

# Fiat-Shamir for Bounded-Depth Adversaries

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## Abstract

We study how to construct hash functions that can securely instantiate the Fiat-Shamir transformation against *bounded-depth* adversaries. The motivation is twofold. First, given the recent fruitful line of research of constructing cryptographic primitives against bounded-depth adversaries under *worst-case complexity assumptions*, and the rich applications of Fiat-Shamir, instantiating Fiat-Shamir hash functions against bounded-depth adversaries under worst-case complexity assumptions might lead to further applications (such as SNARG for P, showing the cryptographic hardness of PPAD, etc.) against bounded-depth adversaries. Second, we wonder whether it is possible to overcome the impossibility results of constructing Fiat-Shamir for arguments [Goldwasser, Kalai, FOCS '03] in the setting where the depth of the adversary is bounded, given that the known impossibility results (against p.p.t. adversaries) are contrived.

Our main results give new insights for Fiat-Shamir against bounded-depth adversaries in both the positive and negative directions. On the positive side, for Fiat-Shamir for proofs with certain properties, we show that weak worst-case assumptions are enough for constructing explicit hash functions that give  $\text{AC}^0[2]$ -soundness. In particular, we construct an  $\text{AC}^0[2]$ -computable correlation-intractable hash family for constant-degree polynomials against  $\text{AC}^0[2]$  adversaries, assuming  $\oplus\text{L}/\text{poly} \not\subseteq \widetilde{\text{Sum}}_{n-c} \circ \text{AC}^0[2]$  for some  $c > 0$ . This is incomparable to all currently-known constructions, which are typically useful for larger classes and against stronger adversaries, but based on arguably stronger assumptions. Our construction is inspired by the Fiat-Shamir hash function by Peikert and Shiehian [CRYPTO '19] and the fully-homomorphic encryption scheme against bounded-depth adversaries by Wang and Pan [EUROCRYPT '22].

On the negative side, we show Fiat-Shamir for arguments is still impossible to achieve against bounded-depth adversaries. In particular,

- Assuming the existence of  $\text{AC}^0[2]$ -computable CRHF against p.p.t. adversaries, for every poly-size hash function, there is a (p.p.t.-sound) interactive argument that is not  $\text{AC}^0[2]$ -sound after applying Fiat-Shamir with this hash function.
- Assuming the existence of  $\text{AC}^0[2]$ -computable CRHF against  $\text{AC}^0[2]$  adversaries, there is an  $\text{AC}^0[2]$ -sound interactive argument such that for every hash function computable by  $\text{AC}^0[2]$  circuits, the argument does not preserve  $\text{AC}^0[2]$ -soundness when applying Fiat-Shamir with this hash function. This is a low-depth variant of Goldwasser and Kalai.

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# Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	The soundness of Fiat-Shamir	1
1.2	Fiat-Shamir and cryptography against bounded-depth adversaries	2
1.3	Our results	3
1.3.1	Positive results	4
1.3.2	Negative results	4
1.4	Related works	6
<b>2</b>	<b>Technical Overview</b>	<b>6</b>
2.1	Positive results	6
2.2	Negative results	7
<b>3</b>	<b>Preliminaries</b>	<b>10</b>
3.1	Circuit	10
3.2	Interactive protocol	12
3.3	Fiat-Shamir for 3-round public coin argument with common reference string	13
<b>4</b>	<b>Correlation Intractability Against Bounded-Depth Adversaries</b>	<b>15</b>
4.1	Backgrounds needed in this section	15
4.1.1	Hard Lattice Problems	15
4.1.2	Fully Homomorphic Encryption	15
4.1.3	Inert Commitment	17
4.1.4	Correlation intractability	18
4.1.5	Cryptographic primitives against bounded-depth circuits	18
4.2	CI from SIS against bounded-depth adversaries	21
4.3	CI from worst-case complexity assumptions	23
4.3.1	Adaptation of inert commitment to $\mathbb{Z}_2$	23
4.3.2	Construction	24
<b>5</b>	<b>Impossibility Result for Universal FS Hash Functions</b>	<b>25</b>
<b>6</b>	<b>Stronger Impossibility Results</b>	<b>29</b>
6.1	Interactive Argument for Central Relation	33
6.2	Reduced Argument for Central Relation	35
6.3	Protocol 1	37
6.4	Protocol 2	40
6.5	Protocol 3	44
<b>A</b>	<b>Detailed Proofs of Almost-Everywhere Security</b>	<b>54</b>
<b>B</b>	<b>Low Complexity CRHF</b>	<b>56</b>
<b>C</b>	<b><math>AC^0[2]</math>-computable, <math>AC^0[2]</math>-proof-of-knowledge, and <math>AC^0[2]</math>-reverse-samplable PCP</b>	<b>57</b>

# 1 Introduction

The Fiat-Shamir transform [FS86] is a generic method for converting public-coin interactive protocols into non-interactive ones while preserving the original protocol’s functionality. First proposed as a practical method to compile identification schemes into digital signatures, the Fiat-Shamir transform was then realized to be an extremely general technique for minimizing interaction in any public-coin protocol. The basic idea of Fiat-Shamir is to replace the verifier’s message in each round (which consists of random coin tosses) with a deterministic hash of the protocol transcript so far. As a typical example, consider a three-round public-coin interactive proof/argument system  $(P, V)$  for a language  $L$ . When proving a statement  $x \in L$ , the prover  $P$  first sends a message  $\alpha$ , the verifier  $V$  responds with random coins  $\beta$ , and then  $P$  sends the last message  $\gamma$ . To convert the interactive protocol  $(P, V)$  into a non-interactive protocol  $(P^{FS}, V^{FS})$ , the Fiat-Shamir transform uses a hash function  $h$  (randomly chosen from a hash family  $\mathcal{H}$ ) and removes the verifier’s coin tosses  $\beta$  by setting  $\beta = h(x\|\alpha)$ <sup>1</sup>. Then  $P^{FS}$  can directly compute  $\beta$  and send  $(\alpha, \beta = h(x\|\alpha), \gamma)$  in one shot without any interaction (actually  $\beta$  can be omitted since it is clear from  $x$ ,  $\alpha$  and the public hash function  $h$ ). See Figure 1 below for a visual explanation.

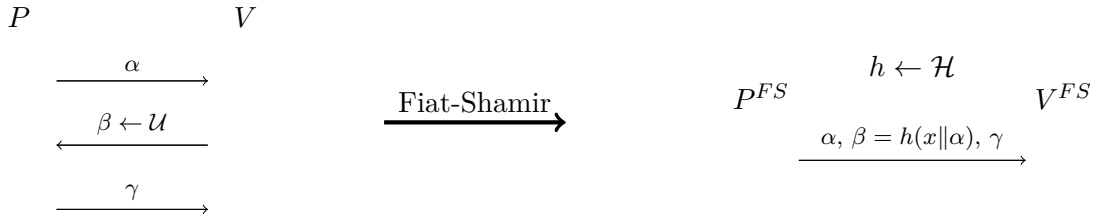


Figure 1: Instantiating Fiat-Shamir on  $(P, V)$  for proving  $x \in L$ .

## 1.1 The soundness of Fiat-Shamir

The central problem of Fiat-Shamir is its soundness – justifying whether and when the Fiat-Shamir transform results in a sound non-interactive protocol has long been a focus of research in cryptography. It was shown by Pointcheval and Stern [PS96] that the soundness of Fiat-Shamir holds in the *random oracle model* (ROM), i.e., the soundness of any constant-round public-coin protocol can be preserved if we model the Fiat-Shamir hash function as a random oracle. However, it is more desirable to prove the soundness of Fiat-Shamir transformation in the *plain model*: the Fiat-Shamir hash should be instantiated by an explicit hash function in contrast to an idealized one, and the security in the random oracle model cannot provide any guarantee here.

In the plain model, the difference between *proofs* and *arguments* becomes crucial. By using proofs, we mean protocols that are sound against *any* cheating provers (can be computationally unbounded), while by using arguments, we mean protocols that are sound against only computationally bounded (probabilistic polynomial-time) cheating provers. We summarize the main positive results here.

- **Fiat-Shamir for proofs.** If a hash function is correlation intractable (CI) then it can securely instantiate Fiat-Shamir for proofs [CCRR18]. In the past few years there has been a long line of work on correlation intractable (CI) hash functions [CCR16; KRR17; CCRR18;

<sup>1</sup>“ $\|$ ” means the concatenation of two strings. Here we use  $h(x\|\alpha)$  but not  $h(x, \alpha)$  to emphasize that  $h$  takes as input the entire transcript till now (consisting of  $x$  and  $\alpha$ ) instead of taking  $x$  and  $\alpha$  separately as two inputs.

HL18; Can+19; PS19; BKM20; HLR21; JJ21; LV22; CGJJZ23; DJJ24] showing that we can securely instantiate Fiat-Shamir on interactive proofs of which the “bad relation” (which is roughly the messages  $(\alpha, \beta)$  that may allow the prover to cheat) meets some special constraints. CI hash functions have already been used for applying Fiat-Shamir to some practical interactive proofs, e.g., the sumcheck protocol and the GKR protocol [JKKZ21], and also for constructing non-interactive cryptographic primitives from standard cryptographic assumptions, e.g., non-interactive zero-knowledge (NIZK) [PS19; BKM20; HLR21; JJ21; DJJ24] and succinct non-interactive arguments (SNARGs) [JKKZ21; CJJ21a; CJJ21b; HJKS22; KLV23; CGJJZ23].

- **Fiat-Shamir for arguments.** In the context of arguments, however, the soundness of Fiat-Shamir is still poorly understood. In some applications of Fiat-Shamir, we do know how to instantiate Fiat-Shamir securely on some special arguments using just CI hash functions (see, e.g., the SNARG constructions from [KVZ21; CJJ21a; CJJ21b; HJKS22; CGJJZ23]). However, the security mainly comes from the statistical property in their soundness such that these arguments can somehow be regarded as proofs – actually we are still using the framework for proofs. Outside the scope of “proof-like” arguments, there are only few positive results about some specific protocols, e.g., Fiat-Shamir for Schnorr’s or Lyubashevsky’s identification schemes [CLMQ21].

As we can see, positive results showing the soundness of Fiat-Shamir in the plain model concentrate almost all on proofs, while the soundness of Fiat-Shamir for arguments remains largely open (instantiating Fiat-Shamir soundly on proofs is intuitively easier since proofs have stronger security guarantees than arguments). Furthermore, there have been impossibility results or strong negative indications on the soundness of Fiat-Shamir for arguments in the plain model. Goldwasser and Kalai [GK03] constructed a set of three (contrived) arguments such that Fiat-Shamir using *any* explicit hash function must be insecure on at least one of them. In addition, Dwork, Naor, Reingold, and Stockmeyer [DNRS99] showed that (constant-round, public-coin) zero-knowledge arguments can also serve as counter-examples for Fiat-Shamir<sup>2</sup>, and constructions of such protocols are known based on various cryptographic assumptions (see, e.g., [Bar01; BKP18; Kiy22]).

## 1.2 Fiat-Shamir and cryptography against bounded-depth adversaries

In this work, we study the soundness of Fiat-Shamir in a new setting where the adversaries’ *parallel time* is further limited. In contrast to the standard security notion in cryptography that the adversaries run in probabilistic polynomial time (p.p.t.) with no further limitation, we consider a relaxed version of security that the adversaries are from *bounded-depth* (and thus bounded parallel time) circuit classes like  $\text{AC}^0[2]$  (poly-size constant-depth circuits with NOT gates and unbounded fan-in OR, AND, and  $\text{MOD}_2$  gates) and  $\text{TC}^0$  (poly-size constant-depth circuits with NOT gates and unbounded fan-in OR, AND, and threshold (THR) gates, where a threshold gate returns 1 if at least half of its inputs are 1, and 0 otherwise). If we can get positive results for Fiat-Shamir against bounded-depth adversaries, it will be very exciting: given the rich applications of (or inspired by) Fiat-Shamir in recent years (such as SNARGs for P, showing the cryptographic hardness of PPAD [Cho+19], etc.), instantiating Fiat-Shamir hash functions against bounded-depth adversaries

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<sup>2</sup>The intuition of [DNRS99] is: we can construct a cheating verifier that sends messages according to the Fiat-Shamir hash function, and the zero-knowledge property guarantees that a simulator can efficiently simulate the view of such a cheating verifier. If the protocol is sound after Fiat-Shamir, the simulator can then be used to decide the language. Therefore, Fiat-Shamir can only be sound when the zero-knowledge protocol proves a language in BPP.

might lead to further applications against bounded-depth adversaries. Furthermore, given the strong negative indications and the extreme lack of positive results on Fiat-Shamir for arguments against p.p.t adversaries, we would like to see if it is possible to bypass the known impossibility results in the bounded-depth setting.

Recently there has been a fruitful sequence of work on constructing cryptographic primitives with security against only bounded-depth adversaries<sup>3</sup>, including one-way functions, pseudorandom generators, collision-resistant hash functions [DVV16], one-way permutations [EWT21], fully homomorphic encryption schemes [CG18; WP22], and non-interactive zero-knowledge [WP22]. Compared to their analogs with the standard p.p.t. security, these primitives are indeed less secure but can rely only on worst-case complexity assumptions or even be unconditional (see, e.g., the construction of CRHF against  $AC^0$  in [DVV16], where  $AC^0$  is the class of poly-size constant-depth circuits with NOT gates and unbounded fan-in OR and AND gates). Here we continue this line of work with a specific focus on Fiat-Shamir in the same setting: the soundness is rather weak (but still non-trivial) against circuit classes as low as  $AC^0[2]$ , while the underlying assumption is likewise weak. The choice of bounded-depth circuit classes is also motivated by the developments in circuit complexity, where strong lower bounds for bounded-depth classes are known. Therefore, it is very likely that we can translate these lower bounds into good hash constructions that are only useful for Fiat-Shamir against the same bounded-depth classes.

Also note that the lowest circuit class we care about is  $AC^0[2]$ , which stands for poly-size constant-depth circuits with NOT gates and OR, AND,  $MOD_2$  gates with unbounded fan-in. We choose  $AC^0[2]$  because our results (as shown in the next section) can indeed work for classes as low as  $AC^0[2]$ , and  $AC^0[2]$  is arguably the smallest circuit class that makes Fiat-Shamir reasonable. In cryptography, almost all hash functions (and other cryptographic primitives) use some kind of linearity or algebra over finite fields, and constructions without the use of parity or modulo gates are rare. To the best of our knowledge, there are only two exceptions about classes lower than  $AC^0[2]$ . The first one is the cryptography in  $AC^0$  by Degwekar, Vaikuntanathan, and Vasudevan [DVV16], but their construction is still inherently using parity, except they use some clever tricks to bound the number of bits in the parity by  $\text{polylog}$ . The other one is the cryptography in  $NC^0$  by Applebaum, Ishai, and Kushilevitz [AIK06] (where  $NC^0$  is the same as  $AC^0$  except that OR and AND gates have only bounded fan-in), but their construction is not robust enough, e.g., their PRG can only have additive stretch.

### 1.3 Our results

Our results include two independent parts that make progress on both the positive side and the negative side. On the positive side, we give new constructions of Fiat-Shamir hash functions for proofs in the bounded-depth setting. Inspired by the correlation intractable hash by Peikert and Shiehian [PS19] and the FHE with bounded-depth security by Wang and Pan [WP22], we construct a new family of correlation intractable hash functions against bounded-depth adversaries. It allows us to generally instantiate Fiat-Shamir, at least on a class of interactive proofs, to obtain non-interactive cryptographic primitives in the bounded-depth setting. On the negative side, unfortunately, we observe that our positive results on proofs are almost the best we can do in the bounded-depth setting. In particular, we show that the known impossibility results for Fiat-Shamir for arguments like Goldwasser and Kalai [GK03] can be extended to the bounded-depth setting.

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<sup>3</sup>This research topic is also referred to as “fine-grained cryptography” like in [DVV16]. We do not use the notion “fine-grained” because in complexity theory it usually refers to unrobust classes like  $DTIME[n^2]$ . We use the name “cryptography against bounded-depth adversaries” to avoid any possible ambiguity.

### 1.3.1 Positive results

We first present the positive results for Fiat-Shamir for *proofs* against bounded-depth cheating provers. In particular, we show new constructions of correlation-intractable (CI) hash functions for relations representable by constant-degree polynomials that are secure against bounded-depth adversaries.

Our construction is inspired by the CI hash function constructed by Peikert and Shiehian [PS19], which uses the FHE scheme of Gentry, Sahai, Waters [GSW13] (henceforth GSW-FHE) as a building block. Our main observation is that the FHE scheme against low-depth adversaries constructed by Wang and Pan [WP22] bears a striking similarity with GSW-FHE. The similarity allows us to replace GSW-FHE with WP-FHE to obtain a CI hash function against low-depth adversaries assuming worst-case complexity assumptions. Our main positive result is:

**Theorem 1.1 (Informally stated, see Theorem 4.18).** Assuming  $\text{NC}^1 \neq \oplus\text{L}/\text{poly}$ , there exists a CI hash function family for constant-degree polynomials against  $\text{NC}^1$  that is computable in  $\text{AC}^0[2]$ .  $\diamond$

The circuit class  $\text{NC}^1$  (which stands for poly-size  $O(\log n)$ -depth circuits with bounded fan-in NOT, OR, and AND gates) is just a typical example and can actually be replaced with lower circuit classes. See Section 4.3 for more details. The worst-case complexity assumption is a standard assumption in the area of cryptography against bounded-depth adversaries: previous constructions of, e.g., one-way functions, pseudorandom generators, collision-resistant hash functions [DVV16] are all based on the same assumption.

### 1.3.2 Negative results

On the negative side, we get two (incomparable) impossibility results in the bounded-depth setting. The first one shows the non-existence of a *universal* Fiat-Shamir hash against bounded-depth adversaries; while the second one extends the work by Goldwasser and Kalai [GK03] showing the existence of a protocol that makes every Fiat-Shamir hash fail even in the bounded-depth setting.

**$\mathcal{C}$ -soundness and  $\mathcal{C}$ -arguments.** For simplicity, we say a protocol has  $\mathcal{C}$ -soundness if it is sound against adversaries computable in the complexity class  $\mathcal{C}$ . Also, we use the notation  $\mathcal{C}$ -arguments for protocols with  $\mathcal{C}$ -soundness. Typical choices of  $\mathcal{C}$  include bounded-depth circuit classes  $\text{AC}^0[2]$ ,  $\text{TC}^0$ , or  $\text{NC}^1$ . When just saying an argument, we refer to a  $\text{P}/\text{poly}$ -argument.

We first (informally) define what is a universal Fiat-Shamir hash in the bounded-depth setting (see definition 5.1 for the detailed definition):

**Definition 1.2 (Universal Fiat-Shamir hash, informal).** For circuit classes  $\mathcal{D} \subseteq \mathcal{C}$ , we say a hash function family  $\mathcal{H}$  is a universal Fiat-Shamir hash from  $\mathcal{C}$  to  $\mathcal{D}$  if Fiat-Shamir using  $\mathcal{H}$  always results in a sound non-interactive  $\mathcal{D}$ -argument starting from any (3-round public-coin) interactive  $\mathcal{C}$ -argument that matches the input and output lengths of  $\mathcal{H}$  (i.e., the protocol's instance + first message length should be  $\mathcal{H}$ 's input length, and the protocol's second message length should be  $\mathcal{H}$ 's output length).  $\diamond$

Note that Definition 1.2 is already enough to capture a large class of hash functions, which is a fixed hash function family as long as the input and output lengths are determined. As an example, the CI hash function in [CCRR18] fits well into this format. However, there also exist



hash functions outside the scope of Definition 1.2. For example, the CI hash from [PS19] does not fit into this definition<sup>4</sup> because its key length depends on some specific property of the interactive proofs we want to collapse, which cannot be fixed in advance given only the input and output lengths (more precisely, its key length depends on how fast we can compute the “bad function” of the protocol). Based on this definition, we give our first negative result:

**Theorem 1.3 (Informally stated, see Theorem 5.2).** Assuming the existence of a CRHF family that is computable in  $\mathcal{D}$  and collision-resistant against  $\mathcal{C}$  with any polynomial shrinkage, there does not exist a universal Fiat-Shamir hash from  $\mathcal{C}$  to  $\mathcal{D}$  with any polynomial input and output lengths.  $\diamond$

Here we further justify our assumption of a low-complexity CRHF. One can examine that the CRHF construction  $f_A(x) = Ax \bmod q$  based on the hardness of short integer solution (SIS) [Ajt96] is actually computable in  $\text{TC}^0$  (and has polynomial shrinkage). Also, the discrete-log (DLOG)-based CRHF construction  $f_{g,h}(x_1, x_2) = g^{x_1} \cdot h^{x_2}$  can also be computed by a  $\text{TC}^0$  circuit using some standard pre-processing techniques. Therefore, low-complexity CRHFs are known from these well-studied cryptographic assumptions, which leads to the following corollary:

**Corollary 1.4.** Assuming SIS/DLOG, there does not exist a universal Fiat-Shamir hash that can soundly transform any interactive argument into a non-interactive  $\text{TC}^0$ -argument.  $\diamond$

Actually, similar results hold also for circuit classes lower than  $\text{TC}^0$ . We present a candidate  $\text{AC}^0[2]$ -computable poly-shrinkage CRHF based on a variant of SIS, indicating the impossibility of a universal Fiat-Shamir hash achieving even only  $\text{AC}^0[2]$ -soundness. See Appendix B for more discussions on the  $\text{AC}^0[2]$ -computable CRHF.

Even more generally, we show that the result of Goldwasser and Kalai [GK03] – albeit looks complicated and requires super-constant depth at a first glance – can be generalized to the bounded-depth setting with adversaries from circuit classes as low as  $\text{AC}^0[2]$ .

**Theorem 1.5 (Informally stated, see Theorem 6.1).** For any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , assuming the existence of a CRHF family with arbitrary polynomial shrinkage that is computable in  $\mathcal{C}$  and collision-resistant against  $\mathcal{C}$ , there exists a 3-round public-coin  $\mathcal{C}$ -argument such that instantiating Fiat-Shamir using any hash function computable in  $\mathcal{C}$  does not result in a sound non-interactive  $\mathcal{C}$ -argument.  $\diamond$

Compared to the previous result in Theorem 1.3 showing impossibility even when we require only some weaker soundness on the Fiat-Shamir-collapsed protocol, Theorem 1.5 shows only the impossibility of Fiat-Shamir hash functions preserving the same level of soundness due to some technical issues. However, instead of saying every FS hash must fail on some tailored protocol, Theorem 1.5 is stronger in the sense that it shows the existence of some fixed protocol that makes every Fiat-Shamir hash fail. The Fiat-Shamir hash is allowed to depend arbitrarily on the fixed interactive protocols (e.g., the third message’s length  $|\gamma|$  or the prover/verifier running time, which are not allowed in Definition 1.2 and Theorem 1.3).

Also note that the CRHF in our assumption can be instantiated (at least for  $\text{AC}^0[2] \subseteq \mathcal{C} \subseteq \text{NC}^1$ ) by the CRHF from [DVV16] that is computable in  $\text{AC}^0[2]$  and secure against  $\text{NC}^1$  based on the worst-case complexity assumption  $\text{NC}^1 \neq \oplus\text{L}/\text{poly}$ .

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<sup>4</sup>Here we are only talking about the formats of these hash functions (e.g., how the key length is chosen) instead of their specific functionalities – of course, we do not have such a universal Fiat-Shamir hash with security against p.p.t. due to [GK03].

## 1.4 Related works

Aside from the results like Goldwasser and Kalai [GK03] showing that there is an interactive argument such that no explicit hash function can collapse the protocol while preserving soundness, there have also been negative results for some restricted classes of protocols, in particular, for protocols related to SNARGs like Kilian’s protocol [Kil92]. Kilian’s protocol is a 4-message succinct argument for any NP language. The idea of collapsing Kilian’s protocol by Fiat-Shamir comes from Micali’s CS proofs [Mic00], which are now usually referred to as succinct non-interactive arguments (SNARGs). While Micali’s construction applies Fiat-Shamir in the random oracle model, there have been negative results on Fiat-Shamir for Kilian’s protocol in the plain model. Gentry and Wichs [GW11] showed a substantial barrier to constructing SNARGs in general (not limited to collapsing Kilian’s protocol), and the problem of securely instantiating Fiat-Shamir on Kilian’s protocol also suffers from this barrier. More recently, Bartusek, Bronfman, Holmgren, Ma, and Rothblum [BBHMR19] showed that Fiat-Shamir with any explicit hash function can never be secure on some contrived instantiation of Kilian’s protocol.

CI hash functions for constant degree polynomial relations against all ppt adversaries exist under various assumptions (for example, in [Can+19; BKM20]), but none of them is computable in  $\text{AC}^0[2]$ . After the initial publication of our work, Dao et al. [DJJ24] construct a CI hash function for degree- $d$  polynomial relations against all ppt adversaries, assuming the hardness of solving random degree- $d$  equations. When  $d$  is a constant, their hash function is also computable in  $\text{AC}^0[2]$ . Let us remark that the assumptions used in their work and our work are technically incomparable, but we think our assumption is arguably weaker since it is a worst-case complexity assumption.

**Organization.** The rest of this paper is organized as follows. We first give an overview of the intuition and techniques underlying our results in Section 2. In the subsequent sections, we present the details of our main results: on the positive side, we present our construction of CI hash functions in Section 4; on the negative side, we first show the impossibility of universal Fiat-Shamir hash functions in Section 5 (which corresponds to Theorem 1.3), and then present the stronger negative result of a universal counter-example for Fiat-Shamir in Section 6 (which corresponds to Theorem 1.5).

## 2 Technical Overview

In this section, we give an overview of the main ideas and techniques underlying our proofs.

### 2.1 Positive results

Our positive result is inspired by the CI hash function in [PS19], which crucially relies on the FHE scheme of Gentry, Sahai, Waters [GSW13] (henceforth GSW-FHE). Our main observation is that the FHE scheme against low-depth adversaries constructed by Wang and Pan [WP22] (henceforth WP-FHE) bears a striking similarity with GSW-FHE, therefore it can be used as in [PS19] to obtain a CI hash function against low-depth adversaries.

Let us start by explaining the intuition of [PS19]. They consider sparse relations defined by efficient functions i.e.  $\{(x, f(x))\}$  for some efficiently computable function  $f$ . Designing a hash function  $h(k, x)$  that is correlation intractable for a single function-defined relation is trivial: simply define  $h(k, x) = f(x) + 1$ . The construction [PS19] utilized the idea: for any  $f$ , a random



hash key will look indistinguishable from a hash key that is specifically designed to be correlation intractable with respect to the relation defined by  $f$ , i.e. the construction achieves the notion of “somewhere correlation intractability”. This idea can be implemented by using any fully homomorphic encryption scheme, i.e., the hash key is the homomorphic encryption of the circuit that computes a fixed function  $g_0$  (hence for any  $f$ , it looks indistinguishable from the encryption of the circuit that computes  $f$ ), and the hash function homomorphically computes  $g_0(x) + 1$  using a universal circuit  $\mathcal{U}(x, \cdot)$  s.t.  $\mathcal{U}(x, f) = f(x)$ . The result of homomorphic evaluation would be a ciphertext of  $g_0(x) + 1$ , so it remains as the last step to decrypt this ciphertext. One idea, as shown in [Can+19], is to put the encryption of the FHE decryption function inside the public key.

$$h(k, x) = \text{Eval}(\text{pk}, \mathcal{U}(x, \cdot), \text{ct}), \text{ where } k = (\text{pk}, \text{ct}), \text{ct} = \text{Enc}(\text{pk}, g_0) \approx \text{Enc}(\text{pk}, \text{Dec}(\text{sk}, f(\cdot)) \oplus 1).$$

Then for any function  $f$ , if  $k$  is sampled according to  $(\text{pk}, \text{Enc}(\text{pk}, \text{Dec}(\text{sk}, f(\cdot)) \oplus 1))$ , we have

$$f(x) = h(k, x) \implies f(x) = \text{Enc}(\text{pk}, \text{Dec}(\text{sk}, f(x)) \oplus 1) \implies \text{Dec}(\text{sk}, f(x)) = \text{Dec}(\text{sk}, f(x)) \oplus 1.$$

However, in this approach, in order to show the hash key  $k$  does not leak FHE secret key, we need to assume circular security. [PS19] bypasses this “decryption problem” based on an observation about the ciphertext of GSW-FHE. Namely, for any vector  $(y_i)_{i \in [n]}$ , if we have the ciphertext of each  $y_i$ , then we can compute  $Ar + y$  where  $A$  is the FHE public key and  $r$  is derived from the randomness used to encrypt each  $y_i$ . Coarsely, if  $y = f(x)$  as the result of homomorphic evaluation, then from  $f(x) = Ar + f(x)$  we find a solution for  $Ar = 0$ . [PS19] manages to reduce breaking SIS assumption to breaking correlation intractability of their construction.

