

SNARGs for NP via Fiat–Shamir in the Plain Model

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Abstract

We consider constructions of succinct non-interactive arguments (SNARGs) for NP in the standard model. Specifically, we revisit the seminal Micali transformation (applying Fiat–Shamir to Kilian’s protocol), which has traditionally only been analyzed in the random oracle model.

We show that the Micali framework can be successfully instantiated in the standard model by leveraging a new interaction between two primitives: a PCP satisfying a property we term *shadow soundness*, and a vector commitment scheme satisfying *function statistical binding*.

We prove a general theorem stating that any language admitting a suitable shadow PCP combined with a compatible vector commitment yields a secure SNARG. We instantiate this paradigm using sub-exponential indistinguishability obfuscation (iO) and sub-exponential learning with error (LWE) to obtain a SNARG for all of NP.

Our result serves as the first concrete validation of the Micali blueprint, and in particular of the Fiat–Shamir transformation, in the standard model. As a corollary, we refute “universal” attacks on the Micali framework by demonstrating that there exist concrete instantiations of the underlying components for which the transformation is sound.

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1 Introduction

Succinct non-interactive arguments (SNARGs) for NP [Mic00] constitute a fundamental primitive in modern cryptography. They allow a prover to convince a verifier of the validity of a statement with a proof whose size is significantly smaller than the time required to verify the statement directly, and ideally, much smaller than the witness itself. This “non-interactive” feature is particularly crucial for real-world applications, enabling scenarios such as delegating computation to untrusted servers, scaling blockchains via rollups, and constructing privacy-preserving cryptocurrencies.

Building on the seminal work of Kilian [Kil92], Micali [Mic00] provided the first construction of a SNARG for NP in the random oracle model (ROM). Since then, there has been tremendous progress in the design of efficient SNARGs. However, the vast majority of efficient constructions are proven secure only within idealized models. Some of these works rely solely on the random oracle model or the generic group model (GGM) to establish security (e.g., [Gro16; BCS16; CY21a; CY21b; ACY23; AHIV17; BBHR18; ZCF24; ACFY24; ACFY25]). Others rely on the random oracle model in addition to other specific cryptographic assumptions (e.g., [BBBPWM18; AGLMS23; AFLN24; BC25]). While these models provide a heuristic rationale for security, they do not guarantee security in the standard model, where the hash function or group is instantiated with concrete algorithms.

A parallel line of work has constructed SNARGs for NP in the common reference string (CRS) model based on various *non-falsifiable* assumptions (e.g., knowledge of exponent assumptions) [Gro10; BCCT12; DFH12; BCCT13; Lip13; GGPR13; BCIOP13; BCP13; BISW17; Bit+14; BISW18; ACLMT23; CLM23]. In the CRS model, the prover and verifier rely on a trusted reference string (or random string) generated during a setup phase.

SNARGs from falsifiable assumptions. Despite their practical significance and widespread deployment, the theoretical foundations of SNARGs remain somewhat unsatisfactory. For a long time, the existence of SNARGs based solely on falsifiable assumptions remained an open question. The first construction of a SNARG for NP from (sub-exponentially) falsifiable assumptions was provided by Sahai and Waters [SW14], who gave a (non-adaptive) construction based on indistinguishability obfuscation (iO) and one-way functions.¹

To get around this challenge, an alternative approach is to relax the target setting—either by restricting the class of languages or by weakening the notion being achieved. Along these lines, several works construct SNARGs from standard falsifiable assumptions for P [CJJ22; KVZ21; HJKS22; CGJJZ23], P/poly [GZ21; WW23; WW15; BCFL23; WW24b; Wee25a; Wee25b], batch NP [CJJ22; CJJ21; GSWW22; WW22; DGKV22; PP22; KLVW23; CGJJZ23; DWW24], monotone policy batch NP [BBKLP23; NWW24; NWW25], and NP languages with propositional proofs of non-membership [JKLM25].

Building adaptively-sound SNARGs for NP from falsifiable assumptions is a challenging problem, as any such result must circumvent known black-box separations [GW11; CGKS23]. While recent works have improved the Sahai-Waters construction to achieve adaptive soundness [WW24a; WZ24; WW25], these results still necessitate the full power of iO. Although iO is a powerful primitive, it is considered a heavy assumption, both in terms of the complexity of its construction and the concrete efficiency of its instantiations. Consequently, constructing SNARGs from standard, well-studied assumptions (such as the hardness of lattice problems) without relying on iO or idealized models

¹Recall that iO alone does not imply one-way functions and must be supplemented with a cryptographic assumption (e.g., one-way functions). However, this additional assumption can sometimes be replaced by a weaker worst-case assumption [KMNPY22].

remains a major open problem in the field. Recently, Devadas et. al [DHKKLM26] constructed a SNARG for NP based on LWE (or other standard assumptions), and a mathematical conjecture about multivariate polynomials over the reals (low-norm Nullstellensatz hypothesis).

The challenge of Fiat–Shamir for arguments. If we allow interactions, the situation is much better. In his seminal work, Kilian [Kil92] showed how to construct succinct *interactive* arguments for NP assuming only the existence of collision-resistant hash functions (CRH); moreover, it was later shown that even multi-collision resistant hash functions suffice [KNY18]. Kilian’s protocol works by having the prover construct a PCP for the statement and commit to it using a vector commitment scheme (typically instantiated via a Merkle tree). The verifier then queries specific locations of the PCP, for which the prover provides openings to the commitment.

To remove interaction, Micali [Mic00] proposed applying the Fiat–Shamir transformation to Kilian’s protocol. The idea is to replace the verifier’s random queries with the output of a cryptographic hash function applied to the prover’s commitment. Micali proved that this construction yields a secure SNARG in the ROM. Consequently, a natural approach to obtain a SNARG from falsifiable assumptions is to instantiate this blueprint using a concrete hash function in the standard model.

In recent years, there has been significant progress in instantiating the Fiat–Shamir heuristic in the standard model. A line of work has successfully established hash functions that can securely instantiate Fiat–Shamir for specific classes of interactive protocols based on standard assumptions (e.g., [CCR16; KRR17; CCRR18; HL18; Can+19; PS19; BKM20; JJ21; HLR21; CJJ22; HJKS22; KLV23]). However, a crucial limitation of these works is that they primarily apply to interactive *proofs* (i.e., protocols with statistical soundness). Kilian’s protocol, however, is an interactive *argument* (i.e., it has only computational soundness) due to its reliance on a succinct commitment scheme.

Standard techniques for instantiating Fiat–Shamir generally fail when compiling argument systems into non-interactive counterparts, rendering the instantiation of Micali’s construction in the standard model a formidable challenge. Indeed, there is a line of work that highlight the risks of replacing the random oracle with a concrete hash function in an argument scheme, regardless of how the hash function is implemented [CGH04; Bar01; GK03; KRS25; AY25].

Furthermore, Bartusek et al. [BBHMR19] identified strong barriers specifically targeting Micali’s blueprint. They constructed a specific CRH for which the Micali transformation results in an unsound protocol for *any* concrete instantiation of the Fiat–Shamir hash function. This implies that any successful instantiation of Micali’s construction cannot treat the CRH as a generic component. Rather, it must leverage some specific structure of the underlying CRH.

1.1 Our results

We show that the Micali transformation can be successfully instantiated in the standard model under standard assumptions. To achieve this, we rely on a new property of probabilistically checkable proofs which we term *shadow PCP*. We show that for any language L admitting such a PCP, the Micali blueprint yields a secure argument system.

Central to this concept is the *shadow algorithm* associated with the PCP. Our construction uses a vector commitment scheme that satisfies *function-statistical-binding* for a specific family of functions \mathcal{F} . The construction is secure provided that \mathcal{F} is sufficiently expressive to compute the shadow algorithm.

Theorem 1. *Let \mathcal{F} be a function family such that 3SAT has a shadow PCP with a shadow algorithm in \mathcal{F} , and there is a vector commitment scheme satisfying function-statistical-binding for \mathcal{F} . Then, under the sub-exponential hardness of LWE, there exists a non-adaptive SNARG for 3SAT.*

We apply this general theorem as follows. We observe that strong assumptions such as indistinguishability obfuscation (iO) allow us to construct vector commitments with function-statistical-binding for all P/poly . Then, we show that every language in NP has a shadow PCP with a shadow algorithm in P/poly , which yields a valid SNARG under these assumptions. While SNARGs from iO are already known, this result provides the first concrete instantiation of the Micali blueprint in the standard model.

Theorem 2. *The following holds:*

1. *Every language in NP has a shadow PCP with a shadow algorithm in P/poly .*
2. *Assuming iO and LWE, there is a vector commitment with function-statistical-binding for P/poly .*
3. *Using Theorem 1, the Micali blueprint can be instantiated in the plain model, yielding a SNARG for all NP with argument size $\tilde{O}(\sqrt{n}) \cdot \text{poly}(\lambda)$.*

1.2 Refuting universal attacks on the Micali framework

As discussed, a line of work has established “universal” impossibility results for the Fiat–Shamir transformation, showing that for certain protocols, the compiled argument is insecure regardless of the concrete hash function used [BBHMR19]. However, such impossibility results generally do not apply to interactive *proofs*. This is because the existence of correlation intractable hash (CIH) functions guarantees that, for a broad class of proofs, a secure instantiation of Fiat–Shamir *does* exist. The mere existence of such a hash function, even if inefficient, serves as a counterexample that rules out any universal attack.

Our work provides a parallel guarantee for the Kilian-Micali *argument* system. By constructing a concrete, secure instantiation of the Micali transformation (via a specific PCP, a vector commitment, and an LWE-based hash), we provide an existential proof that refutes the possibility of universal attacks against this paradigm. Consequently, the Micali framework is not inherently unsound; any successful attack on the transformation must necessarily rely on specific, contrived choices of the underlying components rather than the structure itself.

2 Techniques

We give a high-level overview of our techniques. As mentioned, the general blueprint of the SNARG construction is the work of [Mic00] (see also [CY24]). That is, we use a PCP for NP in which the prover first computes a PCP proof and then commits to it using a specialized vector commitment scheme. The verifier’s PCP randomness is derived via a specialized Fiat–Shamir hash. Finally, the prover provides all the answers to the PCP along with a proof of consistency. We will dive into each of these components separately and describe how they interplay. For clarity of exposition, we focus on achieving a sublinear proof size (i.e., $o(n)$), without optimizing for the precise bound stated in our main theorem, and at end of the overview we give more details on how to achieve the precise bound.

To motivate our specific design, we first recall how the Fiat–Shamir transformation is typically instantiated in the standard model for statistically sound protocols. For 3-message interactive *proofs* (protocols with statistical soundness), secure instantiation is achieved using a correlation intractable hash (CIH) function [CCR16; KRR17; CCRR18; HL18; Can+19; PS19; BKM20; JJ21; HLR21; CJJ22; HJKS22; KLV23]. This works because such protocols induce an underlying *sparse relation*: for any false statement, the set of “bad” verifier challenges (those that lead to acceptance) is negligibly small. A CIH hash function is simply defined to avoid outputting values within this sparse set.

However, this standard paradigm fails for Kilian’s protocol. Because Kilian’s protocol is an interactive *argument*, relying on the computational binding of the vector commitment, there is no underlying sparse relation. Since the committed string is only computationally binding and hidden from the verifier, one cannot define a fixed sparse set of bad challenges in the standard information-theoretic sense. Thus, one cannot directly apply the same CIH approach, and some new ideas are necessary. In particular, we need to have some statistical property hiding under the computational commitment.

In this overview, we describe how we “couple” PCPs with our vector commitment scheme to induce a sparse relation, thereby enabling the use of a correlation-intractable hash function to instantiate the Fiat–Shamir transformation for Kilian’s protocol. Our approach is inspired by previous works that construct SNARGs for subsets of NP using somewhere statistically binding hash [BBHMR19; CJJ21; CJJ22; PP22; DGKV22; KLVW23].

We present the PCP we need in Section 2.1, our VC scheme in Section 2.2, and the final SNARG construction and analyses in Section 2.3.

2.1 PCP shadows

Consider the 3SAT language over n variables. The first component is an information-theoretic PCP construction that satisfies a strong soundness notion we call *shadow soundness*. A shadow is a digest or projection of a PCP string Π (either valid or malicious) into a short state (of size $o(n)$), denoted by z . This compression is performed by a *randomized* algorithm denoted by F .

The shadow z is designed to predict the value of the verifier’s output $\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}, \rho)$. This is achieved via a decider algorithm D that takes the shadow and the PCP randomness ρ as input and outputs a decision bit. The *correctness* property asserts that for any fixed ρ , with high probability (over the randomness of F), it holds that $\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}, \rho) = D(\mathbf{x}, z, \rho)$. Note that the shadow loses the local properties that the proof Π had. While correctness is the primary property, we additionally require two auxiliary properties: *sparsity*, which implies that D accepts a sparse set of randomness for

instances not in the language; and *consistency*, which ensures that proof strings sharing a local view produce consistent shadows. Formally, we provide the following definition.

Definition 1 (Shadow soundness). *A PCP = (\mathbf{P}, \mathbf{V}) has shadow soundness if there exists a function F (computable by a polynomial-size circuit) with randomness complexity r_F and a deterministic algorithm D (a decider) such that for every instance $\mathbf{x} \notin L(R)$, the following holds:*

1. **Correctness.** For any $\tilde{\Pi}$, and verifier randomness $\rho \in \{0, 1\}^r$:

$$\Pr \left[\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}, \rho) \neq \mathsf{D}(\mathbf{x}, z, \rho) \mid \begin{array}{l} \gamma \leftarrow \{0, 1\}^{r_F} \\ z := \mathsf{F}(\mathbf{x}, \tilde{\Pi}; \gamma) \end{array} \right] \leq \epsilon_c(\mathbf{x}).$$

2. **Sparsity.** There exists an efficiently computable set Z where $\mathsf{Im}(\mathsf{F}(\mathbf{x}, \cdot)) \subseteq Z$ such that for any shadow state $z \in Z$:

$$\Pr [\mathsf{D}(\mathbf{x}, z, \rho) = 1 \mid \rho \leftarrow \{0, 1\}^r] \leq \epsilon_s(\mathbf{x}).$$

3. **Consistency.** For every shadow randomness $\gamma \in \{0, 1\}^{r_F}$, verifier randomness $\rho \in \{0, 1\}^r$, $\tilde{\Pi}$ and $\tilde{\Pi}'$ such that $\tilde{\Pi}[Q] = \tilde{\Pi}'[Q]$, where Q is the query set of the PCP verifier $\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho)$:

$$\mathsf{D}(\mathbf{x}, z, \rho) = \mathsf{D}(\mathbf{x}, z', \rho),$$

where $z := \mathsf{F}(\mathbf{x}, \tilde{\Pi}; \gamma)$ and $z' := \mathsf{F}(\mathbf{x}, \tilde{\Pi}'; \gamma)$.

Moreover, we say that PCP has shadow state size s_{PCP} if F outputs at most s_{PCP} bits.

Remark: shadow soundness and ETH. The exponential time hypothesis (ETH) posits that solving 3SAT on n variables requires time exponential in n . This implies that no PCP for 3SAT can have a proof of size $o(n)$, as this would allow solving the problem in $2^{o(n)}$ time by iterating over all proofs. Since our construction yields a shadow state of size $o(n)$, it might appear to contradict ETH (or its randomized variant) by using the shadow as a succinct witness.

However, this approach fails for two main reasons. First, the shadow computation F is randomized. Even if the verifier supplies the randomness, the PCP definition provides no mechanism to ensure the prover generates the shadow using *that* specific randomness rather than a maliciously chosen one. Second, even if F were deterministic, we still cannot verify that the state we are iterating over is a valid image of $\mathsf{F}(\mathbf{x}; \cdot)$. Indeed, the image of F depends on whether the instance is in the language. Thus, if the instance is not in the language, we risk enumerating a state that falsely appears to be a valid witness.

How to use shadow PCPs. The main idea for leveraging shadow PCPs is to require the prover to commit to the PCP string in a way that is statistically binding with respect to the *shadow* of the PCP. To achieve this, we introduce a vector commitment (VC) scheme that satisfies a property we call *function statistical binding* with respect to a family of functions \mathcal{F} . While the commitment scheme is succinct, and thus cannot be statistically binding on the message itself, the function statistically binding property ensures that the commitment is statistically binding *relative to* a specific function $f \in \mathcal{F}$ (provided f has a small output length). The function f will compute the shadow from the PCP.

A crucial requirement for this approach is that the shadow randomness γ must remain hidden from the prover: if the prover knows γ , it could tailor its proof to the specific shadow check. We

achieve this by sampling γ as part of the CRS and requiring the VC scheme to satisfy *function hiding*. Concretely, function hiding guarantees that the public parameters (which depend on γ) do not leak any information about this randomness. As a result, the prover has to commit to the shadow without knowing the underlying randomness, thereby preserving the probabilistic guarantees of the shadow soundness. We elaborate more on our VC below in Section 2.2.

