$ -security with identifiable abort. Moreover, if the key-generation and decryption algorithms of the original scheme make a black-box use of the PRG, then so do the new key-generation and decryption algorithms, and if the original encryption algorithm is independent of the PRG and is in  $\text{NC}^1$  (whenever  $n$  and  $\ell$  are polynomial in  $\lambda$ ) then so is the new encryption algorithm.*

*Threshold secret-sharing.* The proof makes use of a  $\lambda/2$ -out-of- $\lambda$  secret-sharing scheme ( $\text{share}, \text{reconstruct}$ ) where  $\text{share}$  takes a secret  $s$  of length  $\ell$  and generates  $\lambda$  shares  $s_1, \dots, s_\lambda$ , such that the secret can be recovered from any  $(\lambda/2)$ -subset of the shares (via  $\text{reconstruct}$ ) and any smaller subset of shares perfectly-hide the secret. Using Shamir’s secret sharing [42] (over an extension of the binary field) such a scheme can be realized with share size of  $\max(\log \lambda + 1, \ell)$ . In our setting we can assume (WLOG) that  $\ell$  is larger than  $\log \lambda$  (or even larger than some polynomial in  $\lambda$ ) and so the share size can be assumed to be  $\ell$ . Moreover, in this case both the sharing and the reconstruction algorithm can be implemented by an  $\text{NC}^1$  circuit of complexity polynomial in  $\ell$  and  $\lambda$ .

*Remark 3 (Secrecy-preserving identifiable abort).* We remark that our construction provides a useful feature of “Secrecy-preserving identifiable abort”. That is, we can augment the encryption algorithm to output the decryption keys  $(\text{dk}_i^j)_{i \in [n], j \in S}$  as part of the ciphertext, and think of the ciphertext as being composed of two parts: a “tag” that consists of  $S, (\text{ek}_i^j, \text{dk}_i^j)_{i \in [n], j \in S}$  and a “data”  $\{\text{ct}^j\}_{j \in [2\lambda] \setminus S}$ . Note that the secrecy of the message is still preserved even given

the tag information, and so it is safe to append it to ciphertext. Moreover, the abort decision of the decryption algorithm is performed solely based on the “tag”. That is, the decryption algorithm is composed of two stages: detection and recovery. The detection algorithm decides whether to abort or not (and in case of abort it identifies a bad party) solely based on the tag information. If detection passes without abort, then the recovery algorithm should be able to decrypt successfully. This feature allows us to check the abort event without leaking information on the encrypted message, and can be eventually used in order to get a fair protocol at the expense of adding an additional round of interaction.