Our construction of CI against low-depth adversary can be explained in a single sentence: replace GSW-FHE in the construction [PS19] by WP-FHE. We claim that these two FHE schemes, though under different assumptions and are against different adversaries, are similar to each other in a precise sense: WP-FHE can be regarded as the mod-2, noise-free version of GSW-FHE. We provide the following table to sustain this intuition.

	GSW-FHE	WP-FHE
$(\text{pk}, \text{sk})$	$k^T A = e \approx 0$	$k^T A = 0$
Enc	$AR + mG$	$AR + mI$
Dec	$k^T \text{ct} \cdot G^{-1}((0, \dots, 0, q/2)^T)$	$k^T \text{ct} \cdot (0, \dots, 0, 1)^T$
$\text{Eval}^{\text{add}}$	$\text{ct}_0 + \text{ct}_1 - 2\text{ct}_0 \cdot G^{-1}(\text{ct}_1)$	$\text{ct}_0 + \text{ct}_1$
$\text{Eval}^{\text{mul}}$	$\text{ct}_0 \cdot G^{-1}(\text{ct}_1)$	$\text{ct}_0 \cdot \text{ct}_1$

Table 1: Comparison between GSW-FHE and WP-FHE

The replacement allows the hash function to be computable in  $\text{AC}^0[2]$ . Also, we use a result in [EWT21] to show that the security of our construction follows from the worst-case complexity assumption.

## 2.2 Negative results

Our main impossibility result (Theorem 6.1) comes from adapting the impossibility result by Goldwasser and Kalai [GK03] to the bounded-depth settings. For readers familiar with [GK03], here we summarize the main technical challenges and techniques used to obtain a bounded-depth version of [GK03].

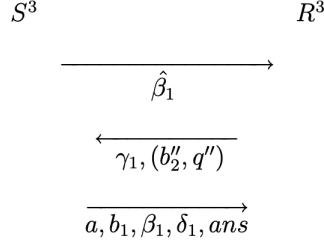


Figure 2: The picture of Protocol 3 from [GK03, Page 32]. Here  $q''$  denotes the CRS of a Fiat-Shamir reduced protocol used in their Protocol 1. Since  $q''$  is sent in the second message of the verifier  $R^3$ ,  $q''$  is supposed to be uniformly random. However, this implies (in a contrived manner) that the Fiat-Shamir hash function applied to Protocol 1 must be a public-coin hash function.

- **Merkle tree hash:** The construction of [GK03] relies on a Merkle tree hash to succinctly commit to messages that may have an arbitrary polynomial size. In our bounded-depth setting, however, the depth of the Merkle tree is inherently limited to a constant. To handle limitation on depth, we base our construction on the stronger assumption of a low-depth CRHF with polynomial shrinkage – then a constant-depth Merkle tree is enough to handle any polynomial-size message.
- **PCP in  $AC^0[2]$ :** [GK03] also uses probabilistic checkable proofs (PCPs) to guarantee the efficiency of the protocols. Since the prover in our setting is only allowed to do bounded-depth computations, we need a PCP satisfying all the required properties (including efficient oracle-construction, proof of knowledge, and reverse sampling as in [GK03; BG08]) within a bounded-depth circuit class. To meet the efficiency requirements here, we present in Appendix C the construction of such a PCP in  $AC^0[2]$ , i.e., a PCP with  $AC^0[2]$ -oracle-construction,  $AC^0[2]$ -proof-of-knowledge, and  $AC^0[2]$ -reverse-sampling.

Now we present the intuition of how to make Fiat-Shamir fail and our first impossibility result that directly follows the intuition (see Theorem 1.3 or 5.2). There is a simple intuition behind all existing contrived impossibility results: the prover in an interactive protocol is never able to predict the verifier’s choice of the next message, but Fiat-Shamir makes the verifier’s messages “predictable”. Consider the standard 3-round public-coin setting where the protocol transcript is  $(\alpha, \beta, \gamma)$ . While sending the first message  $\alpha$ , the prover can never predict the next message  $\beta$  in advance – no matter what prediction it makes, the verifier’s random choice of  $\beta$  coincides with the prediction only with negligible probability. However, things become totally different when we collapse the protocol by Fiat-Shamir: with the help of a randomly chosen hash function  $h \leftarrow \mathcal{H}_{FS}$ , the prover now directly generates  $(\alpha, \beta = h(x||\alpha), \gamma)$  in one shot without the verifier’s random choice. In other words, the next “verifier’s message”  $\beta = h(x||\alpha)$  is just a fixed value after generating  $\alpha$ , and of course, the malicious prover can predict  $\beta$ .

Based on the above observation, we can design an interactive protocol that simply asks the prover to predict the next message: in the first round, the prover tries to predict  $\beta$  by submitting the description of a function  $\alpha = \hat{C}$  (we use  $C$  to denote the circuit of the function and  $\hat{C}$  to denote the encoding of  $C$ ), which means his prediction of  $\beta$  is  $C(\alpha) = C(\hat{C})$ . Then the verifier randomly chooses  $\beta$  and sends it to the prover, ignores the prover’s third message, and finally accepts iff  $\beta = C(\alpha)$  holds (which means the prediction is correct). This is an interactive proof for the empty language: the verifier always rejects except the randomly-chosen  $\beta$  happens to be the fixed value

$C(\alpha)$ , which holds with only negligible probability<sup>5</sup>. After applying Fiat-Shamir, unfortunately, the non-interactive protocol becomes totally broken. Given a Fiat-Shamir hash  $h \leftarrow \mathcal{H}_{FS}$ , the cheating prover can simply send the description of this hash function (i.e., send  $\alpha = \widehat{h(x||\cdot)}$  with the instance  $x$  hardcoded), and then the Fiat-Shamir transformation requires  $\beta$  to be  $\beta = h(x||\alpha)$ , which makes the verifier accept.

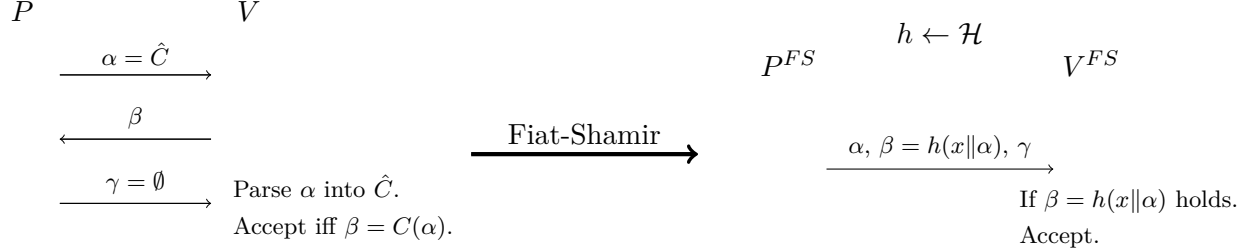


Figure 3: A protocol for the empty language that is not sound after Fiat-Shamir.

This counter-example can work in the bounded-depth setting (since what the cheating prover does is simply copying the Fiat-Shamir hash function). However, there is an implicit limitation: when saying  $\alpha = \widehat{h(x||\cdot)}$ ,  $\beta = h(x||\alpha)$ , we implicitly require the Fiat-Shamir hash  $h$  to have a short enough description that can fit into its input, i.e.  $|h| \leq |\alpha|$ . As a result, this counter-example fails to capture a large class of Fiat-Shamir hash functions with the description length longer than the input length. This limitation somehow makes the counter-example worthless, since Fiat-Shamir hash functions usually have larger sizes: as shown in the work of Canetti, Goldreich, and Halevi [CGH04], a hash function cannot even be correlation intractable (i.e., preserving soundness for proofs) if its key length is shorter than the input length.

In order to bypass this limitation, we made some modifications based on the protocol above. Instead of sending the whole circuit description  $\hat{C}$  in the first round, the prover only commits to such a description by sending a succinct commitment  $\alpha = f(\hat{C})$  ( $f$  is the commitment function) – although the description may be long, its commitment can still be short enough to fit into the Fiat-Shamir hash’s input. After that, the prover in the third round sends  $\gamma = \hat{C}$  in clear to open the commitment, and the verifier decides to accept or reject by checking if  $\alpha = f(\hat{C})$  (the opening is correct) and  $\beta = C(\alpha)$  (the prediction is correct). See Figure 4 for an illustration of the modified protocol. In this case, a cheating prover after Fiat Shamir transformation can still set  $C$  to be the Fiat Shamir hash function  $h(x||\cdot)$ , and it is clear to see the verifier will accept the proof regardless the input  $x$ .

In order to fit into the bounded-depth setting, we instantiate the succinct commitment  $f$  with a CRHF that can be computed in low depth and has enough shrinkage, which leads to our first negative result as shown in Theorem 1.3. Note that the exact shrinkage of CRHF matters here because we cannot boost the shrinkage arbitrarily in the bounded-depth setting: the circuit depth grows as we stack a CRHF several times to build a Merkle tree. The detailed security proof of this protocol is deferred to Section 5.

<sup>5</sup>Note that in an interactive protocol for the empty language, there is no *honest* prover since no instance can be proved (except with negligible probability). Or we can say the honest prover is just a machine that sends all-0 strings of some fixed lengths in each round. We clarify here that when describing the prover’s behaviors, we actually mean what the prover is supposed to do (and the verifier will check it later). For example, by saying the prover sends  $\alpha = \hat{C}$ , we actually mean the cheating prover sends an arbitrarily  $\alpha$  and the verifier will parse  $\alpha$  into the description of a circuit  $C$  when deciding to accept/reject.

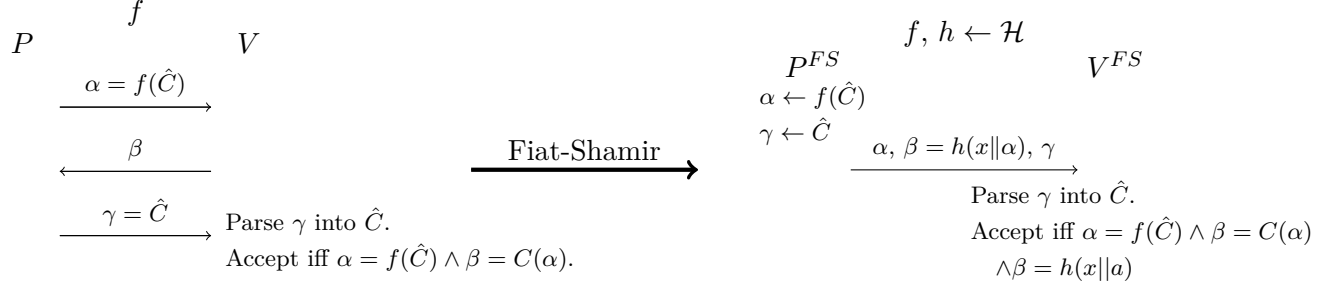


Figure 4: The modified protocol for the empty language.

In the aforementioned counterexample, the hash function size remains bounded by a predetermined polynomial. This paper also explores adapting the findings of Goldwasser and Kalai [GK03] to achieve a more general negative result. Drawing inspiration from their construction, and by carefully addressing circuit depth and the challenges previously mentioned, we present three protocols. We demonstrate that at least one of these protocols must serve as a counterexample to the Fiat-Shamir transformation. Our strategy hinges on a win-win argument involving these three protocols: either an adversary can break the security of one protocol after the Fiat-Shamir transformation, thus invalidating it, or no adversary can compromise the security of another. In the latter case, we can leverage a protocol that is easily broken post-transformation but challenging to prove secure as our counterexample. The actual win-win argument is more intricate, involving all three protocols. For a detailed explanation, please refer to Section 6.

## 3 Preliminaries

### 3.1 Circuit

In the context of this paper, when we refer to circuits, we are specifically referring to boolean circuits designed to accept a fixed number of input bits and produce a fixed number of output bits, with gates inside as computation units. For any given circuit denoted as  $C$ , we employ the notation  $C(x)$  to signify the result produced by circuit  $C$  when it is given input  $x$ . Within the scope of a defined circuit class  $\mathcal{C}$ , we employ the notation  $\hat{C}$  to represent the encoded representation of circuit  $C$ , and we denote the length of this encoding as  $|\hat{C}|$ . Here, we require the encoding satisfying that:

- Hard-wiring any bits into the input of circuit  $C$  will not affect the length of the encoding.
- For all polynomials  $S(n), d(n)$ , there exists a universal circuit class  $\mathcal{U} = \{U_n\}_{n \in \mathbb{N}}$  in  $\mathcal{C}$ , such that for any circuit families  $\{C_n\}_{n \in \mathbb{N}}$  in  $\mathcal{C}$  with encoding length  $S(n)$  and depth  $d(n)$ ,  $U_n$  can evaluate  $C_n$ .

It is worth noting that universal circuits exist in all commonly encountered circuit classes, which ensures the existence of required encoding. We sometimes refer to the length of encoding as circuit size, when we do not explicitly specify encoding of the circuit.

**Circuit classes.** We frequently use the following circuit classes in this paper (cf. [AB09] for a standard reference):

**Definition 3.1 ( $\mathbf{NC}^d$ ).** For every  $d$ , a language  $L$  is in  $\mathbf{NC}^d$  if  $L$  can be decided by a family of circuits  $\{C_n\}$  where  $C_n$  has  $\text{poly}(n)$  size and depth  $O(\log^d n)$ .  $\diamond$

**Definition 3.2 ( $\mathbf{AC}^i$ ).** The class  $\mathbf{AC}^i$  is defined similarly to  $\mathbf{NC}^i$  except gates are allowed to have unbounded fan-in (i.e., the OR and AND gates can be applied to more than two bits).  $\diamond$

We frequently use variants of  $\mathbf{AC}^0$  in this paper. For every integer  $q \geq 2$ , a language  $L$  is in  $\mathbf{AC}^0[q]$  if  $L$  can be decided by circuits consisting of OR, AND,  $\text{MOD}_q$  gates with unbounded fan-in, and NOT gates, of  $\text{poly}(n)$  size and depth  $O(1)$ . For a constant  $c \in \mathbb{N}^+$ ,  $\mathbf{AC}_c^0$  denotes  $\mathbf{AC}^0$  circuits with an explicit depth  $c$ .

**Definition 3.3 ( $\oplus\mathbf{L}/\text{poly}$ ).** A language  $L$  is in  $\oplus\mathbf{L}/\text{poly}$  if the characteristic function  $f(x) = [x \in L]$  satisfies the following: there is a constant  $c$  such that for each  $n$ , there is a non-deterministic Turing Machine  $M_n$  such that for all  $x \in \{0, 1\}^n$ ,  $M_n(x)$  uses at most  $c \log n$  space, and  $f(x)$  equals to the parity of the number of accepting paths of  $M_n(x)$ .  $\diamond$

**Definition 3.4 ( $\widetilde{\text{Sum}}_\delta \circ \mathcal{C}$ ).** For  $\delta$  being a constant or a function of  $n$ , we say a function  $f : \{0, 1\}^* \rightarrow \{0, 1\}$  admits a family of  $\widetilde{\text{Sum}}_\delta \circ \mathcal{C}$  circuits, if  $\exists s(n) \in \text{poly}(n)$  and  $\{C_n : \{0, 1\}^n \rightarrow \{0, 1\}^{s(n)}\} \in \mathcal{C}$ , such that for each  $n$ , there exists a length- $s(n)$  vector  $\alpha_n = (\alpha_{s(n),1}, \alpha_{s(n),2}, \dots, \alpha_{s(n),s(n)}) \in \mathbb{R}^{s(n)}$ ,  $\forall x \in \{0, 1\}^n$ ,

$$|\langle \alpha_n, C_n(x) \rangle - f(x)| \leq \delta. \quad \diamond$$

**Definition 3.5 (Collision resistant hash function family).** For a function family

$$\mathcal{F} = \left\{ f_n : \{0, 1\}^{l_k(n)} \times \{0, 1\}^{l_{in}(n)} \rightarrow \{0, 1\}^{l_{out}(n)} \right\}_{n \in \mathbb{N}}$$

with the key generation algorithm

$$\text{Gen}_{\mathcal{F}} = \left\{ \text{Gen}_{\mathcal{F},n} : \{0, 1\}^* \rightarrow \{0, 1\}^{l_k(n)} \right\},$$

we say it is a collision resistant hash function family, if for any adversary  $\mathcal{A} = \{\mathcal{A}_n\}_{n \in \mathbb{N}}$ , there exists negligible function  $\text{negl}(n)$  that  $\forall n \in \mathbb{N}$ ,

$$\Pr \left[ f_n(k, x_1) = f_n(k, x_2) \wedge x_1 \neq x_2 \mid \begin{matrix} k \leftarrow \text{Gen}_{\mathcal{F},n} \\ x_1, x_2 \leftarrow \mathcal{A}_n(k) \end{matrix} \right] < \text{negl}(n) \quad \diamond$$

We say that a collision resistant hash function family is in  $\mathcal{C}$  iff  $\mathcal{F}$  and  $\text{Gen}_{\mathcal{F}}$  are in  $\mathcal{C}$ . In other words, we require  $\mathcal{F}$  to be uniform, in the sense that each  $\mathcal{C}$  circuit computing  $f_n$  takes both the key  $k \in \{0, 1\}^{l_k(n)}$  and  $x \in \{0, 1\}^{l_{in}(n)}$  as input.

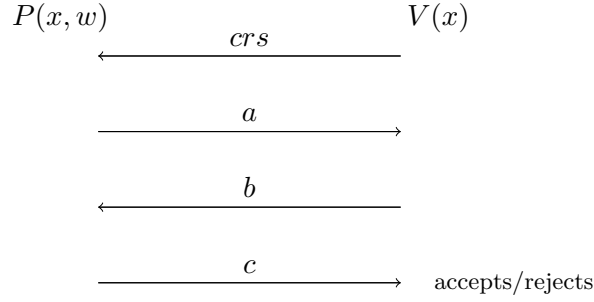
For simplicity, we will also denote this function family as

$$\mathcal{F} = \left\{ \mathcal{F}_n : \{0, 1\}^{l_{in}(n)} \rightarrow \{0, 1\}^{l_{out}(n)} \right\}_{n \in \mathbb{N}}.$$

We use  $f \leftarrow \mathcal{F}_n$  to represent the process of generating a key  $k$  using  $\text{Gen}_{\mathcal{F},n}$  and get a circuit  $f_n(k, \cdot)$  with a key hard-coded in it. The key generation circuit size of  $\mathcal{F}$  is the size of circuit computing  $f \leftarrow \mathcal{F}_n$ , and the evaluation circuit size is the circuit size of  $f \in \mathcal{F}_n$ . These two sum up to the circuit size of  $\mathcal{F}$ . We use  $l_{\mathcal{F}}(n)$  to represent the evaluation circuit size. Sometimes, we may use  $f(x)$  for some  $x$  with length  $|x| < l_{in}(n)$ . You can interpret the input as padding  $x$  to  $l_{in}(n)$  with 0s.

### 3.2 Interactive protocol

**Definition 3.6 (3-round public coin protocol with common reference string (CRS)).** A 3-round protocol with common reference string consists of 2 entities: the prover  $P$  and the verifier  $V$ . Here, the prover  $P$  consists of an interactive circuit family  $\{P_n\}_{n \in \mathbb{N}}$ , and the verifier  $V$  consists of an interactive circuit family  $\{V_n\}_{n \in \mathbb{N}}$ . Here, we let  $V_n$  generate the common reference string. The common input is  $x$  and the auxiliary input for the prover is  $w$ . The process of interaction is shown below:



We may omit the indices if they are clear from the content. We will use  $P(x, w, crs)$  to represent the process of generating the first message and use  $P(x, w, crs, a, b)$  to represent the process of generating the third message when the previous state of  $P$  is clear from the context. We will use  $V(x, crs, a, b, c)$  to represent the process of verification. We will introduce the notation  $V|_a$ , signifying the interactive circuit  $V$  with the first message restricted to  $a$ . Also, we denote by  $V|_{a_1, \dots, a_t}$  the interactive circuit  $V$  with first  $t$  messages fixed. Note that the verifier will not keep the state after sending each message, so this notation is well-defined. We use  $l_{crs}(n), l_a(n), l_b(n), l_c(n)$  to indicate the length of common reference string and each message and use  $l_x(n), l_w(n)$  to represent the length of instance and witness when there is no ambiguity. We say that a 3-round public coin protocol is in  $\mathcal{C}$  if there exist circuits  $\{P_{1,n}\}_{n \in \mathbb{N}}, \{P_{2,n}\}_{n \in \mathbb{N}}$  and  $\{V_{1,n}\}_{n \in \mathbb{N}}, \{V_{2,n}\}_{n \in \mathbb{N}}$  in  $\mathcal{C}$  such that the prover  $P_n$  behaves as follows:

1. Uniformly selects  $r_1, r_2 \leftarrow \{0, 1\}^*$ .
2. Computes the first message  $a \leftarrow P_{1,n}(x, w, crs, r_1)$  and outputs  $a$ , and then waits for the next message  $b$ .
3. Computes the third message  $c \leftarrow P_{2,n}(x, w, crs, a, b, r_1, r_2)$  and outputs  $c$ .

and the verifier  $V_n$  behaves as follows:

1. Uniformly selects  $r \leftarrow \{0, 1\}^*$ .
2. Computes the common reference string  $crs \leftarrow V_{1,n}(r)$  and outputs the once-and-for-all message  $crs$ , and then waits for the message  $a$ .
3. Uniformly selects the second message  $b \leftarrow \{0, 1\}^{l_b(n)}$  and outputs  $b$ , and then waits for the final message  $c$ .
4. Accepts if  $V_{2,n}(x, crs, a, b, c) = 1$ .



We sometimes abbreviate the notation for the interaction for two parties  $P, V$  with common input  $x$  and auxiliary input to the prover  $w$  as  $(P, V)(x, w)$ , and we will use  $(P, V)(x, w) = 1$  to denote the event that  $V$  accepts after the interaction.

**Definition 3.7 (3-round public coin argument with CRS for language  $\mathcal{L}$  against  $\mathcal{D}$ ).** Let  $l_x(n)$  be the length of the instance from  $\mathcal{L}$  on security parameter  $n$ . Let  $\mathcal{R}$  be the relation underlying  $\mathcal{L}$  (i.e.,  $x \in \mathcal{L}$  iff  $\exists w : (x, w) \in \mathcal{R}$ ) and  $l_w(n)$  be the witness length on security parameter  $n$ . A 3-round public coin argument with CRS for language  $\mathcal{L}$  against  $\mathcal{D}$  is a 3-round public-coin protocol  $(P, V)$  with common reference string that satisfies:

- **Completeness:**  $\forall n \in \mathbb{N}, \forall x \in \{0, 1\}^{l_x(n)}, \forall w \in \{0, 1\}^{l_w(n)}$  s.t.  $(x, w) \in \mathcal{R}$ ,

$$\Pr[(P, V)(x, w) = 1] = 1,$$

where the probability is over the randomness of  $P, V$ .

- **Computational soundness against  $\mathcal{D}$ :** For any cheating prover  $\tilde{P} = \{\tilde{P}_n\}_{n \in \mathbb{N}}$  computable in  $\mathcal{D}$ , there exists a negligible function  $\text{negl}(n)$  that,  $\forall n \in \mathbb{N}, \forall x \in \{0, 1\}^{l_x(n)}$  s.t.  $x \notin \mathcal{L}$ ,

$$\Pr[(\tilde{P}, V)(x) = 1] < \text{negl}(n),$$

where the probability is over the randomness of  $\tilde{P}, V$ . Sometimes we also say  $(P, V)$  is secure against  $\mathcal{D}$  for the same meaning.

Additionally, we say  $(P, V)$  is an argument of knowledge in  $\mathcal{C}$  if it satisfies:

- **Argument of knowledge in  $\mathcal{C}$  against  $\mathcal{D}$ :** For all polynomial  $p(n)$ , there exists an extractor  $E^{\tilde{P}}$  in  $\mathcal{C}$  with oracle access to some circuit  $\tilde{P}$  such that for any prover  $\tilde{P} = \{\tilde{P}_n\}_{n \in \mathbb{N}}$  computable in  $\mathcal{D}$  such that for every  $x \in \{0, 1\}^{l_x(n)}$ , if

$$\Pr[(\tilde{P}, V)(x) = 1] \geq \frac{1}{p(n)},$$

then

$$\Pr[\exists w, (x, w) \in \mathcal{R} \text{ and } \forall 1 \leq i \leq |w|, E^{\tilde{P}}(x, i) = w_i] > 1 - \text{negl}(n).$$

Here the relation  $\mathcal{R}$  is the same as the one in **Completeness**. ◇

### 3.3 Fiat-Shamir for 3-round public coin argument with common reference string

**Definition 3.8 (Fiat-Shamir hash function).** Given four polynomials  $l_k(n), l_x(n), l_a(n), l_b(n)$ , a function family of the form

$$\mathcal{H} = \left\{ h_n : \{0, 1\}^{l_k(n)} \times \{0, 1\}^{l_x(n) + l_a(n)} \rightarrow \{0, 1\}^{l_b(n)} \right\}_{n \in \mathbb{N}}$$

with the key generation algorithm

$$\text{Gen}_{\mathcal{H}} = \left\{ \text{Gen}_{\mathcal{H}, n} : \{0, 1\}^* \rightarrow \{0, 1\}^{l_k(n)} \right\}_{n \in \mathbb{N}}$$

is called a Fiat-Shamir hash function family. Here,  $l_x$  is the input length of the protocol,  $l_a$  is the length of the first message, and  $l_b$  is the length of the second message. ◇

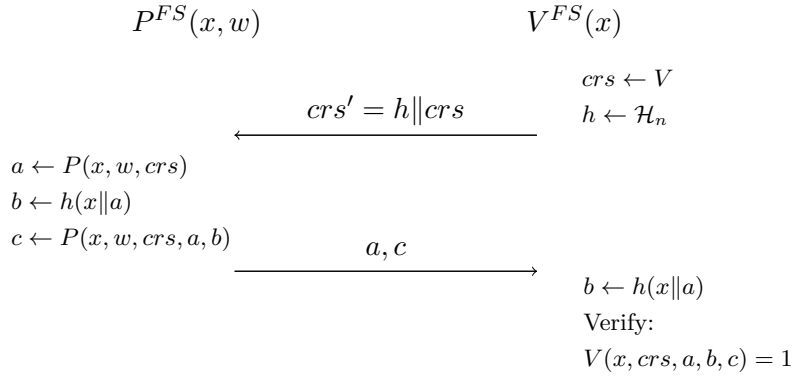
We say that a Fiat-Shamir hash function is in  $\mathcal{C}$  iff  $\mathcal{H}$  and  $\text{Gen}_{\mathcal{H}}$  are computable in  $\mathcal{C}$ . In other words, we require the hash  $\mathcal{H}$  to be uniform, in the sense that each  $\mathcal{C}$  circuit computing  $h_n$  takes both the key  $k \in \{0, 1\}^{l_k(n)}$  and the instance concatenating the first message  $x \| a \in \{0, 1\}^{l_x(n) + l_a(n)}$  as input.