Constructing shadow PCPs. We provide a PCP construction whose shadow can be computed by polynomial-size circuit. Let $\text{PCP} = (\mathbf{P}, \mathbf{V})$ be a PCP for 3SAT with randomness complexity r . We design a compiler that converts PCP to a shadow PCP $\text{PCP}' = (\mathbf{P}', \mathbf{V}')$ when r is small. Specifically, \mathbf{P}' behaves the same as \mathbf{P} ; \mathbf{V}' breaks the set of all original verifier randomness $\rho \in \{0, 1\}^r$ into consecutive blocks of size 2^{r-1} , samples a random block index b , and accepts if and only if the original verifier \mathbf{V} accepts all randomness in block b . Hence, the shadow circuit \mathbf{F} can deterministically compute the new verifier's decision easily for every randomness and record them in a list of size 2^{r-1} . We emphasize that this construction gives *deterministic* shadow function, which is stronger than what shadow PCP requires. To provide full generality, we keep the rest of the discussion with randomized shadow function.

2.2 Vector commitments with function binding

We construct a vector commitment (VC) scheme, called a *function VC*, that satisfies a specialized *function statistically binding* property for a broad family of functions. We believe this construction is of independent interest.

Function vector commitment schemes. Our function VC can be viewed as a programmable somewhere statistically binding (SSB) hash ([HW15; OPWW15]) where the “binding index” is replaced by a “binding function” (the tree algorithm). Recall that an SSB hash is initialized with a secret index i hidden from the adversary; while the hash is compressing (and thus only computationally binding globally), it guarantees that one can *extract* the i -th bit of the message, i.e., it is statistical binding specifically for the i -th bit. Formally, a hash family $\mathcal{H} = \{h_k\}_{k \leftarrow \mathcal{H}.\text{Gen}}$ is an SSB hash if there exists an efficient extractor $\mathcal{H}.\text{Extract}$ such that for any (unbounded) adversary \mathcal{A} and index i ,

$$\Pr \left[\begin{array}{l} \mathcal{H}.\text{Check}(k, v, i, \sigma, \text{pf}) = 1 \\ \wedge \sigma \neq \tilde{\sigma} \end{array} \middle| \begin{array}{l} (k, \text{td}) \leftarrow \mathcal{H}.\text{Gen}(1^\lambda, i) \\ (v, \sigma, \text{pf}) \leftarrow \mathcal{A}(k) \\ \tilde{\sigma} := \mathcal{H}.\text{Extract}(\text{td}, v) \end{array} \right] \leq \text{negl}(\lambda),$$

where v is the hash output chosen by \mathcal{A} , σ is the alleged value at the i -th position of the preimage of v , and pf is an opening proof.

In our case, we initialize the VC with a hidden function f . Although the commitment is succinct, it is statistically binding with respect to the evaluation of f . We formalize this via a property called *function statistically binding*. Specifically, a function VC is a tuple of efficient algorithms

$$\text{VC} = (\text{VC}.\text{Gen}, \text{VC}.\text{Commit}, \text{VC}.\text{Open}, \text{VC}.\text{Check}, \text{VC}.\text{Extract})$$

where $(\text{VC}.\text{Gen}, \text{VC}.\text{Commit}, \text{VC}.\text{Open}, \text{VC}.\text{Check})$ works similarly as a standard VC, and function statistically binding is defined via $\text{VC}.\text{Extract}$:

Definition 2 (Informal). VC is **function statistically binding** if for every function f and (unbounded) adversary A_{VC} ,

$$\Pr \left[\begin{array}{l} \text{VC.Check}(\text{pp}, \text{cm}, Q, a, pf) = 1 \\ \wedge \forall \tilde{m} : (f(\tilde{m}) \neq y \vee \tilde{m}[Q] \neq a) \end{array} \middle| \begin{array}{l} (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, f) \\ (\text{cm}, Q, a, pf) := A_{\text{VC}}(\text{pp}) \\ y := \text{VC.Extract}(\text{td}, \text{cm}) \end{array} \right] \leq \text{negl}(\lambda).$$

Moreover, we require a function VC to satisfy *function hiding*, which ensures that given $f \neq f'$, no efficient adversary can distinguish the public parameters pp and pp' computed using f and f' , respectively.

Construction from iO and LWE. We outline our construction of function VC for all polynomial-size circuits using iO and LWE. In particular, we use the adaptively-sound SNARG in [WW25] based on sub-exponential hardness of iO and one-way functions (OWFs). Note that using this SNARG does not trivialize the problem as we mention in Section 1.2: this construction is the first to securely instantiate the Fiat–Shamir transformation in the Micali blueprint in the plain model. VC works as follows:

- VC.Gen samples an FHE key pair (pk, sk) , computes the encryption of the given circuit ct , and outputs the public parameter $\text{pp} := (\text{pk}, \text{ct})$ and the trapdoor $\text{td} := \text{sk}$.
- $\text{VC.Commit}(\text{pp}, m)$ computes the evaluation of the circuit on input m under encryption.
- VC.Open uses the SNARG prover to prove that the commitment is correctly computed.
- VC.Check checks if the SNARG verifier accepts.
- VC.Extract decrypts the commitment using the FHE secret key.

Function hiding follows from the semantic security of the FHE. Function statistically binding follows from the adaptive soundness of the SNARG. We leave the details of the proof in Section 5.2.

2.3 SNARG construction

Warm-up: designated verifier SNARG. To build intuition, we first describe how to construct a *designated verifier* SNARG (dv-SNARG) using a shadow PCP and a functional vector commitment. In this setting, the verifier holds a secret key—specifically, the trapdoor td of the vector commitment. We then demonstrate how to modify the construction to be *publicly verifiable*.

The designated verifier construction is given as follows.

- \mathcal{P} :
 1. Compute the PCP proof Π .
 2. Commit to Π using the function VC and obtain cm .
 3. Sample a verifier randomness ρ and provide the local openings (Q, a, pf) corresponding to ρ .
 4. Send (cm, Q, a, pf) .
- \mathcal{V} :
 1. Use VC.Decode to extract the PCP shadow z underneath the commitment cm .
 2. Sample verifier randomness ρ (not necessarily the same as the one sampled by the prover).

3. Check the following:

- (a) $\text{VC.Check}(\text{cm}, Q, a, \text{pf}) = 1$;
- (b) $D(\mathbf{x}, z, \rho) = 1$.

By the the function statistically binding property of the VC, we know that if $\text{VC.Check}(\text{cm}, Q, a, \text{pf}) = 1$, there exists a PCP proof Π such that $F(\Pi) = z$. Then the correctness of PCP shadow ensures that the second check using $D(z, \rho)$ is consistent with the PCP verifier check $\mathbf{V}^\Pi(\mathbf{x}; \rho)$.

Consequently, our main challenge is how to convert this dv-SNARG to a publicly verifiable one. The key idea is to use a correlation intractable hash family to “hide” the secret key of the verifier into a sparse relation.

Correlation-intractable hash instead of secret key. We now describe how to modify the construction to be publicly-verifier. The scheme follows the blueprint of Micali’s construction [Kil92; Mic00]: On input an instance \mathbf{x} and a witness \mathbf{w} , the SNARG prover \mathcal{P} computes the PCP proof Π and commits to it using the VC scheme, obtaining a short commitment cm . It then derives the PCP verifier’s randomness ρ via Fiat–Shamir, namely by computing $\rho := h(x, \text{cm})$ (where h is the Fiat–Shamir hash function), and uses ρ to determine the PCP query locations. The prover outputs cm together with the VC openings to the queried positions of Π . The verifier \mathcal{V} recomputes ρ , checks that all openings are valid with respect to cm , and then runs the PCP verifier on the opened symbols.

To prove Theorem 1, we instantiate the above construction using a PCP with shadow soundness, our function VC scheme, and a correlation-intractable hash family. We outline the soundness analysis.

Consider $\mathbf{x} \notin L(R)$. As mentioned at the beginning of this section, one challenge is that interactive arguments only have computational soundness and do not induce sparse relations that allow us to use CIH on. However, since our function VC satisfies function statistically binding, we are able to leverage the statistical soundness of the underlying PCP. More formally, let F be the tree-computable function that computes the PCP shadow and D be the decider. Assume that the SNARG adversary $\tilde{\mathcal{P}}$ successfully fools the SNARG verifier \mathcal{V} , which means that $\tilde{\mathcal{P}}$ outputs $(\text{cm}, Q, a, \text{pf})$ such that

$$\rho = h_{\text{Cl}}(\text{cm}) \text{ and } \text{VC.Check}(\text{pp}, \text{cm}, Q, a, \text{pf}) = 1 \text{ and } \mathbf{V}^{[Q,a]}(\mathbf{x}; \rho) = 1,$$

where h_{Cl} is the CI hash function and \mathbf{V} is the PCP verifier. By the function statistically binding of the function VC, since $\text{VC.Check}(\text{pp}, \text{cm}, Q, a, \text{pf}) = 1$, we can find $\tilde{\Pi}$ such that

$$F(\mathbf{x}, \tilde{\Pi}; \gamma) = \text{VC.Extract}(\text{td}, \text{cm}) \text{ and } \tilde{\Pi}[Q] = a,$$

which implies that

$$\rho = h_{\text{Cl}}(\text{cm}) \text{ and } \mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho) = 1.$$

This enables us to use PCP shadows to bound the SNARG soundness error.

Recall that in the definition of PCP shadows in Section 2.1, it is important that the shadow randomness γ remains hidden from the PCP adversary, as otherwise it’s easy to choose some PCP string $\tilde{\Pi}$ that fools the decider always. In the SNARG construction, the shadow randomness γ is sampled at random and then encrypted with the FHE, and the SNARG adversary only has access to its encryption. Intuitively, if the SNARG adversary were to guess γ , it has to break the FHE. On the other hand, if the SNARG adversary does not know γ , the sparsity property of PCP shadows induces a sparse relation that enables us to use CIH.

To formalize the intuition above, we set $z := \mathsf{F}(\mathbf{x}, \tilde{\Pi}; \gamma)$ and consider two cases: $\mathsf{D}(\mathbf{x}, z, \rho) = 0$ and $\mathsf{D}(\mathbf{x}, z, \rho) = 1$. Specifically, we argue that neither of the following events can happen with high probability:

$$\left[\begin{array}{l} \rho = h_{\mathsf{Cl}}(\mathbf{cm}) \\ \wedge \mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho) = 1 \\ \wedge \mathsf{D}(\mathbf{x}, z, \rho) = 0 \end{array} \right] \text{ and } \left[\begin{array}{l} \rho = h_{\mathsf{Cl}}(\mathbf{cm}) \\ \wedge \mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho) = 1 \\ \wedge \mathsf{D}(\mathbf{x}, z, \rho) = 1 \end{array} \right].$$

The probability of the event on the left-hand side can be bounded by the correctness error of PCP shadows (the first property in Definition 1), which ensures that for any PCP verifier randomness ρ , the PCP verifier $\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho)$ and the shadow decider $\mathsf{D}(\mathbf{x}, z, \rho)$ agree except with small probability over shadow randomness γ . In other words, in order to find $\tilde{\Pi}$ and ρ such that $\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho)$ and $\mathsf{D}(\mathbf{x}, z, \rho)$ disagree with high probability, one has to know the secret randomness γ of the PCP shadow function F . Therefore, if $\tilde{\mathcal{P}}$ succeeds with high probability, we would be able to correctly guess γ using $\tilde{\mathcal{P}}$ with high probability, which violates the security of **FHE**. We note that in the formal analysis in Section 6.2, we additionally rely on the consistency of PCP shadows (the third property in Definition 1).

The other event can be analyzed using the CIH. By the sparsity of PCP shadows (the second property in Definition 1), the following relation is sparse:

$$R_{\mathbf{x}, \mathbf{td}} := \{(\mathbf{cm}, \rho) : \mathsf{D}(\mathbf{x}, z, \rho) = 1 \text{ where } z := \mathsf{VC}.\mathsf{Extract}(\mathbf{td}, \mathbf{cm})\}.$$

Therefore, $\rho = h_{\mathsf{Cl}}(\mathbf{cm})$ and $\mathsf{D}(\mathbf{x}, z, \rho) = 1$ can happen with probability at most the CI hash error. CIH for all sparse relations is not known to follow from LWE alone: existing LWE-based constructions either require the relation to be computable by a bounded-size circuit [PS19], or they rely on relations with an inherent product structure [HLR21]. In our construction, we adopt the latter approach of [HLR21], since the PCP shadow soundness guarantee can be amplified via parallel repetition, which naturally induces a sparse product relation (see details in Sections 4 and 6).

Plugging in the shadow PCP constructed in Section 2.1 and the function VC for circuits in Section 2.2, we can prove Theorem 2.

3 Preliminaries

Definition 3.1. For every function $f: X \rightarrow Y$, the image of f , denoted as $\text{Im}(f)$, is

$$\text{Im}(f) := \{f(x) \in Y : x \in X\}.$$

Definition 3.2. A relation R is a set of pairs (\mathbf{x}, \mathbf{w}) where \mathbf{x} is an instance and \mathbf{w} a witness. The corresponding language $L(R)$ is the set of instances \mathbf{x} for which there exists a witness \mathbf{w} such that $(\mathbf{x}, \mathbf{w}) \in R$.

3.1 Correlation intractability

Definition 3.3. For every relation ensemble $\mathbf{R} = \{R_\phi \subseteq \mathcal{X}_\phi \times \mathcal{W}_\phi\}$, we say that \mathbf{R} is $\tau(\cdot)$ -sparse if for every ϕ and $x \in \mathcal{X}_\phi$,

$$\Pr[(x, y) \in R_\phi \mid y \leftarrow \mathcal{W}_\phi] \leq \tau(\phi).$$

Definition 3.4. A hash family $\mathcal{H} = \{\mathcal{H}_\lambda\}_\lambda$ is **correlation intractable wrt sparse relations** if for every security parameter λ , ϕ , τ -sparse relation R_ϕ , $t_{\text{CI}} \in \mathbb{N}$ and t_{CI} -size adversary \mathbf{A} ,

$$\Pr \left[(x, h(x)) \in R_\phi \mid \begin{array}{l} \text{aux} \leftarrow \mathbf{A} \\ h \leftarrow \mathcal{H}_\lambda \\ x \leftarrow \mathbf{A}(\text{aux}, h) \end{array} \right] \leq \epsilon_{\text{CI}}(\phi, \tau, t_{\text{CI}}).$$

Definition 3.5 (Product relation). A relation $R \subseteq \mathcal{X} \times \mathcal{W}^t$ is a product relation if for every \mathbf{x} , the set $R_{\mathbf{x}} := \{\mathbf{w} : (\mathbf{x}, \mathbf{w} \in R)\}$ is the Cartesian product of sets $S_{\mathbf{x},1}, \dots, S_{\mathbf{x},t}$:

$$R_{\mathbf{x}} = S_{\mathbf{x},1} \times \dots \times S_{\mathbf{x},t}.$$

Definition 3.6 (Efficient product verifiability). A product relation R is T -time product verifiable if there exists a size- T circuit C such that for every \mathbf{x} and its corresponding $S_{\mathbf{x},1}, \dots, S_{\mathbf{x},t}$, $\mathbf{w}_i \in S_{\mathbf{x},i}$ if and only if $C(\mathbf{x}, \mathbf{w}_i, i) = 1$.

Definition 3.7 (Product sparsity). A product relation $R \subseteq \mathcal{X} \times \mathcal{W}^t$ has sparsity τ if for every \mathbf{x} and its corresponding $S_{\mathbf{x},1}, \dots, S_{\mathbf{x},t}$, $|S_{\mathbf{x},i}| \leq \tau |\mathcal{W}|$.

Theorem 3.8 ([HLR21]). Let \mathbf{R} be the ensemble of all T -time verifiable product relation $R_\lambda \subseteq \mathcal{X} \times \mathcal{W}^{t_\lambda}$ with product sparsity τ , where $t_\lambda > \lambda/(1-\tau)$. There exists a hash family $\mathcal{H}_{\text{CI}} = \{\mathcal{H}_{\text{CI}}^{(\lambda)} : \mathcal{X} \rightarrow \mathcal{W}^{t_\lambda}\}_{\lambda \in \mathbb{N}}$ that is correlation intractable for \mathbf{R} under the hardness of LWE. Moreover, \mathcal{H}_{CI} depends only on $\mathcal{X}, \mathcal{W}, T, t_\lambda, \tau$ and can be evaluated in time $\text{poly}(\log |\mathcal{X}|, t_\lambda, T)$.