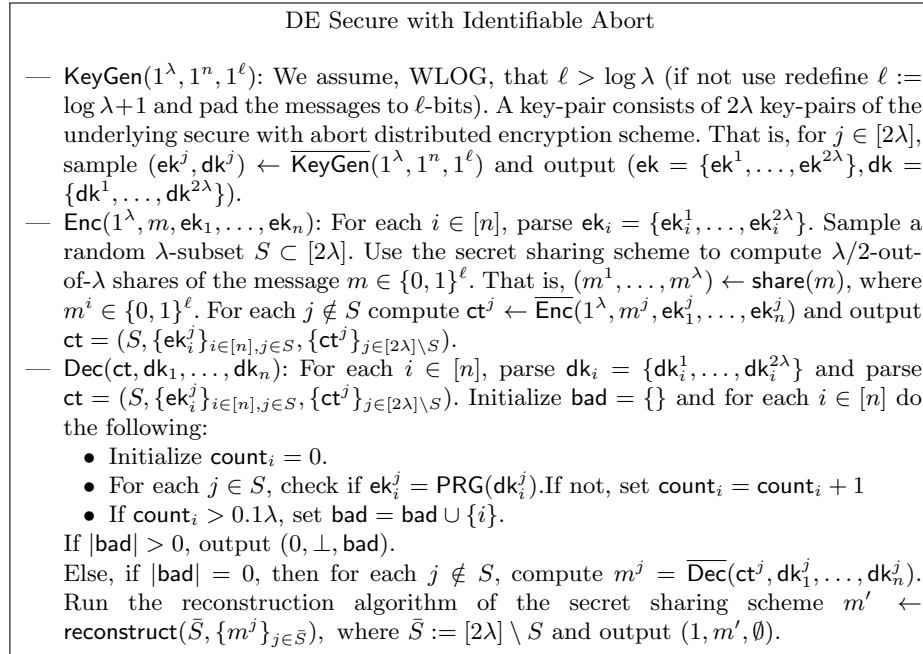


Fig. 3: A distributed encryption scheme that satisfies  $(n - 1)$ -security with identifiable abort

**Lemma 5.** *The construction in Figure 3 satisfies  $(n - 1)$ -security with identifiable abort.*

We defer the proof of this Lemma to the full version of this paper.

## 5 Elementary Reduction using Distributed Encryption

In this section, we prove our main positive result. We show that existence of a distributed encryption scheme implies existence of a non-interactive reduction from any efficiently computable functionality  $f$  to a constant-degree functionality  $g$ , such that if the distributed encryption scheme satisfies security with identifiable abort then so does the reduction.

**Theorem 12.** Let  $f = \{f_\lambda\}$  be an  $n$ -party efficiently-computable functionality where  $n = n(\lambda)$  is polynomial in the security parameter. Assuming the existence of a distributed encryption scheme,  $(\text{KeyGen}, \text{Enc}, \text{Dec})$ , with  $(n - 1)$  security with identifiable abort (resp., with  $(n - 1)$  full security), there exists an  $n$ -input functionality  $g$  such that  $f$  elementary reduces to  $g$  with  $(n - 1)$  security with identifiable abort (resp., with  $(n - 1)$  full security). Moreover,  $g$  can be computed by an  $\text{NC}^0$ -circuit with oracle gates to  $\text{Enc}(1^\lambda, 1^n, 1^\ell, \cdot)$ , where  $\ell$  is a fixed polynomial in  $\lambda$  and  $n$ .

The encryption algorithm of the distributed encryption scheme from Theorem 11 is in  $\text{NC}^1$ , and so, by Remark 1, we derive Theorem 3. The elementary reduction promised in Theorem 12 is described in Section 5.1 and its analysis is deferred to the full-version of this paper.

### 5.1 Proof of Theorem 12: The Reduction

**Notation.** Let  $(\text{KeyGen}, \text{Enc}, \text{Dec})$  be a distributed encryption scheme with decryption key space  $\{0, 1\}^\lambda$  and message space  $\{0, 1\}^\ell$  that achieves security with abort (or identifiable abort). We assume w.l.o.g., that  $\ell = 2n\lambda + 2$ . We also assume (w.l.o.g.) for the sake of simplicity that the functionality returns the same output to all parties.

Looking ahead, for our elementary reduction we will encrypt messages under two key vectors. For this we consider a *double encryption gadget* denoted by  $(\text{Doub.Enc}, \text{Doub.Dec})$ , defined as follows:

- $\text{Doub.Enc}(1^\lambda, m, \vec{\text{ek}}_1, \vec{\text{ek}}_2)$ : The double encryption algorithm samples a random  $r \leftarrow \{0, 1\}^\ell$ , computes two ciphertexts,  $\text{ct}_1 \leftarrow \text{Enc}(1^\lambda, m \oplus r, \vec{\text{ek}}_1)$  and  $\text{ct}_2 \leftarrow \text{Enc}(1^\lambda, r, \vec{\text{ek}}_2)$  and outputs  $\text{ct} = (\text{ct}_1, \text{ct}_2)$ .
- $\text{Doub.Dec}(\text{ct}, \vec{\text{dk}}_1, \vec{\text{dk}}_2)$ : The double decryption algorithm parses  $\text{ct} = (\text{ct}_1, \text{ct}_2)$ , decrypts the two ciphertexts  $m_1 = \text{Dec}(\text{ct}_1, \vec{\text{dk}}_1)$  and  $m_2 = \text{Dec}(\text{ct}_2, \vec{\text{ek}}_2)$  and outputs  $m = m_1 \oplus m_2$ .