For simplicity, we will also denote this function family as

$$\mathcal{H} = \left\{ \mathcal{H}_n : \{0, 1\}^{l_x(n) + l_a(n)} \rightarrow \{0, 1\}^{l_b(n)} \right\}_{n \in \mathbb{N}}.$$

We use  $h \leftarrow \mathcal{H}_n$  to represent the process of generating a key  $k$  using  $\text{Gen}_{\mathcal{H}, n}$  and get a circuit  $h_n(k, \cdot)$  with a key hard-coded in it. The key generation circuit size of  $\mathcal{H}$  is the size of the circuit computing  $h \leftarrow \mathcal{H}_n$ , and the evaluation circuit size is the circuit size of  $h \in \mathcal{H}_n$ . These two sum up to the circuit size of  $\mathcal{H}$ . We use  $l_{\mathcal{H}}(n)$  to represent the evaluation circuit size.

**Definition 3.9 (The Fiat-Shamir transform).** Given a 3-round public coin protocol  $(P, V)$  with common reference string and a Fiat-Shamir hash function family  $\mathcal{H}, \text{Gen}_{\mathcal{H}}$ . The Fiat-Shamir transform on  $(P, V)$  with respect to  $\mathcal{H}$  results in a new protocol  $(P^{FS}, V^{FS})$ . The prover  $P^{FS}$  consists of a circuit family  $\{P_n^{FS}\}_{n \in \mathbb{N}}$  and the verifier  $V^{FS}$  consists of a circuit family  $\{V_n^{FS}\}_{n \in \mathbb{N}}$ . The protocol interacts as follows:



For  $(P^{FS}, V^{FS})$  proving language  $\mathcal{L}$ , we define several properties:

- **Completeness:** Let  $\mathcal{R}$  be the relation underlying  $\mathcal{L}$  and  $l_w(n)$  be the witness length. Then  $\forall n \in \mathbb{N}, \forall x \in \{0, 1\}^{l_x(n)}, \forall w \in \{0, 1\}^{l_w(n)}$  s.t.  $(x, w) \in \mathcal{R}$

$$\Pr [(P^{FS}, V^{FS})(x, w) = 1] = 1,$$

where the probability is over the randomness of  $P^{FS}, V^{FS}$ .

- **Computational Soundness against  $\mathcal{D}$ :** For each adversary  $P^* = \{P_n^*\}_{n \in \mathbb{N}}$  computable in  $\mathcal{D}$ , there exists a negligible function  $\text{negl}(n)$  that,  $\forall n \in \mathbb{N}, \forall x \in \{0, 1\}^{l_x(n)}$  s.t.  $x \notin \mathcal{L}$ ,

$$\Pr [(P^*, V^{FS})(x) = 1] < \text{negl}(n),$$

where the probability is over the randomness of  $P^*, V^{FS}$ .

If  $(P, V)$  is 3-round public coin argument with CRS for language  $\mathcal{L}$  against  $\mathcal{D}$ , and  $(P^{FS}, V^{FS})$  satisfies **completeness** and **computational soundness against  $\mathcal{D}$** , we say that applying Fiat-Shamir transformation to the argument with  $\mathcal{H}$  gives an argument against adversary in  $\mathcal{D}$  for  $\mathcal{L}$ . Sometimes we also say that it is secure against  $\mathcal{D}$  for the same meaning.

## 4 Correlation Intractability Against Bounded-Depth Adversaries

In this section we show positive results for Fiat-Shamir for proofs against bounded-depth adversaries. We first observe that the construction of correlation intractable (CI) hash functions of Peikert and Shiehian [PS19] is computable in  $\text{TC}^0$ , therefore it has already implied the existence of a CI hash function family computable in  $\text{TC}^0$  against adversaries in circuit class  $\mathcal{D} \supseteq \text{TC}^0$ , assuming SIS is hard against  $\mathcal{D}$ . We then show our main result: the construction of CI hash functions computable in  $\text{AC}^0[2]$  against adversaries in any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , assuming  $\oplus\text{L}/\text{poly} \not\subseteq \widetilde{\text{Sum}}_{n^{-c}} \circ \mathcal{C}$  for some constant  $c > 0$ , which is a worst-case complexity assumption.

The rest of Section 4 is organized as follows. In Section 4.1 we provide the background needed for this section. In Section 4.2 we present the construction in [PS19]. The reasons we choose to present the construction in [PS19] are:

- We emphasize that the construction and hardness reduction can be computed in  $\text{TC}^0$ ;
- The full construction makes the latter construction (which is our main result) more understandable.

Then in Section 4.3 we present our main construction of CI hash function computable in  $\text{AC}^0[2]$  against low-depth adversaries.

### 4.1 Backgrounds needed in this section

#### 4.1.1 Hard Lattice Problems

**Definition 4.1.** The  $\text{SIS}_{n,m,q,\beta}$  problem is, given a uniformly random matrix  $A \in \mathbb{Z}_q^{n \times m}$ , find a non-zero integral vector  $z \in \mathbb{Z}^m$  such that  $Az \equiv 0 \pmod{q}$  and  $\|z\| \leq \beta$ .  $\diamond$

**Definition 4.2.** The  $\text{LWE}_{n,m,q,\chi}$  problem is to distinguish, with non-negligible advantage, given a uniformly random matrix  $A \in \mathbb{Z}_q^{n \times m}$ ,  $s^T A + e^T \in \mathbb{Z}_q^m$  where  $s \leftarrow \mathbb{Z}_q^n$  and  $e \leftarrow \chi^m$  from a uniformly random vector in  $\mathbb{Z}_q^m$ .  $\diamond$

#### 4.1.2 Fully Homomorphic Encryption

**Definition 4.3 (Strongly Fully Homomorphic Encryption (sFHE) for  $\mathcal{D}$  against  $\mathcal{C}$ ).** A sFHE scheme for  $\mathcal{D}$  circuits is a function family  $\text{FHE} = \{\text{FHEGen}_n, \text{Enc}_n, \text{Dec}_n, \text{Eval}_n\}_{n \in \mathbb{N}}$  with the following syntax.

- $\text{FHEGen}_n$  returns a public/secret key pair  $(\text{pk}, \text{sk})$ .
- $\text{FHEGen}'_n$  returns a public key  $\text{pk}$ .
- $\text{Enc}_n(\text{pk}, m \in \{0, 1\}; r \in \{0, 1\}^*)$  returns a ciphertext  $\text{ct}$  using random bits  $r$ .
- $\text{Dec}_n(\text{sk}, \text{ct})$  (deterministically) returns a message  $m \in \{0, 1\}$ .
- $\text{Eval}_n(\text{pk}, f \in \mathcal{D}, (\text{ct}_1, \text{ct}_2, \dots, \text{ct}_s))$  (deterministically) return a ciphertext  $\text{ct}$  ( $s$  is the input size of  $f$ ).
- $\text{RandEval}_n(\text{pk}, f \in \mathcal{D}, (m_1, \dots, m_s), (r_1, \dots, r_s))$  (deterministically) returns a randomness  $r \in \mathcal{R}$  (again  $s$  is the input size of  $f$ ).

Furthermore, it satisfies the following properties:

- **Correctness:** we have  $m = \text{Dec}_n(\text{sk}, \text{Enc}_n(\text{pk}, m; r))$  for all  $n \in \mathbb{N}$  and  $m \in \{0, 1\}$  with probability 1 over  $(\text{pk}, \text{sk}) \leftarrow \text{FHEGen}_n$  and  $r \leftarrow \{0, 1\}^*$ .
- **CPA security:** For any adversary  $\mathcal{A} = \{\mathcal{A}_n\} \in \mathcal{C}$ ,

$$\left| \Pr[\mathcal{A}_n(\text{pk}) = 1 \mid (\text{pk}, \text{sk}) \leftarrow \text{FHEGen}_n] - \Pr[\mathcal{A}_n(\text{pk}) = 1 \mid \text{pk} \leftarrow \text{FHEGen}'_n] \right| < \text{negl}(n),$$

and the two distribution families

$$\{(\text{pk}, \text{Enc}(\text{pk}, 0)) : \text{pk} \leftarrow \text{FHEGen}'_n\}, \{(\text{pk}, \text{Enc}(\text{pk}, 1)) : \text{pk} \leftarrow \text{FHEGen}'_n\}$$

are statistically indistinguishable.

- **Strong homomorphism:** for every function family  $f = \{f_n\} \in \mathcal{D}$ , all  $n \in \mathbb{N}$ , all  $(\text{pk}, \text{sk})$  generated by  $\text{FHEGen}_n$  and all  $m_1, \dots, m_s \in \{0, 1\}$  and  $r_1, \dots, r_s \in \mathcal{R}$  ( $s = s(n)$  is the input size of  $f_n$ ), we have

$$\begin{aligned} & \text{Eval}_n(\text{pk}, f_n, (\text{Enc}(\text{pk}, m_1; r_1), \dots, \text{Enc}(\text{pk}, m_s; r_s))) \\ &= \text{Enc}_n(\text{pk}, f_n(m_1, \dots, m_s); \text{RandEval}_n(\text{pk}, f_n, (m_1, \dots, m_s), (r_1, \dots, r_s))). \end{aligned} \quad \diamond$$

**Remark.** Both GSW-FHE and WP-FHE defined later are sFHE schemes for at least bounded-degree polynomials under certain assumptions, although our proof does not rely on this fact. Also, in these two schemes,  $\text{RandEval}$  is given implicitly by  $\text{Eval}$ .

**Definition 4.4 (Lattice Gadgets over  $\mathbb{Z}_q$ ).** For a positive integer modulus  $q$ , let  $l = \lceil \lg q \rceil$ . We define the “gadget” vector as

$$g^T = (1, 2, \dots, 2^{l-1}) \in \mathbb{Z}_q^l.$$

For every  $u \in \mathbb{Z}_q$ , there is an efficiently computable binary vector  $g^{-1}(u) \in \{0, 1\}^l$  such that  $g \cdot g^{-1}(u) \equiv u \pmod{q}$ , i.e., the binary representation of  $u$ . We treat  $g^{-1} : \mathbb{Z}_q \rightarrow \{0, 1\}^l$  as a function that computes binary decomposition.

The gadget matrix is defined as  $G_n = I_n \otimes g^T$ , and sometimes we drop the subscript  $n$ . Similarly, we define the function  $G^{-1} = (I \otimes g^{-1}) : \mathbb{Z}_q^n \rightarrow \{0, 1\}^{nl}$ , which applies  $g^{-1}$  to each coordinate and concatenates the results. For any  $u \in \mathbb{Z}_q^n$ , we have

$$G \cdot G^{-1}(u) = u. \quad \diamond$$

**Construction 1 (GSW-FHE).** GSW-FHE is given by the function family  $\text{GSW-FHE} = \{\text{GSW-FHEGen}_n, \text{GSW-Enc}_n, \text{GSW-Dec}_n, \text{GSW-Eval}_n\}_{n \in \mathbb{N}}$ , parameterized by the lattice dimension  $n$ , the error distribution  $\chi$ , the modulus  $q$ , and the number of samples  $m = n \lceil \log q \rceil$ . We assume these parameters are chosen properly so that  $\text{LWE}_{n-1, 2m, q, \chi}$  is believed to be hard.

- $\text{GSW-FHEGen}_n$ :

1. Take  $A' \leftarrow \mathbb{Z}_q^{(n-1) \times 2m}$ ,  $s' \leftarrow \mathbb{Z}_q^{n-1}$ , and  $e \leftarrow \chi^{2m}$ .
2. Compute  $b = A'^T s' + e \in \mathbb{Z}_q^{2m}$ .

3. Return

$$\text{pk} = A = \begin{pmatrix} A' \\ b^T \end{pmatrix} \in \mathbb{Z}_q^{n \times 2m}, \text{sk} = k = \begin{pmatrix} -s' \\ 1 \end{pmatrix} \in \mathbb{Z}_q^n.$$

(Note that  $k^T A = e^T \approx 0$ .)

- $\text{GSW-FHEGen}'_n$ : return  $\text{pk} = A \leftarrow \mathbb{Z}_q^{n \times 2m}$  sampled uniformly at random.
- $\text{GSW-Enc}_n(\text{pk} = A, \mu \in \{0, 1\})$ :
  1. Take  $R \leftarrow \{0, 1\}^{2m \times m} \in \mathbb{Z}_q^{2m \times m}$ .
  2. Return  $\text{ct} = AR + \mu G \in \mathbb{Z}_q^{n \times m}$ .

We allow  $\text{GSW-Enc}_n$  to take a vector in  $\mathbb{Z}_2^m$  as the input, instead of a single bit. In this case, the encryption of each dimension of that vector (using independent randomness) is concatenated together by each row. That is, for a length- $m$  vector  $x$ ,  $\text{GSW-Enc}(\text{pk} = A, x) = AR + x^T \otimes I_n \otimes g^T$ , where  $R \leftarrow \mathbb{Z}_2^{2m \times m^2}$ .

- $\text{GSW-Dec}_n(\text{sk} = k, \text{ct})$ :
  1. Take  $w = (0, 0, \dots, 0, \lceil q/2 \rceil)^T \in \mathbb{Z}_q^n$ .
  2. Compute the value of  $V = k^T \text{ct} \cdot G^{-1}(w)$ , output the decrypted message as  $\left\lceil \frac{V}{q/2} \right\rceil$ .
- $\text{GSW-Eval}_n$ . We describe it by giving how to homomorphically compute addition and multiplication in  $\mathbb{Z}_q$ .
  - $\text{GSW-Eval}_n^{\text{add}}(\text{pk} = A, (\text{ct}_0, \text{ct}_1))$ : return  $\text{ct}_0 + \text{ct}_1 - 2\text{ct}_0 \cdot G^{-1}(\text{ct}_1) \in \mathbb{Z}_q^{n \times m}$ .
  - $\text{GSW-Eval}_n^{\text{mul}}(\text{pk} = A, (\text{ct}_0, \text{ct}_1))$ : return  $\text{ct}_0 \cdot G^{-1}(\text{ct}_1) \in \mathbb{Z}_q^{n \times m}$ . ◇

**Remark.** For any constant-degree polynomial function family  $\{f_n\}$ , the corresponding circuit family computing  $\text{GSW-Eval}_n(\text{pk}, f_n, (\text{ct}_1, \dots))$  is in  $\text{TC}^0$ . WP-FHE, which will be defined later, has a stronger property: the circuit family computing homomorphic evaluation of constant-degree polynomial function is in  $\text{AC}^0[2]$ .

#### 4.1.3 Inert Commitment

Let  $A \in \mathbb{Z}_q^{n \times 2m}$  be the public key of GSW-FHE, and let  $C_i = AR_i + x_i G$  be the homomorphic encryption of scalar  $x_i \in \{0, 1\}$ , for  $i \in [m]$ . Then we concatenate all  $C_i$ 's together, and view it as a commitment (relative to  $A$ ) to  $x^T = (x_1, \dots, x_m)^T$  under randomness  $R = (R_1, \dots, R_m)$ , i.e.

$$C = (C_1, \dots, C_m) = AR + x^T \otimes G = AR + x^T \otimes I_n \otimes g^T = \text{GSW-Enc}(A, x).$$

Since any matrix  $M \in \mathbb{Z}_q^{n \times m}$  can be “vectorized” as an  $v_M \in \mathbb{Z}_q^{nm}$ , so that  $(x^T \otimes I_n) \cdot v_M = Mx$ , we have

$$c_M = C \cdot G^{-1}(v_M) = A \underbrace{(R \cdot G^{-1}(v_M))}_{r_M} + (x^T \otimes I_n \otimes g^T) \cdot (I_m \otimes I_n \otimes g^{-t}) v_M = Ar_M + Mx \in \mathbb{Z}_q^n.$$

We view  $c_M$  as an “inert commitment” to  $Mx \in \mathbb{Z}_q^n$ , and we write it as  $\text{InertEval}(M, C)$ .

**Definition 4.5 (Inert Commitment).** Given  $C \in \mathbb{Z}_q^{n \times m^2}$  as the homomorphic encryption of some length- $m$  vector, and  $M \in \mathbb{Z}_q^{n \times m}$  as a matrix, we write

$$\text{InertEval}(M, C) := c_M = C \cdot G^{-1}(v_M),$$

where  $v_M \in \mathbb{Z}_2^{nm}$  is the vector satisfies  $(x^t \otimes I_n) \cdot v_M = Mx$  for any length- $m$  vector  $x$ , obtained by reordering the elements of  $M$ .  $\diamond$

#### 4.1.4 Correlation intractability

**Definition 4.6.** We say a relation  $\mathcal{R} \subseteq \mathcal{X} \times \mathcal{Y}$  is searchable in a set of functions  $\mathcal{F}$  if there exists a function  $f : \mathcal{X} \rightarrow \mathcal{Y}$  in  $\mathcal{F}$  such that if  $(x, y) \in \mathcal{R}$  then  $y = f(x)$ .

We say a relation class  $\mathcal{S} = \{\mathcal{S}_n\}_{n \in \mathbb{N}}$  (i.e. a set of relations for each  $n$ ) is searchable in a function family  $\mathcal{F} = \{\mathcal{F}_n\}_{n \in \mathbb{N}}$  if for each  $n \in \mathbb{N}$ , for all  $\mathcal{R} \in \mathcal{S}_n$ ,  $\mathcal{R}$  is searchable in  $\mathcal{F}_n$ .  $\diamond$

**Definition 4.7.** Let  $\mathcal{S} = \{\mathcal{S}_n\}$  be a relation class and  $\mathcal{C}$  be a circuit class. A hash function family

$$\mathcal{H} = \left\{ h_n : \{0, 1\}^{l_k(n)} \times \{0, 1\}^{l_{in}(n)} \rightarrow \{0, 1\}^{l_{out}(n)} \right\}$$

with a key generation algorithm

$$\text{Gen}_{\mathcal{H}} = \left\{ \text{Gen}_{\mathcal{H}, n} : \{0, 1\}^* \rightarrow \{0, 1\}^{l_k(n)} \right\}$$

is correlation intractable for  $\mathcal{S}$  against  $\mathcal{C}$  if for every circuit family  $\mathcal{A} = \{\mathcal{A}_n\} \in \mathcal{C}$ , there exists a negligible function  $\text{negl}(\cdot)$  such that for every  $n \in \mathbb{N}$ , for every  $\mathcal{R} \in \mathcal{S}_n$ ,

$$\Pr \left[ (x, h_n(k, x)) \in \mathcal{R} \mid \begin{array}{l} k \leftarrow \text{Gen}_{\mathcal{H}, n} \\ x \leftarrow \mathcal{A}_n(k) \end{array} \right] < \text{negl}(n).$$

We omit the polynomials  $l_k(n), l_{in}(n), l_{out}(n)$  when they are clear from the explicit construction.  $\diamond$

#### 4.1.5 Cryptographic primitives against bounded-depth circuits

We consider the capability of adversaries as some circuit class that at least contains  $\text{AC}^0[2]$  (thus can compute matrix multiplication in  $\mathbb{Z}_2$ ), with the assumption that the same circuit class augmented by an error-tolerant majority gate is not able to compute  $\oplus\text{L}/\text{poly}$ .

**Assumption 4.8.** For a certain circuit class  $\mathcal{C}$  s.t.  $\text{AC}^0[2] \subseteq \mathcal{C}$ , there exists a constant  $c > 0$  s.t.  $\oplus\text{L}/\text{poly} \not\subseteq \widetilde{\text{Sum}}_{1/n^c} \circ \mathcal{C}$ .

For example, Assumption 4.8 is widely believed to be true for  $\mathcal{C} \in \{\text{AC}^0[2], \text{TC}^0, \text{NC}^1\}$ .

**Remark.** When  $\mathcal{C} = \text{NC}^1$ , the assumption above is equivalent to  $\oplus\text{L}/\text{poly} \neq \text{NC}^1$  as in [DVV16].

In the following we introduce two distributions **ZeroSamp** and **OneSamp**. By using the result from randomized encoding [IK00; AIK06], any algorithm that distinguishes these two distributions can be used to compute functions in  $\oplus\text{L}/\text{poly}$ . Therefore, from the hardness of  $\oplus\text{L}/\text{poly}$  (as in Assumption 4.8), we can show that it is hard to distinguish **ZeroSamp** from **OneSamp**. Please see [DVV16] for more detailed discussion.



**Definition 4.9 (ZeroSamp, OneSamp).** Let  $n$  be the security parameter. For  $r^{(1)} \in \mathbb{Z}_2^{n(n-1)/2}$ , and  $r^{(2)} \in \mathbb{Z}_2^{n-1}$ , denote

$$L(r^{(1)}) = \begin{pmatrix} 1 & r_1^{(1)} & r_2^{(1)} & \cdots & r_{n-1}^{(1)} \\ & 1 & r_n^{(1)} & \cdots & r_{2n-3}^{(1)} \\ & & \ddots & \ddots & \vdots \\ & & & 1 & r_{n(n-1)/2}^{(1)} \\ & & & & 1 \end{pmatrix}, R(r^{(2)}) = \begin{pmatrix} 1 & 0 & 0 & 0 & r_1^{(2)} \\ & 1 & 0 & 0 & r_2^{(2)} \\ & & \ddots & \vdots & \vdots \\ & & & 1 & r_{n-1}^{(2)} \\ & & & & 1 \end{pmatrix}.$$

Also, let  $M_0^n, M_1^n$  be the following  $n \times n$  matrices:

$$M_0^n = \begin{pmatrix} \mathbf{0}^T & 0 \\ I_{n-1} & \mathbf{0} \end{pmatrix}, M_1^n = \begin{pmatrix} \mathbf{0}^T & 1 \\ I_{n-1} & \mathbf{0} \end{pmatrix} \quad (I_{n-1} \text{ is the identity matrix of rank } n-1).$$

Then we define two sampling procedures:

- **ZeroSamp**( $n$ ): take  $r^{(1)} \leftarrow \{0, 1\}^*$ ,  $r^{(2)} \leftarrow \{0, 1\}^*$  and output  $L(r^{(1)})M_0^n R(r^{(2)})$ .
- **OneSamp**( $n$ ): take  $r^{(1)} \leftarrow \{0, 1\}^*$ ,  $r^{(2)} \leftarrow \{0, 1\}^*$  and output  $L(r^{(1)})M_1^n R(r^{(2)})$ .

Note that the output of **ZeroSamp**( $n$ ) always has rank  $n-1$ , and the output of **OneSamp**( $n$ ) always has rank  $n$ . What's more, the random bits used by  $A \leftarrow \text{ZeroSamp}(n)$  also gives the kernel of  $A$ , and therefore we sometimes use  $A, k \leftarrow \text{ZeroSamp}(n)$  where  $k$  s.t.  $Ak = 0$  is additionally given by **ZeroSamp**( $n$ ).

If the security parameter  $n$  is clear from context, we may drop it and use the notation **ZeroSamp**, **OneSamp**.  $\diamond$

Previous literature discovered that  $\text{NC}^1$  circuits cannot distinguish **ZeroSamp** and **OneSamp** if  $\oplus\text{L}/\text{poly} \neq \text{NC}^1$ . We extend this idea from  $\text{NC}^1$  to other circuit classes that contain  $\text{AC}^0[2]$ , as stated in the following lemma.

**Lemma 4.10 (See Lemma 4.3 of [DVV16] for  $\mathcal{C} = \text{NC}^1$ ).** For any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , if Assumption 4.8 holds for  $\mathcal{C}$ , there is a negligible function  $\text{negl}(\cdot)$  such that for any family  $\mathcal{F} = \{f_n\}$  in  $\mathcal{C}$ , for an infinite number of values of  $n$ ,

$$| \Pr[f_n(M) = 1 \mid M \leftarrow \text{ZeroSamp}(n)] - \Pr[f_n(M) = 1 \mid M \leftarrow \text{OneSamp}(n)] | < \text{negl}(n). \quad \diamond$$

**Remark.** As Remark 3.1 of [DVV16] points out, from worst-case complexity assumptions, we can only achieve infinitely-often primitives, as if we assume  $\mathcal{D} \not\subseteq \mathcal{C}$  where  $\mathcal{C}, \mathcal{D}$  are circuit classes, we only mean that there exists a function family  $\{f_n\} \in \mathcal{D}$ , such that for any function family  $\{g_n\} \in \mathcal{C}$ ,  $f_n \neq g_n$  for infinitely many  $n$ .

However, as long as we strengthen the assumption from the previous one to that there exists  $\{f_n\} \in \mathcal{D}$ , for all  $\{g_n\} \in \mathcal{C}$ ,  $\exists n_0$  such that  $f_n \neq g_n$  for all  $n > n_0$ , we can achieve the conventional almost-everywhere security. We state this observation below. All our constructions assuming 4.8 automatically achieve almost-everywhere security using the strengthened assumption, and we only state theorems in the infinitely-often secure version for brevity.

**Assumption 4.11 (Strengthened assumption).** For a certain circuit class  $\mathcal{C}$  s.t.  $\text{AC}^0[2] \subseteq \mathcal{C}$ , there exists  $c > 0$  s.t.  $\exists \{f_n\} \in \oplus \text{L}/\text{poly}$  such that for any function family  $\{g_n\} \in \widetilde{\text{Sum}}_{1/n^c} \circ \mathcal{C}$ ,  $\exists n_0$  such that  $f_n \neq g_n$  for all  $n > n_0$ .

**Lemma 4.12.** For any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , if Assumption 4.11 holds for  $\mathcal{C}$ , there is a negligible function  $\text{negl}(\cdot)$  such that for any family  $\mathcal{F} = \{f_n\}$  in  $\mathcal{C}$ , for all but infinitely many  $n$ ,

$$| \Pr[f_n(M) = 1 \mid M \leftarrow \text{ZeroSamp}(n)] - \Pr[f_n(M) = 1 \mid M \leftarrow \text{OneSamp}(n)] | < \text{negl}(n). \quad \diamond$$

Since we extend previous work from  $\text{NC}^1$  to general circuit classes  $\mathcal{C}$ , and our previous lemmas 4.10, 4.12 are slightly different from those in literature (see lemma 4.3 of [DVV16], where  $n = n(\lambda)$  is polynomial of security parameter), we include proofs of those lemmas in Appendix A.

**Construction 2 (WP-FHE [WP22]).** WP-FHE is given by the function family  $\text{WP-FHE} = \{ \text{WP-FHEGen}_n, \text{WP-Enc}_n, \text{WP-Dec}_n, \text{WP-Eval}_n \}_{n \in \mathbb{N}}$ .

- $\text{WP-FHEGen}_n$ : Take  $A^T, k \leftarrow \text{ZeroSamp}(n)$ , and set  $\text{pk} = A, \text{sk} = k$ .
- $\text{WP-FHEGen}'_n$ : Take  $A^T \leftarrow \text{OneSamp}(n)$ , and then output  $\text{pk} = A$ .
- $\text{WP-Enc}_n(\text{pk} = A, m \in \{0, 1\})$ : Take  $R \leftarrow \mathbb{Z}_2^{n \times n}$ , then return  $\text{ct} = AR + mI_n \in \mathbb{Z}_2^{n \times n}$ . We allow  $\text{WP-Enc}_n$  to take a vector in  $\mathbb{Z}_2^n$  as input, instead of a single bit. In this case, the encryption of each dimension of that vector (using independent randomness) is concatenated together by each row. That is, for a length- $n$  vector  $x$ ,  $\text{WP-Enc}(\text{pk} = A, x) = AR + x^T \otimes I_n$ , where  $R \leftarrow \mathbb{Z}_2^{n \times n^2}$ .
- $\text{WP-Dec}_n(\text{sk} = k, \text{ct})$ : Let  $c$  be the  $n$ -th column vector of  $\text{ct}$ , and then return  $k \cdot c$ .
- $\text{WP-Eval}_n$ . We describe it by giving how to homomorphically compute addition and multiplication in  $\mathbb{Z}_2$ .
  - $\text{WP-Eval}_n^{\text{add}}(\text{pk} = A, (\text{ct}_0, \text{ct}_1))$ : return  $\text{ct}_0 + \text{ct}_1 \in \mathbb{Z}_2^{n \times n}$ .
  - $\text{WP-Eval}_n^{\text{mul}}(\text{pk} = A, (\text{ct}_0, \text{ct}_1))$ : return  $\text{ct}_0 \text{ct}_1 \in \mathbb{Z}_2^{n \times n}$ .  $\diamond$

**Remark.** We emphasize the striking similarity between GSW-FHE and WP-FHE. The  $(\text{pk}, \text{sk})$  pairs of both schemes are  $(\text{pk} = A, \text{sk} = k)$  where  $A$  is a matrix,  $k$  is a vector with  $k^T A \approx 0$  in GSW-FHE, and  $k^T A = 0$  in WP-FHE. What's more, if we treat the identity matrix  $I$  as  $G$ 's analog in  $\mathbb{Z}_2$ , then the encryption of both schemes is  $\text{Enc}(\text{pk} = A, m) = AR + mG$ . Similarly, homomorphic addition of both schemes is adding two ciphertexts together, and  $\text{Eval}^{\text{mul}}(\text{ct}_0, \text{ct}_1) = \text{ct}_0 G^{-1}(\text{ct}_1)$  for both schemes. Recall Table 1 as a summary of the above observations.