3.2 Non-interactive arguments

A non-interactive argument for a relation R (in the common reference string model) is a tuple of algorithms $\text{SNARG} = (\text{Setup}, \mathcal{P}, \mathcal{V})$ satisfying the following properties.

Definition 3.9. $\text{SNARG} = (\text{Setup}, \mathcal{P}, \mathcal{V})$ has **perfect completeness** if for every security parameter $\lambda \in \mathbb{N}$, instance size bound $n \in \mathbb{N}$, public parameter $\text{pp} \in \mathcal{G}(1^\lambda, n)$, and instance-witness pair $(\mathbf{x}, \mathbf{w}) \in R$,

$$\Pr[\mathcal{V}(\text{pp}, \mathbf{x}, \pi) = 1 \mid \pi \leftarrow \mathcal{P}(\text{pp}, \mathbf{x}, \mathbf{w})] = 1.$$

Definition 3.10. $\text{SNARG} = (\text{Setup}, \mathcal{P}, \mathcal{V})$ has **non-adaptive soundness error** ϵ_{SNARG} if for every security parameter $\lambda \in \mathbb{N}$, instance $\mathbf{x} \notin L(R)$, circuit size bound $t_{\text{SNARG}} \in \mathbb{N}$, and t_{SNARG} -size circuit $\tilde{\mathcal{P}}$,

$$\Pr \left[\mathcal{V}(\mathbf{pp}, \mathbf{x}, \pi) = 1 \mid \begin{array}{l} \mathbf{pp} \leftarrow \mathcal{G}(1^\lambda, n) \\ \pi \leftarrow \tilde{\mathcal{P}}(\mathbf{pp}) \end{array} \right] \leq \epsilon_{\text{SNARG}}(\lambda, \mathbf{x}, t_{\text{ARG}}).$$

Definition 3.11. $\text{SNARG} = (\text{Setup}, \mathcal{P}, \mathcal{V})$ has **adaptive soundness error** ϵ_{SNARG} if for every security parameter $\lambda \in \mathbb{N}$, instance size bound $n \in \mathbb{N}$, circuit size bound $t_{\text{SNARG}} \in \mathbb{N}$, and t_{SNARG} -size circuit $\tilde{\mathcal{P}}$,

$$\Pr \left[\begin{array}{l} |\mathbf{x}| \leq n \\ \wedge \mathbf{x} \notin L(R) \\ \wedge \mathcal{V}(\mathbf{pp}, \mathbf{x}, \pi) = 1 \end{array} \mid \begin{array}{l} \mathbf{pp} \leftarrow \mathcal{G}(1^\lambda, n) \\ \pi \leftarrow \tilde{\mathcal{P}}(\mathbf{pp}) \end{array} \right] \leq \epsilon_{\text{SNARG}}(\lambda, \mathbf{x}, t_{\text{ARG}}).$$

Theorem 3.12 ([WW25]). *Assume the existence of sub-exponential indistinguishability obfuscation (iO) for Boolean circuits and sub-exponential one-way functions (OWF), there exists a SNARG for any NP relation R that satisfies the following:*

- *proof size* $\text{poly}(\lambda)$;
- *public parameter size* $\text{poly}(\lambda, |R|)$, where $|R|$ is the size of the Boolean circuit computing R ;
- *perfect completeness*;
- *adaptive soundness error* $\text{negl}(\lambda)$.

3.3 Probabilistically checkable proofs

A *probabilistically checkable proof* (PCP) is an information-theoretic proof system where a probabilistic verifier has oracle access to a proof string.

Definition 3.13 (Completeness). $\text{PCP} = (\mathbf{P}, \mathbf{V})$ for a relation R has **perfect completeness** if, for every instance-witness pair $(\mathbf{x}, \mathbf{w}) \in R$,

$$\Pr [\mathbf{V}^\Pi(\mathbf{x}) = 1 \mid \Pi \leftarrow \mathbf{P}(\mathbf{x}, \mathbf{w})] = 1.$$

Definition 3.14 (Soundness). $\text{PCP} = (\mathbf{P}, \mathbf{V})$ for a relation R has **soundness error** ϵ_{PCP} if, for every instance $\mathbf{x} \notin L(R)$ and (unbounded) circuit $\tilde{\mathbf{P}}_{\text{PCP}}$,

$$\Pr [\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}) = 1 \mid \tilde{\Pi} \leftarrow \tilde{\mathbf{P}}_{\text{PCP}}] \leq \epsilon_{\text{PCP}}(\mathbf{x}).$$

We consider several efficiency measures for a PCP:

- the *proof alphabet* Σ is the alphabet over which a PCP string is written;
- the *proof length* ℓ is the number of alphabet symbols in the PCP string;
- the *query complexity* $q \in [\ell]$ is the number of queries that the PCP verifier makes to the PCP string (each query is an index in $[\ell]$ and is answered by the corresponding symbol in Σ in the PCP string);
- the *randomness complexity* r is the number of random bits used by the PCP verifier.

An efficiency measure may be a function of the instance \mathbf{x} (e.g., of its size $|\mathbf{x}|$).

Theorem 3.15 ([BS05; Din07; BMVY25]). *There is a PCP for 3SAT that satisfies the following:*

- *perfect completeness*;
- *soundness error* $\epsilon_{\text{PCP}} = 1/2$;
- *non-adaptive verifier*;
- *query complexity* $q = O(1)$;
- *randomness complexity* $r = \log n + O(\log \log n)$;
- *proof length* $\ell = n \cdot \text{polylog} n$;
- *alphabet* $\{0, 1\}$.

3.4 Merkle tree

We recall the construction of the Merkle vector commitment scheme, adapted from [CY24].

Definition 3.16. For $\ell \in \mathbb{N}$, $T_\ell = (V_\ell, E_\ell)$ is the (perfect) **binary tree graph** of depth

$$d := \log_2 \ell$$

where the vertex set V_ℓ and edge set E_ℓ are defined as follows:

$$\begin{aligned} V_\ell &:= \{(j, i) : j \in \{0, 1, \dots, d\}, i \in [2^j]\} , \\ E_\ell &:= \{((j-1, i), (j, 2i-b)) : j \in \{1, \dots, d\}, i \in [2^{j-1}], b \in \{1, 0\}\} . \end{aligned}$$

Definition 3.17. We make the following notational definitions:

- The **root vertex** of T_ℓ is the vertex $(0, 1)$.
- The **leaf vertices** of T_ℓ are the vertices $\{(d, i)\}_{i \in [\ell]}$.
- A vertex (j, i) is **odd** if i is odd and it is **even** if i is even.
- The **sibling** of a non-root vertex (j, i) (i.e., with $j > 0$) is $(j, i+1)$ if (j, i) is odd and is $(j, i-1)$ if (j, i) is even.
- The **path** from the i -th leaf vertex (d, i) to the root vertex is denoted by $\text{path}(i)$; the vertex in $\text{path}(i)$ that is in layer j is denoted $\mathbf{p}(i, j) \in \{j\} \times [2^j]$.
- The **copath** from the i -th leaf vertex (d, i) to the root vertex is denoted by $\text{copath}(i)$, and is the list of siblings of each vertex in $\text{path}(i)$, except the root vertex (which has no siblings); the vertex in $\text{copath}(i)$ that is in layer j is denoted $\bar{\mathbf{p}}(i, j) \in \{j\} \times [2^j]$ (and is the sibling of $\mathbf{p}(i, j)$).
- For $I \subseteq [\ell]$, $\text{path}(I) := \cup_{i \in I} \text{path}(i)$ and $\text{copath}(I) := \cup_{i \in I} \text{copath}(i)$ (viewing lists as sets).

Using this notation we can write:

$$\text{path}(i) = \left(\mathbf{p}(i, j) \right)_{j \in \{0, 1, \dots, d\}} \text{ and } \text{copath}(i) = \left(\bar{\mathbf{p}}(i, j) \right)_{j \in \{1, \dots, d\}} .$$

For every $i \in [\ell]$, $\mathbf{p}(i, 0) = (0, 1)$ is the root vertex and $\mathbf{p}(i, d) = (d, i)$ is the i -th leaf.

Construction 3.18. Given $d+1$ hash families $\mathcal{H}_0, \dots, \mathcal{H}_d$, we construct the Merkle commitment scheme as follows:

- $\text{MT.Gen}(1^\lambda, \ell, \text{seed}_0, \dots, \text{seed}_d)$:
 1. For $i \in \{0, \dots, d\}$: Sample $(h_i, \text{td}_i) \leftarrow \mathcal{H}_i(\text{seed}_i)$.
 2. Set $\mathbf{pp} := (h_i)_{i \in \{0, \dots, d\}}$.
 3. Set $\mathbf{td} := (\text{td}_i)_{i \in \{0, \dots, d\}}$.
 4. Output $(\mathbf{pp}, \mathbf{td})$.

- $\text{MT}.\text{Commit}(\text{pp}, m)$:

1. Parse pp as $(h_i)_{i \in \{0, \dots, d\}}$.
2. For each message location $i = 1, \dots, \ell$: Compute $c_{(d,i)} := h_d(i, m[i])$. Note that in the leaf level, we hash both the value at location i and the location itself.
3. For each layer $j = d-1, \dots, 0$ and for each $i = 1, \dots, 2^j$: Compute $c_{(j,i)} := h_j(c_{(j+1,2i-1)}, c_{(j+1,2i)})$.
4. Set the Merkle commitment $\text{cm} := c_{(0,1)}$.
5. Set the auxiliary information $\text{aux} := ((c_{(j,i)})_{i \in [2^j]})_{j=0}^d$, which we can visualize in the following way:

$$\text{aux} = \begin{bmatrix} c_{(0,1)} \\ c_{(1,1)} & c_{(1,2)} \\ c_{(2,1)} & c_{(2,2)} & c_{(2,3)} & c_{(2,4)} \\ \vdots & \vdots & \vdots & \vdots & \ddots \\ c_{(d,1)} & \cdots & \cdots & \cdots & \cdots & c_{(d,2^d)} \end{bmatrix}.$$

6. Output (cm, aux) .

- $\text{MT}.\text{Open}(\text{pp}, \text{aux}, \mathcal{Q})$:

1. For every $i \in \mathcal{Q}$, set the authentication path for location i :

$$\text{auth}_i := (c_{\bar{p}(i,j)})_{j \in \{1, \dots, d\}}.$$

2. Output the opening proof $\text{pf} := (\text{auth}_i)_{i \in \mathcal{Q}}$.

- $\text{MT}.\text{Check}(\text{pp}, \text{cm}, \mathcal{Q}, \text{ans}, \text{pf})$:

1. Parse pf as $(\text{auth}_i)_{i \in \mathcal{Q}}$.
2. For every $i \in \mathcal{Q}$, check that auth_i authenticates the value $\text{ans}[i]$ as the i -th opening relative to the Merkle commitment cm by computing $(c_{p(i,j)})_{j \in \{0,1, \dots, d\}}$:
 - (a) Compute the commitment $c_{(d,i)} := h_d(\text{ans}[i])$;
 - (b) Compute the commitments $(c_{p(i,j)})_{j \in \{0,1, \dots, d-1\}}$ as follows:
 - For each layer $j = d-1, \dots, 1, 0$:
 - If $p(i, j+1)$ is an odd vertex then set $c_L := c_{p(i,j+1)}$ and $c_R := c_{\bar{p}(i,j+1)}$;
 - If $p(i, j+1)$ is an even vertex then set $c_L := c_{\bar{p}(i,j+1)}$ and $c_R := c_{p(i,j+1)}$;
 - Compute the commitment $c_{p(i,j)} := h_j(c_L, c_R)$.
 - (c) Check that $\text{cm} = c_{(0,1)}$.

In the construction above, each query $i \in \mathcal{Q}$ has a separate authentication path auth_i . We introduce the operation Merge that takes in a list of authentication paths $(\text{auth}_i)_{i \in \mathcal{Q}}$ as input and works as follows:

$\text{Merge}((\text{auth}_k)_{k \in \mathcal{Q}})$:

1. For every vertex (j, i) in the tree:
 - (a) If there is no $i \in \mathcal{Q}$ such that (j, i) is included, set $c_{(j,i)} := \perp$.
 - (b) If (j, i) is included in some paths, and there is no inconsistency across paths, set $c_{(j,i)}$ to be the corresponding value in the path.
 - (c) If (j, i) has inconsistency values across different paths, output \perp .
2. Output $(c_{(j,i)})_{j \in d, i \in [2^j]}$.

Definition 3.19 (Collision resistant hash function). A hash family $\mathcal{H} = \{\mathcal{H}_\lambda\}_\lambda$ is **collision resistant** if for every security parameter $\lambda \in \mathbb{N}$, $t \in \mathbb{N}$ and t -size adversary A ,

$$\Pr \left[\begin{array}{c|c} x \neq x' & h \leftarrow \mathcal{H}(\lambda) \\ h(x) = h(x') & (x, x') \leftarrow A(h) \end{array} \right] \leq \epsilon_{\text{CRHF}}(\lambda, t).$$

Lemma 3.20. Let \mathcal{H} be a collision resistant hash family with error ϵ_{CRHF} . For every $\lambda \in \mathbb{N}$, $t \in \mathbb{N}$, and t -size adversary A ,

$$\Pr \left[\begin{array}{c|c} \text{MT.Check(pp, cm, } \mathcal{Q}, \text{ans, pf)} = 1 & \begin{array}{l} \text{For } i \in \{0, \dots, d\} : \\ h_i \leftarrow \mathcal{H}(\lambda) \\ \text{pp} := (h_i)_{i \in \{0, \dots, d\}} \\ (\text{cm, } \mathcal{Q}, \text{ans, pf} := (\text{auth}_i)_{i \in \mathcal{Q}}) \leftarrow A(\text{pp}) \end{array} \\ \wedge \text{Merge}((\text{auth}_i)_{i \in \mathcal{Q}}) = \perp & \end{array} \right] \leq \epsilon_{\text{CRHF}}(\lambda, t).$$

Proof. It is easy to see that if A is able to find inconsistent authentication paths that are accepted by MT.Check , it can find collisions in h_{CRHF} . \square

3.5 Learning with errors

Definition 3.21 (LWE distribution). For any positive integers $n, q \in \mathbb{N}$, vector $\mathbf{s} \in \mathbb{Z}^n$, and error distribution χ over \mathbb{Z} , the learning with error (LWE) distribution $A_{\mathbf{s}, \chi}$ is defined by uniformly sampling a vector $\mathbf{a} \in \mathbb{Z}^n$, sampling error \mathbf{e} from χ , and outputting $(\mathbf{a}, \langle \mathbf{a}, \mathbf{s} \rangle + \mathbf{e} \bmod q) \in \mathbb{Z}_q^n \times \mathbb{Z}_q$. χ is usually the discrete Gaussian of parameter $\alpha \cdot q$. The modulus-to-noise ratio is $\frac{q}{\alpha \cdot q} = 1/\alpha$.

Definition 3.22 (Sub-exponential hardness of LWE). Fix the security parameter $\lambda \in \mathbb{N}$. Consider n, q and χ that depend on λ . In particular, let $n = \Theta(\lambda)$ be the LWE secret vector size. Let $q = \text{poly}(\lambda)$ be the LWE modulus. The sub-exponential LWE assumption $\text{LWE}_{n, q, \chi}$ states that for every $c > 1$, there exists c' such that no non-uniform probabilistic $2^{\lambda^{1/c}}$ -size adversary can distinguish, with probability more than $2^{-\lambda^{1/c'}}$, between (i) the distribution $A_{\mathbf{s}, \chi}$ for a random $\mathbf{s} \leftarrow \mathbb{Z}_q^n$; and (ii) the uniform distribution over $\mathbb{Z}_q^n \times \mathbb{Z}_q$.

3.6 Fully homomorphic encryption

A **fully homomorphic encryption scheme** with alphabet Σ , message size ℓ and cipher text size n is a tuple of efficient algorithms $\text{FHE} = (\text{FHE.Gen}, \text{FHE.Enc}, \text{FHE.Dec}, \text{FHE.Eval})$ such that:

- $\text{FHE.Gen}(1^\lambda)$ is a randomized algorithm that takes as input the security parameter and outputs a public key pk and a secret key sk .
- $\text{FHE.Enc}(\text{pk}, m)$ is a randomized algorithm that takes as input the public key pk and a message m and outputs a cipher text ct .
- $\text{FHE.Dec}(\text{sk}, \text{ct})$ is a deterministic algorithm that takes as input the secret key sk and a cipher text ct and outputs a message m' .
- $\text{FHE.Eval}(\text{pk}, f, \text{ct}_1, \dots, \text{ct}_k)$ is a deterministic algorithm that takes as input the public key pk , a circuit f that takes in k inputs and output a string in Σ^ℓ , and a vector of cipher texts $(\text{ct}_1, \dots, \text{ct}_k)$ and outputs another cipher text ct' .