Let  $C$  be a boolean circuit that represents  $f$ . We assume without loss of generality that the fan-in and fan-out of every gate in  $C$  is two, since any circuit can be transformed to satisfy this condition with constant multiplicative overhead in the size. Let  $W$  be the set of all wires in this circuit  $C$ . Let  $W_{\text{in}} \subset W$  be the set of input wires and  $W_{\text{out}} \subset W$  be the set of output wires.

**Reduction.** The reduction proceeds as follows:

- **Pre-Processing.** For each wire  $w \in W$  in the circuit  $C$  and for every  $(a, b) \in \{0, 1\}^2$ , each party  $i$ , with input  $x_i$ , samples  $(\text{ek}_{i,a,b}^w, \text{dk}_{i,a,b}^w) \leftarrow \text{KeyGen}(1^\lambda)$ . Each party then invokes the oracle implementing functionality  $g$  on its actual input  $x_i$  and on these keys  $\{\text{ek}_{i,a,b}^w, \text{dk}_{i,a,b}^w\}_{w \in W, (a,b) \in \{0,1\}^2}$ .
- **$g$ -Oracle.** Upon invocation, oracle  $g$  parses the inputs as

$$\left\{ x_i, \left\{ \text{ek}_{i,a,b}^w, \text{dk}_{i,a,b}^w \right\}_{w \in W, (a,b) \in \{0,1\}^2} \right\}_{i \in [n]}$$

and sets  $x = x_1 || \dots || x_n$ . For each wire  $w \in W$ , it samples a random mask  $\delta^w \leftarrow_{\$} \{0, 1\}$  and for each  $(a, b) \in \{0, 1\}^2$ , it sets  $\vec{\text{ek}}_{a,b}^w = (\text{ek}_{1,a,b}^w, \dots, \text{ek}_{n,a,b}^w)$  and  $\vec{\text{dk}}_{a,b}^w = (\text{dk}_{1,a,b}^w, \dots, \text{dk}_{n,a,b}^w)$ . Also, for each  $w \in W$  and each  $a \in \{0, 1\}$ , we use  $\vec{\text{ek}}_a^w$  to denote  $\vec{\text{ek}}_{a,0}^w || \vec{\text{ek}}_{a,1}^w$  and  $\vec{\text{dk}}_a^w$  to denote  $\vec{\text{dk}}_{a,0}^w || \vec{\text{dk}}_{a,1}^w$ . It then proceeds as follows:

1. **Gates:** For every gate  $G \in C$  in the circuit, with incoming wires  $a, b$  and outgoing wires  $c, d$ , it computes four values defined as follows. For each  $(\alpha, \beta) \in \{0, 1\}^2$ , it computes  $\gamma_{\alpha, \beta} = G(\alpha \oplus \delta^a, \beta \oplus \delta^b)$  and

$$m_{\alpha, \beta} = ((\vec{\text{dk}}_{\gamma_{\alpha, \beta} \oplus \delta^c}^c || \gamma_{\alpha, \beta} \oplus \delta^c) || (\vec{\text{dk}}_{\gamma_{\alpha, \beta} \oplus \delta^d}^d || \gamma_{\alpha, \beta} \oplus \delta^d))$$

$$\text{ct}_{\alpha, \beta}^G \leftarrow \text{Doub.Enc}(1^\lambda, m_{\alpha, \beta}, \vec{\text{ek}}_{\alpha, \beta}^a, \vec{\text{ek}}_{\beta, \alpha}^b).$$

2. **Output:** For every gate  $G \in C$  in the circuit, and for each  $(\alpha, \beta) \in \{0, 1\}^2$ , output all the four ciphertexts  $\text{ct}_{\alpha, \beta}^G$ . Let  $y_w$  denote the value induced by  $x$  on wire  $w$ . For each input wire  $w$ , output the masked input  $\hat{y}_w := y_w \oplus \delta^w$  along with the decryption key  $\vec{\text{dk}}_{\hat{y}_w}^w$  corresponding to the masked input. For each output wire  $w \in W_{\text{out}}$ , output the mask  $\delta^w$ .