Our proof uses the following lemma:

**Lemma 4.13 ([EWT21]).** For any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , if Assumption 4.8 holds for  $\mathcal{C}$ , then  $\{p_A(x) = Ax : A \leftarrow \text{OneSamp}\}$  is a collection of one-way permutations against  $\mathcal{C}$ , that is, for any adversary family  $\{\mathcal{A}_n\}_{n \in \mathbb{N}} \in \mathcal{C}$ , there exists a negligible function  $\text{negl}(\cdot)$  such that for infinitely many  $n$ ,

$$\Pr \left[ Ay = Ax \mid \begin{array}{l} A \leftarrow \text{OneSamp}(n) \\ x \leftarrow \mathbb{Z}_2^n \\ y \leftarrow \mathcal{A}_n(A, Ax) \end{array} \right] < \text{negl}(n). \quad \diamond$$

[EWT21] only proves the lemma for  $\mathcal{C} = \text{NC}^1$ , but actually their proof can be applied to any circuit class  $\mathcal{C}$  that satisfies requirement 4.8. We give a sketch of their proof.

**Proof sketch.** The idea is to use the adversary  $\{\mathcal{A}_n\}_{n \in \mathbb{N}}$  that breaks one-wayness with probability  $1/p(n)$  to distinguish **ZeroSamp** and **OneSamp**. First, checking  $Ay = Ax$  involves only matrix multiplication, so we can assume  $\mathcal{A}_n$  returns  $y$  with  $Ay = Ax$  or  $\perp$ . Since  $\{\mathcal{A}_n\}_{n \in \mathbb{N}} \in \mathcal{C}$  cannot distinguish **ZeroSamp** and **OneSamp**, we have

$$\Pr \left[ Ay = Ax \mid \begin{array}{l} A \leftarrow \text{ZeroSamp}(n) \\ x \leftarrow \mathbb{Z}_2^n \\ y \leftarrow \mathcal{A}_n(A, Ax) \end{array} \right] > \frac{1}{p(n)} - \text{negl}(n) > \frac{1}{p'(n)}.$$

For  $A$  sampled from **ZeroSamp**, whenever  $\mathcal{A}_n$  finds  $y$  s.t.  $Ay = Ax$ , we have probability  $\frac{1}{2}$  that  $x \neq y$  due to the randomness of  $x$  (recall  $A$  is of rank  $n - 1$ , so  $y$  has two solutions), in which case we have  $x - y$  as a non-trivial kernel of  $A$ . Therefore by invoking  $\mathcal{A}_n$  we have non-negligible probability to obtain the kernel of  $A$ , which can be used to distinguish **ZeroSamp** and **OneSamp** (recall that the output of **OneSamp** is always full-rank).

We emphasize that only matrix multiplication in  $\mathbb{Z}_2$  is used in this reduction, and thus the reduction is computable in  $\mathcal{C} \supseteq \text{AC}^0[2]$ .  $\square$

## 4.2 CI from SIS against bounded-depth adversaries

In this subsection, we follow the construction of [PS19] to show that it can be computed in  $\text{TC}^0$ , yielding a CI hash against bounded-depth adversary under the super-weak assumption of SIS against bounded-depth adversaries.

**Theorem 4.14.** For any circuit class  $\mathcal{C}$  that contains  $\text{TC}^0$ , for any polynomial  $S(n)$  and constant  $d$ , assuming the hardness of  $\text{SIS}_{n,m+1,q,\beta}$  for  $q = \text{poly}(n), l = \lceil \log q \rceil, m = nl$  and sufficiently large  $\beta = m^{O(d)}$  against  $\mathcal{C}$ , there exists a hash family computable in  $\text{TC}^0$  that is CI for any relation class searchable by size- $S(n)$ <sup>6</sup>, degree- $d$  polynomials  $\{f_n : \{0, 1\}^n \rightarrow \{0, 1\}^m\}_{n \in \mathbb{N}}$ , against adversaries in  $\mathcal{C}$ .  $\diamond$

This theorem is proven by the construction exhibited in this subsection (see Construction 3, Lemma 4.16). By lemma B.3, when  $n$  is large enough, by setting  $q \geq n^{\Omega(d)}$  s.t.  $q \geq \beta \cdot n^{\Omega(1)}$ , there is an polynomial time reduction from  $n^{\Omega(d)}$ -approximate SIVP to  $\text{SIS}_{n,m+1,q,\beta}$ .

**Remark.** The main difficulty in computing the construction in [PS19] lies in computing the sum of polynomially many numbers in  $\mathbb{Z}_q$ , where  $q$  is polynomially large.

**Remark.** The hash function is only CI for constant-degree polynomials because  $\text{TC}^0$  circuits can only perform a constant number of homomorphic multiplications (which involve matrix multiplications). Therefore, achieving constant-degree polynomials is the best we can do with FHE-based constructions.

**Construction 3.** The hash family  $\mathcal{H} = \{h_n\}_{n \in \mathbb{N}}$  with key generation algorithm  $\text{Gen}_{\mathcal{H}} = \{\text{Gen}_{\mathcal{H},n}\}_{n \in \mathbb{N}}$  is parameterized by an arbitrary circuit size  $S(n) = \text{poly}(n)$  and depth  $d$ . Let  $\mathcal{U}(C, x) = C(x)$  denote the universal circuit for size- $S$ , degree- $d$  polynomials (hence, it is also a constant degree polynomial itself). We write  $q = q(n), l = \lceil \log q \rceil, m = nl$ .

<sup>6</sup>Here “size” means the encoding length of the constant degree polynomial.

- $\text{Gen}_{\mathcal{H},n}$ : generate  $A \leftarrow \mathbb{Z}_q^{n \times 2m}$  and  $C \leftarrow \text{GSW-Enc}(A, 0^{S(n)}) = AR + 0^{S(n)} \otimes G$ , where  $R \in \mathbb{Z}^{2m \times m}$ . Choose a uniform random  $a \leftarrow \mathbb{Z}_q^n$ , output the hash key  $k = (a, C)$ .
- $h_n(k = (a, C), x \in \{0, 1\}^n)$ : let circuit  $U_x(\cdot) = \mathcal{U}(x, \cdot)$ , and output

$$G_n^{-1}[a + \text{InertEval}(G_n, \text{GSW-Eval}(U_x, C))] \in \{0, 1\}^m. \quad \diamond$$

**Remark.** We do not use the term “fully homomorphic commitment” (which is implicitly given by sFHE schemes) in [PS19], since computational binding is not satisfied for that “commitment”. However, the construction is essentially the same with the one in [PS19].

We first show this hash function family can be computed in  $\text{TC}^0$ , then show its correlation intractability. The latter property directly follows the proof of Theorem 3.4 in [PS19].

**Lemma 4.15.** Construction 3 can be computed by  $\text{TC}^0$  circuits.  $\diamond$

**Proof.** Computing  $\text{Gen}_{\mathcal{H},n}$  and  $h_n$  only requires:

- Computing iterative sum mod  $q = \text{poly}(n)$ ; (In this construction, we only need to compute the product of a normal matrix (with each element in  $\mathbb{Z}_q$ ) and a binary matrix (with each element in  $\{0, 1\}$ ), so it suffices to compute iterative sum in  $\mathbb{Z}_q$ .)
- Generating universal circuit  $U_x$  from  $x$ ; (we only need to replace some input gates with binary values.)
- Computing  $G_n^{-1}$ , i.e. bit decomposition, which is trivial since we store a number in  $\mathbb{Z}_q$  as a binary number.

All these tasks can be computed in  $\text{TC}^0$ .  $\square$

**Lemma 4.16.** Assuming the hardness of  $\text{SIS}_{n,m,q,\beta}$  for a sufficiently large  $\beta = m^{O(d)}$  against  $\mathcal{C}$  adversary, Construction 3 is correlation intractable (cf. Theorem 4.14).  $\diamond$

**Proof.** Let  $\mathcal{A} = \{\mathcal{A}_n\}_{n \in \mathbb{N}} \in \mathcal{C}$  be any adversary that breaks correlation intractability against  $\{f_n\}$ , i.e.

$$\Pr \left[ h_n(k = (a, C), x) = f_n(x) \mid \begin{array}{l} A \leftarrow \mathbb{Z}_q^{n \times 2m} \\ C \leftarrow \text{GSW-Enc}(A, 0^{S(n)}) \\ a \leftarrow \mathbb{Z}_q^n \\ x \leftarrow \mathcal{A}_n(k) \end{array} \right]$$

is non-negligible.

First, we change  $C \leftarrow \text{GSW-Enc}(A, 0^{S(n)})$  to  $C \leftarrow \text{GSW-Enc}(A, f)$  for  $f = f_n$  by hybrid argument. It can be done because the distribution of  $C$  is statistically indistinguishable by the following lemma.

**Lemma 4.17 (Item 1 of Proposition 2.10 in [PS19]).** For any  $x \in \mathbb{Z}_q^n$ , the statistical distance between the distribution of  $(A \leftarrow \mathbb{Z}_q^{n \times 2m}, C = \text{GSW-Enc}(A, x))$  and uniformly random is in  $\text{negl}(m)$  by the leftover hash lemma.  $\diamond$

Therefore,

$$\Pr \left[ h_n(k = (a, C), x) = f_n(x) \mid \begin{array}{l} A \leftarrow \mathbb{Z}_q^{n \times 2m} \\ C \leftarrow \text{GSW-Enc}(A, f_n) \\ a \leftarrow \mathbb{Z}_q^n \\ x \leftarrow \mathcal{A}_n(k) \end{array} \right]$$

is also non-negligible. Then we can use  $\mathcal{A}$  to break SIS. Since  $h_n(k, x) = f_n(x)$  implies that

$$\begin{aligned} G_n \cdot f_n(x) &= G_n \cdot h_n(k, x) \\ &= a + \text{InertEval}(G_n, \text{GSW-Eval}(U_x, C)) \\ &= a + (Ar + G_n \cdot f_n(x)) \\ &= A'z + G_n \cdot f_n(x), \end{aligned}$$

where

$$A' = \begin{bmatrix} a & A \end{bmatrix} \in \mathbb{Z}_q^{n \times (m+1)}, z = (1, r) \in \mathbb{Z}^{m+1}.$$

Note that  $\|z\| = m^{O(d)}$  as  $U_x$  is done by universally computing depth- $d$  circuits.

So our SIS attacker works as follows: given an SIS instance  $A'$ , the attacker takes  $A$  as the last  $m$  columns of  $A'$  and generates  $C \leftarrow \text{GSW-Enc}(A, f)$  with randomness  $R$  retained. After taking  $x \leftarrow \mathcal{A}_n(k)$ , it simulates the computation of  $h_n(k, x)$  to get  $r$ , then outputs  $z = (1, r)$ . The attacker is in  $\mathcal{C}$  since the reduction is in  $\text{TC}^0$ .  $\square$

### 4.3 CI from worst-case complexity assumptions

In this subsection, we bypass the reliance on the lattice assumptions, which therefore also allows the hash function to be computable in  $\text{AC}^0[2]$ , by applying techniques from [PS19] to WP-FHE (see Construction 2) instead of GSW-FHE (see Construction 1). This approach provides the construction of a hash function family that is computable in  $\text{AC}^0[2]$  and correlation-intractable for any relation searchable in constant-degree polynomials (with bounded circuit size) against any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , assuming  $\oplus \text{L}/\text{poly} \not\subseteq \widetilde{\text{Sum}}_{n-c} \circ \mathcal{C}$  for some  $c > 0$ . The result can be stated as follows:

**Theorem 4.18.** For any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , if Assumption 4.8 holds for  $\mathcal{C}$ , for any polynomial  $S(n)$  and constant  $d$ , there exists a hash family computable in  $\text{AC}^0[2]$  that is CI for any relation class searchable by degree- $d$  polynomials  $\{f_n : \{0, 1\}^n \rightarrow \{0, 1\}^n\}_{n \in \mathbb{N}}$  computable by circuits of size  $S(n)$ , against adversaries in  $\mathcal{C}$  (following the “infinitely many” version of security).  $\diamond$

#### 4.3.1 Adaptation of inert commitment to $\mathbb{Z}_2$

In our construction, all computation are performed in  $\mathbb{Z}_2$ , hence we restate the inert commitment in  $\mathbb{Z}_2$ , i.e, set  $q = 2$ . Although it is just the special case for  $q = 2$ , we emphasize that in this case,  $G$  is simplified to the identify matrix (as what we observed in WP-FHE), hence the inert commitment is greatly simplified.

**Definition 4.19 (Inert Commitment in  $\mathbb{Z}_2$ ).** Given  $C = \text{WP-Enc}(A, x) \in \mathbb{Z}_2^{n \times n^2}$  as the homomorphic encryption of some length- $n$  vector, and  $M \in \mathbb{Z}_2^{n \times n}$  as a matrix, we write

$$\text{InertEval}(M, C) := c_M = C \cdot v_M,$$

where  $v_M \in \mathbb{Z}_2^{n^2}$  is the vector satisfies  $(x^T \otimes I_n) \cdot v_M = Mx$  for any length- $n$  vector  $x$ , obtained by reordering the elements of  $M$ .  $\diamond$

### 4.3.2 Construction

Here we present the construction of the CI hash family to prove Theorem 4.18.

**Construction 4.** The hash family  $\mathcal{H} = \{h_n\}_{n \in \mathbb{N}}$  with the key generation algorithm  $\text{Gen}_{\mathcal{H}} = \{\text{Gen}_{\mathcal{H},n}\}_{n \in \mathbb{N}}$  is parameterized by an arbitrary circuit size  $S(n) = \text{poly}(n)$  and depth  $d$ . Let  $U(C, x) = C(x)$  denote a universal circuit for size- $S$ , degree- $d$  polynomials.

- $\text{Gen}_{\mathcal{H},n}$ : generate  $A \leftarrow \text{OneSamp}$  and  $C \leftarrow \text{WP-Enc}(A, 0^{S(n)})$ , choose a uniformly random  $a \leftarrow \mathbb{Z}_2^n$  and output the hash key  $k = (a, C)$ .
- $h_n(k = (a, C), x \in \{0, 1\}^n)$ : define the circuit  $U_x(\cdot)$  as  $U_x(\cdot) = U(x, \cdot)$  and output

$$a + \text{InertEval}(I_n, \text{WP-Eval}(U_x, C)) \in \{0, 1\}^n. \quad \diamond$$

**Proof of Theorem 4.18.** We prove that for any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , Construction 4 is a CI hash family against  $\mathcal{C}$  if Assumption 4.8 holds for  $\mathcal{C}$ . Let  $\mathcal{A} = \{\mathcal{A}_n\} \in \mathcal{C}$  be any adversary family that breaks CI for some sequence of polynomials  $\{f_n\}$ . Since given  $x$ , we can check whether  $h_n((a, C), x) = f_n(x)$  in  $\mathcal{C}$  (which only involves matrix multiplication and computing  $f_n(x)$ ), w.l.o.g., we assume that  $\mathcal{A}_n$  always outputs some  $x \in \{0, 1\}^n$  s.t.  $h_n((a, C), x) = f_n(x)$  with non-negligible probability or outputs  $\perp$  after taking  $k = (a, C)$  sampled according to  $\text{Gen}_{\mathcal{H},n}$  as input.

We abuse the notation to let  $f_n \in \{0, 1\}^{S(n)}$  also denote the encoding of the circuit that computes this function. The idea is to apply the hybrid argument to change the input distribution of  $\mathcal{A}_n$ . We observe that the following two distribution are equivalent, since  $A$  (sampled from  $\text{OneSamp}$ ) is always full-rank, which makes  $AR$  below being uniformly random. Hence the two distributions are indistinguishable for  $\mathcal{C}$  circuits.

- $\mathcal{D}_n^0 = \{(a, \text{WP-Enc}(A, 0^{S(n)}) = AR + 0^{S(n)} \otimes I_n) : a \leftarrow \mathbb{Z}_2^n, A \leftarrow \text{OneSamp}, R \leftarrow \mathbb{Z}_2^{n \times nS(n)}\}$ .
- $\mathcal{D}_n^1 = \{(a, \text{WP-Enc}(A, f_n) = AR + f_n \otimes I_n) : a \leftarrow \mathbb{Z}_2^n, A \leftarrow \text{OneSamp}, R \leftarrow \mathbb{Z}_2^{n \times nS(n)}\}$ .

**Lemma 4.20.** For any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , if Assumption 4.8 holds for  $\mathcal{C}$ , any circuit family  $\{\mathcal{A}_n\} \in \mathcal{C}$  cannot distinguish  $\mathcal{D}_n^0$  and  $\mathcal{D}_n^1$ , i.e.,

$$|\Pr[\mathcal{A}_n(k) = 1 \mid k \leftarrow \mathcal{D}_n^0] - \Pr[\mathcal{A}_n(k) = 1 \mid k \leftarrow \mathcal{D}_n^1]| < \text{negl}(n). \quad \diamond$$

So after switching the input to  $\mathcal{A}_n$  from  $k \leftarrow \mathcal{D}_n^0$  to  $k' \leftarrow \mathcal{D}_n^1$ ,  $\mathcal{A}_n$  should also output  $x \in \{0, 1\}^n$  s.t.  $h_n(k' = (a, \text{WP-Enc}(A, f_n)), x) = f_n(x)$  with non-negligible probability. Since

$$\begin{aligned} f_n(x) &= h_n(k', x) \\ &= a + \text{InertEval}(I_n, \text{WP-Eval}(U_x, \text{WP-Enc}(A, f_n))) \\ &= a + \text{InertEval}(I_n, AR + f_n(x)^t \otimes I_n) \\ &= a + Ar_{I_n} + f_n(x), \end{aligned}$$

we have  $Ar_{I_n} = a$  (in  $\mathbb{Z}_2$ ). So if we record the randomness used to compute  $\text{WP-Enc}(A, f_n)$ , by calculating  $h_n(k', x)$ , we are able to compute  $r_{I_n} = A^{-1}a$ . However, this allows us to invert  $p_A(x) = Ax$ , which is impossible by Lemma 4.13.  $\square$



## 5 Impossibility Result for Universal Fiat-Shamir Hash Functions

In this section, we show an impossibility result for the universal Fiat-Shamir hash function. We show that for any function family  $\mathcal{H}$ , we can construct an argument whose soundness cannot be preserved after applying the Fiat-Shamir transformation with  $\mathcal{H}$ .

**Definition 5.1** ( $(l_x, l_a, l_b)$ -universal Fiat-Shamir hash from  $\mathcal{C}$  to  $\mathcal{D}$ ). Given circuit classes  $\mathcal{D} \subseteq \mathcal{C}$  and functions  $l_x(n), l_a(n), l_b(n)$ , we say a Fiat-Shamir hash function family

$$\mathcal{H} = \left\{ \mathcal{H}_n : \{0, 1\}^{l_x(n) + l_a(n)} \rightarrow \{0, 1\}^{l_b(n)} \right\}_{n \in \mathbb{N}}$$

is an  $(l_x, l_a, l_b)$ -universal Fiat-Shamir hash from  $\mathcal{C}$  to  $\mathcal{D}$  if for every 3-round public-coin  $\mathcal{C}$ -argument with first message length  $l_a(n)$  and second message length  $l_b(n)$  that proves instances of length  $l_x(n)$ , applying Fiat-Shamir with  $\mathcal{H}$  always gives a sound non-interactive  $\mathcal{D}$ -argument.  $\diamond$

**Theorem 5.2.** For circuit classes  $\mathcal{D} \subseteq \mathcal{C}$ , assume there exists a collision-resistant hash function family computable in  $\mathcal{D}$  and collision resistant against  $\mathcal{C}$  with arbitrary polynomial compression. Then for any functions  $l_a(n), l_b(n) \in \text{poly}(n)$  such that  $l_x(n), l_a(n) \in \omega(n^\varepsilon)$  for some  $\varepsilon > 0$  and  $l_b(n) \in \omega(\log(n))$ , there is no  $(l_x, l_a, l_b)$ -universal Fiat-Shamir hash from  $\mathcal{C}$  to  $\mathcal{D}$  that is computable in  $\mathcal{C}$ .  $\diamond$

The proof of Theorem 5.2 is done by showing that for any hash family  $\mathcal{H}$ , there is an interactive  $\mathcal{C}$ -argument for the empty language such that an adversary in  $\mathcal{D}$  can break the reduced protocol after Fiat-Shamir with  $\mathcal{H}$ . Note that the empty language here can be generalized to any language  $\mathcal{L}$  (except some corner cases that the soundness is trivial, like  $\mathcal{L}$  does not have a  $\mathcal{C}$ -argument or there is no  $x \notin \mathcal{L}$ ). This can be achieved by modifying the verifier of the interactive  $\mathcal{C}$ -argument for  $\mathcal{L}$  to additionally accept the view that convinces the verifier of the empty language's protocol.

Here we first give the intuition before stating the proof. For the empty language, there exists a trivial protocol that the verifier just rejects anything. But to make the protocol insecure after the Fiat-Shamir transformation, we will replace the verifier with one that accepts with negligible probability. Intuitively, the new verifier will accept the view which convinces him that the prover can predict the second message before it is revealed. To convince the verifier, the prover needs to show that he knows a circuit which can output the second message if it takes the first message as the input, before the second message is revealed. As the second message is chosen at random, the prover cannot predict it during the real interaction. So, with this new verifier, the argument is still secure.

After applying the Fiat-Shamir transformation, the Fiat-Shamir hash function can be used by the malicious prover as the circuit to predict the second message.

However, there exists a little problem in the idea above. There is a limitation on the length of the first message, so the malicious prover cannot send the entire circuit in the first message if it is too long. To circumvent this problem, we allow the prover to first send a commitment of the circuit and reveal the circuit in the third message.

This idea is similar to the first idea of [GK03], which lets the verifier accept the view which convinces him the prover can predict the verifier's next message. But our idea is much simpler because currently the circuit size is fixed before we decide the protocol.

**Proof of theorem 5.2.** In the whole proof, all encoding of circuits or circuit sizes are considered under circuit class  $\mathcal{C}$ .

For any  $\mathcal{D} \subseteq \mathcal{C}$ , for any  $l_x(n), l_a(n), l_b(n) \in \text{poly}(n)$ , consider any hash function family  $\mathcal{H} = \mathcal{H}_n : \{0, 1\}^{l_x(n)+l_a(n)} \rightarrow \{0, 1\}^{l_b(n)}_{n \in \mathbb{N}}$  computable in  $\mathcal{C}$ . From the assumptions, we know there exists a collision resistant hash function family

$$\mathcal{F} = \left\{ \mathcal{F}_n : \{0, 1\}^{l_{\mathcal{H}}(n)} \rightarrow \{0, 1\}^{l_a(n)} \right\}_{n \in \mathbb{N}}.$$

Here we will construct an argument  $(P, V)$  for the empty language that applying Fiat-Shamir with  $\mathcal{H}$  cannot preserve soundness (and thus  $\mathcal{H}$  is not a universal Fiat-Shamir hash):

- Common input:  $x \in \{0, 1\}^{l_x(n)}$ .
  - Auxiliary input to the prover (or witness): none
1.  $V$ : Compute  $f \leftarrow \mathcal{F}_n$  Output  $crs = f$ .
  2.  $P$ : On input  $(x, w, crs)$ :
    - (a) Parse  $crs$  as  $f$ .
    - (b) Let  $\hat{C}$  be an arbitrary string  $\in \{0, 1\}^{l_{\mathcal{H}}(n)}$ , which denotes a circuit.
    - (c) Compute  $a = f(\hat{C})$  and output it.
  3.  $V$ : On input  $(x, crs, a)$ , get public coin  $b \leftarrow \{0, 1\}^{l_b(n)}$  and output it.
  4.  $P$ : On input  $(x, w, crs, a, b)$ , output  $c = \hat{C}$ .
  5.  $V$ : On input  $(x, crs, a, b, c)$ :
    - (a) Parse  $crs$  as  $f$ .
    - (b) Parse  $c$  as  $\hat{C} \in \{0, 1\}^{l_{\mathcal{H}}(n)}$ .
    - (c) Check whether  $a = f(\hat{C})$ , reject if it is not the case.
    - (d) Accept if  $\hat{C}$  is a valid encoding with input size  $l_a(n)$  and output size  $l_b(n)$  and  $C(a) = b$ . Here, the evaluation of  $C$  is calculated by a universal circuit in  $\mathcal{C}$ , which is capable of computing any  $h \in \mathcal{H}_n$ .
    - (e) Otherwise, reject.

The lengths of four messages are  $l_{\mathcal{F}}(n), l_a(n), l_b(n), l_{\mathcal{H}}(n)$  respectively, which satisfy the requirement of applying Fiat-Shamir transformation with  $\mathcal{H}$ . Let the protocol obtained by applying Fiat-Shamir transformation be  $(P^{FS}, V^{FS})$ .

Now, we should examine the security before applying Fiat-Shamir transformation and the insecurity after it. We prove the security by constructing an adversary for the CRHF  $\mathcal{F}$ .

Suppose  $P^* = \{P_n^*\}_{n \in \mathbb{N}}$  is the adversary that breaks  $(P, V)$  with non-negligible probability. The construction of the adversary  $\mathcal{A} = \{\mathcal{A}_n\}_{n \in \mathbb{N}}$  for  $\mathcal{F}$  is described below:

On input  $f$ :

1. Compute  $crs = f$  and  $a \leftarrow P^*(x, crs)$ , the first message of  $(P^*, V)(x)$ . Here,  $x \in \{0, 1\}^{l_x(n)}$  is the input that the interaction between  $P^*$  and  $V$  results in acceptance with the highest probability.

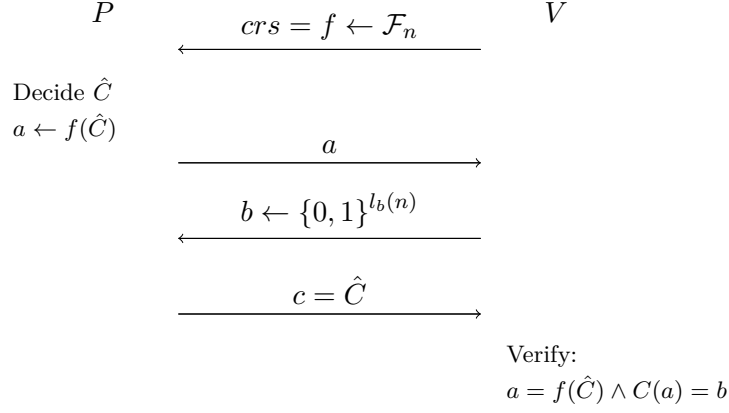


Figure 5: Argument  $(P, V)$

2. Compute  $b_1 \leftarrow V(x, crs, a)$  and  $b_2 \leftarrow V(x, crs, a)$ , the second message of  $(P^*, V)(x)$  with different random bits.
3. Compute  $c_1 \leftarrow P^*(x, crs, a, b_1)$  and  $c_2 \leftarrow P^*(x, crs, a, b_2)$ , the third message of  $(P^*, V)(x)$ .
4. Output  $c_1$  and  $c_2$ .

Clearly, the adversary is in  $\mathcal{C}$ , so we only need to show it can succeed with non-negligible probability.