We require the following properties for an FHE scheme:

- *Correctness*: For every $\lambda \in \mathbb{N}$ and message m ,

$$\Pr \left[\mathsf{FHE}.\mathsf{Dec}(\mathsf{sk}, \mathsf{FHE}.\mathsf{Enc}(\mathsf{pk}, m)) = m \mid (\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{FHE}.\mathsf{Gen}(1^\lambda) \right] = 1.$$

- *Semantic security*: For every $\lambda \in \mathbb{N}$, adversary time bound $t_{\mathsf{FHE}} \in \mathbb{N}$, and t_{FHE} -time adversary \mathcal{A} ,

$$\left| \Pr \left[b = 1 \left| \begin{array}{l} (\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{FHE}.\mathsf{Gen}(1^\lambda) \\ (m_0, m_1, \mathsf{aux}) \leftarrow \mathcal{A}(\mathsf{pk}) \\ \mathsf{ct} \leftarrow \mathsf{FHE}.\mathsf{Enc}(\mathsf{pk}, m_0) \\ b \leftarrow \mathcal{A}(\mathsf{aux}, \mathsf{pk}, \mathsf{ct}) \end{array} \right. \right] - \Pr \left[b = 1 \left| \begin{array}{l} (\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{FHE}.\mathsf{Gen}(1^\lambda) \\ (m_0, m_1, \mathsf{aux}) \leftarrow \mathcal{A}(\mathsf{pk}) \\ \mathsf{ct} \leftarrow \mathsf{FHE}.\mathsf{Enc}(\mathsf{pk}, m_1) \\ b \leftarrow \mathcal{A}(\mathsf{aux}, \mathsf{pk}, \mathsf{ct}) \end{array} \right. \right] \right| \leq \epsilon_{\mathsf{FHE}}(\lambda, t_{\mathsf{FHE}}).$$

- e_{FHE} -*expansion*: For every $\lambda \in \mathbb{N}$, message m , and $(\mathsf{pk}, \mathsf{sk}) \in \mathsf{Supp}(\mathsf{FHE}.\mathsf{Gen}(1^\lambda))$,

$$|\mathsf{FHE}.\mathsf{Enc}(\mathsf{pk}, m)| \leq e_{\mathsf{FHE}}(\lambda, |m|).$$

- c_{FHE} -*compactness*: For every $\lambda \in \mathbb{N}$, circuit f that takes in k inputs and output a string in Σ^ℓ , inputs (m_1, \dots, m_k) , $(\mathsf{pk}, \mathsf{sk}) \in \mathsf{Supp}(\mathsf{FHE}.\mathsf{Gen}(1^\lambda))$, $\mathsf{ct}_i \in \mathsf{Supp}(\mathsf{FHE}.\mathsf{Enc}(\mathsf{pk}, m_i))$ for every $i \in [k]$,

$$|\mathsf{FHE}.\mathsf{Eval}(\mathsf{pk}, f, (\mathsf{ct}_1, \dots, \mathsf{ct}_k))| \leq c_{\mathsf{FHE}}(\lambda, |f(m_1, \dots, m_k)|).$$

- *Perfect homomorphism*: For every $\lambda \in \mathbb{N}$, $(\mathsf{pk}, \mathsf{sk}) \in \mathsf{Supp}(\mathsf{FHE}.\mathsf{Gen}(1^\lambda))$, circuit f , and inputs (m_1, \dots, m_k) , consider $n_i \in \mathsf{Supp}(\mathsf{FHE}.\mathsf{Enc}(\mathsf{pk}, m_i))$ for every $i \in [k]$, it holds that

$$\mathsf{FHE}.\mathsf{Dec}(\mathsf{sk}, \mathsf{FHE}.\mathsf{Eval}(\mathsf{pk}, f, \mathsf{ct}_1, \dots, \mathsf{ct}_k)) = f(m_1, \dots, m_k).$$

There is a long line of work that constructs FHE using LWE. The theorem below states the existence of FHE with parameters and security that we need in this paper.

Theorem 3.23 ([BGV12; Bra12; GSW13; BDGM19]). *Assume the sub-exponential hardness of LWE holds. Let $\lambda \in \mathbb{N}$ be the security parameter, there exists FHE for all circuits of depth $\mathsf{poly}(\lambda)$ that satisfies the following:*

- *size of the secret key* $\mathsf{poly}(\lambda)$;
- *size of public key* $\mathsf{poly}(\lambda)$;
- *expansion* $e_{\mathsf{FHE}}(\lambda, \ell) = \ell \cdot \mathsf{poly}(\lambda)$;
- *compactness* $c_{\mathsf{FHE}}(\lambda, \ell) = \ell \cdot \mathsf{poly}(\lambda)$;
- *perfect correctness*;
- *sub-exponential semantic security*: for every $c > 1$, there exists c' such that if $t_{\mathsf{FHE}} \leq 2^{\lambda^{1/c'}}$, then $\epsilon_{\mathsf{FHE}}(\lambda, t_{\mathsf{FHE}}) \leq 2^{-\lambda^{1/c'}}$;
- *perfect homomorphism*.

The following lemma generalizes semantic security to hold for a list of n messages.

Lemma 3.24 (Multi-message semantic security). *For every $\lambda \in \mathbb{N}$, $n \in \mathbb{N}$, adversary time bound $t_{\mathsf{FHE}} \in \mathbb{N}$, and t_{FHE} -time adversary \mathcal{A} ,*

$$\begin{aligned} & \left| \Pr \left[b = 0 \left| \begin{array}{l} (\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{FHE}.\mathsf{Gen}(1^\lambda) \\ ((m_{0,i})_{i \in [n]}, (m_{1,i})_{i \in [n]}) \leftarrow \mathcal{A}(\mathsf{pk}) \\ \text{For } i \in [n] : \\ \quad \mathsf{ct}_i \leftarrow \mathsf{FHE}.\mathsf{Enc}(\mathsf{pk}, m_{0,i}) \\ \quad b \leftarrow \mathcal{A}(\mathsf{pk}, (\mathsf{ct}_i)_{i \in [n]}) \end{array} \right. \right] - \Pr \left[b = 0 \left| \begin{array}{l} (\mathsf{pk}, \mathsf{sk}) \leftarrow \mathsf{FHE}.\mathsf{Gen}(1^\lambda) \\ ((m_{0,i})_{i \in [n]}, (m_{1,i})_{i \in [n]}) \leftarrow \mathcal{A}(\mathsf{pk}) \\ \text{For } i \in [n] : \\ \quad \mathsf{ct}_i \leftarrow \mathsf{FHE}.\mathsf{Enc}(\mathsf{pk}, m_{1,i}) \\ \quad b \leftarrow \mathcal{A}(\mathsf{pk}, (\mathsf{ct}_i)_{i \in [n]}) \end{array} \right. \right] \right| \\ & \leq n \cdot \epsilon_{\mathsf{FHE}}(\lambda, t_{\mathsf{FHE}}). \end{aligned}$$

Proof. Let \mathcal{A} be an adversary described in the lemma statement. We construct the following adversary \mathcal{B} for the semantic security of \mathbf{FHE} :

- $\mathcal{B}(\mathbf{pk})$:
 1. Compute $((m_{0,i})_{i \in [n]}, (m_{1,i})_{i \in [n]}) \leftarrow \mathcal{A}(\mathbf{pk})$.
 2. Sample $i \leftarrow [n]$.
 3. Output $(\mathbf{aux} := (i, ((m_{0,j})_{j \in [n]}, (m_{1,j})_{j \in [n]})), m_{0,i}, m_{1,i})$.
- $\mathcal{B}(\mathbf{aux}, \mathbf{pk}, \mathbf{ct})$:
 1. Parse \mathbf{aux} as $(i, (i, ((m_{0,j})_{j \in [n]}, (m_{1,j})_{j \in [n]})))$.
 2. For $j < i$: Compute $\mathbf{ct}_j \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, m_{0,j})$.
 3. For $j > i$: Compute $\mathbf{ct}_j \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, m_{1,j})$.
 4. Set $\mathbf{ct}_i := \mathbf{ct}$.
 5. Compute $b \leftarrow \mathcal{A}(\mathbf{pk}, (\mathbf{ct}_j)_{j \in [n]})$.

We define p_i as follows:

$$p_i := \Pr \left[b = 1 \left| \begin{array}{l} (\mathbf{pk}, \mathbf{sk}) \leftarrow \mathbf{FHE}.\mathbf{Gen}(1^\lambda) \\ ((m_{0,j})_{j \in [n]}, (m_{1,j})_{j \in [n]}) \leftarrow \mathcal{A}(\mathbf{pk}) \\ \text{For } j \leq i : \mathbf{ct}_j \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, m_{0,j}) \\ \text{For } j > i : \mathbf{ct}_j \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, m_{1,j}) \\ b \leftarrow \mathcal{A}(\mathbf{pk}, (\mathbf{ct}_j)_{j \in [n]}) \end{array} \right. \right].$$

Therefore, we remain to bound $|p_n - p_1|$. Notice that

$$\Pr \left[b = 1 \left| \begin{array}{l} (\mathbf{pk}, \mathbf{sk}) \leftarrow \mathbf{FHE}.\mathbf{Gen}(1^\lambda) \\ (m_0, m_1) \leftarrow \mathcal{B}(\mathbf{pk}) \\ \mathbf{ct} \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, m_0) \\ b \leftarrow \mathcal{B}(\mathbf{pk}, (\mathbf{ct}_j)_{j \in [n]}) \end{array} \right. \right] = \frac{1}{n} \cdot \sum_{i=1}^n p_i.$$

Moreover,

$$\Pr \left[b = 1 \left| \begin{array}{l} (\mathbf{pk}, \mathbf{sk}) \leftarrow \mathbf{FHE}.\mathbf{Gen}(1^\lambda) \\ (m_0, m_1) \leftarrow \mathcal{B}(\mathbf{pk}) \\ \mathbf{ct} \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, m_1) \\ b \leftarrow \mathcal{B}(\mathbf{pk}, (\mathbf{ct}_j)_{j \in [n]}) \end{array} \right. \right] = \frac{1}{n} \cdot \sum_{i=1}^n p_{i-1}.$$

Hence,

$$\epsilon_{\mathbf{FHE}}(\lambda, t_{\mathbf{FHE}}) \geq \left| \frac{1}{n} \cdot \sum_{i=1}^n p_i - \frac{1}{n} \cdot \sum_{i=1}^n p_{i-1} \right| = \frac{1}{n} |p_n - p_1|.$$

□

The lemma below reformulates the semantic security to hide the randomness of a function under encryption. In particular, if we encrypt a randomized function with a uniformly sampled randomness, no efficient adversary would be able to guess the randomness with high probability.

Lemma 3.25 (Randomness hiding). *Fix $\mathbf{FHE} = (\mathbf{FHE}.\mathbf{Gen}, \mathbf{FHE}.\mathbf{Enc}, \mathbf{FHE}.\mathbf{Eval}, \mathbf{FHE}.\mathbf{Dec})$. For every $\lambda \in \mathbb{N}$, randomized function f , adversary running time $t \in \mathbb{N}$, and t -time adversary A , the following holds:*

$$\Pr \left[\rho' = \rho \left| \begin{array}{l} \rho \leftarrow \{0,1\}^\ell \\ (\mathbf{sk}, \mathbf{pk}) \leftarrow \mathbf{FHE}.\mathbf{Gen}(1^\lambda) \\ \mathbf{ct} \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, f_\rho) \\ \rho' \leftarrow A(\mathbf{pk}, \mathbf{ct}) \end{array} \right. \right] \leq \frac{1}{2^\ell} + \epsilon_{\mathbf{FHE}}(\lambda, t).$$

Proof. Assume for contradiction that there exists an adversary A such that the probability in the lemma statement is greater than $\frac{1}{2^\ell} + \epsilon_{\mathbf{FHE}}(\lambda, t)$. We construct an adversary A' that breaks the semantic security of \mathbf{FHE} . Let ρ be a randomly sampled element from $\{0,1\}^\ell$. Let $m_0 := \mathbf{0}$ and $m_1 := f_\rho$.

$A'_{m_0, m_1}(\mathbf{pk}, \mathbf{ct})$:

1. Run $\rho' \leftarrow A(\mathbf{pk}, \mathbf{ct})$.
2. If ρ' is such that $f_\rho = f_{\rho'}$, output 1.
3. Otherwise, output 0.

$$\begin{aligned} & \left| \Pr \left[b = 1 \left| \begin{array}{l} \rho \leftarrow \{0,1\}^\ell \\ m_0 := \mathbf{0} \\ m_1 := f_\rho \\ (\mathbf{pk}, \mathbf{sk}) \leftarrow \mathbf{FHE}.\mathbf{Gen}(1^\lambda) \\ \mathbf{ct} \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, m_1) \\ b \leftarrow A'_{m_0, m_1}(\mathbf{pk}, \mathbf{ct}) \end{array} \right. \right] - \Pr \left[b = 1 \left| \begin{array}{l} \rho \leftarrow \{0,1\}^\ell \\ m_0 := \mathbf{0} \\ m_1 := f_\rho \\ (\mathbf{pk}, \mathbf{sk}) \leftarrow \mathbf{FHE}.\mathbf{Gen}(1^\lambda) \\ \mathbf{ct} \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, m_0) \\ b \leftarrow A'_{m_0, m_1}(\mathbf{pk}, \mathbf{ct}) \end{array} \right. \right] \right| \\ &= \left| \Pr \left[b = 1 \left| \begin{array}{l} \rho \leftarrow \{0,1\}^\ell \\ m_0 := \mathbf{0} \\ m_1 := f_\rho \\ (\mathbf{pk}, \mathbf{sk}) \leftarrow \mathbf{FHE}.\mathbf{Gen}(1^\lambda) \\ \mathbf{ct} \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, m_1) \\ b \leftarrow A'_{m_0, m_1}(\mathbf{pk}, \mathbf{ct}) \end{array} \right. \right] - \frac{1}{2^\ell} \right| \\ &> \frac{1}{2^\ell} + \epsilon_{\mathbf{FHE}}(\lambda, t) - \frac{1}{2^\ell} \\ &= \epsilon_{\mathbf{FHE}}(\lambda, t), \end{aligned}$$

where the equality holds since when \mathbf{ct} is an encryption of m_0 it contains no information about ρ , and thus the output ρ' of A is independent from sampling ρ and thus $\rho = \rho'$ with probability exactly $2^{-\ell}$, and the inequality holds because of our assumption. \square

3.7 Non-interactive batch arguments

Definition 3.26 (Batched index relation). *A **batched index relation** R is a set of tuples $(\mathbf{i}, (\mathbf{x}_1, \dots, \mathbf{x}_k), (\mathbf{w}_1, \dots, \mathbf{w}_k))$. The corresponding **language** $L(R)$ is the set of tuples $(\mathbf{i}, (\mathbf{x}_1, \dots, \mathbf{x}_k))$ for which there exist witnesses $(\mathbf{w}_1, \dots, \mathbf{w}_k)$ such that $(\mathbf{i}, (\mathbf{x}_1, \dots, \mathbf{x}_k), (\mathbf{w}_1, \dots, \mathbf{w}_k)) \in R$.*

A non-interactive batch argument (BARG) is a tuple of algorithms $\mathbf{BARG} = (\mathbf{Setup}_{\mathbf{BG}}, \mathbf{P}_{\mathbf{BG}}, \mathbf{V}_{\mathbf{BG}})$ with the following interface:

- $\mathbf{Setup}_{\text{BG}}(1^\lambda, k, 1^m, i) \rightarrow \mathbf{pp}_{\text{BG}}$: On input the security parameter $\lambda \in \mathbb{N}$, the number of instances $k \in \mathbb{N}$, the witness size $m \in \mathbb{N}$, and an index $i \in [k]$, $\mathbf{Setup}_{\text{BG}}$ outputs a trapdoor public parameter \mathbf{pp}_{BG} .
- $\mathbf{P}_{\text{BG}}(\mathbf{pp}_{\text{BG}}, \mathbf{i}, (\mathbf{x}_1, \dots, \mathbf{x}_k), (\mathbf{w}_1, \dots, \mathbf{w}_k)) \rightarrow \pi_{\text{BG}}$: On input the public parameter \mathbf{pp}_{BG} , an index \mathbf{i} , and k instance-witness pairs $(\mathbf{x}_1, \dots, \mathbf{x}_k), (\mathbf{w}_1, \dots, \mathbf{w}_k)$, \mathbf{P}_{BG} outputs a proof π_{BG} .
- $\mathbf{V}_{\text{BG}}(\mathbf{pp}_{\text{BG}}, \mathbf{i}, (\mathbf{x}_1, \dots, \mathbf{x}_k), \pi_{\text{BG}}) \rightarrow b$: On input the public parameter \mathbf{pp}_{BG} , an index \mathbf{i} , k instances $(\mathbf{x}_1, \dots, \mathbf{x}_k)$, and a proof π_{BG} , \mathbf{V}_{BG} outputs a decision bit $b \in \{0, 1\}$.