— **Post-Processing.** Upon receiving  $\{\text{ct}_{\alpha, \beta}^G\}_{(\alpha, \beta) \in \{0, 1\}^2}$  for each gate  $G \in C$ ,  $(\vec{\text{dk}}_{\hat{y}_w}^w, \hat{y}_w)$  for each input wire  $w \in W_{\text{in}}$ , and  $\delta^w$  for each output wire  $w \in W_{\text{out}}$  from the  $g$ -oracle, each party locally computes the following.

1. Traverse the circuit according to a topological order from inputs to outputs, and for each gate  $G$ , with incoming wires  $a, b$  and outgoing wires  $c, d$ , compute  $m_{\hat{y}_a, \hat{y}_b} := \text{Doub.Dec}(\text{ct}_{\hat{y}_a, \hat{y}_b}^G, \vec{\text{dk}}_{\hat{y}_a, \hat{y}_b}^w, \vec{\text{dk}}_{\hat{y}_b, \hat{y}_a}^w)$ , and parse  $m_{\hat{y}_a, \hat{y}_b} = ((\vec{\text{dk}}_{\hat{y}_c}^c || \hat{y}_c) || (\vec{\text{dk}}_{\hat{y}_d}^d || \hat{y}_d))$ .
2. If any of the decryption algorithms abort (and identifiably abort resp.), then output that  $\perp$  (and  $(\perp, \text{bad})$  resp.). Else, for each output wire  $w \in W_{\text{out}}$ , output  $\hat{y}_w \oplus \delta^w$ .

*Remark 4 (An interactive variant with fairness).* By changing  $g$  into a reactive functionality to which the parties are allowed to make 2 sequential calls, one can obtain full fairness. First, let us assume that the ciphertexts of the underlying distributed encryption scheme are augmented with tags as explained in Remark 3. Next, break  $g$  to a pair of functionalities  $g_1$  and  $g_2$  as follows. The input to  $g_1$  is the same as in  $g$  but its output consists of the ciphertext tuples that are computed for each gate, together with an encrypted version of all other outputs of  $g$ . The encryption is performed by using a one-time pad where the key  $K$  is chosen using the internal randomness of the functionality. Given these values each party checks if the ciphertexts of the gates are valid using the public detection algorithm. If a party  $P_i$ , detects a problem it sends a flag-bit  $b_i = 1$  to the functionality  $g_2$ , if no problem occurs the flag is set to zero. The functionality  $g_2$  releases the key  $K$  if and only if none of the flags indicate that there is a problem. The original postprocessing can be applied when  $g_2$  releases the key; otherwise the parties abort.

The current analysis can be easily adopted to show that the reduction achieves full fairness. While the current description assumes that the functionalities maintain a shared state (the key  $K$ ) one can easily remove it using secret sharing and message-authentication codes. Specifically, we augment  $g_1$  and let it send to each party  $i$ , a share  $K_i$  of the key  $K$  (computed via  $n$ -out-of- $n$  secret sharing), a sequence of authentication keys  $A_i = (A_{i,1}, \dots, A_{i,n})$  and a vector of  $n$  authentication tags  $T_i = (\text{MAC}_{A_{1,i}}(K_i), \dots, \text{MAC}_{A_{n,i}}(K_i))$  where MAC is a one-time secure information-theoretic MAC. The functionality  $g_2$  receives from each party  $P_i$  a flag bit,  $b_i$ , as before, together with  $(K_i, A_i, T_i)$ . If all the validity bits are OK, and all the tags pass the authentication, the functionality recovers the key  $K$  and send it to all parties. Otherwise, it sends an abort signal.

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