**Claim 5.3.** Assume there exists polynomial  $q(n)$ , for infinite many  $n$ ,  $\exists x \in \{0, 1\}^{l_x(n)}$ ,

$$\Pr[(P^*, V)(x) = 1] > 1/q(n),$$

then  $A$  can break  $\mathcal{F}$  with non-negligible probability. Formally, there exists a polynomial  $p(n)$ , for infinite many  $n \in \mathbb{N}$ ,

$$\Pr \left[ f(x_1) = f(x_2) \wedge x_1 \neq x_2 \mid \begin{array}{l} f \leftarrow \mathcal{F}_n \\ (x_1, x_2) \leftarrow A(f) \end{array} \right] > 1/p(n), \quad \diamond$$

**Proof.** The adversary  $A$  for breaking the collision resistance of  $f$  sets  $f$  as the  $crs$  in the protocol  $(P^*, V)$ , then runs  $P^*$  on  $crs$  to get started. So, for infinite many  $n \in \mathbb{N}$ , with probability  $1/2q(n)$  over the generation of  $crs$  and  $a$  in adversary  $A$ , we have

$$\Pr[(P^*, V(x)|_{crs})(x) = 1] > \frac{1}{2q(n)}. \quad (1)$$

Here  $P^*$  will follow from the state after the generation of  $crs$  and  $a$  in adversary  $\mathcal{A}$ , which means  $P^*$ 's first message will be restricted to  $a$ .

Since  $b_1, b_2$  are generated independently, we have for infinite many  $n \in \mathbb{N}$ , with probability  $1/2q(n)$  over the generation of  $f$  and  $a$ ,

$$\Pr \left[ \begin{array}{l} (P^*, V|_{crs, b_1})(x) = 1 \wedge \\ (P^*, V|_{crs, b_2})(x) = 1 \wedge \\ b_1 \neq b_2 \end{array} \mid crs, b_1, b_2 \leftarrow A(f) \right] > \frac{1}{4q^2(n)} - \text{negl}(n).$$

Same as was in Eqn. (1), here both  $P^*$  will follow from the state after the generation of  $crs$  and  $a$  in adversary  $\mathcal{A}$ , which means they will both reply  $a$  as the first message.

As a result, for infinite many  $n \in \mathbb{N}$ ,

$$\Pr \left[ \begin{array}{l} V(x, crs, a, b_1, c_1) = 1 \wedge \\ V(x, crs, a, b_2, c_2) = 1 \wedge \\ b_1 \neq b_2 \end{array} \middle| \begin{array}{l} f \leftarrow \mathcal{F}_n \\ crs, a, b_1, b_2, c_1, c_2 \leftarrow A(f) \end{array} \right] > \frac{1}{8q^3(n)} - \text{negl}(n).$$

This indicates that for infinite many  $n \in \mathbb{N}$ ,

$$\Pr \left[ f(x_1) = f(x_2) \wedge x_1 \neq x_2 \middle| \begin{array}{l} f \leftarrow \mathcal{F}_n \\ (x_1, x_2) \leftarrow A(f) \end{array} \right] > \frac{1}{8q^3(n)} - \text{negl}(n). \quad \square$$

Next, we will prove the insecurity of the argument after applying Fiat-Shamir transformation by directly constructing an adversary. The construction of adversary  $P^* = \{P_n^*\}_{n \in \mathbb{N}}$  for  $(P^{FS}, V^{FS})$  is shown below:

On input  $x, crs' = (k_h, crs)$ :

1. Parse  $crs'$  as  $h, f$ , the Fiat-Shamir hash function and the CRHF for commitment.
2. Let  $C = h(x \parallel \cdot)$ , hard-coding  $x$  into  $h$ . Let  $c = \hat{C}$ . Note that length of  $\hat{C}$  is bounded by  $l_{\mathcal{H}}(n)$ .
3. Compute  $a \leftarrow f(c)$ .
4. Output  $a, c$ .

Note that the adversary is in  $\mathcal{D}$  because it does not need to evaluate  $h$ .

**Claim 5.4.**  $P^*$  can break  $(P^{FS}, V^{FS})$  with probability 1. Formally,  $\forall n \in \mathbb{N}, \forall x \in \{0, 1\}^{l_x(n)}$ ,

$$\Pr[(P^*, V^{FS})(x) = 1] = 1. \quad \diamond$$

**Proof.** Following  $V_n^{FS}$ , parsing  $crs'$  as  $h, f$ , parsing  $c$  as  $\hat{C}$ , we can directly know that

- $a = f(c)$ ,
- $\hat{C}$  can be calculated by the universal circuit.
- $b = C(a) = h(x \parallel a)$ ,

which satisfies the requirement for  $V_n^{FS}$  to accept.  $\square$

Till now, we prove the security before applying Fiat-Shamir transformation, and the insecurity after applying Fiat-Shamir transformation, which completes the proof of theorem 5.2.  $\square$

**Remark.** Actually, the counter-example in our proof works even if we consider an arbitrary poly-size Fiat-Shamir hash that is not necessarily computable in  $\mathcal{C}$ . Recall that the prover after Fiat-Shamir does not need to send the second message  $b = h(x \parallel a)$  since it is clear from  $h, x$ , and  $a$ . Therefore, the cheating prover after Fiat-Shamir can simply copy the description of the Fiat-Shamir hash from the CRS and evaluate the value of  $f$  on it – all are computable in  $\mathcal{D}$ .

## 6 Stronger Impossibility Results: Universal Counter-Examples for All Fiat-Shamir Hash Functions

In this section, we aim to prove stronger impossibility results by exchanging the order of quantifiers. That is, we want to find a protocol that applying the Fiat-Shamir transformation with any function ensemble cannot preserve the soundness, just like [GK03]. Following the main idea in the last section, we let the adversary show his ability to predict the second message before the verifier reveals it.

**Theorem 6.1.** For any circuit class  $\mathcal{C}$  that  $\text{AC}^0[2] \subseteq \mathcal{C}$ , if there exists collision resistant hash function family computable in  $\mathcal{C}$  and collision resistant against  $\mathcal{C}$  with arbitrary polynomial compression, then there exists a 3-round public coin protocol with CRS  $(P, V)$  such that for all function ensemble  $H$  computable in  $\mathcal{C}$  the following conditions are satisfied:

- $(P, V)$  is a 3-round public coin argument for some language  $\mathcal{L}$  secure against any adversary in  $\mathcal{C}$ , and  $P$  is computable in  $\mathcal{C}$ .
- Applying the Fiat-Shamir transformation on  $(P, V)$  with  $\mathcal{H}$  results in a protocol  $(P^{FS}, V^{FS})$  that is insecure against some adversary in  $\mathcal{C}$ .  $\diamond$

**Notations** Before starting the proof, we will first clarify some notations or conventions that we will frequently use. Throughout the section, we assume  $\mathcal{C}$  is fixed,  $\mathcal{F} = \left\{ \mathcal{F}_n : \{0, 1\}^{n^{0.2}} \rightarrow \{0, 1\}^{n^{0.1}} \right\}_{n \in \mathbb{N}}$  is a collision resistant hash function family used in a tree commitment, which will be introduced later,  $\text{Comm} = \left\{ \text{Comm}_n : \{0, 1\}^{5n} \rightarrow \{0, 1\}^n \right\}$  is a collision resistant hash function family which is used for another commitment. When we use  $\text{Comm}$  to commit to some  $x$ , we will concatenate  $x$  with the randomness  $r \in \{0, 1\}^n$  and then apply  $\text{Comm}$  on  $(x, r)$ . If the input of  $\text{Comm}$  is shorter than  $5n$ , we assume it is padded with 0s. Moreover, we will use  $\mathcal{G} = \{\mathcal{G}_n\}_{n \in \mathbb{N}}$ ,  $\mathcal{H} = \{\mathcal{H}_n\}_{n \in \mathbb{N}}$  as potential Fiat-Shamir hash function families. Typically, we will use  $\mathcal{H}$  as the Fiat-Shamir hash function for our whole protocol, while using  $\mathcal{G}$  as the Fiat-Shamir hash function inside the construction.  $\mathcal{G}_1, \mathcal{G}_2$  will be used if there are more than one Fiat-Shamir hash functions used in the construction. We require  $\mathcal{H}, \mathcal{G}, \mathcal{G}_1, \mathcal{G}_2$  to be computable in  $\mathcal{C}$  throughout the whole section. In the whole section, all encodings of circuits and circuit sizes are considered under circuit class  $\mathcal{C}$ .

**Definition 6.2 (Tree Commitment).** A tree-commitment to  $x \in \{0, 1\}^*$ , with respect to the function  $f : \{0, 1\}^{n^{0.2}} \rightarrow \{0, 1\}^{n^{0.1}}$ , is defined as follows. Consider a  $n^{0.1}$ -branch tree of depth  $\log_{n^{0.1}}(|x|)$ , where each node has a label in  $\{0, 1\}^{n^{0.1}}$ . The leaves are labeled by the bits of  $x$  ( $n^{0.1}$  bits per leaf). Each internal node is labeled by the string obtained by first concatenating all labels of its children and applying  $f$  to it. More specifically, if the labels of its children is  $a_1, a_2, \dots, a_{n^{0.1}} \in \{0, 1\}^{n^{0.1}}$  the label of this node is  $f(a_1 \| a_2 \| \dots \| a_{n^{0.1}})$ . The tree commitment to  $x$ , with respect to  $f$ , is denoted by  $\text{TC}_f(x)$ , and consists of the label of the root and the depth of the tree. For a specific bit, suppose the leaf that contains this bit is  $l$ . Define the authentication path for that bit to be the concatenation of all labels of nodes that lie between  $l$  and the root. Note that the number of bits of an authentication path is  $\log_{n^{0.1}}(|x|)n^{0.1}$ . For  $x$  of length  $n^c$ , the authentication path is of length  $10cn^{0.1} = O(n^{0.1})$  bits.  $\diamond$

**Remark.** The tree commitment itself can be used as a CRHF, with arbitrary polynomial input size and  $n^{0.1}$  output size, when  $f$  is sampled from the CRHF family. The advantage of using tree

commitment instead of CRHF as commitment is that we can open the string locally on a bit by outputting its authentication path. Also note that the verification of an authentication path can be done in low depth regardless of the depth of the tree. The binding property is satisfied since if an adversary outputs something different from the committed one, a collision can always be found somewhere on the path.

Normally, tree commitment only needs  $2n$  to  $n$  hash functions, but in low depth setting, this is not enough to achieve constant depth. Thus we need the stretch to be polynomial. Any CRHF with polynomial stretch can be used here, and the only reason for us to use  $n^{0.2} \rightarrow n^{0.1}$  function is to make the size of authentication path fit in  $O(n)$  and facilitate later analysis.

An important idea in this proof follows from the construction in the proof of Theorem 5.2. That is, we want to modify the verifier so that the verifier accepts the view that convinces him the prover knows his second message before it is revealed. In the previous construction, we let the adversary prove this by first sending a commitment of circuit  $C$ , and then reveal that  $C$  can output the second message  $b$  when taking the first message  $a$  as the input. This can be abstracted as a relation, which we denote as the *Central Relation*. The Central Relation characterizes the fact that the adversary wants to prove he has the witness for  $f\|a\|b$  that satisfies certain requirements, where  $f$  is the function used for commitment and  $a, b$  is the first and second message respectively. In the construction of the proof of theorem 5.2, the adversary directly shows the witness to prove the knowledge, but we will use some succinct proof to achieve this goal later.

**Definition 6.3 (Central Relation).** For all  $n \in \mathbb{N}$ . Define

$$\mathcal{R} = \left\{ (f\|a\|b, \hat{C}\|\Pi) \mid \begin{array}{l} \text{TC}_f(\tilde{C}) = a \wedge C(a) = b \wedge |\tilde{C}| \leq n^{\ln n} \\ \Pi \text{ is a computation history of } \text{TC}_f(\tilde{C}), C(a) \end{array} \right\}$$

Here,  $a, b \in \{0, 1\}^n$ ,  $f \in \mathcal{F}_n$ .  $C$  is a circuit and  $\hat{C}$  is the encoding for  $C$  with input size  $n$  and output size  $n$  regarding to  $\mathcal{C}$ . The computation history of circuit evaluation contains outputs of all gates.  $\tilde{C}$  is a special encoding of  $C$  that satisfies the following requirements:

- Transformation between  $\hat{C}$  and  $\tilde{C}$  can be computed in  $\mathcal{C}$ .
- It has high minimum distance. That is for any different  $C_1, C_2$ , we require  $\tilde{C}_1$  and  $\tilde{C}_2$  differ in at least polynomial fraction of all bits.  $\diamond$

**Remark.** Although verifying  $\text{TC}_f(\tilde{C}) = a \wedge C(a) = b$  may be difficult as we do not limit the depth of  $C$  for now, we can verify computation history to check those equations. Thus, the central relation can be verified in constant depth. Also, the size of  $C$  is bounded by  $n^{\ln n}$ , which means the relation is  $\text{NTIME}(n^{\ln n})$  instead of NP, and we will address this problem with the PCP proof system that we will introduce later.

Now, we will introduce the main process of our proof. We construct three protocols for the empty language. We want to construct the protocol that the verifier only accepts some views that occur with negligible probability, but the adversary can make these views occur frequently after the Fiat-Shamir transform:

- The first protocol  $(P_1, V_1)$  follows the straightforward idea that implements a succinct 2-round protocol with CRS for central relation after  $f, a, b$  is determined in the first two rounds, which



gives the adversary potential ability to show he knows the witness of  $f||a||b$  in central relation. As the adversary can use the Fiat-Shamir hash function as the witness and can compute the history  $\Pi$  itself, it can convince the verifier that he knows the witness, which implies the insecurity after applying Fiat-Shamir. However, we do not know if such a 2-round protocol satisfies the soundness we need, so we are not sure about the security.

- The second protocol  $(P_2, V_2)$  goes from a different way. After the verifier determines  $f$ , the adversary can determine  $a, b_1, b_2$  that  $b_1 \neq b_2$  and try to prove he knows the witness for both instances  $(f, a, b_1)$  and  $(f, a, b_2)$  in central relation, with a 3-round secure protocol with CRS. As  $a$  serves as the commitment of the witness, it is hard for the adversary to find two different  $C$ s, i.e., the witness for both  $(f, a, b_1)$  and  $(f, a, b_2)$ , which indicates its security. But for this protocol, the insecurity after applying Fiat-Shamir is hard to argue.
- Then, we find the third protocol that resides between the first one and the second one. We can show the third protocol is secure if the second one is secure after applying Fiat-Shamir, and we can show the third protocol after applying Fiat-Shamir is insecure if the first one is insecure on its own.

With the existence of the third protocol, we can show at least one of the three protocols can be used as a protocol required in the theorem.

The whole proof follows the idea in [GK03], but some technical problems need to be addressed:

- We need to fit all cryptographic tools into a low-depth circuit class. Some of them such as the commitment scheme used in [GK03] are not known in low-depth circuit class currently.
- In the tree commitment scheme, we require the inner hash function to have polynomial stretch, which is used to keep the depth constant.
- Since the circuit size in central relation is bounded by  $n^{\ln n}$  instead of a polynomial, super-constant depth may still occur even with polynomial-stretch hash function. We resolve this by requiring the prover to give all computation history to facilitate the verification. Due to the fact that honest prover does not need to do anything, and malicious prover can have depth depending on the Fiat-Shamir hash function, we can eventually achieve constant depth.

To start, we first introduce the 2-round protocol that is used in the first protocol but not guaranteed to be secure, and the 3-round protocol used in the second protocol, as mentioned above. Here, we require the protocol to be succinct, thus we cannot directly send the circuit as the former construction. [Kil92] and [BG08] give a 3-round argument with CRS for NEXP language that satisfies argument of knowledge, which can be used for proving our central relation. To make it fit in  $AC^0[2]$ , we need to use a specific PCP system. Note that our PCP system is similar to the one from [GK03; BG08], except that we additionally require some components to be computable in  $AC^0[2]$  to meet our bounded-depth requirements here.

**Definition 6.4 (Probabilistic verifier).** A probabilistic verifier for an NEXP language  $L$  is a polynomial-size circuit  $V_{pcp}$  that is given a input  $x$ , and oracle access to a proof  $\pi$ , which we will denote by  $V_{pcp}^\pi$ . We say that  $V_{pcp}$  has randomness complexity  $r(n)$  and query complexity  $q(n)$  with respect to polynomials  $r(n)$  and  $q(n)$  if for any input  $x$  such that  $|x| = l_x(n)$ ,

1.  $V_{pcp}^\pi(x)$  uses at most  $r(n)$  random bits.

2.  $V_{pcp}^\pi(x)$  queries at most  $q(n)$  times to the oracle.

As a special note, we additionally require  $V_{pcp}$  to be *non-adaptive*, i.e., the locations queried by  $V_{pcp}$  depend only on the input  $x$  and its internal randomness, independently of the query answers of previous queries. More precisely,  $V_{pcp}$  can be decomposed into a pair of algorithms  $(Q_{pcp}, D_{pcp})$  such that on input  $x$  and internal randomness  $r$ ,  $V_{pcp}$  makes the queries  $Q_{pcp}(x, r) = (\phi_1, \phi_2, \dots, \phi_{q(n)})$  to obtain the answers  $(b_1, b_2, \dots, b_{q(n)})$ , and then outputs the decision  $D_{pcp}(x, r, b_1, b_2, \dots, b_{q(n)})$ .  $\diamond$

**Theorem 6.5.** For the central relation  $\mathcal{R}$ , there exists a PCP system  $(P_{pcp}, V_{pcp})$  where  $V_{pcp}$  is a probabilistic verifier for  $\mathcal{R}$  with randomness complexity  $\text{polylog}(n)$  and query complexity  $\text{polylog}(n)$ . This system satisfies:

- **Completeness:** For all  $(x, w) \in \mathcal{R}$ ,

$$\Pr [V_{pcp}^\pi(x) = 1 \mid \pi \leftarrow P_{pcp}(x, w)] = 1.$$

Note that here  $|w|$  might be super-polynomial in  $|x|$ .

- **Soundness:** For all  $x$  such that there does not exist  $w$  satisfying  $(x, w) \in \mathcal{R}$ , for any proof  $\pi^*$ ,

$$\Pr [V_{pcp}^{\pi^*}(x) = 1] < \frac{1}{2},$$

where the randomness is over the internal randomness of  $V_{pcp}$ .

- **AC<sup>0</sup>[2]-oracle-construction:**  $P_{pcp}$  is an AC<sup>0</sup>[2] circuit, i.e., the oracle  $\pi$  can be constructed in AC<sup>0</sup>[2] given the input  $x$  and the witness  $w$ .
- **AC<sup>0</sup>[2]-proof-of-knowledge:** There exists an extractor  $E_{pcp}$  in AC<sup>0</sup>[2] such that for any input  $x$  and proof  $\tilde{\pi}$  if

$$\Pr [V_{pcp}^{\tilde{\pi}}(x) = 1] \geq 1 - \frac{1}{\log^5 n},$$

then there exists a witness  $w$  satisfying  $\mathcal{R}(x, w) = 1$  such that for any  $1 \leq i \leq |w|$ ,

$$\Pr [E_{pcp}^{\tilde{\pi}}(x, i) = w_i] \geq \frac{2}{3}.$$

- **AC<sup>0</sup>[2]-samplable:**  $Q_{pcp}$  is an AC<sup>0</sup>[2] circuit, i.e., the queries made by  $V_{pcp}$  can be sampled in AC<sup>0</sup>[2].
- **AC<sup>0</sup>[2]-reverse-samplable:** Suppose that  $\text{Rand}_V(x, i, j)$  is the set of *internal randomness* of  $V_{pcp}$  such that the  $i$ -th query to the proof  $\pi$  is at position  $j$  when given the input  $i$  (i.e., the set of  $r$  such that the  $i$ -th output of  $Q_{pcp}(x, r)$  is  $j$ ). There is an AC<sup>0</sup>[2] circuit  $S_{pcp}$  such that, given any input  $x, i, j$  and some randomness  $r \in \{0, 1\}^{\text{polylog}(n)}$ , output some internal random strings for  $V_{pcp}$ , such that the distribution  $\{S_{pcp}(x, i, j; r) \mid r\}$  is the uniform distribution over  $\text{Rand}_V(x, i, j)$ .  $\diamond$

Theorem 6.5 essentially follows from the PCP construction in [Par21; CWY23], but we include a sketch of the proof in Appendix C.

Recall that if we want to use a PCP system to prove the central relation we have to address the problem that the witness is of super-polynomial size. But the above PCP system guarantees

the existence of a polynomial  $p(\cdot)$  such that the proof  $\pi$  generated is of length  $p(|x| + |w|)$ . In other words, if the witness  $\hat{C} \parallel \Pi$  in the central relation is of some fixed polynomial length (which is the case in later applications), the proof  $\pi$  is also fixed polynomial size.

Later on we consider running  $n^{0.1}$  PCPs in parallel to make the probability of accepting a wrong statement to negligible. When we say  $V_{pcp}$  later, we refer to the verifier that runs  $n^{0.1}$  PCPs in parallel and accepts if and only if all verifications are passed.

In later protocols we use PCP together with the tree commitment technique, i.e. we would first compute the PCP proof  $\pi \leftarrow P_{pcp}$  and then use a tree commitment to compress the proof into a length  $n$  message  $\beta = \text{TC}_{f^{TC}}(\pi)$ . For PCP queries, we output the authentication path on tree commitment to open the queried bits. Since the tree is of constant depth with  $O(n^{0.2})$ -length authentication path and we run  $n^{0.1}$  PCP verification in parallel, we can use a string  $\gamma \in \{0, 1\}^n$  to represent all queries and use  $\delta \in \{0, 1\}^n$  to represent all answers, pad zeros if needed.

## 6.1 Interactive Argument for Central Relation

According to [Kil92], there is an argument  $(P_{Kil}, V_{Kil})$  for central relation  $\mathcal{R}$  based on  $(P_{pcp}, V_{pcp})$  for  $\mathcal{R}$ . Recall  $\mathcal{F}$  is the CRHF used for tree commitment. The protocol is shown below:

- Common input:  $f \parallel a \parallel b$ .
  - Auxiliary input for the prover:  $w = \hat{C} \parallel \Pi$ .
1.  $V_{Kil}$  : Output  $crs = f^{TC} \leftarrow \mathcal{F}_n$ .
  2.  $P_{Kil}$  : On input  $(f \parallel a \parallel b, w, crs)$  :
    - (a) Compute PCP proof  $\pi \leftarrow P_{pcp}(f \parallel a \parallel b, w)$ .
    - (b) Compute  $\beta \leftarrow \text{TC}_{f^{TC}}(\pi)$  and output  $\beta$ .
  3.  $V_{Kil}$  : On input  $(f \parallel a \parallel b, crs, \beta)$ , select random tape  $\gamma$  for  $V_{pcp}$  and output  $\gamma$ .
  4.  $P_{Kil}$ : On input  $(f \parallel a \parallel b, w, crs, \beta, \gamma)$ , run  $Q_{pcp}$  on random tape  $\gamma$  to obtain the queries and let the authentication paths along with the answers to these queries be  $\delta$ . Output  $\delta$ .
  5.  $V_{Kil}$ : On input  $(f \parallel a \parallel b, crs, \beta, \gamma, \delta)$ , accept iff:
    - (a) The authentication paths in  $\delta$  are consistent under the tree commitment scheme.
    - (b)  $V_{pcp}$  accepts after receiving answers in  $\delta$ .

**Lemma 6.6.**  $(P_{Kil}, V_{Kil})$  is a 3-round argument with CRS for language  $\mathcal{R}$  against  $\mathcal{C}$ , that  $P_{Kil}$  is in  $\mathcal{C}$  and the protocol satisfies argument of knowledge in  $\text{AC}^0[2]$ .  $\diamond$

**Proof.** We can obtain completeness directly from the completeness of probabilistic verification. For soundness and argument of knowledge, we prove them together below since soundness is implied by argument of knowledge. We try to prove that there exists an simulated oracle  $\tilde{\pi}^{\tilde{P}}$  such that for any prover  $\tilde{P}$  and a polynomial  $p(n)$ , if for any valid  $f \parallel a \parallel b$ ,

$$\Pr \left[ (\tilde{P}, V_{Kil})(f \parallel a \parallel b) = 1 \right] \geq \frac{1}{p(n)}$$

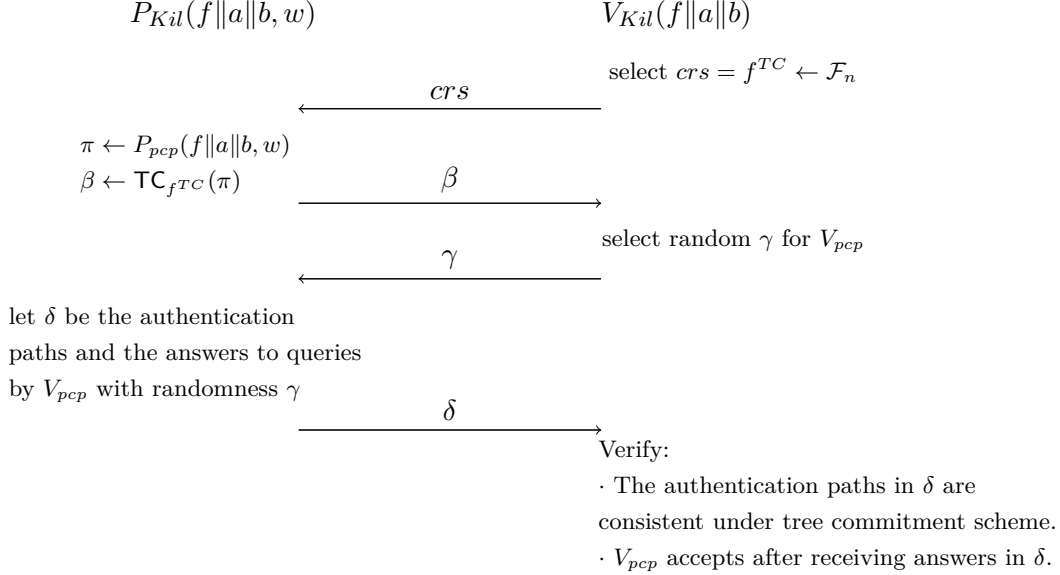


Figure 6: Interactive Argument for the Central Relation

then

$$\Pr \left[ V_{pcp}^{\tilde{\pi}}(f||a||b) = 1 \right] \geq \frac{1}{8(p(n))^2}.$$

Note that the probability here is the probability that  $\tilde{\pi}$  passes all  $n^{0.1}$  parallel verification. Since all verifications are independent, the probability that  $\tilde{\pi}$  passes a single verification is greater than  $1 - \frac{1}{\log^5 n}$ . Then by the  $AC^0[2]$ -proof-of-knowledge of our PCP system, we are done with the proof. Suppose that the prover  $\tilde{P}$  convinces  $V_{Kil}$  on input  $(f||a||b)$  with probability  $\frac{1}{p(n)}$ . Define the state after the first two steps to be good if

$$\Pr \left[ V_{Kil}(f||a||b, crs, \beta, \gamma, \delta) = 1 \mid \begin{array}{l} \gamma \leftarrow \{0, 1\}^n \\ \delta \leftarrow \tilde{P}(f||a||b, crs, \beta, \gamma) \end{array} \right] \geq \frac{1}{2p(n)},$$

where  $crs, \beta$  are generated in the first two steps. By averaging argument, the probability that the state is good is at least  $\frac{1}{2p(n)}$ . Later on when we refer to  $\tilde{P}$  we refer to a prover after the first two steps condition on it's in a good state.