Definition 3.27 (Completeness). $\text{BARG} = (\mathbf{Setup}_{\text{BG}}, \mathbf{P}_{\text{BG}}, \mathbf{V}_{\text{BG}})$ is perfectly complete if for every $\lambda \in \mathbb{N}$, $k \in \mathbb{N}$, $i \in [k]$, and $(\mathbf{i}, (\mathbf{x}_1, \dots, \mathbf{x}_k), (\mathbf{w}_1, \dots, \mathbf{w}_k)) \in R$,

$$\Pr \left[\mathbf{V}_{\text{BG}}(\mathbf{pp}_{\text{BG}}, \mathbf{i}, (\mathbf{x}_1, \dots, \mathbf{x}_k), \pi_{\text{BG}}) = 1 \mid \begin{array}{l} \mathbf{pp}_{\text{BG}} \leftarrow \mathbf{Setup}_{\text{BG}}(1^\lambda, k, 1^m, i) \\ \pi_{\text{BG}} \leftarrow \mathbf{P}_{\text{BG}}(\mathbf{pp}_{\text{BG}}, \mathbf{i}, (\mathbf{x}_1, \dots, \mathbf{x}_k), (\mathbf{w}_1, \dots, \mathbf{w}_k)) \end{array} \right] = 1.$$

Definition 3.28 (Index hiding). $\text{BARG} = (\mathbf{Setup}_{\text{BG}}, \mathbf{P}_{\text{BG}}, \mathbf{V}_{\text{BG}})$ has index hiding error ζ_{BG} if for every $\lambda \in \mathbb{N}$, $k \in \mathbb{N}$, $m \in \mathbb{N}$, indices $i_0 \neq i_1 \in [k]$, adversary size $t_{\text{BG}} \in \mathbb{N}$, and t_{BG} -time adversary A ,

$$\left| \Pr \left[A(\mathbf{pp}_{\text{BG}}) = 1 \mid \mathbf{pp}_{\text{BG}} \leftarrow \mathbf{Setup}_{\text{BG}}(1^\lambda, k, 1^m, i_0) \right] - \Pr \left[A(\mathbf{pp}_{\text{BG}}) = 1 \mid \mathbf{pp}_{\text{BG}} \leftarrow \mathbf{Setup}_{\text{BG}}(1^\lambda, k, 1^m, i_1) \right] \right| \leq \zeta_{\text{BG}}(\lambda, k, t_{\text{BG}}).$$

Definition 3.29 (Semi-adaptive somewhere soundness). $\text{BARG} = (\mathbf{Setup}_{\text{BG}}, \mathbf{P}_{\text{BG}}, \mathbf{V}_{\text{BG}})$ has semi-adaptive somewhere soundness error ϵ_{BG} if for every $\lambda \in \mathbb{N}$, $k \in \mathbb{N}$, $m \in \mathbb{N}$, index $i \in [k]$, adversary size $t_{\text{BG}} \in \mathbb{N}$, and t_{BG} -time adversary \mathbf{P}_{BG} ,

$$\Pr \left[\begin{array}{l} \mathbf{V}_{\text{BG}}(\mathbf{pp}_{\text{BG}}, \mathbf{i}, (\mathbf{x}_1, \dots, \mathbf{x}_k), \tilde{\pi}_{\text{BG}}) = 1 \\ \wedge (\mathbf{i}, \mathbf{x}_i) \notin L(R) \end{array} \mid \begin{array}{l} \mathbf{pp}_{\text{BG}} \leftarrow \mathbf{Setup}_{\text{BG}}(1^\lambda, k, 1^m, i) \\ (\mathbf{i}, (\mathbf{x}_1, \dots, \mathbf{x}_k), \tilde{\pi}_{\text{BG}}) \leftarrow \tilde{\mathbf{P}}_{\text{BG}}(\mathbf{pp}_{\text{BG}}) \end{array} \right] \leq \epsilon_{\text{BG}}(\lambda, k, t_{\text{BG}}).$$

Theorem 3.30 ([PP22; DGKV22]). Under the sub-exponential hardness of LWE, for every $R \in \mathbf{NP}$ with witness size m , there exists a semi-adaptive somewhere sound BARG for k instances that satisfies the following:

- perfect completeness;
- the public parameter \mathbf{pp}_{BG} is of size $\text{poly}(\lambda, \log k, m)$;
- the proof π_{BG} is of size $O(m + \lambda^{10})$;²
- for every $c > 1$ and $t_{\text{BG}} \leq 2^{\lambda^{1/c}}$, there exists c' such that the semi-adaptive somewhere soundness error $\epsilon_{\text{BG}}(\lambda, t_{\text{BG}}) \leq 2^{-\lambda^{1/c'}}$;
- for every $c > 1$ and $t_{\text{BG}} \leq 2^{\lambda^{1/c}}$, there exists c' such that the index hiding error is at most $\zeta_{\text{BG}}(\lambda, t_{\text{BG}}) \leq 2^{-\lambda^{1/c'}}$.

²Constructions of rate-1 BARGs (e.g., [PP22; DGKV22]) usually write proof size to be $m + \text{poly}(\lambda)$. We trace the parameters in [PP22] and an obvious upper bound on the proof size is $O(m + \lambda^{10})$.

4 PCP shadows

We define and construct PCPs with *shadow soundness*. Informally, this notion requires that, given an instance \mathbf{x} and a (malicious) PCP proof $\tilde{\Pi}$, there exists an efficiently computable *shadow* z that succinctly represents the PCP verifier's behavior with respect to its randomness: namely, there exists a decider such that, given the instance \mathbf{x} and the shadow z , it outputs the verifier's decision for any verifier randomness ρ with high probability. We then show that there exists a PCP for the canonical NP-complete language 3SAT that satisfies shadow soundness, and whose shadow can be computed by *polynomial-size circuits*.

Definition 4.1 (Shadow soundness). *A PCP = (\mathbf{P}, \mathbf{V}) has shadow soundness if there exists a function F (computable by a polynomial-size circuit) with randomness complexity r_F and a deterministic algorithm D (a decider) such that for every instance $\mathbf{x} \notin L(R)$, the following holds:*

1. **Correctness.** For any $\tilde{\Pi}$, and verifier randomness $\rho \in \{0, 1\}^r$:

$$\Pr \left[\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}, \rho) \neq \mathsf{D}(\mathbf{x}, z, \rho) \mid \begin{array}{l} \gamma \leftarrow \{0, 1\}^{r_F} \\ z := \mathsf{F}(\mathbf{x}, \tilde{\Pi}; \gamma) \end{array} \right] \leq \epsilon_c(\mathbf{x}).$$

2. **Sparsity.** There exists an efficiently computable set Z where $\mathsf{Im}(\mathsf{F}(\mathbf{x}, \cdot)) \subseteq Z$ such that for any shadow state $z \in Z$:

$$\Pr [\mathsf{D}(\mathbf{x}, z, \rho) = 1 \mid \rho \leftarrow \{0, 1\}^r] \leq \epsilon_s(\mathbf{x}).$$

3. **Consistency.** For every shadow randomness $\gamma \in \{0, 1\}^{r_F}$, verifier randomness $\rho \in \{0, 1\}^r$, $\tilde{\Pi}$ and $\tilde{\Pi}'$ such that $\tilde{\Pi}[Q] = \tilde{\Pi}'[Q]$, where Q is the query set of the PCP verifier $\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho)$:

$$\mathsf{D}(\mathbf{x}, z, \rho) = \mathsf{D}(\mathbf{x}, z', \rho),$$

where $z := \mathsf{F}(\mathbf{x}, \tilde{\Pi}; \gamma)$ and $z' := \mathsf{F}(\mathbf{x}, \tilde{\Pi}'; \gamma)$.

Moreover, we say that PCP has shadow state size s_{PCP} if F outputs at most s_{PCP} bits. F has size at most t_F and D has size at most t_D .

In our construction of SNARG (Section 6), we actually rely on a stronger sparsity property, called the *product sparsity*.

Definition 4.2 (Product sparsity). *We say PCP = (\mathbf{P}, \mathbf{V}) has shadow soundness with product sparsity with product parameter t if there exists a deterministic algorithm D' such that for every \mathbf{x} , z , and $\rho = (\rho_1, \dots, \rho_t)$ where $\rho_i \in \{0, 1\}^{\frac{r}{t}}$,*

$$\mathsf{D}(\mathbf{x}, z, \rho) = \bigwedge_{i \in [t]} \mathsf{D}'(\mathbf{x}, z, \rho_i).$$

Moreover, there exists an efficiently computable set Z where $\mathsf{Im}(\mathsf{F}(\mathbf{x}, \cdot)) \subseteq Z$ such that for any state $z \in Z$ and $i \in [t]$:

$$\Pr \left[\mathsf{D}'(\mathbf{x}, z, \rho_i) = 1 \mid (\rho_1, \dots, \rho_t) \leftarrow \{0, 1\}^{t \cdot \frac{r}{t}} \right] \leq \epsilon_s(\mathbf{x}).$$

Remark 4.3. PCP that satisfies product sparsity with error ϵ_s and product parameter t also satisfies sparsity with error ϵ_s^t . We use product sparsity because in the SNARG construction in Section 6, we use correlation intractable hash functions for sparse product relations (see Theorem 3.8). If there exists correlation intractable hash functions for all sparse relations, it suffices to use plain sparsity.

4.1 Shadow PCP for NP

The theorem below describe the PCP we build to construct the SNARG in Section 6.

Theorem 4.4. *There is a PCP for 3SAT that satisfies the following:*

- *perfect completeness;*
- *soundness error* $\epsilon_{\text{PCP}} = 2^{-(\log n)^2}$;
- *non-adaptive verifier;*
- *query complexity* $q \leq \tilde{O}(n^{\frac{10}{11}})$;
- *randomness complexity* $r \leq \tilde{O}((\log n)^3)$;
- *proof length* $\ell = \tilde{O}(n)$;
- *alphabet* $\{0, 1\}^{O(1)}$;
- *shadow soundness with:*
 1. *shadow state size* $s_T = O(\sqrt{n})$;
 2. *shadow circuit size* $t_T = \text{poly}(n)$;
 3. *shadow randomness complexity* $r_F = 0$;
 4. *product sparsity error* $\epsilon_s = 1/2$ and *product parameter* $t = 1$;
 5. *correctness error* $\epsilon_c = 0$;

Proof. We start by describing the PCP construction, then we present and analyze the circuit that computes its shadow.

PCP construction. Let $\text{PCP} = (\mathbf{P}, \mathbf{V})$ be the PCP for 3SAT in Theorem 3.15. Fix $B \in \mathbb{N}$. Set $t := 2^r/B$. We break $\{0, 1\}^r$ into t consecutive blocks of size B : R_1, \dots, R_t . $\text{PCP}' = (\mathbf{P}', \mathbf{V}')$ works as follows:

- *Generating the proof string:* \mathbf{P}' runs $\mathbf{P}(\mathbf{x}, \mathbf{w})$ to get the PCP proof Π and sends Π to \mathbf{V} .
- *Verifier's checks:*
 1. Sample $b \leftarrow [t]$.
 2. For every $\rho \in R_b$: Check if $\mathbf{V}^\Pi(\mathbf{x}; \rho) = 1$.

We claim that the soundness error of PCP' is ϵ_{PCP} . Note that by soundness of PCP , there are at most $\epsilon_{\text{PCP}} \cdot 2^r$ many accepting verifier randomness. Therefore, there are at most $\frac{\epsilon_{\text{PCP}} \cdot 2^r}{B} = \epsilon_{\text{PCP}} \cdot t$ many randomness blocks that contain only accepting verifier randomness. Therefore, \mathbf{V}' accepts with probability at most ϵ_{PCP} . Hence, PCP' satisfies the following:

- non-adaptive verifier;
- perfect completeness;
- soundness error ϵ_{PCP} ;
- proof length ℓ ;
- randomness complexity $\log t$;
- query complexity $q \cdot B$;
- alphabet Σ .

Shadow circuit construction. The following circuit F gives shadow soundness for 3SAT:

$\mathsf{F}(\mathbf{x}, \tilde{\Pi})$:

1. For every PCP verifier randomness $\rho \in \{0, 1\}^r$: let $b_\rho := \mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho)$.

2. Initialize $z := 0^t$.
3. For every randomness block $b \in [t]$: let $z[b] := \bigwedge_{\rho \in R_b} z_\rho$.
4. Output z .

It's easy to see that the circuit size of F is $\text{poly}(n)$. Moreover, the shadow state size is $\sqrt{2^r}$ if we choose $B := \sqrt{2^r}$.

Correctness. Fix $\tilde{\Pi}$ and PCP verifier randomness b . F computes exactly the new PCP verifier \mathbf{V}' .

Sparsity. Since the soundness error of PCP' is $1/2$ and the correctness error for the shadow circuit is 0 , the sparsity error is $1/2$.

Consistency. This follows directly from the structure of PCP' . □

4.2 Amplification of shadow soundness

We prove a parallel repetition theorem for amplifying shadow soundness of PCP.

Theorem 4.5. *Consider PCP that satisfies the following:*

- *perfect completeness;*
- *soundness error ϵ_{PCP} ;*
- *proof length ℓ ;*
- *randomness complexity r ;*
- *query complexity q ;*
- *alphabet Σ ;*
- *shadow soundness with:*
 1. shadow state size s_{PCP} ;
 2. shadow circuit size t_{F} ;
 3. shadow randomness complexity r_{F} ;
 4. sparsity error ϵ_s ;
 5. correctness error ϵ_c .

Let $\text{PCP}_t := \text{PR}[\text{PCP}, t]$ be the t -wise parallel repetition of PCP specified in Construction 4.7. PCP_t satisfies the following:

- *perfect completeness;*
- *soundness error ϵ_{PCP}^t ;*
- *proof length ℓ ;*
- *randomness complexity $t \cdot r$;*
- *query complexity $t \cdot q$;*
- *alphabet Σ ;*
- *shadow soundness with:*
 1. shadow state size s_{PCP} ;
 2. shadow circuit size t_{F} ;
 3. shadow randomness complexity r_{F} ;
 4. product sparsity error ϵ_s and product parameter t ;
 5. correctness error $2t \cdot \epsilon_c$.

Corollary 4.6. *There is a PCP for 3SAT that satisfies the following:*

- *perfect completeness*;
- *soundness error* $\epsilon_{\text{PCP}} = 2^{-(\log n)^2}$;
- *non-adaptive verifier*;
- *query complexity* $q \leq \tilde{O}(n^{\frac{10}{11}})$;
- *randomness complexity* $r \leq \tilde{O}((\log n)^3)$;
- *proof length* $\ell = \tilde{O}(n)$;
- *alphabet* $\{0, 1\}^{O(1)}$;
- *shadow soundness with*:
 1. *shadow state size* $s_T = O(\sqrt{n})$;
 2. *shadow circuit size* $t_T = \text{poly}(n)$;
 3. *shadow randomness complexity* $r_F = 0$;
 4. *product sparsity error* $\epsilon_s = 1/2$ and *product parameter* $t = (\log n)^2$;
 5. *correctness error* $\epsilon_c = 0$;

Construction 4.7. Consider $\text{PCP} = (\mathbf{P}, \mathbf{V})$. We first recall how the t -wise parallel repetition $\text{PCP}_t = (\vec{\mathbf{P}}, \vec{\mathbf{V}})$ works:

- **Generating the PCP proof:** $\vec{\mathbf{P}}$ computes $\Pi \leftarrow \mathbf{P}(\mathbf{x}, \mathbf{w})$ and sends Π to $\vec{\mathbf{V}}$.
- **Verifier's checks:**
 1. $\vec{\mathbf{V}}$ samples $(\rho_1, \dots, \rho_t) \leftarrow \{0, 1\}^{t \cdot r}$.
 2. $\vec{\mathbf{V}}$ accepts iff for every $i \in [t]$, $\mathbf{V}^\Pi(\mathbf{x}; \rho_i) = 1$.

Soundness. We show that the soundness error of PCP_t is ϵ_{PCP}^t . Let $\tilde{\Pi}$ be a malicious PCP proof string. We bound the following probability:

$$\begin{aligned} & \Pr \left[\vec{\mathbf{V}}^{\tilde{\Pi}}(\mathbf{x}; \rho_1, \dots, \rho_t) = 1 \mid (\rho_1, \dots, \rho_t) \leftarrow \{0, 1\}^{t \cdot r} \right] \\ &= \left(\Pr \left[\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho) = 1 \mid \rho \leftarrow \{0, 1\}^r \right] \right)^t \\ &\leq \epsilon_{\text{PCP}}^t. \end{aligned}$$

Tree algorithm. Let T be the tree algorithm for PCP and D be the decider. We construct T_t, D_t for PCP_t as follows:

- $T_t(\mathbf{x}, \Pi; \gamma)$: Output $z := T(\mathbf{x}, \Pi; \gamma)$.
- $D_t(\mathbf{x}, z, \rho_i)$: Output 1 iff $D(\mathbf{x}, z, \rho_i) = 1$.