The analysis is similar to [BG08]. For a query  $\phi$ , a query index  $i \in \{1, \dots, q(n)\}$ , a possible answer  $\sigma \in \{0, 1\}$  and  $\tau \in [0, 1]$ , we say that  $\sigma$  is  $\tau$ -strong for  $(i, \phi)$  if condition on the  $i$ -th query being  $\phi$ , the probability that  $\tilde{P}$  answers the  $i$ -th query with  $\sigma$  while the authentication path matches  $\beta$  is at least  $\tau$ . [BG08] observes that the probability that the  $V_{Kil}$  accepts and receives only  $\tau$ -strong answers is at least  $\frac{1}{2p(n)} - q(n)\tau$ . This is because answers that are not  $\tau$ -strong is unlikely to appear. When  $V_{Kil}$  accepts, the probability that the answer for the  $i$ -th query is not a  $\tau$ -strong query is less than  $\tau$ . Thus by union bound, the probability that the  $V_{Kil}$  accepts and receives only  $\tau$ -strong answers is at least  $\frac{1}{2p(n)} - q(n)\tau$ . By setting  $\tau$  to be  $\frac{1}{4q(n)p(n)}$ , we only need to prove that condition on all the queries have an answer that is  $\tau$ -strong, all answers will be extracted successfully with probability  $1 - \text{negl}$ . The simulated oracle  $\tilde{\pi}^{\tilde{P}}$  on query  $\phi$  works as follows:

1. Set the answer  $e = \perp$ .
2. For position  $i = 1, 2, \dots, q(n)$  do the following:

- (a) Generate  $n\tau^{-1}$  independent randomness  $\gamma_{i,1}, \dots, \gamma_{i,n\tau^{-1}}$  by calling  $S_{pcp}(x, i, \phi)$   $tbd$  times with independent randomness.
  - (b) Run  $\tilde{P}$  when the third messages are  $\gamma_{i,1}, \dots, \gamma_{i,n\tau^{-1}}$  and obtain the all the answer for the  $i$ -th query. (These are the responses for query  $\phi$ ).
  - (c) Consider only the answers where its authentication path matches  $\beta$ , update  $e$  to those answers. If some of them contradict each other or contradict with  $e$ , aborts.
3. (Virtual Step: not executed in the actual execution) Pick a random  $i$  and generate a random  $\gamma$  from  $S_{pcp}$ , run the above procedure to see if the result is valid and contradicts to  $e$ .
  4. Return  $e$  as the response to the oracle query, if  $e = \perp$ , aborts.

To see why this oracle makes  $V_{pcp}$  accepts, we need two observations. First, the probability that the oracle aborts is negligible when called by  $V_{pcp}$ . This is because in the case that it aborts, we find a collision on the authentication path and  $V_{pcp}^{\tilde{\pi}\tilde{P}}$  is efficient. Besides that, all answers found by the oracle must have its opposite answer being not  $\tau$ -strong, otherwise we can also find a collision by running the virtual step. Second, the  $\tau$ -strong answer is found with  $1 - \text{negl}$  probability. This is because we try  $S_{pcp}$  for  $n\tau^{-1}$  times independently and the failure probability is  $(1 - \tau)^{n\tau^{-1}} \approx e^{-n}$ .  $\square$

## 6.2 Reduced Argument for Central Relation

Now we introduce a reduced argument  $(P_{Mic}, V_{Mic})$  for central relation that is similar to the previous argument. This is a 2-round protocol with CRS. One can imagine it to be some kind of compressed version of the previous argument by Fiat-Shamir-like transformation but there are some nuances:

- Two Fiat-Shamir transformations may be applied on the original protocol in parallel. That means, in the reduced protocol, the prover will generate the verifier's public coin message twice with two different Fiat-Shamir hash functions, and need to pass the verification for both messages.
- Instead of sending  $\beta$  in the first round, we send the commitment of  $\beta$ , denoted as  $\hat{\beta}$ . This is employed to address some details in later proofs, especially the insecurity of  $(P_2^{FS}, V_2^{FS}), (P_3^{FS}, V_3^{FS})$ , which will be introduced later.
- We separate the message from verifier as the CRS and the first message. The CRS can be generated by a private coin generator, and the first message must be generated with public coins. This distinction is made to facilitate the integration of the reduced protocol into later 3-round protocols. Specifically, our aim is to incorporate the CRS from this protocol into the CRS of the 3-round protocol, while placing the first message from this protocol into the second message (the one sent by the verifier) in the 3-round protocol.

Let  $\mathcal{F}, \text{Comm}$  be two CRHFs as mentioned in the beginning of this section. We will give two versions of this argument  $(P_{Mic}^1, V_{Mic}^1)$  and  $(P_{Mic}^2, V_{Mic}^2)$ .  $(P_{Mic}^1, V_{Mic}^1)$  only uses one Fiat-Shamir hash function, while  $(P_{Mic}^2, V_{Mic}^2)$  uses two.

For the first version, let  $\mathcal{G}$  be a Fiat-Shamir hash function which will be clear in the content when we analyze or utilize the protocol.  $(P_{Mic}^1, V_{Mic}^1)$  works as follows:

- Common input:  $f\|a\|b$ .

- Auxiliary input for the prover:  $w = \hat{C} \parallel \Pi$ .
1.  $V_{Mic}^1$ : Select  $f^{TC} \leftarrow \mathcal{F}_n$ ,  $\text{comm} \leftarrow \text{Comm}_n$ ,  $g \leftarrow \mathcal{G}$  and output  $\text{crs} = (f^{TC}, g, \text{comm})$ . Later, we will denote this process as  $\text{crs} \leftarrow \text{Gen}_{Mic}^{\mathcal{G}}$ .
  2.  $V_{Mic}^1$ : Select the randomness for  $\text{comm}$ ,  $r_c \leftarrow \{0, 1\}^n$  and output  $r_c$ .
  3.  $P_{Mic}^1$ : On input  $(f \parallel a \parallel b, w, \text{crs}, r_c)$ :
    - (a) Compute PCP proof  $\pi \leftarrow P_{pcp}(f \parallel a \parallel b, w)$ .
    - (b) Compute  $\beta \leftarrow \text{TC}_{f^{TC}}(\pi)$ .
    - (c) Compute  $\hat{\beta} \leftarrow \text{comm}(\beta \parallel r_c)$ .
    - (d) Compute  $\gamma \leftarrow g(\hat{\beta})$ .
    - (e) Run  $Q_{pcp}$  on  $\gamma$  to obtain the queries of  $V_{pcp}$  and let the authentication paths along with the answers to the queries be  $\delta$ .
    - (f) Output  $\text{ans} = (\beta, \hat{\beta}, \gamma, \delta)$ .
  4.  $V_{Mic}^1$ : On input  $(f \parallel a \parallel b, \text{crs}, \text{ans})$ , accept iff:
    - (a)  $\hat{\beta} = \text{comm}(\beta \parallel r_c)$ .
    - (b)  $\gamma = g(\hat{\beta})$ .
    - (c)  $V_{pcp}$  accept with random tape  $\gamma$  and query responses  $\delta$ .

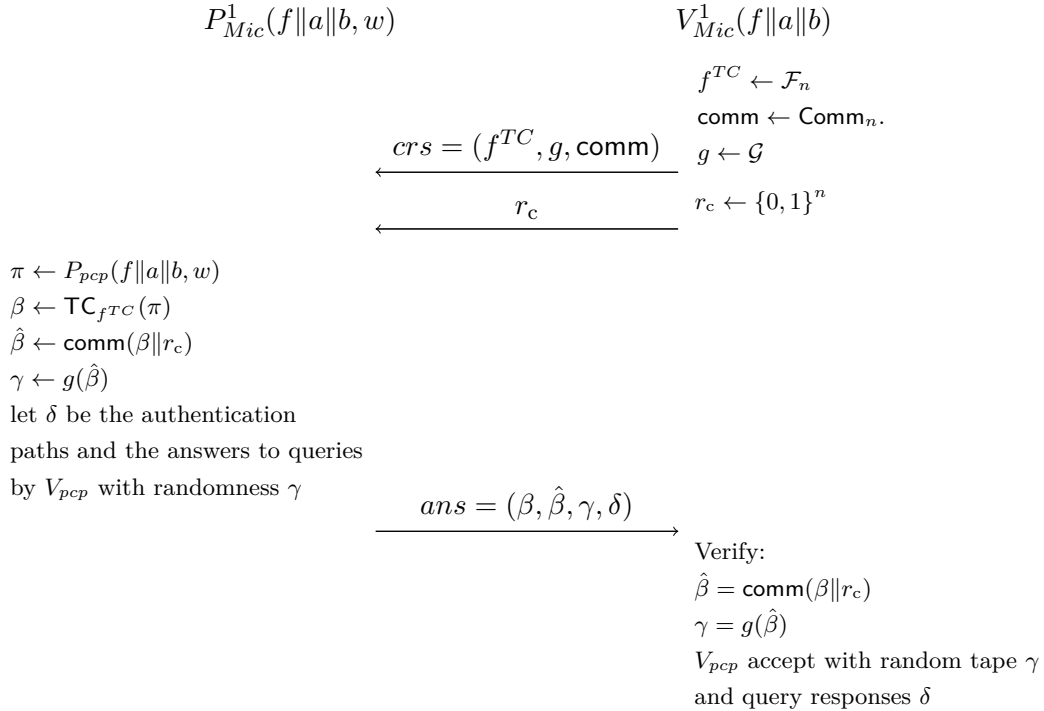


Figure 7: Reduced Argument for the Central Relation  $(P_{Mic}^1, V_{Mic}^1)$

For the second version, let  $\mathcal{G}_1, \mathcal{G}_2$  be two Fiat-Shamir hash functions which will be clear in the content.  $(P_{Mic}^2, V_{Mic}^2)$  works as follows:

- Common input:  $f\|a\|b$ .
  - Auxiliary input for the prover:  $w = \hat{C}\|\Pi$ .
1.  $V_{Mic}^2$ : Select  $f^{TC} \leftarrow \mathcal{F}_n$ ,  $\text{comm} \leftarrow \text{Comm}_n$ ,  $g_1 \leftarrow \mathcal{G}_1$ ,  $g_2 \leftarrow \mathcal{G}_2$  and output  $\text{crs} = (f^{TC}, g_1, g_2, \text{comm})$ .  
Later, we will denote this process as  $\text{crs} \leftarrow \text{Gen}_{Mic}^{\mathcal{G}_1, \mathcal{G}_2}$ .
  2.  $V_{Mic}^2$ : Select the randomness for  $\text{comm}$ ,  $r_c \leftarrow \{0, 1\}^n$  and output  $r_c$ .
  3.  $P_{Mic}^2$ : On input  $(f\|a\|b, w, \text{crs}, r_c)$ :
    - (a) Compute PCP proof  $\pi \leftarrow P_{pcp}(f\|a\|b, w)$ .
    - (b) Compute  $\beta \leftarrow \text{TC}_{f^{TC}}(\pi)$ .
    - (c) Compute  $\hat{\beta} \leftarrow \text{comm}(\beta\|r_c)$ .
    - (d) Compute  $\gamma_1 \leftarrow g_1(\hat{\beta})$  and  $\gamma_2 \leftarrow g_2(\hat{\beta})$ .
    - (e) Run  $Q_{pcp}$  on  $\gamma_1, \gamma_2$  to obtain the queries and let the authentication paths along with the answers to the queries be  $\delta_1, \delta_2$ , respectively.
    - (f) Output  $\text{ans} = (\beta, \hat{\beta}, \gamma_1, \gamma_2, \delta_1, \delta_2)$ .
  4.  $V_{Mic}^2$ : On input  $(f\|a\|b, \text{crs}, \text{ans})$ , accept iff:
    - (a)  $\hat{\beta} = \text{comm}(\beta\|r_c)$ .
    - (b)  $\gamma_1 = g_1(\hat{\beta})$  and  $\gamma_2 = g_2(\hat{\beta})$ .
    - (c)  $V_{pcp}$  accept with random tape  $\gamma_1, \gamma_2$  and query responses  $\delta_1, \delta_2$ , respectively.

Note that those two reduced protocols maintains the completeness of the previous protocol  $(P_{Kil}, V_{Kil})$ , but there is no guarantee about the soundness. Our following proof will consider both cases whether the protocol has soundness.

### 6.3 Protocol 1

In the first protocol  $(P_1, V_1)$ , the reduced protocol is applied to enable the prediction of the next message of the verifier after the Fiat Shamir transformation. In the CRS we generate the function  $f$  for central relation, then we let the prover send  $a$  and the verifier send  $b$ , to determine the instance of central relation. After the instance is determined, we invoke  $(P_{Mic}^2, V_{Mic}^2)$  to prove it. Note that although interaction of  $(P_{Mic}^2, V_{Mic}^2)$  starts after  $f, a, b$  is determined, the CRS of  $(P_{Mic}^2, V_{Mic}^2)$  should be incorporated into the CRS of  $(P_1, V_1)$ , because it may be generated with private coins. Since the adversary can choose  $a$  after he learns the CRS of  $(P_{Mic}^2, V_{Mic}^2)$ , it seems like we need  $(P_{Mic}^2, V_{Mic}^2)$  to satisfy some strong soundness to keep  $(P_1, V_1)$  itself secure. Actually we will not prove the exact soundness of  $(P_{Mic}^2, V_{Mic}^2)$ , because we use the third protocol  $(P_3, V_3)$  to deal with the situation that  $(P_1, V_1)$  is not secure.

With function ensemble  $\mathcal{G}_1, \mathcal{G}_2$ , which we determine later, protocol  $(P_1, V_1)$  is constructed as follows:

- Common input:  $x \in \{0, 1\}^{l_x(n)}$ .
- Auxiliary input to the prover: none.

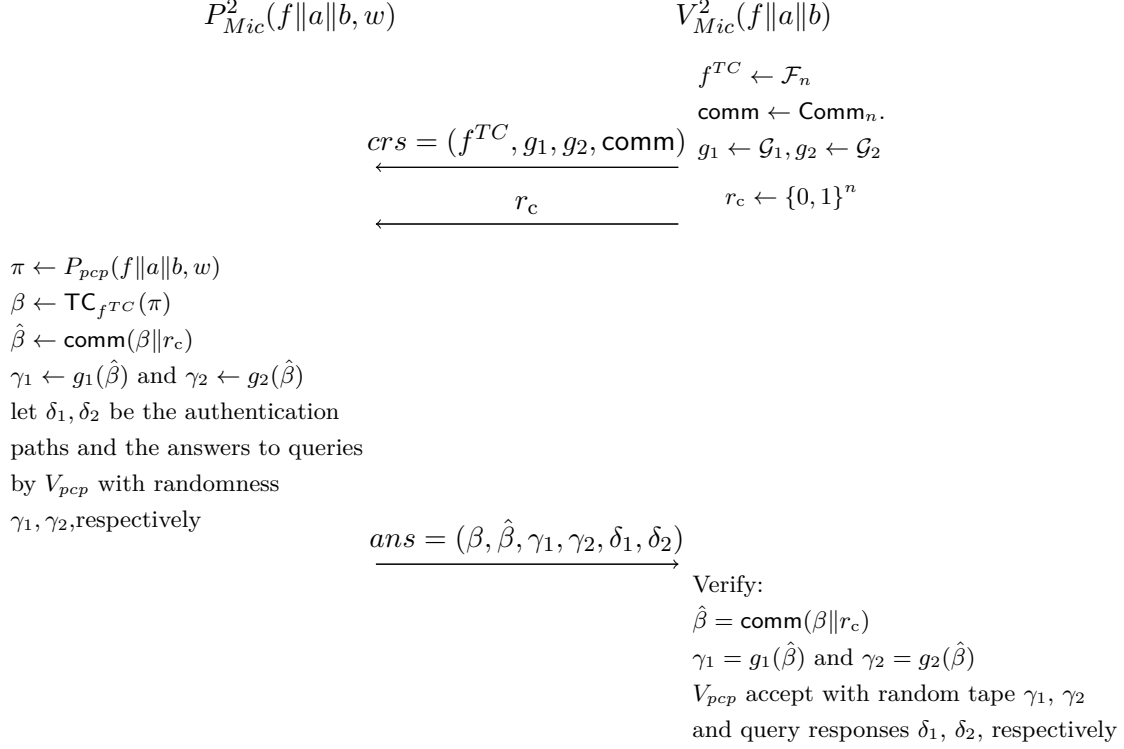


Figure 8: Reduced Argument for the Central Relation  $(P_{Mic}^2, V_{Mic}^2)$

1.  $V_1$ :
  - (a) Compute  $f \leftarrow F_n$ .
  - (b) Compute  $crs' = (f^{TC}, g_1, g_2, \text{comm}) \leftarrow \text{Gen}_{Mic}^{\mathcal{G}_1, \mathcal{G}_2}$ .
  - (c) Let  $crs = (f, crs')$  and output it.
2.  $P_1$ : On input  $(x, crs)$ , output an arbitrary  $a \in \{0, 1\}^n$ .
3.  $V_1$ : On input  $(x, crs, a)$ , output random  $b, r_c \leftarrow \{0, 1\}^n$ .
4.  $P_1$ : On input  $(x, crs, a, b\|r_c)$ , outputs  $ans$ .
5.  $V_1$ : On input  $(x, crs, a, b\|r_c, ans)$ :
  - (a) Parse  $crs$  as  $f, crs'$ .
  - (b) Accept if and only if  $V_{Mic}^2(f\|a\|b, crs', r_c, ans) = 1$ .

**Lemma 6.7.** For all function ensemble  $\mathcal{H} \in \mathcal{C}$ , apply the Fiat-Shamir transform on  $(P_1, V_1)$  with respect to  $\mathcal{H}$  gives  $(P_1^{FS}, V_1^{FS})$  that is not a non-interactive public coin argument for empty language against  $\mathcal{C}$  adversary.  $\diamond$

The insecurity of  $(P_1^{FS}, V_1^{FS})$  is relatively straight-forward. As the adversary knows the witness for the central relation.



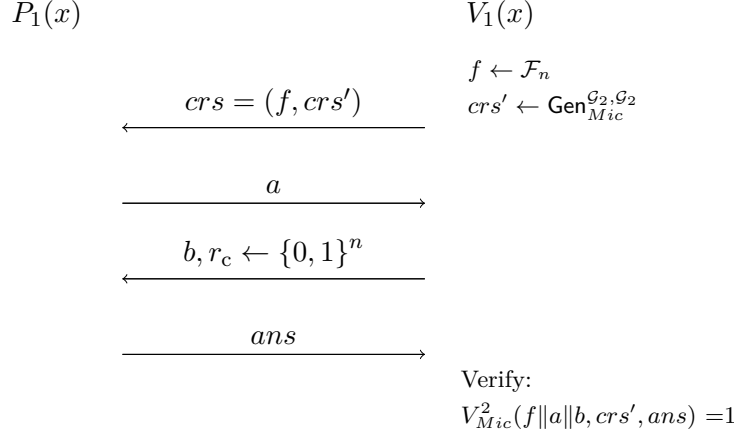


Figure 9: Protocol 1

**Proof.** Here we construct an adversary  $P^*$  for  $(P_1^{FS}, V_1^{FS})$  as below:

On input  $(x, h \| crs)$ :

1. Parse  $crs$  as  $f, crs'$ .
2. Hard-code  $x$  into the input of  $h$  and truncate the output to only contain  $b$ , to get  $C$ . Compute the encoding  $\tilde{C}$ .
3. Compute  $a \leftarrow \text{TC}_f(\tilde{C}), b \leftarrow C(a)$ , and record the computation history  $\Pi$ .
4. Compute  $(b, r_c) \leftarrow h(x \| a)$ .
5. Emulate  $(P_{Mic}, V_{Mic}|_{crs'})$  with input  $f \| a \| b$  and witness  $\hat{C} \| \Pi$ , to produce  $ans$ .
6. Output  $a, ans$ .

Note that  $P^*$  is in  $\mathcal{C}$  and it can always succeed due to the completeness of  $(P_{Mic}^2, V_{Mic}^2)$ .  $\square$

The completeness of  $(P_1, V_1)$  is also trivial, as the language is empty and the honest prover can just output some fixed strings. However, we cannot prove the security of  $(P_1, V_1)$  directly. Here, we consider 2 cases:

- $(P_1, V_1)$  is secure. In this case,  $(P_1, V_1)$  is the protocol that the theorem states.
- $(P_1, V_1)$  is not secure. In this case, we want to prove the insecurity of  $(P_3^{FS}, V_3^{FS})$ , which will be introduced later.

Instead of directly discussing the security of  $(P_1, V_1)$ , we use another notation for this:

**Definition 6.8 (IMPERSONATOR).** For any Fiat-Shamir hash function family  $\mathcal{G}_1, \mathcal{G}_2 \in \mathcal{C}$ , define the statement  $\exists \text{IMPERSONATOR}$  to be the following. There exists a polynomial  $p(n)$  and  $\mathcal{C}$  circuit families  $P^{IMP} = \{P_n^{IMP}\}_{n \in \mathbb{N}}$  and  $F^{IMP} = \{F_n^{IMP}\}_{n \in \mathbb{N}}$  such that for infinite many  $n \in \mathbb{N}$ ,

$$\Pr \left[ (P^{IMP}(aux), V_{Mic}^2|_{crs})(f \| a \| b) = 1 \mid \begin{array}{l} f \leftarrow \mathcal{F}_n, b \leftarrow \{0, 1\}^n \\ crs \leftarrow \text{Gen}_{Mic}^{\mathcal{G}_1, \mathcal{G}_2} \\ a, aux \leftarrow F^{IMP}(f, crs) \end{array} \right] \geq \frac{1}{p(n)}. \quad \diamond$$

We can observe that this is equivalent to the security of  $(P_1, V_1)$ , as the IMPERSONATOR  $P^{IMP}, F^{IMP}$  can be used as the adversary.

**Lemma 6.9.** If there exists  $\mathcal{G}_1, \mathcal{G}_2 \in \mathcal{C}$  such that  $\neg \exists \text{IMPERSONATOR}$  then with respect to  $\mathcal{G}_1, \mathcal{G}_2$ ,  $(P^1, V^1)$  is a 3-round public coin argument for empty language against adversary in  $\mathcal{C}$ .  $\diamond$

**Proof.** It follows directly from the fact that the definition of  $\neg \exists \text{IMPERSONATOR}$  is exactly the soundness condition.  $\square$

## 6.4 Protocol 2

In the second protocol  $(P_2, V_2)$ , we are not aiming to construct some protocol that is easy to break after Fiat-Shamir transformation, but some protocol that is definitely secure. In the protocol, we first generate function  $f$  for central relation in the CRS, then let the prover decide  $a, b_1, b_2$  that  $b_1 \neq b_2$  and use two parallel  $(P_{Kil}, V_{Kil})$  to prove the knowledge of witness of  $f\|a\|b_1$  and  $f\|a\|b_2$ . It is impossible for the adversary to know the witnesses for both  $f\|a\|b_1$  and  $f\|a\|b_2$ , due to the collision resistance of the tree commitment, so it is definitely secure. In the protocol, although  $a, b_1, b_2, \beta_1, \beta_2$  are determined before sending the first message, we will not send all of them in the first message. Instead, a special version of commitments of them will be sent, due to some complicated details in the proof.

Protocol  $(P_2, V_2)$  is constructed as follows:

- Common input:  $x \in \{0, 1\}^{l_x(n)}$ .
  - Auxiliary input to the prover: none.
1.  $V_2$ :
    - (a) Compute  $f, f^{TC} \leftarrow \mathcal{F}_n$ .
    - (b) Compute  $\text{comm} \leftarrow \text{Comm}_n$  and  $r_c, r' \leftarrow \{0, 1\}^n$ .
    - (c) Compute  $\gamma'_1 \leftarrow \{0, 1\}^n$ .
    - (d) Let  $crs = (f, f^{TC}, \text{comm}, r_c, r', \gamma'_1)$  and output it.
  2.  $P_2$ : On input  $(x, crs)$ :
    - (a) Decide  $a, b_1, b_2 \in \{0, 1\}^n$ .
    - (b) Decide  $\beta_1, \beta_2 \in \{0, 1\}^n$ .
    - (c) Compute  $\hat{\beta}_2 = \text{comm}(\beta_2 \| (\text{comm}(\beta_1 \| a \| b_1 \| b_2 \| r_c) \oplus r'))$ , the commitment of  $a, b_1, b_2, \beta_1, \beta_2$ . Recall that shorter inputs can be padded to the correct length by padding 0s.
    - (d) Output  $\hat{\beta}_2$ .
  3.  $V_2$ : On input  $(x, crs, \hat{\beta}_2)$ , output random  $\gamma''_1, \gamma_2 \in \{0, 1\}^n$ .
  4.  $P_2$ : On input  $(x, crs, \hat{\beta}_2, \gamma''_1 \| \gamma_2)$ :
    - (a) Decide  $\delta_1, \delta_2 \in \{0, 1\}^n$ .
    - (b) Output  $a, b_1, b_2, \beta_1, \beta_2, \delta_1, \delta_2$ .
  5.  $V_2$ : On input  $(x, crs, \hat{\beta}_2, \gamma''_1 \| \gamma_2, a \| b_1 \| b_2 \| \beta_1 \| \beta_2 \| \delta_1 \| \delta_2)$ ,

- (a) Parse  $crs$  as  $f, f^{TC}, \text{comm}, r_c, r', \gamma'_1$ .
- (b) Check  $b_1 \neq b_2$ .
- (c) Check  $\hat{\beta}_2 = \text{comm}(\beta_2 \| (\text{comm}(\beta_1 \| a \| b_1 \| b_2 \| r_c) \oplus r'))$ .
- (d) Check  $V_{Kil}(f \| a \| b_1, f^{TC}, \beta_1, \gamma'_1 \oplus \gamma''_1, \delta_1) = 1$ .
- (e) Check  $V_{Kil}(f \| a \| b_2, f^{TC}, \beta_2, \gamma_2, \delta_2) = 1$ .
- (f) Accept if and only if all checks are passed.

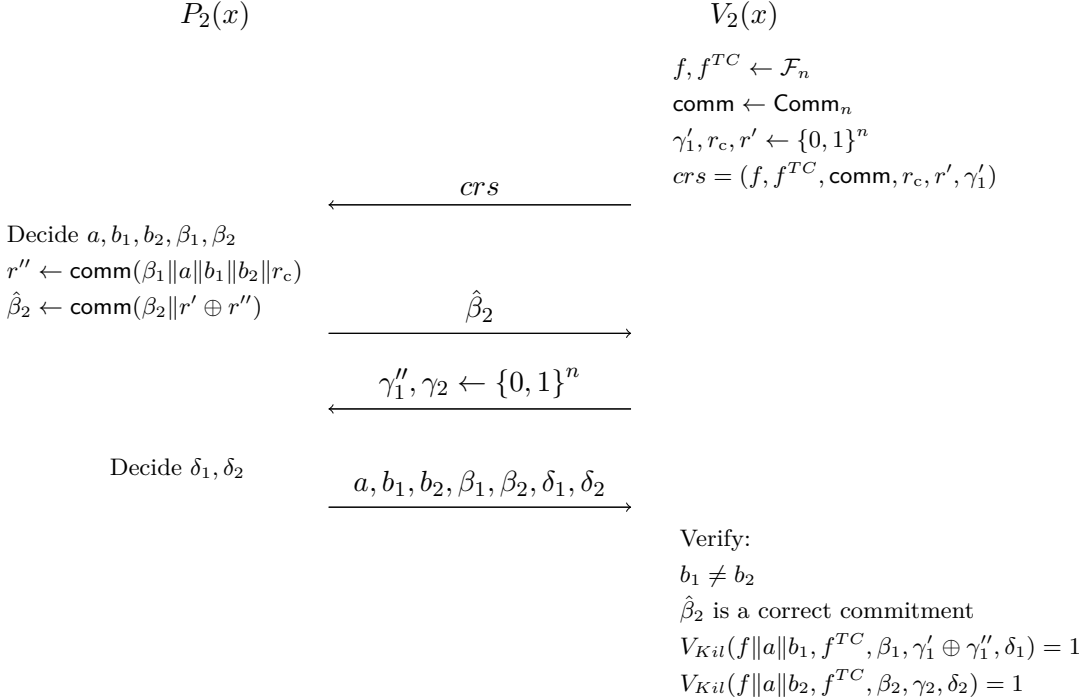


Figure 10: Protocol 2

Here we first prove the security of  $(P_2, V_2)$ . The intuition is to reduce the security to the security of CRHF. If there is an adversary that breaks  $(P_2, V_2)$ , due to the argument of knowledge of  $(P_{Kil}, V_{Kil})$ , we can actually get  $f, a, b_1, b_2, C_1, C_2$  such as  $(f \| a \| b_1, \hat{C}_1 \| \Pi) \in \mathcal{R}$  and  $(f \| a \| b_2, \hat{C}_2 \| \Pi) \in \mathcal{R}$ . Because  $C_1(a) = b_1 \wedge C_2(a) = b_2 \wedge b_1 \neq b_2$ , we know  $C_1, C_2$  must be two different circuits, which breaks the collision resistant property of  $\text{TC}_{f^{TC}}$ .

**Lemma 6.10.**  $(P_2, V_2)$  is a 3-round public coin argument for empty language against adversary in  $\mathcal{C}$ .  $\diamond$

**Proof.** Completeness is trivially satisfied. Now we prove soundness by contradiction. Suppose there exists an adversary circuit family  $P^*$  in  $\mathcal{C}$  and a polynomial  $p(n)$  along with instance  $x$  such that

$$\Pr[(P^*, V_2)(x) = 1] \geq \frac{1}{p(n)}.$$

Then we can construct circuit families  $\tilde{F}$ ,  $\tilde{P}_1$  and  $\tilde{P}_2$  in  $\mathcal{C}$  such that there exists a polynomial  $p'(n)$  and

$$\Pr \left[ \begin{array}{l} (\tilde{P}_1(aux), V_{Kil}|_{crs})(f \| a \| b_1) = 1 \wedge \\ (\tilde{P}_2(aux), V_{Kil}|_{crs})(f \| a \| b_2) = 1 \end{array} \middle| (crs, a, b_1, b_2, aux) \leftarrow \tilde{F}(f, f^{TC}) \right] \geq \frac{1}{p'(n)}$$

where the randomness is over  $f, f^{TC} \leftarrow \mathcal{F}_n$  and the randomness of all these circuits.

- $\tilde{F}$  works as follows:

1. Select  $\text{comm} \leftarrow \text{Comm}_n$  and  $r_c, r', \gamma'_1 \leftarrow \{0, 1\}^n$ .
2. Let  $crs' = (f, f^{TC}, \text{comm}, r_c, r', \gamma'_1)$ .
3. Select a random tape  $r_p$  for  $P^*$ . Emulate the interaction

$$(\hat{\beta}_2, (\gamma''_1, \gamma_2), (a, b_1, b_2, \beta_1, \beta_2, \delta_1, \delta_2)) \leftarrow (P^*, V_2|_{crs'})(x)$$

where  $P^*$  uses  $r_p$  as its randomness.

4. Let  $crs = f^{TC}, aux = (\beta_1, \beta_2, r_p, crs')$  and output  $(crs, a, b_1, b_2, aux)$ .

- $\tilde{P}_1(aux)$  works as follows:

1.  $crs$  from  $V_{Kil}|_{crs}$  and parse it as  $f^{TC}$ .
2. Parse  $aux$  as  $(\beta_1, \beta_2, r_p, crs')$ .
3. Output  $\beta_1$ .
4. Receive  $\gamma_1^1$  from  $V_{Kil}|_{crs}$ .
5. Select  $\gamma_2^1 \leftarrow \{0, 1\}^n$  and emulate the interaction

$$(\hat{\beta}_2, (\gamma'_1 \oplus \gamma_1^1, \gamma_2^1), (a', b'_1, b'_2, \beta'_1, \beta'_2, \delta'_1, \delta'_2)) \leftarrow (P^*, V_2|_{crs', (\gamma'_1 \oplus \gamma_1^1, \gamma_2^1)})(x)$$

where  $P^*$  is invoked using the same random tape  $r_p$  as the emulation in  $\tilde{F}$ .

6. Output  $\delta'_1$ .

- $\tilde{P}_2(aux)$  works as follows:

1.  $crs$  from  $V_{Kil}|_{crs}$  and parse it as  $f^{TC}$ .
2. Parse  $aux$  as  $(\beta_1, \beta_2, r_p, crs')$ .
3. Output  $\beta_2$ .
4. Receive  $\gamma_2^2$  from  $V_{Kil}|_{crs}$ .
5. Select  $\gamma_1^2 \leftarrow \{0, 1\}^n$  and emulate the interaction

$$(\hat{\beta}_2, (\gamma_1^2, \gamma_2^2), (a'', b''_1, b''_2, \beta''_1, \beta''_2, \delta''_1, \delta''_2)) \leftarrow (P^*, V_2|_{crs', (\gamma_1^2, \gamma_2^2)})(x)$$

where  $P^*$  is invoked using the same random tape  $r_p$  as the emulation in  $\tilde{F}$ .

6. Output  $\delta''_2$ .

To see that  $\tilde{F}, \tilde{P}_1$  and  $\tilde{P}_2$  satisfy the conditions above. Notice that

1.  $\gamma'_1 \oplus \gamma_1^1, \gamma_2^1, \gamma_1^2$  and  $\gamma_2^2$  are uniform random strings thus we can emulate these interaction correctly.
2. Since we invoke  $P^*$  with the same randomness  $r_p$  every time, the first output  $\hat{\beta}_2$  will be the same every time. And since  $\text{Comm}$  is collision resistant, we have

$$(a, b_1, b_2, \beta_1, \beta_2) = (a', b'_1, b'_2, \beta'_1, \beta'_2) = (a'', b''_1, b''_2, \beta''_1, \beta''_2).$$

3.  $V_{Kil}|_{crs}$  will accept the transcript  $(\beta_1, \gamma_1^1, \delta_1')$  since it is exactly one of the accept condition for  $V_2$ . For the same reason  $V_{Kil}|_{crs}$  will also accept the transcript  $(\beta_2, \gamma_2^2, \delta_2'')$ .

Given  $\tilde{F}$ ,  $\tilde{P}_1$  and  $\tilde{P}_2$  we can find a collision for  $f$  and thus contradict to our assumption that  $\mathcal{F}$  is collision resistant. By the argument of knowledge property, given oracle access to  $\tilde{F}$ ,  $\tilde{P}_1$  and  $\tilde{P}_2$ , there exists a extractor circuit family  $E = \{E_n\}_{n \in \mathbb{N}}$  such that:

$$\Pr \left[ \begin{array}{l} \exists w_1, w_2, ((f||a||b_1), w_1) \in \mathcal{R} \wedge \forall i, w_{1,i} = E^{\tilde{P}_1(au)}(f||a||b_1, i) \wedge \\ ((f||a||b_2), w_2) \in \mathcal{R} \wedge \forall i, w_{2,i} = E^{\tilde{P}_2(au)}(f||a||b_2, i) \end{array} \right] > 1 - \text{negl}(n).$$

With high probability we can obtain valid witnesses  $w_1$  and  $w_2$  simultaneously. Let  $C_1$  be the circuit in  $w_1$  and  $C_2$  be the circuit in  $w_2$ , we have  $TC_f(\tilde{C}_1) = TC_f(\tilde{C}_2) = a$  and  $C_1 \neq C_2$ . To find a collision of  $f$ , we select a random position  $i$ , the probability that the  $i$ -th positions of  $\tilde{C}_1$  and  $\tilde{C}_2$  are different is non-negligible, because the encoding of circuits has high minimum distance. Thus by traversing the path from position  $i$  to the tree root on both tree commitments we can obtain a collision for  $f$ . Here, the depth of tree commitments has no guarantee to be low, but as computation history in the witness records hash value in each node, we check the existence of collision on the path concurrently.  $\square$

For  $(P_2^{FS}, V_2^{FS})$ , we do not know how to prove the insecurity. So, we also separate this situation into 2 cases:

- $(P_3, V_3)$ , the protocol we will introduce later, is not secure. In this case, we can prove  $(P_2^{FS}, V_2^{FS})$  is also not secure.
- $(P_3, V_3)$  is secure.

Here, we use strong-IMPERSONATOR to characterize the security of  $(P_3, V_3)$ .

**Definition 6.11 (strong-IMPERSONATOR).** For any Fiat-Shamir hash function family  $\mathcal{G} \in \mathcal{C}$ , define statement  $\exists \text{strong-IMPERSONATOR}$  to be the following. There exists a polynomial  $p(n)$  and  $\mathcal{C}$  circuit families  $P_1^{sIMP}$ ,  $P_2^{sIMP}$  and  $F^{sIMP}$  such that for infinite many  $n \in \mathbb{N}$ ,

$$\Pr \left[ \begin{array}{l} (P_1^{sIMP}(aux), V_{Kil}|_{f^{TC}})(f||a||b_1) = 1 \wedge \\ (P_2^{sIMP}(aux), V_{Mic}^1|_{crs})(f||a||b_2) = 1 \end{array} \middle| \begin{array}{l} f \leftarrow \mathcal{F}_n, b_2 \leftarrow \{0, 1\}^n \\ crs = (f^{TC}, g, \text{comm}) \leftarrow \text{Gen}_{Mic}^{\mathcal{G}} \\ a, b_1, aux \leftarrow F^{sIMP}(f, crs) \end{array} \right] \geq \frac{1}{p(n)} \quad \diamond$$

**Lemma 6.12.** If for any function ensemble  $\mathcal{H} \in \mathcal{C}$  there exists strong-IMPERSONATOR, then applying the Fiat-Shamir transform on  $(P_2, V_2)$  with respect to  $\mathcal{H}$  gives  $(P_2^{FS}, V_2^{FS})$  that is not a non-interactive public coin argument for empty language against  $\mathcal{C}$  adversary.  $\diamond$

**Proof.** Assume  $h \leftarrow \mathcal{H}$  is the transformation function. The adversary  $P^*$  works as follows:

On input  $(x, h||crs)$ :

1. Parse  $crs$  as  $f, f^{TC}, \text{comm}, r_c, r', \gamma_1'$ .
2. Hard-code  $x$  into the input of  $h$ , and truncate the output to only contain  $\gamma_2$ , to get  $h'$ . Let  $crs' = (f^{TC}, h', \text{comm})$ .

3. Emulate

$$(a, b_1, aux) \leftarrow F_n^{sIMP}(f, crs')$$

4. Emulate

$$(f^{TC}, \beta_1, *, *) \leftarrow (P_1^{sIMP}(aux), V_{Kil}|_{f^{TC}})(f||a||b_1)$$

5. Select  $b_2 \leftarrow \{0, 1\}^n$  and compute  $r'' \leftarrow \text{Comm}(\beta_1||a||b_1||b_2||r_c)$

6. Emulate

$$(crs, r' \oplus r'', (\beta_2, \hat{\beta}_2, \gamma_2, \delta_2)) \leftarrow (P_2^{sIMP}(aux), V_{Mic}^1|_{crs', r' \oplus r''})(f||a||b_2)$$

7.  $(\gamma_1'', *) = h(\hat{\beta}_2)$  and emulate

$$(\beta_1, *, \delta_1) \leftarrow (P_1^{sIMP}(aux), V_{Kil}|_{f^{TC}, \gamma_1' \oplus \gamma_1''})$$

8. Output  $(\hat{\beta}_2, (a, b_1, b_2, \beta_1, \beta_2, \delta_1, \delta_2))$ .

Consider the conditions that  $V_2$  accepts:

1. Since  $b_2 \leftarrow \{0, 1\}^n$  is an independent random string, the condition  $b_1 \neq b_2$  holds with probability  $1 - 2^{-n}$ .
2.  $\gamma_1'$  is uniformly random thus the call to  $V_{Kil}|_{f^{TC}, \gamma_1' \oplus \gamma_1''}$  is a valid call.
3.  $r' \oplus r''$  is uniform random since  $r'$  is uniform random, thus we can call  $V_{Mic}^1|_{crs', r' \oplus r''}$  correctly and obtain  $\hat{\beta}_2 = \text{Comm}(\beta_2, r'_c)$ . Together with  $r'_c = r' \oplus \text{Comm}(\beta_1||a||b_1||b_2||r_c)$ , we pass  $\hat{\beta}_2 = \text{comm}(\beta_2||(\text{comm}(\beta_1||a||b_1||b_2||r_c) \oplus r'))$ .
4.  $V_{Kil}(f||a||b_1, f^{TC}, \beta_1, \gamma_1' \oplus \gamma_1'', \delta_1) = 1$  and  $V_{Kil}(f||a||b_2, f^{TC}, \beta_2, \gamma_2, \delta_2) = 1$  are satisfied by the definition of  $\exists\text{strong-IMPERSONATOR}$ .

Since  $P^*$  above is in  $\mathcal{C}$ ,  $(P_2^{FS}, V_2^{FS})$  is not a non-interactive public coin argument for empty language against  $\mathcal{C}$  adversary.  $\square$

## 6.5 Protocol 3

In the third protocol  $(P_3, V_3)$ , we first generate function  $f$  for central relation in the CRS, then let the prover decide  $a, b_1$  while letting the verifier choose  $b_2$ . One  $(P_{Kil}, V_{Kil})$  is invoked on instance  $f||a||b_1$ , while one  $(P_{Mic}^1, V_{Mic}^1)$  is invoked on instance  $f||a||b_2$ . Components used in  $(P_{Kil}, V_{Kil})$  are labeled with subscript 1, and components used in  $(P_{Mic}^1, V_{Mic}^1)$  are labeled with subscript 2. Again, we use a commitment of  $a, b_1, \beta_1$ , instead of sending them in the first message, because it is necessary if we want to use IMPERSONATOR to break  $(P_3^{FS}, V_3^{FS})$ . All the  $\oplus$  here is used to make the view of IMPERSONATOR same as an uniform distribution after the Fiat-Shamir transformation.

With function ensemble  $\mathcal{G}$ , which we determine later, protocol  $(P_3, V_3)$  is constructed as follows:

- Common input:  $x \in \{0, 1\}^{l_x(n)}$ .

- Auxiliary input to the prover: none.

1.  $V_3$ :

- Compute  $f \leftarrow F_n$ .
- Compute  $crs' = (f^{TC}, g, \text{comm}) \leftarrow \text{Gen}_{Mic}^G$ .
- Compute  $b'_2, r_{c,1}, r'_{c,2}, r' \leftarrow \{0, 1\}^n$ .
- Let  $crs = (f, crs', b'_2, r_{c,1}, r'_{c,2}, r')$  and output it.

2.  $P_3$ : On input  $(x, crs)$ :

- Parse  $crs$  as  $f, f^{TC}, g, \text{comm}, b'_2, r_{c,1}, r'_{c,2}, r'$ .
- Decide  $a, b_1 \in \{0, 1\}^n$ .
- Decide  $\beta_1 \in \{0, 1\}^n$ .
- Compute  $\hat{\beta}_1 \leftarrow \text{comm}(\beta_1 \| (\text{comm}(a \| b_1 \| r_{c,1}) \oplus r'))$ , the commitment of  $a, b_1, \beta_1$ .
- Output  $\hat{\beta}_1$ .

3.  $V_3$ : On input  $(x, crs, \hat{\beta}_1)$ , output random  $b''_2, r''_{c,2}, \gamma_1 \leftarrow \{0, 1\}^n$ .

4.  $P_3$ : On input  $(x, crs, \hat{\beta}_1, b''_2 \| r''_{c,2} \| \gamma_1)$ :

- Decide  $\delta_1$  and  $ans$ .
- Output  $a, b_1, \beta_1, \delta_1, ans$ .

5.  $V_3$ : On input  $(x, crs, \hat{\beta}_1, b''_2 \| r''_{c,2} \| \gamma_1, a \| b_1 \| \beta_1 \| \delta_1 \| ans)$ :

- Parse  $crs$  as  $f, crs', b'_2, r_{c,1}, r'_{c,2}, r'$ .
- Parse  $crs'$  as  $f^{TC}, g, \text{comm}$ .
- Check  $\hat{\beta}_1 = \text{comm}(\beta_1 \| (\text{comm}(a \| b_1 \| r_{c,1}) \oplus r'))$ .
- Check  $V_{Kil}(f \| a \| b_1, f^{TC}, \beta_1, \gamma_1, \delta_1) = 1$ .
- Check  $V_{Mic}^1(f \| a \| (b'_2 \oplus b''_2), crs', r'_{c,2} \oplus r''_{c,2}, ans) = 1$ .

In the second protocol, we have defined the strong-IMPERSONATOR, which is actually the adversary for  $(P_3, V_3)$ .

**Lemma 6.13.** If  $\exists \mathcal{G} \in \mathcal{C}$ ,  $\neg \exists \text{strong-IMPERSONATOR}$ , then there exists a function ensemble  $\mathcal{G} \in \mathcal{C}$  such that  $(P_3, V_3)$  is a 3-round public coin argument for empty language against adversary in  $\mathcal{C}$ .  $\diamond$

**Proof.** It is trivial, since  $(\neg(\forall \mathcal{G} \exists \text{strong-IMPERSONATOR}))$  is exact the soundness condition. Note that  $b'_2, r_c, r'_c, r'$  do not help in breaking the protocol.  $\square$

After the Fiat-Shamir transformation,  $(P_3^{FS}, V_3^{FS})$  is similar to a protocol that first runs  $(P_{Mic}^1, V_{Mic}^1)$  with  $\mathcal{H}$  for  $f \| a \| b_1$  and then runs  $(P_{Mic}^1, V_{Mic}^1)$  with  $\mathcal{G}$  for  $f \| a \| b_2$ . The IMPERSONATOR can break  $(P_{Mic}^2, V_{Mic}^2)$ , and we can use it to break two  $(P_{Mic}^1, V_{Mic}^1)$  with different hash functions.

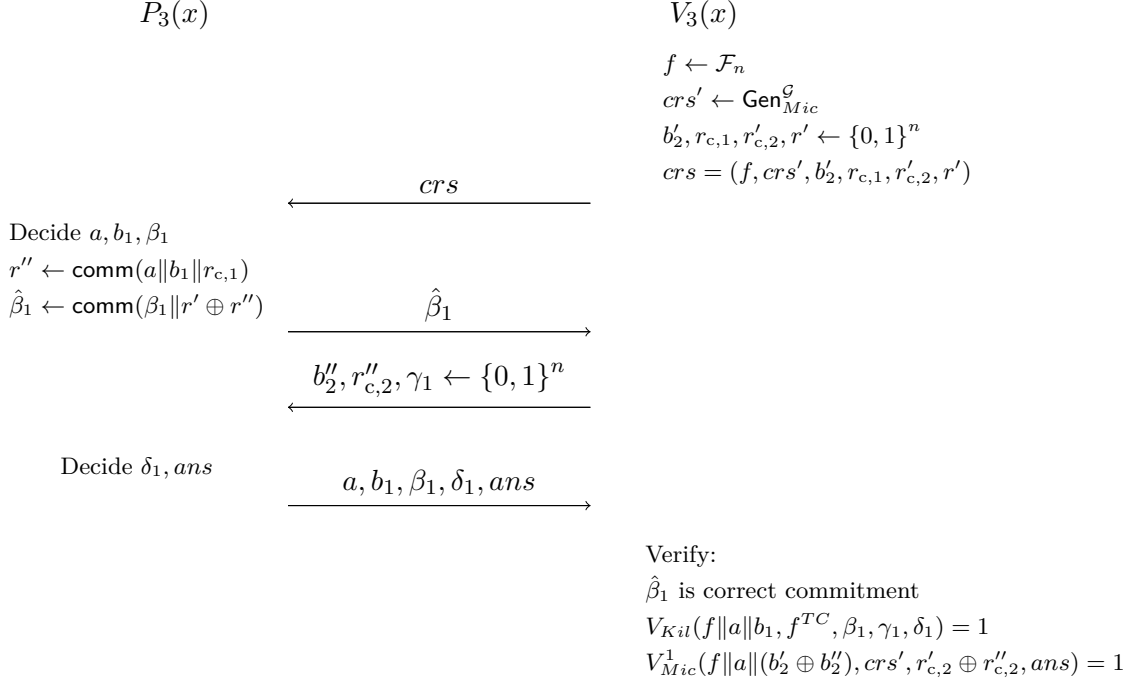


Figure 11: Protocol 3

**Lemma 6.14.** If  $\forall \mathcal{G}_1, \mathcal{G}_2 \in \mathcal{C}$ , there exists IMPERSONATOR, then for all function ensemble  $\mathcal{G}, \mathcal{HC}$ , applying the Fiat-Shamir transformation on  $(P_3, V_3)$  with respect to  $\mathcal{H}$  gives  $(P_3^{FS}, V_3^{FS})$  that is not a non-interactive public coin argument for empty language against  $\mathcal{C}$  adversary.  $\diamond$

**Proof.** For any  $\mathcal{H}$  and input  $x$ , let  $\mathcal{H}'$  be the function ensemble obtained by hard-coding  $x$  into input of all  $h \in \mathcal{H}$  and truncating all  $h \in \mathcal{H}$  to only output last  $n$  bits,  $\gamma_1$ .

By assumption, we know for  $\mathcal{H}', \mathcal{G}$ , there exists IMPERSONATOR, denoted as  $P^{IMP}$  and  $F^{IMP}$ . Without loss of generality, we assume that  $crs$  is included in  $aux$  where  $a, aux \leftarrow F^{IMP}(f, crs)$ .

**Claim 6.15.** From  $P^{IMP}, F^{IMP}$ , we can construct  $P_{\mathcal{H}'}^{IMP}$  and  $P_{\mathcal{G}}^{IMP}$  in  $\mathcal{C}$  with polynomial  $p(n)$ , that for infinite many  $n \in \mathbb{N}$ ,

$$\Pr \left[ \begin{array}{l} (P_{\mathcal{H}'}^{IMP}(aux), V_{Mic}^1|_{crs_1})(f \| a \| b_1) = 1 \wedge \\ (P_{\mathcal{G}}^{IMP}(aux), V_{Mic}^1|_{crs_2})(f \| a \| b_2) = 1 \end{array} \middle| \begin{array}{l} f \leftarrow \mathcal{F}_n \\ b_1, b_2 \leftarrow \{0, 1\}^n \\ crs \leftarrow \text{Gen}_{Mic}^{\mathcal{H}', \mathcal{G}} \\ a, aux \leftarrow F^{IMP}(f, crs) \end{array} \right] > 1/p(n),$$

Here,  $crs_1, crs_2$  are the modified  $crs = (f^{TC}, h', g, \text{comm})$  that  $g$  is removed and  $h'$  is removed respectively.  $\diamond$

**Proof.** We show the construction of  $P_{\mathcal{H}'}^{IMP}$  below,  $P_{\mathcal{G}}^{IMP}$  can be constructed similarly:

On input  $(aux, f \| a \| b, crs_1, r_c)$ :

1. Get  $crs$  from  $aux$ .
2. Parse  $crs$  as  $f^{TC}, h', g, \text{comm}$ .



3. Emulate

$$(crs, r_c, (\hat{\beta}, \beta, \gamma_1, \gamma_2, \delta_1, \delta_2)) \leftarrow (P^{IMP}, V_{Mic}^2|_{crs, r_c})(f\|a\|b)$$

4. Output  $ans = (\beta, \hat{\beta}, \gamma_1, \delta_1)$ .

From the definition of  $P^{IMP}, F^{IMP}$ , we know there exists a polynomial  $q(n)$ , with non-negligible probability over choice of  $f, crs$  and  $a, aux \leftarrow F(f, crs)$ ,

$$\Pr[(P^{IMP}(aux), V_{Mic}^2|_{crs})(f\|a\|b) = 1 \mid b \leftarrow \{0, 1\}^n] > \frac{1}{q(n)}.$$

From the construction above, we know with non-negligible probability over the choice of  $f, crs$  and  $a, aux$ ,

$$\begin{aligned} & \Pr \left[ \begin{array}{l} (P_{\mathcal{H}'}^{IMP}(aux), V_{Mic}^1|_{crs_1})(f\|a\|b_1) = 1) \wedge \\ (P_{\mathcal{G}}^{IMP}(aux), V_{Mic}^1|_{crs_2})(f\|a\|b_2) = 1) \end{array} \mid b_1, b_2 \leftarrow \{0, 1\}^n \right] \\ &= \Pr[(P^{IMP}(aux), V_{Mic}^2|_{crs})(f\|a\|b) = 1 \mid b \leftarrow \{0, 1\}^n]^2 \\ &\geq \frac{1}{q^2(n)}, \end{aligned}$$

which proves the claim.  $\square$

Here, we use  $P_{\mathcal{H}'}^{IMP}, P_{\mathcal{G}}^{IMP}, F^{IMP}$  to construct an adversary  $P^*$  for  $(P_3^{FS}, V_3^{FS})$  as below:

On input  $(x, h\|crs)$ :

1. Parse  $crs$  as  $f, crs', b'_2, r_{c,1}, r'_{c,2}, r'$ .
2. Parse  $crs'$  as  $f^{TC}, g, \text{comm}$ .
3. Compute  $a, aux \leftarrow F^{IMP}(f, crs')$ .
4. Compute  $b_1 \leftarrow \{0, 1\}^n$  and  $r'' \leftarrow \text{comm}(a\|b_1\|r_{c,1})$ .
5. Let  $h'$  be the corresponding function of  $h$  in  $\mathcal{H}'$ , and emulate

$$(f^{TC}\|h'\|\text{comm}, r' \oplus r'', (\beta_1, \hat{\beta}_1, \gamma, \delta)) \leftarrow (P_{\mathcal{H}'}^{IMP}(aux), V_{Mic}^1|_{f^{TC}\|h'\|\text{comm}, r' \oplus r''})(f\|a\|b_1)$$

6. Compute  $b'_2, r''_{c,2}, \gamma_1 \leftarrow h(x\|\hat{\beta}_1)$  and  $b_2 = b'_2 \oplus b''_2$ .
7. Emulate

$$(f^{TC}\|g\|\text{comm}, r'_{c,2} \oplus r''_{c,2}, ans) \leftarrow (P_{\mathcal{G}}^{IMP}(aux), V_{Mic}^1|_{f^{TC}\|g\|\text{comm}, r'_{c,2} \oplus r''_{c,2}})(f\|a\|b_2)$$

8. Output  $\hat{\beta}_1, (a, b_1, \beta_1, \delta_1, ans)$ .

**Claim 6.16.** There exists a polynomial  $p(n)$ , that for infinite many  $n$ , for all  $x \in \{0, 1\}^n$ ,

$$\Pr[(P^*, V_3)(x) = 1] \geq \frac{1}{p(n)},$$

where the probability is over  $P^*$  and  $V_3$ .  $\diamond$

**Proof.** According to claim 6.15, we know for infinite many  $n \in \mathbb{N}$ ,

$$\Pr \left[ \begin{array}{l} (P_{\mathcal{H}'}^{IMP}(aux), V_{Mic}^1|_{crs_1})(f\|a\|b_1) = 1 \wedge \\ (P_{\mathcal{G}}^{IMP}(aux), V_{Mic}^1|_{crs_2})(f\|a\|b_2) = 1 \end{array} \middle| \begin{array}{l} f \leftarrow \mathcal{F}_n, b_1, b_2 \leftarrow \{0, 1\}^n \\ crs \leftarrow \text{Gen}_{Mic}^{\mathcal{H}', \mathcal{G}} \\ a, aux \leftarrow F^{IMP}(f, crs) \end{array} \right] > 1/p(n).$$

Now we claim similarly that for infinite many  $n$ , for all  $x \in \{0, 1\}^n$ ,

$$\Pr \left[ \begin{array}{l} (P_{\mathcal{H}'}^{IMP}(aux), V_{Mic}^1|_{crs_1, r' \oplus r''})(f\|a\|b_1) = 1 \wedge \\ (P_{\mathcal{G}}^{IMP}(aux), V_{Mic}^1|_{crs_2, r'_c \oplus r''_c})(f\|a\|b'_2 \oplus b''_2) = 1 \end{array} \middle| \begin{array}{l} crs = (f, crs', b'_2, r_{c,1}, r'_{c,2}, r') \leftarrow V_3 \\ a, aux \leftarrow F^{IMP}(f, crs') \\ r''_{c,2}, b''_2 \leftarrow P^*(x, crs) \end{array} \right] > 1/p(n),$$

which is because  $b'_2, r'_{c,2}, r'$  is selected uniformly and independently in  $\{0, 1\}^n$ . Here,  $crs_1, crs_2$  is the CRS that  $g$  is removed from  $crs'$  and  $h'$  is removed from  $crs'$  respectively. As a result, with non-negligible probability over interaction  $(P^*, V_3)(x)$ , the verifier accepts because the following conditions hold:

- $V_{Mic}^1(f\|a\|b_1, crs_1, r' \oplus r'', ans_1)$  accepts, which indicates:
  - $(*, *, \gamma_1) = h(x\|\hat{\beta}_1)$ .
  - $V_{Kil}(f^{TC}, \beta_1, \gamma_1, \delta_1)$  accepts.
  - $\hat{\beta}_1 = \text{comm}(\beta_1\|(\text{comm}(a\|b_1\|r_{c,1}) \oplus r'))$
- $V_{Mic}^1(f\|a\|(b'_2 \oplus b''_2), crs_2, r'_c \oplus r''_c, ans_2)$  accepts. □

Finally, we conclude that one of these three protocols is the required protocol in Theorem 6.1. There are three cases:

1. If  $\exists \mathcal{G}_1, \mathcal{G}_2 \in \mathcal{C}$  that  $\neg \exists \text{IMPERSONATOR}$ , then
  - $(P_1, V_1)$  is a 3-round public coin argument for empty language in  $\mathcal{C}$  secure against any adversary in  $\mathcal{C}$ .
  - Applying the Fiat-Shamir transformation on  $(P_1, V_1)$  with any  $\mathcal{H} \in \mathcal{C}$  results in a protocol  $(P_1^{FS}, V_1^{FS})$  that is insecure against some adversary in  $\mathcal{C}$ .
2. If  $\forall \mathcal{G} \in \mathcal{C}$  that  $\exists \text{strong-IMPERSONATOR}$ , then
  - $(P_2, V_2)$  is a 3-round public coin argument for empty language in  $\mathcal{C}$  secure against any adversary in  $\mathcal{C}$ .
  - Applying the Fiat-Shamir transformation on  $(P_2, V_2)$  with any  $\mathcal{H} \in \mathcal{C}$  results in a protocol  $(P_2^{FS}, V_2^{FS})$  that is insecure against some adversary in  $\mathcal{C}$ .
3. If  $\exists \mathcal{G} \in \mathcal{C}$  that  $\neg \exists \text{strong-IMPERSONATOR}$  and  $\forall \mathcal{G}_1, \mathcal{G}_2 \in \mathcal{C}$  that  $\exists \text{IMPERSONATOR}$ , then with respect to this  $\mathcal{G}$ ,
  - $(P_3, V_3)$  is a 3-round public coin argument for empty language in  $\mathcal{C}$  secure against any adversary in  $\mathcal{C}$ .
  - Applying the Fiat-Shamir transformation on  $(P_3, V_3)$  with any  $\mathcal{H} \in \mathcal{C}$  results in a protocol  $(P_3^{FS}, V_3^{FS})$  that is insecure against some adversary in  $\mathcal{C}$ .