We first analyze the product sparsity. Fix $z \in \text{Im}(T_t)$. For every $i \in [t]$, we bound the following probability:

$$\Pr \left[D_t(\mathbf{x}, z, \rho_i) = 1 \mid (\rho_1, \dots, \rho_t) \leftarrow \{0, 1\}^{t \cdot r} \right] \leq \epsilon_s.$$

Now we analyze correctness. Fix $\tilde{\Pi}$ and verifier randomness $(\rho_1, \dots, \rho_t) \leftarrow \{0, 1\}^{t \cdot r}$. We bound the following probability:

$$\Pr \left[\vec{\mathbf{V}}^{\tilde{\Pi}}(\mathbf{x}; \rho_1, \dots, \rho_t) \neq \bigwedge_{i \in [t]} D_t(\mathbf{x}, z, \rho_i) \mid \begin{array}{l} \gamma \leftarrow \{0, 1\}^{r_T} \\ z := T_t(\mathbf{x}, \tilde{\Pi}; \gamma) \end{array} \right]$$

$$\begin{aligned}
&= \Pr \left[\begin{array}{l} \forall i \in [t], \mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho_i) = 1 \\ \wedge \exists i \in [t], \mathsf{D}(\mathbf{x}, z, \rho_i) = 0 \end{array} \middle| \begin{array}{l} \gamma \leftarrow \{0, 1\}^{r\tau} \\ z := \mathsf{T}(\mathbf{x}, \tilde{\Pi}; \gamma) \end{array} \right] \\
&\quad + \Pr \left[\begin{array}{l} \exists i \in [t], \mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho_i) = 0 \\ \wedge \forall i \in [t], \mathsf{D}(\mathbf{x}, z, \rho_i) = 1 \end{array} \middle| \begin{array}{l} \gamma \leftarrow \{0, 1\}^{r\tau} \\ z := \mathsf{T}(\mathbf{x}, \tilde{\Pi}; \gamma) \end{array} \right] \\
&\leq 2t \cdot \epsilon_c.
\end{aligned}$$

5 Function vector commitment scheme

We introduce a new notion of vector commitment schemes, called *function vector commitment (VC) scheme*, that allow one to commit to a vector m relative a function f . Specifically, *(statistical) binding* requires that for every $m \neq m'$ such that $f(m) \neq f(m')$, the corresponding commitments \mathbf{cm} and \mathbf{cm}' are distinct. In fact, we enforce a stronger property, called *function statistically binding*, which requires that, given a trapdoor, a commitment and a set of accepting local openings, an (inefficient) extractor can recover m that is consistent with both the commitment and the local openings.

We begin by formally defining function VC in Section 5.1. Then, in Section 5.2, we construct a function VC for polynomial-size circuits.

5.1 Definition

A *function vector commitment (VC) scheme* over alphabet Σ for a family of function \mathcal{F} is a tuple of algorithms

$$\text{VC} = (\text{VC.Gen}, \text{VC.Commit}, \text{VC.Open}, \text{VC.Check}, \text{VC.Extract})$$

with the following syntax:

- $\text{VC.Gen}(1^\lambda, f) \rightarrow (\mathbf{pp}, \mathbf{td})$: On input a security parameter $\lambda \in \mathbb{N}$ and description of a function f , VC.Gen samples public parameter \mathbf{pp} and a corresponding trapdoor \mathbf{td} .
- $\text{VC.Commit}(\mathbf{pp}, m) \rightarrow (\mathbf{cm}, \mathbf{aux})$: On input a public parameter \mathbf{pp} and a message m , VC.Commit produces a commitment \mathbf{cm} and the corresponding auxiliary state \mathbf{aux} .
- $\text{VC.Open}(\mathbf{pp}, \mathbf{aux}, Q) \rightarrow \mathbf{pf}$: On input a public parameter \mathbf{pp} , an auxiliary state \mathbf{aux} , and a query set $Q \subseteq [\ell]$, VC.Open outputs an opening proof string \mathbf{pf} attesting that $m[Q]$ is a restriction of m to Q .
- $\text{VC.Check}(\mathbf{pp}, \mathbf{cm}, Q, a, \mathbf{pf}) \rightarrow \{0, 1\}$: On input a public parameter \mathbf{pp} , a commitment \mathbf{cm} , a query set $Q \subseteq [\ell]$, an answer string $a \in \Sigma^Q$, and an opening proof string \mathbf{pf} , VC.Check determines if \mathbf{pf} is a valid proof for $a \in \Sigma^Q$ being a restriction of the message committed in \mathbf{cm} to Q .
- $\text{VC.Extract}(\mathbf{td}, \mathbf{cm}) \rightarrow y$: On input the trapdoor \mathbf{td} and a commitment \mathbf{cm} , VC.Extract outputs deterministically a string y .

Moreover, VC has the following property.

Definition 5.1 (Completeness). *VC has perfect completeness if for every security parameter $\lambda \in \mathbb{N}$, message $m \in \Sigma^\ell$, auxiliary function $f \in \mathcal{F}$, and query set $Q \subseteq [\ell]$,*

$$\Pr \left[\text{VC.Check}(\mathbf{pp}, \mathbf{cm}, Q, m[Q], \mathbf{pf}) = 1 \middle| \begin{array}{l} (\mathbf{pp}, \mathbf{td}) \leftarrow \text{VC.Gen}(1^\lambda, f) \\ (\mathbf{cm}, \mathbf{aux}) \leftarrow \text{VC.Commit}(\mathbf{pp}, m) \\ \mathbf{pf} \leftarrow \text{VC.Open}(\mathbf{pp}, \mathbf{aux}, Q) \end{array} \right] = 1.$$

Definition 5.2 (Function hiding). *VC is functional-hiding if for every security parameter $\lambda \in \mathbb{N}$, auxiliary functions $f, f' \in \mathcal{F}$, and t_{VC} -size adversary A_{VC} ,*

$$\begin{aligned} & \left| \Pr \left[A_{\text{VC}}(\mathbf{pp}) = 1 \middle| (\mathbf{pp}, \mathbf{td}) \leftarrow \text{VC.Gen}(1^\lambda, f) \right] - \Pr \left[A_{\text{VC}}(\mathbf{pp}) = 1 \middle| (\mathbf{pp}, \mathbf{td}) \leftarrow \text{VC.Gen}(1^\lambda, f') \right] \right| \\ & \leq z_{\text{VC}}(\lambda, t_{\text{VC}}). \end{aligned}$$

Definition 5.3 (Function statistically binding). *VC is **function statistically binding** if for every security parameter $\lambda \in \mathbb{N}$, auxiliary function $f \in \mathcal{F}$, adversary size $t_{\text{VC}} \in \mathbb{N}$, and t_{VC} -size adversary A_{VC} , the following holds:*

$$\Pr \left[\begin{array}{l} \text{VC.Check(pp, cm, Q, a, pf)} = 1 \\ \wedge \forall \tilde{m} : (\tilde{m}[Q] \neq a \vee f(\tilde{m}) \neq y) \end{array} \middle| \begin{array}{l} (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, f) \\ (\text{cm}, Q, a, pf) := A_{\text{VC}}(\text{pp}) \\ y := \text{VC.Extract}(\text{td}, \text{cm}) \end{array} \right] \leq \kappa_{\text{VC}}(\lambda, t_{\text{VC}}).$$

Similarly to the FHE randomness hiding property Lemma 3.25, the following lemma states that no efficient adversary can guess the randomness of the function with high probability. This property is useless in the analysis of SNARG soundness in Section 6.2.

Lemma 5.4 (Randomness hiding). *Fix VC. For every $\lambda \in \mathbb{N}$, randomized function f , adversary size $t_{\text{VC}} \in \mathbb{N}$, and t_{VC} -time adversary A , the following holds:*

$$\Pr \left[\rho' = \rho \middle| \begin{array}{l} \rho \leftarrow \{0, 1\}^r \\ (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, f_\rho) \\ \rho' \leftarrow A(\text{pp}) \end{array} \right] \leq \frac{1}{2^r} + z_{\text{VC}}(\lambda, t_{\text{VC}}).$$

Proof. Assume for contradiction that there exists an adversary A such that the probability in the lemma statement is greater than $\frac{1}{2^r} + z_{\text{VC}}(\lambda, t_{\text{VC}})$. We construct an adversary A' that breaks the function hiding of VC. Let ρ be a randomly sampled element from $\{0, 1\}^r$.

$A'(\text{pp})$:

1. Run $\rho' \leftarrow A(\text{pp})$.
2. If ρ' is such that $f_\rho = f_{\rho'}$, output 1.
3. Otherwise, output 0.

The following holds:

$$\begin{aligned} & \left| \Pr \left[b = 1 \middle| \begin{array}{l} \rho \leftarrow \{0, 1\}^r \\ (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, \mathbf{0}) \\ b \leftarrow A'(\text{pp}) \end{array} \right] - \Pr \left[b = 1 \middle| \begin{array}{l} \rho \leftarrow \{0, 1\}^r \\ (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, f_\rho) \\ b \leftarrow A'(\text{pp}) \end{array} \right] \right| \\ &= \left| \Pr \left[b = 1 \middle| \begin{array}{l} \rho \leftarrow \{0, 1\}^r \\ (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, f_\rho) \\ b \leftarrow A'(\text{pp}) \end{array} \right] - \frac{1}{2^r} \right| \\ &> \frac{1}{2^r} + z_{\text{VC}}(\lambda, t_{\text{VC}}) - \frac{1}{2^r} \\ &= z_{\text{VC}}(\lambda, t_{\text{VC}}), \end{aligned}$$

where the equality holds since when pp is generated using $\mathbf{0}$, it contains no information about ρ , and thus the output ρ' of A' is independent from sampling ρ and thus $\rho = \rho'$ with probability exactly 2^{-r} , and the inequality holds because of our assumption. \square

5.2 Function VC for circuits

Theorem 5.5. *Assume iO and LWE are the sub-exponentially secure. There exists VC for P/poly with circuit size t and state size s such that for every security parameter $\lambda \in \mathbb{N}$, $\lambda_{\text{FHE}} = \lambda_{\text{FHE}}(\lambda)$, and $\lambda_{\text{SNARG}} = \lambda_{\text{SNARG}}(\lambda)$ VC satisfies the following:*

- *perfect completeness*;
- *for every $c > 1$ and $t_{VC} \leq 2^{\lambda_{FHE}^{1/c}}$, there exists c' such that the function hiding error $z_{VC}(\lambda, t_{VC}) \leq d \cdot 2^{-\lambda_{FHE}^{1/c'}}$;*
- *for every $c > 1$ and t_{VC} where $t_{VC} \leq 2^{\lambda_{SNARG}}$, there exists c' such that the function statistically binding error is at most $\kappa_{VC}(\lambda, t_{VC}) \leq \text{negl}(\lambda_{SNARG})$;*
- *commitment size $s \cdot \text{poly}(\lambda_{FHE})$;*
- *public parameter size $\text{poly}(\lambda, \lambda_{SNARG}, \lambda_{FHE}, t)$;*
- *trapdoor size $\text{poly}(\lambda_{FHE})$;*
- *proof size $\text{poly}(\lambda_{SNARG})$.*

Let $\mathbf{FHE} = (\mathbf{FHE}.\mathbf{Gen}, \mathbf{FHE}.\mathbf{Enc}, \mathbf{FHE}.\mathbf{Eval}, \mathbf{FHE}.\mathbf{Dec})$ be the FHE in Theorem 3.23. For every x , let \mathcal{U}_x be the universal circuit such that on input a circuit description f , $\mathcal{U}_x(f) := f(x)$. Let $\mathbf{SNARG} = (\mathbf{Setup}, \mathcal{P}, \mathcal{V})$ be the SNARG from Theorem 3.12 for the following language L in \mathbf{NP} :

$$L := \{(\mathbf{pp} = (\mathbf{pk}, \mathbf{ct}_f), \mathbf{cm}, \mathbf{Q}, \mathbf{a}) : \exists m, m[\mathbf{Q}] = \mathbf{a}, \mathbf{FHE}.\mathbf{Eval}(\mathbf{pk}, \mathcal{U}_m, \mathbf{ct}_f) = \mathbf{cm}\}.$$

We construct \mathbf{VC} for circuits as follows:

- $\mathbf{VC}.\mathbf{Gen}(1^\lambda, f)$:
 1. Compute $(\mathbf{pk}, \mathbf{sk}) \leftarrow \mathbf{FHE}.\mathbf{Gen}(1^{\lambda_{FHE}})$.
 2. Compute $\mathbf{ct}_f \leftarrow \mathbf{FHE}.\mathbf{Enc}(\mathbf{pk}, f)$.
 3. Compute $\mathbf{pp}_{SNARG} \leftarrow \mathbf{Setup}(1^{\lambda_{SNARG}})$.
 4. Output $(\mathbf{pp} := (\mathbf{pk}, \mathbf{ct}_f, \mathbf{pp}_{SNARG}), \mathbf{td} := \mathbf{sk})$.
- $\mathbf{VC}.\mathbf{Commit}(\mathbf{pp}, m)$:
 1. Parse \mathbf{pp} as $(\mathbf{pk}, \mathbf{ct}_f, \mathbf{pp}_{SNARG})$.
 2. Compute $\mathbf{cm} := \mathbf{FHE}.\mathbf{Eval}(\mathbf{pk}, \mathcal{U}_m, \mathbf{ct}_f)$.
 3. Output $(\mathbf{cm}, \mathbf{aux} := (\mathbf{cm}, m))$.
- $\mathbf{VC}.\mathbf{Open}(\mathbf{pp}, \mathbf{aux}, \mathbf{Q})$:
 1. Parse \mathbf{pp} as $(\mathbf{pk}, \mathbf{ct}_f, \mathbf{pp}_{SNARG})$.
 2. Set $\mathbf{a} := m[\mathbf{Q}]$.
 3. Output $\mathbf{pf} \leftarrow \mathcal{P}(\mathbf{pp}_{SNARG}, \mathbf{cm}, \mathbf{Q}, \mathbf{a})$.
- $\mathbf{VC}.\mathbf{Check}(\mathbf{pp}, \mathbf{cm}, \mathbf{Q}, \mathbf{a}, \mathbf{pf})$:
 1. Parse \mathbf{pp} as $(\mathbf{pk}, \mathbf{ct}_f, \mathbf{pp}_{SNARG})$.
 2. Output $\mathcal{V}((\mathbf{pp}_{SNARG}, \mathbf{cm}, \mathbf{Q}, \mathbf{a}), \mathbf{pf})$.
- $\mathbf{VC}.\mathbf{Extract}(\mathbf{td}, \mathbf{cm})$:
 1. Parse \mathbf{td} as \mathbf{sk} .
 2. Output $\mathbf{FHE}.\mathbf{Dec}(\mathbf{sk}, \mathbf{cm})$.

Completeness. Completeness follows from completeness of \mathbf{SNARG} .

Function hiding. $z_{VC}(\lambda, A_{VC}) \leq \epsilon_{FHE}(\lambda, A_{VC})$ from semantic security of \mathbf{FHE} .