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## A Detailed Proofs of Almost-Everywhere Security

To begin with, we state several properties of ZeroSamp and OneSamp that is implicit in [IK00] or [AIK06].

**Lemma A.1.** For any function family  $\{f_\lambda\} \in \oplus L/\text{poly}$ , there exists a randomized circuit family  $\{\mathcal{F}_\lambda\} \in \text{AC}^0[2]$  and a polynomial  $n = n(\lambda)$  such that for any  $x \in \{0, 1\}^\lambda$ ,

- $\{\mathcal{F}_\lambda(x)\} \equiv \text{ZeroSamp}(n(\lambda))$ , if  $f_\lambda(x) = 0$ ;
- $\{\mathcal{F}_\lambda(x)\} \equiv \text{OneSamp}(n(\lambda))$ , if  $f_\lambda(x) = 1$ . ◇

**Lemma A.2.** The following statements about matrix  $A \in \mathbb{Z}_2^{n \times n}$  are equivalent, and they are still equivalent if all get modified by the texts in brackets:

- $A$  is the output of ZeroSamp (OneSamp) using any randomness.
- $A$  is in the form of

$$\begin{pmatrix} a_{1,1} & a_{1,2} & a_{1,3} & \cdots & a_{1,n-1} & a_{1,n} \\ 1 & a_{2,2} & a_{2,3} & \cdots & a_{2,n-1} & a_{2,n} \\ & 1 & a_{3,3} & \cdots & a_{3,n-1} & a_{3,n} \\ & & 1 & \cdots & a_{4,n-1} & a_{4,n} \\ & & & \ddots & \vdots & \vdots \\ & & & & 1 & a_{n,n} \end{pmatrix},$$

and  $\det A = 0$  ( $\det A = 1$ ).

- The two distributions are equivalent:

$$\begin{aligned} & \{L(r^{(1)})AR(r^{(2)}) : r^{(1)} \leftarrow \{0, 1\}^*, r^{(2)} \leftarrow \{0, 1\}^*\} \equiv \text{ZeroSamp}(n) \\ & \left( \{L(r^{(1)})AR(r^{(2)}) : r^{(1)} \leftarrow \{0, 1\}^*, r^{(2)} \leftarrow \{0, 1\}^*\} \equiv \text{OneSamp}(n) \right). \end{aligned} \quad \diamond$$

With all these properties, we restate lemma 4.3 of [DVV16] after extending the adversary class.



**Lemma A.3 (Minor extension of lemma 4.3 of [DVB16]).** For any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , assuming Assumption 4.8 holds for  $\mathcal{C}$ , there is a polynomial  $n = n(\lambda)$  and a negligible function  $\text{negl}(\cdot)$  such that for any family  $\mathcal{F} = \{f_\lambda\}$  in  $\mathcal{C}$ , for infinitely many  $\lambda$ ,

$$\left| \Pr_{M \leftarrow \text{ZeroSamp}(n(\lambda))} [f_\lambda(M) = 1] - \Pr_{M \leftarrow \text{OneSamp}(n(\lambda))} [f_\lambda(M) = 1] \right| < \text{negl}(\lambda). \quad \diamond$$

The difference between this lemma and lemma 4.10 is the existence of the polynomial  $n = n(\lambda)$ . In fact this lemma trivially implies lemma 4.10, as for any infinitely long sequence  $\lambda_1, \lambda_2, \dots \in \mathbb{N}$ ,  $n(\lambda_1), n(\lambda_2), \dots$  is also an infinitely long sequence.

**Proof.** The idea is by lemma A.1, any circuit that distinguishes **ZeroSamp** and **OneSamp** can be used to compute any language in  $\oplus \text{L/poly}$ .

Assume for any polynomial  $n = n(\lambda)$ , there exists a constant  $d > 0$  and an adversary  $\mathcal{A} = \{\mathcal{A}_\lambda\} \in \mathcal{C}$  s.t. for all but finitely many  $\lambda$ ,  $\mathcal{A}_\lambda$  distinguishes **ZeroSamp**( $n(\lambda)$ ) and **OneSamp**( $n(\lambda)$ ) by probability  $\lambda^{-d}$ . By lemma A.1, we can directly link the output of the circuit  $\mathcal{F}_\lambda$  (that computes **ZeroSamp** or **OneSamp**) to  $\mathcal{A}_\lambda$  to compute any language in  $\oplus \text{L/poly}$ . As  $\Pr[\mathcal{A}_\lambda(\mathcal{F}_\lambda(x)) = 1 | f(x) = 0]$  and  $\Pr[\mathcal{A}_\lambda(\mathcal{F}_\lambda(x)) = 1 | f(x) = 1]$  only differs by  $\lambda^{-d}$ , we need to do error reduction to enlarge this gap to  $1 - \text{poly}(\lambda)^{-1}$ .

Let  $p = \Pr[\mathcal{A}_\lambda(\text{ZeroSamp}) = 1]$  and  $q = \Pr[\mathcal{A}_\lambda(\text{OneSamp}) = 1]$ , then the error reduction is done by taking many samples and checking whether  $\mathcal{A}_\lambda$  outputs 1 on more than  $\frac{p+q}{2}$  of the samples. If  $\mathcal{C}$  can compute majority function, then the entire reduction is done in  $\mathcal{C}$ ; otherwise, for any  $c > 0$ , we can complete the reduction in  $\text{Sum}_{1/\lambda^c} \circ \mathcal{C}$ , as taking polynomially many samples allows us to approximate  $\Pr[\mathcal{A}_\lambda(\mathcal{F}_\lambda) = 1]$  by error  $\lambda^{-c}$  with exponentially small failure probability for any  $c > 0$ .  $\square$

Although we can prove almost everywhere security under the strengthened assumption 4.11, we cannot get rid of the polynomial  $n = n(\lambda)$  by directly using the same proof idea.

**Lemma A.4.** For any circuit class  $\mathcal{C} \supseteq \text{AC}^0[2]$ , assuming Assumption 4.11 holds for  $\mathcal{C}$ , there is a polynomial  $n = n(\lambda)$  and a negligible function  $\text{negl}(\cdot)$  such that for any family  $\mathcal{F} = \{f_\lambda\}$  in  $\mathcal{C}$ , for all but infinitely many  $\lambda$ ,

$$\left| \Pr_{M \leftarrow \text{ZeroSamp}(n(\lambda))} [f_\lambda(M) = 1] - \Pr_{M \leftarrow \text{OneSamp}(n(\lambda))} [f_\lambda(M) = 1] \right| < \text{negl}(\lambda). \quad \diamond$$

In order to get rid of the polynomial  $n = n(\lambda)$ , we use a simple observation that for any  $n' > n$  and any circuit that distinguishes **ZeroSamp**( $n'$ ) and **OneSamp**( $n'$ ), we can use the same circuit to distinguish **ZeroSamp**( $n$ ) and **OneSamp**( $n$ ).

**Lemma A.5.** There exists a constant  $c$ , such that for any  $n' > n$  and circuit  $C'$  with circuit size  $s$  and depth  $d$  that distinguishes **ZeroSamp**( $n'$ ) and **OneSamp**( $n'$ ) by some probability, there exists a circuit  $C$  that distinguishes **ZeroSamp**( $n$ ) and **OneSamp**( $n$ ) with the same probability, with circuit size at most  $cs$  and depth at most  $cd$ .  $\diamond$

**Proof.** For any matrix  $M \in \mathbb{Z}_2^{n \times n}$  obtained from  $\text{ZeroSamp}(n)$  (or  $\text{OneSamp}(n)$ ), we define

$$M' = \begin{bmatrix} & & 0 & 0 & \cdots & 0 & 0 \\ & M & 0 & 0 & \cdots & 0 & 0 \\ & & 0 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix} \implies \det M' = \det M.$$

Therefore, by lemma A.2, since  $M'$  has the correct form and  $\det M' = \det M$ ,  $M'$  is also an output of  $\text{ZeroSamp}(n')$  (or  $\text{OneSamp}(n')$ ); furthermore, by the same lemma, take  $r^{(1)} \leftarrow \{0, 1\}^*$ ,  $r^{(2)} \leftarrow \{0, 1\}^*$ , the distribution of  $\{L(r^{(1)})M'R(r^{(2)})\}$  is exactly  $\text{ZeroSamp}(n')$  (or  $\text{OneSamp}(n')$ ).

The circuit  $C$  is constructed by expanding  $M$  to  $M'$  and computing  $L(r^{(1)})M'R(r^{(2)})$  before invoking  $C'$ . The overhead is minor.  $\square$

**Proof of lemma 4.12.** If we have an adversary  $\{\mathcal{A}_n\} \in \mathcal{C}$  that distinguishes  $\text{ZeroSamp}$  and  $\text{OneSamp}$  with non-negligible probability for infinitely many  $n$ , then for any polynomial  $p(n)$ , we can construct  $\{\mathcal{B}_n\} \in \mathcal{C}$  to break lemma A.4, i.e.  $\exists$  a polynomial  $q(n)$ , for infinitely many  $n$ ,

$$\left| \Pr_{M \leftarrow \text{ZeroSamp}(p(n))} [\mathcal{B}_n(M) = 1] - \Pr_{M \leftarrow \text{OneSamp}(p(n))} [\mathcal{B}_n(M) = 1] \right| > \frac{1}{q(n)}.$$

By lemma A.5, if  $\{\mathcal{A}_n\}$  distinguishes  $\text{ZeroSamp}$  and  $\text{OneSamp}$  for  $\{n_i\}_{i \in \mathbb{N}}$ , we construct  $\{\mathcal{B}_n\}$  as:

- If  $n = \max\{n : p(n) \leq n_i\}$  for some  $i$ ,  $\mathcal{B}_n$  is the distinguisher constructed from  $\mathcal{A}_{n_i}$ .
- Otherwise,  $\mathcal{B}_n$  outputs 0.

Then  $\{\mathcal{B}_n\} \in \mathcal{C}$  and we can easily see that for all  $n = \max\{n : p(n) \leq n_i\}$ ,  $\mathcal{B}_n$  succeeds by non-negligible probability.  $\square$

## B Low Complexity CRHF

We propose candidates for collision resistant hash functions with arbitrary polynomial shrinkage computable in  $\text{AC}^0[c]$  for some constant  $c \geq 2$  against p.p.t. adversaries.

**Definition B.1 (SIS $^\infty$ ).** For any  $n, m, q, B \in \mathbb{N}^+$ ,  $q \geq 4$  define the short integer solution problem  $\text{SIS}_{n,m,q,B}^\infty$  as follows: Given  $\mathbf{A} \in \mathbb{Z}_q^{n \times m}$ , find a non-zero vector  $\mathbf{x} \in \{-B, -B+1, \dots, B-1, B\}^m$  such that

$$\mathbf{A}\mathbf{x} = \mathbf{0} \bmod q.$$

We are mostly interested in the case where  $B = 1$  and  $q = 2^k$  for some constant  $k \geq 2$ . When  $q = 2^k$  for some constant  $k \geq 2$ , the function  $f : \{0, 1\}^m \rightarrow \mathbb{Z}_q^n, \mathbf{x} \mapsto \mathbf{A} \cdot \mathbf{x} \bmod q$  is computable in  $\text{AC}^0[2]$ . Note that when  $m \geq (n+1)^k$ , there is a polynomial time classical algorithm that solves  $\text{SIS}_{n,m,2^k,1}^\infty$ , see [CLZ22, Appendix]. However, when  $m < n^k$ , we do not know any polynomial time algorithm.

In fact, as long as for some constant  $\delta > 0$ , for some constant  $k \geq 2$ ,  $\text{SIS}_{n,n^{1+\delta},2^k,1}^\infty$  is hard, then there exists CRHFs with arbitrary polynomial shrinkage computable in  $\text{AC}^0[2]$ , by stacking constant levels of CRHFs with compression rates of  $n^{1+\delta}$  to  $n$ .

Our conjecture is

**Conjecture B.2.** For any constant  $\varepsilon \in (0, 0.99)$ , for any  $4 \leq q \in O(1)$ , for any  $n, m \in \mathbb{N}^+$  such that  $m \in O(n^{1+\varepsilon})$ . There is no  $\text{poly}(n)$  time algorithm that solves  $\text{SIS}_{n,m,q,1}^\infty$ .  $\diamond$

Note that if Conj. B.2 is true, then we have a CRHF family with arbitrary polynomial compression computable in  $\text{AC}^0[q]$ . The best classical and quantum algorithms against Conj. B.2 requires  $m$  to be at least in  $O(n^2)$  [KOW25].

Let us remark that the hardness of the variant of  $\text{SIS}_{n,m,q,1}^\infty$  in Conjecture B.2 is not known to be as hard as worst-case lattice problems, as opposed to the “standard SIS” problem (cf. Def 4.1) where the solution is bounded in its  $\ell_2$  norm, for which we know worst-case to average case reductions [Ajt96; MR07; MP13]. We recall the precise statement from [MP13].

**Lemma B.3 (Theorem 3.8 of [MP13]).** Let  $n, m \in \mathbb{N}^+$ ,  $S = \{\mathbf{z} \in \mathbb{Z}^m \setminus \{\mathbf{0}\} \mid \|\mathbf{z}\| < \beta \wedge \|\mathbf{z}\|_\infty < \beta_\infty\}$  for some real  $\beta \geq \beta_\infty > 0$ , and  $q \geq \beta \cdot n^{\Omega(1)}$  be an integer modulus with at most  $\text{poly}(n)$  integer divisors less than  $\beta_\infty$ . Then for some  $\gamma = \max\{1, \beta\beta_\infty/q\} \cdot O(\beta\sqrt{n})$ , there is an efficient quantum reduction from  $\text{SIVP}_{\gamma\omega_n}$  on  $n$ -dimensional lattices to solving  $\text{SIS}_{n,m,q}$  within set  $S$  with non-negligible probability.  $\diamond$

We observe that to apply Lemma B.3, we must use  $q \geq \sqrt{n}$ , but then we do not know how to compute the SIS function in  $\text{AC}^0[c]$  for any constant  $c$ .

Although the variant of SIS mentioned in Conj. B.2 does not have a worst-case to average-case reduction, its hardness is still studied in the literature, see [CLZ22; KOW25] for details. Also, SIS with those parameters are related to practical post-quantum signatures like Dilithium. So those parameters have been considered by the cryptography community, although not well-studied compared to the standard SIS.

## C $\text{AC}^0[2]$ -computable, $\text{AC}^0[2]$ -proof-of-knowledge, and $\text{AC}^0[2]$ -reverse-samplable PCP

In this section, we give a short sketch of how the PCP proof system in Theorem 6.5 is constructed. We begin by recalling the theorem.

**Theorem 6.5.** For the central relation  $\mathcal{R}$ , there exists a PCP system  $(P_{pcp}, V_{pcp})$  where  $V_{pcp}$  is a probabilistic verifier for  $\mathcal{R}$  with randomness complexity  $\text{polylog}(n)$  and query complexity  $\text{polylog}(n)$ . This system satisfies:

- **Completeness:** For all  $(x, w) \in \mathcal{R}$ ,

$$\Pr[V_{pcp}^\pi(x) = 1 \mid \pi \leftarrow P_{pcp}(x, w)] = 1.$$

Note that here  $|w|$  might be super-polynomial in  $|x|$ .

- **Soundness:** For all  $x$  such that there does not exist  $w$  satisfying  $(x, w) \in \mathcal{R}$ , for any proof  $\pi^*$ ,

$$\Pr[V_{pcp}^{\pi^*}(x) = 1] < \frac{1}{2},$$

where the randomness is over the internal randomness of  $V_{pcp}$ .

- **AC<sup>0</sup>[2]-oracle-construction:**  $P_{pcp}$  is an AC<sup>0</sup>[2] circuit, i.e., the oracle  $\pi$  can be constructed in AC<sup>0</sup>[2] given the input  $x$  and the witness  $w$ .
- **AC<sup>0</sup>[2]-proof-of-knowledge:** There exists an extractor  $E_{pcp}$  in AC<sup>0</sup>[2] such that for any input  $x$  and proof  $\tilde{\pi}$  if

$$\Pr[V_{pcp}^{\tilde{\pi}}(x) = 1] \geq 1 - \frac{1}{\log^5 n},$$

then there exists a witness  $w$  satisfying  $\mathcal{R}(x, w) = 1$  such that for any  $1 \leq i \leq |w|$ ,

$$\Pr[E_{pcp}^{\tilde{\pi}}(x, i) = w_i] \geq \frac{2}{3}.$$

- **AC<sup>0</sup>[2]-samplable:**  $Q_{pcp}$  is an AC<sup>0</sup>[2] circuit, i.e., the queries made by  $V_{pcp}$  can be sampled in AC<sup>0</sup>[2].
- **AC<sup>0</sup>[2]-reverse-samplable:** Suppose that  $\text{Rand}_V(x, i, j)$  is the set of *internal randomness* of  $V_{pcp}$  such that the  $i$ -th query to the proof  $\pi$  is at position  $j$  when given the input  $i$  (i.e., the set of  $r$  such that the  $i$ -th output of  $Q_{pcp}(x, r)$  is  $j$ ). There is an AC<sup>0</sup>[2] circuit  $S_{pcp}$  such that, given any input  $x, i, j$  and some randomness  $r \in \{0, 1\}^{\text{polylog}(n)}$ , output some internal random strings for  $V_{pcp}$ , such that the distribution  $\{S_{pcp}(x, i, j, r) \mid r\}$  is the uniform distribution over  $\text{Rand}_V(x, i, j)$ .  $\diamond$

Our PCP system is identical to the canonical, smooth, strong, and AC<sup>0</sup>[2]-locally decodable construction in [CWY23], which is based on the work by Paradise [Par21] with the size of the underlying field  $\mathbb{F}$  for the low-degree extension being  $2^{2 \cdot 3^\ell}$ . Since  $\text{polylog}(n)$  query complexity is enough for our use, we only need one copy of the Reed-Muller-based PCP, without any composition. Indeed, one may easily check that their PCP also has the other properties we mentioned here (prover and verifier implementable by AC<sup>0</sup>[2] circuits of  $\text{poly}(n)$  size and reverse samplability).

Below, we give a brief sketch of why the prover can be implemented in AC<sup>0</sup>[2] and the reverse samplability in AC<sup>0</sup>[2], assuming the familiarity of [CWY23]. In their terminology, we show that if the good predicate  $V(x, y)$  (which is  $\mathcal{R}$  in our paper) is an AC<sup>0</sup>[2] circuit, then the canonical mapping  $\Pi_V$  (which is  $P_{pcp}$  in our paper) can also be computed by an AC<sup>0</sup>[2] circuit. We will then briefly mention why the verifier is in AC<sup>0</sup>[2] and its queries are reverse samplable in AC<sup>0</sup>[2]. Note that AC<sup>0</sup>[2]-proof-of-knowledge follows directly from strongness and AC<sup>0</sup>[2]-local-decodability. So we only show that there is a prover in AC<sup>0</sup>[2] outputting the PCP proof  $\pi$  given a witness  $w$  to the original relation  $\mathcal{R}$ .

**Proof sketch of Theorem 6.5** Suppose that the relation  $\mathcal{R}$  is computable by an AC<sup>0</sup>[2] circuit of wire complexity  $s$ .

**The prover** We begin by showing that the prover (the canonical mapping  $\Pi_V$ ) can be computed by an AC<sup>0</sup>[2] circuit.

Our first step is to convert the relation  $\mathcal{R}$  by a 3-CNF formula  $\varphi(x, w')$  of size  $O(s)$ , such that for each  $x \in \{0, 1\}^n$ ,

$$\exists w, (x, w) \in \mathcal{R} \iff \exists w', \varphi(x, w'),$$

where a satisfying  $w'$  can be computed by AC<sup>0</sup>[2] circuits given  $x$  and  $w$  where  $(x, w) \in \mathcal{R}$ .

For P/poly circuits, this is the standard reduction from CktSAT to 3SAT, but we need to be very careful for  $\text{AC}^0[2]$  circuits to ensure that  $w'$  can be computed in  $\text{AC}^0[2]$ . To do so, we define  $\ell$  new variables for each gate of fan-in  $\ell$ . Suppose, without loss of generality, that the gate is  $H(g_1, \dots, g_\ell) = g_1 \wedge g_2 \wedge \dots \wedge g_\ell$ , where  $g_1, \dots, g_\ell$  are outputs of lower gates (with possible negations). Then we define

$$v_i = \bigwedge_{j=1}^i g_j.$$

Then the 3-CNF contains clauses that describe  $v_1 = g_1$  and  $v_i = v_{i-1} \wedge g_i$ . We then use  $v_\ell$  as the output as the gate  $H$  for further uses. Note that for  $H$  being an  $\oplus$  gate, we can still use a constant number of clauses to describe  $v_i = v_{i-1} \oplus g_i$ . In addition, we have a clause asserting that the output gate of the circuit  $\mathcal{R}$  evaluates to 1. This results in a 3-CNF of size  $O(s)$ .

We still need to show that each  $v_i$  can be computed in  $\text{AC}^0[2]$ . This is true since we can evaluate each  $v_i$  by a single gate given  $g_1, \dots, g_\ell$ . For example, if  $H$  is an  $\wedge$ -gate, then  $v_i = g_1 \wedge g_2 \wedge \dots \wedge g_i$ , which is a single  $\wedge$ -gate. Since the original circuit for  $\mathcal{R}$  is of constant depth, we can also compute each  $v_i$  in  $\text{AC}^0[2]$ .

We then show that the canonical proof of the PCP in [CWY23] is computable in  $\text{AC}^0[2]$  if the predicate is a 3-CNF. Recall that we only do a PCP based on the Reed-Muller code. Here, the proof  $\pi$  is constructed by first computing an low-degree extension of  $w$  over a field  $\mathbb{F}$  with  $|\mathbb{F}| = 2^{2 \cdot 3^\ell}$  for some  $\ell \in \mathbb{N}$  and  $|\mathbb{F}| \leq \text{polylog}(s)$ , then encoding each value in the field  $\mathbb{F}$  by a Boolean string of length  $b = O(\log|\mathbb{F}|)$  by a constant-rate error-correcting code. The latter ECC can be easily computed by  $\text{AC}^0[2]$  circuits since  $b = O(\log \log s)$ , so the ECC encoding can be implemented by a look-up table of size  $2^b = \text{polylog}(s)$ .

We now describe the low-degree extension in more details. Suppose, w.l.o.g., that  $|w| = s$ . Let  $m = \lceil \log s / \log \log s \rceil$ , and  $h$  be the smallest power of 2 such that  $h^m \geq s$ .<sup>7</sup>

We view the string  $w$  as a function  $[h]^m \rightarrow \{0, 1\}$  (we pad the string  $w$  with 0 when necessary). Then we identify  $[h]$  with  $h$  distinct elements in  $\mathbb{F}$  such that the 0 and 1 in  $[h]$  are mapped to the 0 and 1 in  $\mathbb{F}$ , so  $w$  can be viewed as a partial function from  $\mathbb{F}^m$  to  $\mathbb{F}$ . We then compute the unique polynomial  $\hat{A} : \mathbb{F}^m \rightarrow \mathbb{F}$  with degree at most  $h - 1$  in each variable, which agrees with  $w$  on all inputs from  $[h]^m$ . We will output (the ECC encoding of) the truth table of  $\hat{A}$  as the proof  $\pi$ , which is  $\hat{A}(x)$  for all  $x \in \mathbb{F}^m$ .

The translation of  $w$  to the function  $[h]^m \rightarrow \{0, 1\}$  can be easily done in  $\text{AC}^0[2]$  given  $h$  as a power of 2. We can also translate easily this into  $\mathbb{F}^m$  since the mapping from  $[h]$  to  $\mathbb{F}$  can be arbitrary. The only hard part is the low-degree extension, where we need to evaluate a multi-variate polynomial interpolation. Fortunately, the points given are the product set  $[h]^m$ , so we can use the Lagrange interpolation on each variable respectively. In particular, suppose that  $[h]$  is mapped to  $a_0, a_1, \dots, a_{h-1}$  in  $\mathbb{F}$  respectively, and by viewing  $w$  as a function  $[h]^m \rightarrow \{0, 1\}$ ,  $w(y)$  is the function value of  $y \in [h]^m$ , then

$$\hat{A}(x) = \sum_{y \in [h]^m} w(y) \prod_{i=1}^m \prod_{j \in [h], j \neq y_i} \frac{x_i - a_j}{a_{y_i} - a_j}. \quad \square$$

The denominator does not depend on  $x$ , so it can be hardwired into the circuit. Each enumerator is an iterated multiplication of  $m \cdot (h - 1) \leq \text{polylog}(s)$  terms, so it can be computed in  $\text{AC}^0[2]$  of  $\text{poly}(s)$  size by [HV06]. So the polynomial  $\hat{A}(x)$  can be evaluated by  $\text{AC}^0[2]$  circuits.

<sup>7</sup>Here we modify the construction in [CWY23] a little bit by taking  $h$  to be a power of 2. This is to ensure that any integer in  $[s]$  can be easily encoded into  $[h]^m$ . This will not change the complexity too much since  $h^m \leq 2^m \cdot s \leq s^2$ .

**The verifier** We now turn to the verifier. Again, we focus on the PCP based on low-degree extension.

Recall that in the [Par21] PCP, the verifier non-adaptively queries different parts of the proof oracle on a few random lines over the field  $\mathbb{F}^m$ . Hence, locations being queried are independent of the relation  $\mathcal{R}$ , and can be easily computed by an  $\text{AC}^0[2]$  circuit of  $\text{polylog}(s)$  size given the randomness of the verifier. To sample the internal randomness for the  $i$ -th query on the line  $a + x \cdot b$ , where  $a, b \in \mathbb{F}^m$  are the offset and slope of the line and  $x \in \mathbb{F}$ , we only need to sample  $a$  and  $b$  such that  $a + i \cdot b$  is equal to some specific outcome. This can be done in  $\text{AC}^0[2]$  with our  $\mathbb{F}$ .