Function statistically binding. We bound the following probability:

$$\begin{aligned}
& \Pr \left[\begin{array}{l} \text{VC.Check}(\text{pp}, \text{cm}, \text{Q}, \text{a}, \text{pf}) = 1 \\ \wedge \forall \tilde{m} : (\tilde{m}[\text{Q}] \neq \text{a} \vee f(\tilde{m}) \neq y) \end{array} \middle| \begin{array}{l} ((\text{pk}, \text{ct}_f, \text{pp}_{\text{SNARG}}), \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, f) \\ (\text{cm}, \text{Q}, \text{a}, \text{pf}) := A_{\text{VC}}(\text{pp}) \\ y := \text{VC.Extract}(\text{td}, \text{cm}) \end{array} \right] \\
&= \Pr \left[\begin{array}{l} \mathcal{V}((\text{pp}_{\text{SNARG}}, \text{cm}, \text{Q}, \text{a}), \text{pf}) = 1 \\ \wedge \forall \tilde{m} : (\tilde{m}[\text{Q}] \neq \text{a} \vee f(\tilde{m}) \neq y) \end{array} \middle| \begin{array}{l} ((\text{pk}, \text{ct}_f, \text{pp}_{\text{SNARG}}), \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, f) \\ (\text{cm}, \text{Q}, \text{a}, \text{pf}) := A_{\text{VC}}(\text{pp}) \\ y := \text{VC.Extract}(\text{td}, \text{cm}) \end{array} \right] \\
&= \Pr \left[\begin{array}{l} \mathcal{V}((\text{pp}_{\text{SNARG}}, \text{cm}, \text{Q}, \text{a}), \text{pf}) = 1 \\ \wedge \forall \tilde{m} : (\tilde{m}[\text{Q}] \neq \text{a} \vee f(\tilde{m}) \neq y) \\ \wedge \exists m : (m[\text{Q}] = \text{a} \wedge \text{FHE.Eval}(\text{pk}, \mathcal{U}_m, \text{ct}_f) = \text{cm}) \end{array} \middle| \begin{array}{l} ((\text{pk}, \text{ct}_f, \text{pp}_{\text{SNARG}}), \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, f) \\ (\text{cm}, \text{Q}, \text{a}, \text{pf}) := A_{\text{VC}}(\text{pp}) \\ y := \text{VC.Extract}(\text{td}, \text{cm}) \end{array} \right] \\
&+ \Pr \left[\begin{array}{l} \mathcal{V}((\text{pp}_{\text{SNARG}}, \text{cm}, \text{Q}, \text{a}), \text{pf}) = 1 \\ \wedge \forall \tilde{m} : (\tilde{m}[\text{Q}] \neq \text{a} \vee f(\tilde{m}) \neq y) \\ \wedge \forall m : (m[\text{Q}] \neq \text{a} \vee \text{FHE.Eval}(\text{pk}, \mathcal{U}_m, \text{ct}_f) \neq \text{cm}) \end{array} \middle| \begin{array}{l} (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, f) \\ (\text{cm}, \text{Q}, \text{a}, \text{pf}) := A_{\text{VC}}(\text{pp}) \\ y := \text{VC.Extract}(\text{td}, \text{cm}) \end{array} \right] \\
&= 0 + \epsilon_{\text{SNARG}}(\lambda, A_{\text{VC}}).
\end{aligned}$$

6 SNARG from function VC and shadow PCP

Theorem 6.1. *Fix a family of functions \mathcal{F} . Let PCP be a shadow PCP for 3SAT with a shadow function in \mathcal{F} that satisfies the following:*

- *perfect completeness;*
- *query complexity q ;*
- *shadow soundness with:*
 1. *shadow state size s_T ;*
 2. *shadow circuit size t_T ;*
 3. *shadow randomness complexity r_F ;*
 4. *product sparsity error ϵ_s and product parameter t ;*
 5. *correctness error ϵ_c .*

Let VC be a function VC for \mathcal{F} that satisfies the following:

- *perfect completeness;*
- *the function hiding error $z_{VC} = z_{VC}(\lambda, t_{VC})$;*
- *function statistically binding error $\kappa_{VC} = \kappa_{VC}(\lambda, t_{VC})$;*
- *commitment size s_{cm} ;*
- *public parameter size s_{pp} ;*
- *proof size s_{pf} .*

Let \mathcal{H}_{CI} be a correlation-intractable hash family for sparse product relations that satisfies the following:

- *error $\epsilon_{CI} = \epsilon_{CI}(\lambda, t_{CI})$;*
- *hash key size s_{CI} .*

Let SNARG be the argument constructed in Section 6.1. For every $\lambda \in \mathbb{N}$, instance $\mathbf{x} \notin L(R)$, and circuit size bound $t_{SNARG} \in \mathbb{N}$, assume $t_{SNARG} = \text{poly}(n)$, the non-adaptive soundness error ϵ_{SNARG} of SNARG satisfies:

$$\epsilon_{SNARG}(\lambda, t_{SNARG}) \leq z_{VC}(\lambda, O(t_{SNARG})) + \kappa_{VC}(\lambda, O(t_{SNARG})) + \epsilon_{CI}(\lambda, O(t_{SNARG})) + \epsilon_c + \epsilon_c \cdot 2^{r_F} \cdot z_{VC}(t_{VC}),$$

where $t_{VC} = O(t_{SNARG} + 2^{r_F} \cdot s_{PCP} + t_D)$. The proof size as of SNARG satisfies:

$$as \leq s_{cm} + q \cdot \log \ell + q \cdot \log |\Sigma| + s_{pf}.$$

The public parameter size s_{pp} of SNARG satisfies:

$$s_{pp} \leq s_{pp} + s_{CI}.$$

Corollary 6.2. *Assume iO and LWE are sub-exponentially hard. The Micali SNARG has non-adaptive soundness error $\epsilon_{SNARG} = \text{negl}(\lambda)$, argument size $\tilde{O}(\sqrt{n}) \cdot \text{poly}(\lambda)$, and public parameter size $\text{poly}(\lambda, n)$.*

Proof. We apply Theorem 6.1 with the PCP from Corollary 4.6, the VC from Theorem 5.5, and the CIH from Theorem 3.8. Set $\lambda_{FHE} := \lambda$ and $\lambda_{SNARG} := \lambda$.

Soundness error. Since $t_{SNARG} = \text{poly}(n) < 2^{\lambda_{FHE}^{1/c}}$ for some $c > 1$, $z_{VC}(\lambda, t_{SNARG}) = \text{negl}(n)$. Similarly, $\kappa_{VC}(\lambda, t_{SNARG}) = \text{negl}(n)$. We know that $\epsilon_{CI}(\lambda, t_{SNARG}) = \text{negl}(\lambda)$ because $\epsilon_s = 1/2$ with product parameter $\text{polylog}(n)$. Also, $\epsilon_c = 0$.

Proof size. We bound the size of cm , (Q, a) , and pf separately.

- *Commitment size:* Note that the PCP shadow has state size $O(\sqrt{n})$. According to Theorem 5.5, the size of the commitment \mathbf{cm} is $\sqrt{n} \cdot \mathbf{poly}(\lambda_{\mathsf{FHE}}) = O(\sqrt{n}) \cdot \mathbf{poly}(\lambda)$.
- *Query and answer size:* PCP has proof length $\ell = \tilde{O}(n)$, query complexity $\mathbf{q} \leq O(\sqrt{n})$, and alphabet $\{0, 1\}^{O(1)}$. Hence, we need $O(\mathbf{q} \cdot \log \ell) = \tilde{O}(\sqrt{n})$ bits to represent \mathbf{Q} and $O(\mathbf{q}) = O(\sqrt{n})$ bits to represent \mathbf{a} . In total, $|\mathbf{Q}| + |\mathbf{a}| = \tilde{O}(\sqrt{n})$.
- *Opening proof size:* According to Theorem 5.5, the size of \mathbf{pf} is $\mathbf{poly}(\lambda_{\mathsf{SNARG}}) = \mathbf{poly}(\log n, \lambda)$. Therefore, the argument proof size is $\tilde{O}(\sqrt{n}) \cdot \mathbf{poly}\lambda$.

Public parameter size. It is obvious that the size of public parameter is dominated by the size of public parameter of VC, which is $\mathbf{poly}(\lambda, n)$ by Theorem 5.5. □

6.1 SNARG construction

We construct $\mathsf{SNARG} = (\mathsf{Setup}, \mathcal{P}, \mathcal{V})$ as follows:

- $\mathsf{Setup}(1^\lambda)$:

1. Sample $(\mathbf{pp}, \mathbf{td}) \leftarrow \mathsf{VC}.\mathsf{Gen}(1^\lambda, \{0^{s\tau}\})$.
2. Sample $h_{\mathsf{Cl}} \leftarrow \mathcal{H}_{\mathsf{Cl}}(\lambda)$.
3. Output $\mathbf{pp} := (\mathbf{pp}, h_{\mathsf{Cl}})$.

- $\mathcal{P}(\mathbf{pp}, \mathbf{x}, \mathbf{w})$:

1. Parse \mathbf{pp} as $(\mathbf{pp}, h_{\mathsf{Cl}})$.
2. Compute $\Pi \leftarrow \mathbf{P}(\mathbf{x}, \mathbf{w})$.
3. Compute $(\mathbf{cm}, \mathbf{aux}) := \mathsf{VC}.\mathsf{Commit}(\mathbf{pp}, \Pi)$.
4. Compute $\rho := h_{\mathsf{Cl}}(\mathbf{cm})$.
5. Compute the PCP verifier query set \mathbf{Q} using \mathbf{x} , ρ and Π .
6. Compute $\mathbf{pf} := \mathsf{VC}.\mathsf{Open}(\mathbf{pp}, \mathbf{aux}, \mathbf{Q})$ and $\mathbf{a} := \Pi[\mathbf{Q}]$.
7. Output $\pi := (\mathbf{cm}, \mathbf{Q}, \mathbf{a}, \mathbf{pf})$.

- $\mathcal{V}(\mathbf{pp}, \mathbf{x}, \pi)$:

1. Parse \mathbf{pp} as $(\mathbf{pp}, h_{\mathsf{Cl}})$.
2. Parse π as $(\mathbf{cm}, \mathbf{Q}, \mathbf{a}, \mathbf{pf})$.
3. Check the following:
 - $\rho = h_{\mathsf{Cl}}(\mathbf{cm})$;
 - $\mathsf{VC}.\mathsf{Check}(\mathbf{pp}, \mathbf{cm}, \mathbf{Q}, \mathbf{a}, \mathbf{pf}) = 1$;
 - $\mathbf{V}^{[\mathbf{Q}, \mathbf{a}]}(\mathbf{x}; \rho) = 1$.
4. If any of the above checks fail, output 0, otherwise, output 1.

6.2 SNARG soundness

Let F and D be the PCP function and decider, respectively. Let $\tilde{\mathcal{P}}$ be an adversary for the SNARG with running time t_{SNARG} . Our goal is to bound the following probability:

$$\Pr \left[\mathcal{V}(\mathbf{pp}, \mathbf{x}, \pi, \rho) = 1 \mid \begin{array}{l} \mathbf{pp} \leftarrow \mathsf{Setup}(1^\lambda) \\ \pi := \tilde{\mathcal{P}}(\mathbf{pp}) \\ \rho := h_{\mathsf{Cl}}(\mathbf{cm}) \end{array} \right].$$

By definition of the construction, the above can be written as

$$\Pr \left[\begin{array}{l} \text{VC.Check}(\text{pp}, \text{cm}, \text{Q}, \text{a}, \text{pf}) = 1 \\ \wedge \mathbf{V}^{[\text{Q}, \text{a}]}(\text{x}, \rho) = 1 \end{array} \middle| \begin{array}{l} (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, \{0^{s\tau}\}) \\ h_{\text{cl}} \leftarrow \mathcal{H}_{\text{cl}}(\lambda) \\ (\text{cm}, \text{Q}, \text{a}, \text{pf}) := \tilde{\mathcal{P}}(\text{pp}, h_{\text{cl}}) \\ \rho := h_{\text{cl}}(\text{cm}) \end{array} \right].$$

Consider the following adversary A_{VC} for function hiding of VC:

$A_{\text{VC}}(\text{pp})$:

1. Sample $h_{\text{cl}} \leftarrow \mathcal{H}_{\text{cl}}(\lambda)$.
2. Compute $(\text{cm}, \text{Q}, \text{a}, \text{pf}) := \tilde{\mathcal{P}}(\text{pp}, h_{\text{cl}})$.
3. Compute $\rho := h_{\text{cl}}(\text{cm})$.
4. Output 1 iff the following checks pass:
 - (a) $\text{VC.Check}(\text{pp}, \text{cm}, \text{Q}, \text{a}, \text{pf}) = 1$;
 - (b) $\mathbf{V}^{[\text{Q}, \text{a}]}(\text{x}; \rho) = 1$.

The running time of A_{VC} is $O(t_{\text{SNARG}})$. By function hiding of VC, the following holds:

$$\begin{aligned} & \Pr \left[\begin{array}{l} \text{VC.Check}(\text{pp}, \text{cm}, \text{Q}, \text{a}, \text{pf}) = 1 \\ \wedge \mathbf{V}^{[\text{Q}, \text{a}]}(\text{x}; \rho) = 1 \end{array} \middle| \begin{array}{l} (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, \{0^{s\tau}\}) \\ h_{\text{cl}} \leftarrow \mathcal{H}_{\text{cl}}(\lambda) \\ (\text{cm}, \text{Q}, \text{a}, \text{pf}) := \tilde{\mathcal{P}}(\text{pp}, h_{\text{cl}}) \\ \rho := h_{\text{cl}}(\text{cm}) \end{array} \right] \\ &= \Pr [A_{\text{VC}}(\text{pp}) = 1 \mid (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, \{0^{s\tau}\})] \\ &\leq \Pr [A_{\text{VC}}(\text{pp}) = 1 \mid (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, \ell, \mathcal{F}(\text{x}, \cdot))] + z_{\text{VC}}(\lambda, O(t_{\text{SNARG}})) \\ &= \Pr \left[\begin{array}{l} \text{VC.Check}(\text{pp}, \text{cm}, \text{Q}, \text{a}, \text{pf}) = 1 \\ \wedge \mathbf{V}^{[\text{Q}, \text{a}]}(\text{x}; \rho) = 1 \end{array} \middle| \begin{array}{l} (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, \ell, \mathcal{F}(\text{x}, \cdot)) \\ h_{\text{cl}} \leftarrow \mathcal{H}_{\text{cl}}(\lambda) \\ (\text{cm}, \text{Q}, \text{a}, \text{pf}) := \tilde{\mathcal{P}}(\text{pp}, h_{\text{cl}}) \\ \rho := h_{\text{cl}}(\text{cm}) \end{array} \right] + z_{\text{VC}}(\lambda, O(t_{\text{SNARG}})). \end{aligned}$$

Using Definition 5.3, the following upper bounds the probability above:

$$\Pr \left[\begin{array}{l} \mathbf{V}^{[\text{Q}, \text{a}]}(\text{x}; \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[\text{Q}] = \text{a} \wedge \mathcal{F}(\text{x}, \tilde{\Pi}; \gamma) = z \end{array} \middle| \begin{array}{l} (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, \ell, \mathcal{F}(\text{x}, \cdot)) \\ h_{\text{cl}} \leftarrow \mathcal{H}_{\text{cl}}(\lambda) \\ (\text{cm}, \text{Q}, \text{a}, \text{pf}) := \tilde{\mathcal{P}}(\text{pp}, h_{\text{cl}}) \\ \rho := h_{\text{cl}}(\text{cm}) \\ z := \text{VC.Extract}(\text{td}, \text{cm}) \end{array} \right] + \kappa_{\text{VC}}(\lambda, O(t_{\text{SNARG}})).$$

Let us define the experiment above as Exp . Formally, we have:

$$\text{Exp} := \left[\begin{array}{l} (\text{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, \ell, \mathcal{F}(\text{x}, \cdot)) \\ h_{\text{cl}} \leftarrow \mathcal{H}_{\text{cl}}(\lambda) \\ (\text{cm}, \text{Q}, \text{a}, \text{pf}) := \tilde{\mathcal{P}}(\text{pp}, h_{\text{cl}}) \\ \rho = (\rho_1, \dots, \rho_t) := h_{\text{cl}}(\text{cm}) \\ z := \text{VC.Extract}(\text{td}, \text{cm}) \end{array} \right].$$

By the law of total probability, the above probability is equal to:

$$\Pr_{\text{Exp}} \left[\begin{array}{l} \mathbf{V}^{[\text{Q}, \text{a}]}(\text{x}, \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[\text{Q}] = \text{a} \wedge \mathcal{F}(\text{x}, \tilde{\Pi}) = z \\ \wedge \mathbf{D}(\text{x}, z, \rho) = 1 \end{array} \right] + \Pr_{\text{Exp}} \left[\begin{array}{l} \mathbf{V}^{[\text{Q}, \text{a}]}(\text{x}, \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[\text{Q}] = \text{a} \wedge \mathcal{F}(\text{x}, \tilde{\Pi}) = z \\ \wedge \mathbf{D}(\text{x}, z, \rho) = 0 \end{array} \right].$$

We use the security of the CIH and the function VC to bound the above probabilities, respectively.

6.2.1 Security from CIH

Claim 6.3. *Let ϵ_{CI} be the error for the CI hash family \mathcal{H}_{CI} , the following holds:*

$$\Pr_{\text{Exp}} \left[\begin{array}{l} \mathbf{V}^{[\mathbf{Q}, \mathbf{a}]}(\mathbf{x}, \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[\mathbf{Q}] = \mathbf{a} \wedge \mathbf{F}(\mathbf{x}, \tilde{\Pi}) = z \\ \wedge \mathbf{D}(\mathbf{x}, z, \rho) = 1 \end{array} \right] \leq \epsilon_{\text{CI}}(\lambda, O(t_{\text{SNARG}})).$$

Proof. Using the product sparsity of PCP shadow soundness (Definition 4.2), there exists a deterministic algorithm \mathbf{D}' such that for every \mathbf{x} , z , and $\rho = (\rho_1, \dots, \rho_t) \in \{0, 1\}^{t \cdot \frac{r}{t}}$,

$$\mathbf{D}(\mathbf{x}, z, \rho) = \bigwedge_{i \in [t]} \mathbf{D}'(\mathbf{x}, z, \rho_i).$$

For every trapdoor td sampled by $\text{VC}.\text{Gen}$, we define a sparse relation $R_{\mathbf{x}, \text{td}}$:

$$R_{\mathbf{x}, \text{td}} := \left\{ (\mathbf{cm}, \rho) : \begin{array}{l} z := \text{VC}.\text{Extract}(\text{td}, \mathbf{cm}) \\ z \in Z \\ \forall i \in [t], \mathbf{D}'(\mathbf{x}, z, \rho_i) = 1 \end{array} \right\}.$$

We show that for any $\mathbf{x} \notin L(R)$, the relation $R_{\mathbf{x}, \text{td}}$ is a ϵ_s -sparse product relation. For any $\mathbf{cm} \in L(R_{\mathbf{x}, \text{td}})$, (i.e., $\text{VC}.\text{Extract}(\text{td}, \mathbf{cm}) \in Z$), its witness set can be written as follows:

$$\{\rho = (\rho_1, \dots, \rho_t) \in \{0, 1\}^r : \forall i \in [t], \mathbf{D}'(\mathbf{x}, z, \rho_i) = 1\} = S^t,$$

where $S := \{\rho \in \{0, 1\}^{r/t} : \mathbf{D}(\mathbf{x}, z, \rho) = 1\}$. Moreover, by the product sparsity of the shadow soundness of PCP,

$$\begin{aligned} & \Pr \left[(\mathbf{cm}, \rho_i) \in S \mid \rho_i \leftarrow \{0, 1\}^{r/t} \right] \\ &= \Pr \left[\mathbf{D}'(\mathbf{x}, z, \rho_i) = 1 \mid \begin{array}{l} z := \text{VC}.\text{Extract}(\text{td}, \mathbf{cm}) \\ \rho_i \leftarrow \{0, 1\}^{r/t} \end{array} \right] \\ &\leq \epsilon_s. \end{aligned}$$

We construct an adversary $\mathbf{A}_{\mathbf{x}}$ against the CIH hash using the relation $R_{\mathbf{x}, \text{td}}$ as follows:

- $\mathbf{A}_{\mathbf{x}}$:

1. Sample $\gamma \leftarrow \{0, 1\}^{r_F}$.
2. Sample $(\mathbf{pp}, \text{td}) \leftarrow \text{VC}.\text{Gen}(1^\lambda, \mathbf{F}(\mathbf{x}, \cdot; \gamma))$.
3. Output $\mathbf{aux} := (\mathbf{pp}, \text{td})$.

- $\mathbf{A}_{\mathbf{x}}(\mathbf{aux}, h_{\text{CI}})$:

1. Parse \mathbf{aux} as (\mathbf{pp}, td) .
2. Compute $(\mathbf{cm}, \mathbf{Q}, \mathbf{a}, \mathbf{pf}) := \tilde{\mathcal{P}}(\mathbf{pp}, h_{\text{CI}})$.
3. Output \mathbf{cm} .

We can conclude that:

$$\begin{aligned}
& \Pr_{\text{Exp}} \left[\begin{array}{l} \mathbf{V}^{[Q,a]}(\mathbf{x}, \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[Q] = a \wedge F(\mathbf{x}, \tilde{\Pi}; \gamma) = z \\ \wedge D(\mathbf{x}, z, \rho) = 1 \end{array} \right] \\
& \leq \Pr \left[(cm, \rho) \in R_{\mathbf{x}, \text{td}} \left| \begin{array}{l} (\mathbf{pp}, \text{td}) \leftarrow A_{\mathbf{x}} \\ h_{\text{cl}} \leftarrow \mathcal{H}_{\text{cl}}(\lambda) \\ cm := A_{\mathbf{x}}((\mathbf{pp}, \text{td}), h_{\text{cl}}) \\ \rho := h_{\text{cl}}(cm) \end{array} \right. \right] \\
& = \Pr \left[(cm, h_{\text{cl}}(cm)) \in R_{\mathbf{x}, \text{td}} \left| \begin{array}{l} (\mathbf{pp}, \text{td}) \leftarrow A_{\mathbf{x}} \\ h_{\text{cl}} \leftarrow \mathcal{H}_{\text{cl}}(\lambda) \\ cm := A_{\mathbf{x}}((\mathbf{pp}, \text{td}), h_{\text{cl}}) \end{array} \right. \right] \\
& \leq \epsilon_{\text{cl}}(\lambda, \epsilon_s, O(t_{\text{SNARG}})) .
\end{aligned}$$

□

6.2.2 Security from FVC

Claim 6.4. *Let z_{VC} be the function hiding error of VC, the following holds:*

$$\Pr_{\text{Exp}} \left[\begin{array}{l} \mathbf{V}^{[Q,a]}(\mathbf{x}, \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[Q] = a \wedge F(\mathbf{x}, \tilde{\Pi}; \gamma) = z \\ \wedge D(\mathbf{x}, z, \rho) = 0 \end{array} \right] \leq \epsilon_c + \epsilon_c \cdot 2^{r_F} \cdot z_{\text{VC}}(t_{\text{VC}}) ,$$

where $t_{\text{VC}} = O(t_{\text{SNARG}} + 2^{r_F} \cdot s_{\text{PCP}} + t_D)$.

Proof. According to PCP shadow consistency Definition 4.1, the following holds:

$$\begin{aligned}
& \Pr_{\text{Exp}} \left[\begin{array}{l} \mathbf{V}^{[Q,a]}(\mathbf{x}, \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[Q] = a \wedge F(\mathbf{x}, \tilde{\Pi}; \gamma) = z \\ \wedge D(\mathbf{x}, z, \rho) = 0 \end{array} \right] \\
& = \Pr \left[\begin{array}{l} \mathbf{V}^{[Q,a]}(\mathbf{x}, \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[Q] = a \wedge F(\mathbf{x}, \tilde{\Pi}; \gamma) = z \\ \wedge D(\mathbf{x}, z, \rho) = 0 \end{array} \left| \begin{array}{l} \gamma \leftarrow \{0, 1\}^{r_F} \\ (\mathbf{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, \ell, F(\mathbf{x}, \cdot; \gamma)) \\ h_{\text{cl}} \leftarrow \mathcal{H}_{\text{cl}}(\lambda) \\ (cm, Q, a, pf) := \tilde{\mathcal{P}}(\mathbf{pp}, h_{\text{cl}}) \\ \rho := h_{\text{cl}}(cm) \\ z := \text{VC.Extract}(\text{td}, cm) \end{array} \right. \right] \\
& \leq \Pr \left[\begin{array}{l} \mathbf{V}^{[Q,a]}(\mathbf{x}, \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[Q] = a \wedge F(\mathbf{x}, \tilde{\Pi}; \gamma) = z \\ \wedge D(\mathbf{x}, z, \rho) = 0 \\ \wedge \mathbf{D}(\mathbf{x}, z', \rho) = 0 \end{array} \left| \begin{array}{l} \gamma \leftarrow \{0, 1\}^{r_F} \\ (\mathbf{pp}, \text{td}) \leftarrow \text{VC.Gen}(1^\lambda, \ell, F(\mathbf{x}, \cdot; \gamma)) \\ h_{\text{cl}} \leftarrow \mathcal{H}_{\text{cl}}(\lambda) \\ (cm, Q, a, pf) := \tilde{\mathcal{P}}(\mathbf{pp}, h_{\text{cl}}) \\ \rho := h_{\text{cl}}(cm) \\ z := \text{VC.Extract}(\text{td}, cm) \\ \tilde{\Pi}' := \sigma^\ell \\ \tilde{\Pi}'[Q] := a \\ z' := F(\mathbf{x}, \tilde{\Pi}'; \gamma) \end{array} \right. \right] .
\end{aligned}$$

We define the last experiment above as Exp' .

First note that

$$\Pr_{\text{Exp}'} \left[\begin{array}{l} \mathbf{V}^{[Q,a]}(\mathbf{x}, \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[Q] = a \wedge F(\mathbf{x}, \tilde{\Pi}; \gamma) = z \\ \wedge D(\mathbf{x}, z, \rho) = 0 \\ \wedge D(\mathbf{x}, z', \rho) = 0 \end{array} \right] \leq \Pr_{\text{Exp}'} \left[\begin{array}{l} \mathbf{V}^{[Q,a]}(\mathbf{x}, \rho) = 1 \\ \wedge D(\mathbf{x}, z', \rho) = 0 \end{array} \right].$$

For every \mathbf{x} , ρ , and $\tilde{\Pi}$, we define the set

$$S_{\mathbf{x}, \rho, \tilde{\Pi}} := \{\gamma \in \{0, 1\}^{r_F} : D(\mathbf{x}, F(\mathbf{x}, \tilde{\Pi}; \gamma), \rho) = 0\}.$$

By correctness of PCP shadow soundness (Definition 4.1), we know that for every $\mathbf{x} \notin L(R)$, $\tilde{\Pi}$ and every ρ such that $\mathbf{V}^{\tilde{\Pi}}(\mathbf{x}; \rho) = 1$,

$$\Pr \left[D(\mathbf{x}, z, \rho) = 0 \mid \begin{array}{l} \gamma \leftarrow \{0, 1\}^{r_T} \\ z := F(\mathbf{x}, \tilde{\Pi}; \gamma) \end{array} \right] \leq \epsilon_c(\mathbf{x}).$$

Therefore,

$$|S_{\mathbf{x}, \rho, \tilde{\Pi}}| \leq \epsilon_c(\mathbf{x}) \cdot 2^{r_F}.$$

We can deduce that,

$$\Pr_{\text{Exp}'} \left[\begin{array}{l} \mathbf{V}^{[Q,a]}(\mathbf{x}, \rho) = 1 \\ \wedge D(\mathbf{x}, z', \rho) = 0 \end{array} \right] \leq \Pr_{\text{Exp}'} \left[\begin{array}{l} \mathbf{V}^{\tilde{\Pi}'}(\mathbf{x}; \rho) = 1 \\ \wedge \gamma \in S_{\mathbf{x}, \rho, \tilde{\Pi}'} \end{array} \right] \leq \Pr_{\text{Exp}'} \left[\begin{array}{l} |S_{\mathbf{x}, \rho, \tilde{\Pi}'}| \leq \epsilon_c(\mathbf{x}) \cdot 2^{r_F} \\ \wedge \gamma \in S_{\mathbf{x}, \rho, \tilde{\Pi}'} \end{array} \right].$$

By definition of conditional probability, we can deduce that

$$\begin{aligned} & \Pr_{\text{Exp}'} \left[\begin{array}{l} |S_{\mathbf{x}, \rho, \tilde{\Pi}'}| \leq \epsilon_c(\mathbf{x}) \cdot 2^{r_F} \\ \wedge \gamma \in S_{\mathbf{x}, \rho, \tilde{\Pi}'} \end{array} \right] \\ &= \Pr_{\substack{\text{Exp}' \\ \gamma^* \leftarrow S_{\mathbf{x}, \rho, \tilde{\Pi}'}}} \left[\begin{array}{l} \gamma^* = \gamma \\ \wedge |S_{\mathbf{x}, \rho, \tilde{\Pi}'}| \leq \epsilon_c(\mathbf{x}) \cdot 2^{r_F} \\ \wedge \gamma \in S_{\mathbf{x}, \rho, \tilde{\Pi}'} \end{array} \right] \left(\Pr_{\substack{\text{Exp}' \\ \gamma^* \leftarrow S_{\mathbf{x}, \rho, \tilde{\Pi}'}}} \left[\begin{array}{l} \gamma^* = \gamma \\ \text{conditioned on} \\ |S_{\mathbf{x}, \rho, \tilde{\Pi}'}| \leq \epsilon_c(\mathbf{x}) \cdot 2^{r_F} \\ \wedge \gamma \in S_{\mathbf{x}, \rho, \tilde{\Pi}'} \end{array} \right] \right)^{-1} \\ &\leq \Pr_{\substack{\text{Exp}' \\ \gamma^* \leftarrow S_{\mathbf{x}, \rho, \tilde{\Pi}'}}} [\gamma^* = \gamma] \left(\Pr_{\substack{\text{Exp}' \\ \gamma^* \leftarrow S_{\mathbf{x}, \rho, \tilde{\Pi}'}}} \left[\begin{array}{l} \gamma^* = \gamma \\ \text{conditioned on} \\ |S_{\mathbf{x}, \rho, \tilde{\Pi}'}| \leq \epsilon_c(\mathbf{x}) \cdot 2^{r_F} \\ \wedge \gamma \in S_{\mathbf{x}, \rho, \tilde{\Pi}'} \end{array} \right] \right)^{-1} \\ &\leq \Pr_{\substack{\text{Exp}' \\ \gamma^* \leftarrow S_{\mathbf{x}, \rho, \tilde{\Pi}'}}} [\gamma^* = \gamma] \cdot \epsilon_c(\mathbf{x}) \cdot 2^{r_F}, \end{aligned}$$

where the last inequality follows because

$$\Pr_{\substack{\text{Exp}' \\ \gamma^* \leftarrow S_{\mathbf{x}, \rho, \tilde{\Pi}'}}} \left[\begin{array}{l} \gamma^* = \gamma \\ \text{conditioned on} \\ |S_{\mathbf{x}, \rho, \tilde{\Pi}'}| \leq \epsilon_c(\mathbf{x}) \cdot 2^{r_F} \\ \wedge \gamma \in S_{\mathbf{x}, \rho, \tilde{\Pi}'} \end{array} \right] \geq \frac{1}{\epsilon_c(\mathbf{x}) \cdot 2^{r_F}}.$$

We proceed to bound the remaining probability above.

Consider the following function VC adversary A_{VC} :

$A_{VC}(\mathbf{pp})$:

1. Run $(\mathbf{cm}, \mathbf{Q}, \mathbf{a}, \mathbf{pf}) := \tilde{\mathcal{P}}(\mathbf{pp}, h_{\mathbf{cl}})$.
2. Initialize $\tilde{\Pi}' := (\sigma)^\ell$, where σ is an arbitrary element in Σ .
3. Set $\tilde{\Pi}'[\mathbf{Q}] := \mathbf{a}$.
4. Sample uniformly at random $\gamma^* \leftarrow S_{\mathbf{x}, \rho, \tilde{\Pi}'}$.
5. Output γ^* .

Notice that Step 4 in A_{VC} can be implemented as follows:

1. Initialize an empty set $S := \emptyset$.
2. For every $\gamma \in \{0, 1\}^{r_F}$:
 - Compute $z := \mathbf{F}(\mathbf{x}, \tilde{\Pi}'; \gamma)$.
 - If $D(\mathbf{x}, z, \rho) = 0$ then add γ to S .
3. Sample uniformly at random $\gamma^* \leftarrow S$.
4. Output γ^* .

Hence, the running time of A_{VC} is $t_{VC} = O(t_{SNARG} + 2^{r_F} \cdot s_{PCP} + t_D)$.

From Lemma 5.4 and construction of A_{VC} ,

$$\Pr_{\substack{\mathbf{Exp}' \\ \gamma^* \leftarrow S_{\mathbf{x}, \rho, \tilde{\Pi}'}}} [\gamma^* = \gamma] = \Pr_{\substack{\mathbf{Exp}' \\ \gamma^* \leftarrow A_{VC}(\mathbf{pp}_{VC})}} [\gamma^* = \gamma] \leq \frac{1}{2^{r_F}} + z_{VC}(\lambda, t_{VC}).$$

Hence,

$$\begin{aligned} \Pr_{\mathbf{Exp}'} \left[\begin{array}{l} \mathbf{V}^{[\mathbf{Q}, \mathbf{a}]}(\mathbf{x}, \rho) = 1 \\ \wedge \exists \tilde{\Pi} : \tilde{\Pi}[\mathbf{Q}] = \mathbf{a} \wedge \mathbf{F}(\mathbf{x}, \tilde{\Pi}; \gamma) = z \\ \wedge D(\mathbf{x}, z, \rho) = 0 \\ \wedge D(\mathbf{x}, z', \rho) = 0 \end{array} \right] &\leq \left(\frac{1}{2^{r_F}} + z_{VC}(\lambda, t_{VC}) \right) \cdot \epsilon_{\mathbf{c}}(\mathbf{x}) \cdot 2^{r_F} \\ &= \epsilon_{\mathbf{c}}(\mathbf{x}) + \epsilon_{\mathbf{c}}(\mathbf{x}) \cdot 2^{r_F} \cdot z_{VC}(\lambda, t_{VC}). \end{aligned}$$

□

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