

# New Techniques for Zero-Knowledge: Leveraging Inefficient Provers to Reduce Assumptions, Interaction, and Trust

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**Abstract.** We present a transformation from NIZK with *inefficient provers* in the uniform random string (URS) model to ZAPs (two message witness indistinguishable proofs) with *inefficient provers*. While such a transformation was known for the case where the prover is efficient, the security proof breaks down if the prover is inefficient. Our transformation is obtained via new applications of Nisan-Wigderson *designs*, a combinatorial object originally introduced in the derandomization literature. We observe that our transformation is applicable both in the setting of super-polynomial provers/poly-time adversaries, as well as a new fine-grained setting, where the prover is polynomial time and the verifier/simulator/zero knowledge distinguisher are in a lower complexity class, such as  $\text{NC}^1$ . We also present  $\text{NC}^1$ -fine-grained NIZK in the URS model for all of  $\text{NP}$  from the worst-case assumption  $\oplus L/\text{poly} \not\subseteq \text{NC}^1$ .

Our techniques yield the following applications:

1. ZAPs for AM from Minicrypt assumptions (with super-polynomial time provers),
2.  $\text{NC}^1$ -fine-grained ZAPs for NP from worst-case assumptions,
3. Protocols achieving an “offline” notion of NIZK (oNIZK) in the standard (no-CRS) model with uniform soundness in both the super-polynomial setting (from Minicrypt assumptions) and the  $\text{NC}^1$ -fine-grained setting (from worst-case assumptions). The oNIZK notion is sufficient for use in indistinguishability-based proofs.

## 1 Introduction

A long and important line of research has been dedicated to understanding the necessary and sufficient assumptions for the existence of computational zero knowledge (CZK) proofs (with potentially unbounded provers) for a language  $\mathcal{L}$  [BMO90, OW93, IOS94]. This line of research culminated with the work of Ong and Vadhan [OV08] which fully resolved the question by proving that a language in  $\text{NP}$  has a CZK protocol if and only if the language has an “instance-dependent” commitment scheme. The minimal assumptions required in the *non-interactive* zero knowledge (NIZK) setting—assuming unbounded provers and a common *reference*

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string (CRS)<sup>4</sup> (sometimes called the “public parameters” setting)—are also well-understood. The work of Pass and Shelat [Ps05], showed that (non-uniform) one-way functions are sufficient for NIZK with unbounded provers in the CRS model for all of AM, whereas NIZK with unbounded provers in the CRS model for a hard-on-average language implies the existence of (non-uniform) one-way functions.

While the NIZK of Pass and Shelat [Ps05] indeed minimizes interaction and assumptions, it critically utilizes trusted setup to generate a structured CRS sampled from a particular distribution. In contrast, motivated by concerns of subversion of public parameters [BFS16] and considerations from the blockchain community [BBC<sup>+</sup>17, BBHR18, BBHR19], a recent line of research has focused on “transparent” setup that does not require a trusted party, but simply access to a shared source of public randomness such as the NIST randomness beacon, or a uniform random string (URS).<sup>5</sup> In the URS model, it is well known that NIZK with unbounded provers follows from one-way permutations (OWP) [FLS99]. However, even agreeing upon a genuinely random string to implement the URS model may be infeasible in some cases.

We investigate what can be proven with “zero-knowledge” in a truly trust-free setting, with *minimal interaction and assumptions*. In particular, we extend the above line of work on minimizing assumptions to other types of “zero knowledge” primitives, such as ZAPs (two message witness indistinguishable (WI) proofs), non-interactive witness indistinguishable proofs (NIWI), and, ultimately, a type of NIZK with uniform soundness (and no URS/CRS).

Our primary goal is to understand the relationship between ZAPs and zero-knowledge primitives that can be constructed from minimal assumptions in the *inefficient prover* setting. Once we construct ZAPs, we will show that NIWI and a type of NIZK with uniform soundness can also be constructed (note that while these implications are already known in the efficient-prover setting [BOV07, BP04], hurdles are introduced by removing this constraint). Ultimately, we are interested in obtaining constructions of ZAPs from *Minicrypt* [Imp95] assumptions only.<sup>6</sup> To further motivate our focus on the *inefficient prover* setting, note that barriers are known for constructions of ZAPs from Minicrypt assumptions when the prover is required to be efficient. Indeed, efficient-prover ZAPs are known to be equivalent to efficient-prover NIZK in the URS model [DN07] (assuming one-way functions exist), and efficient-prover NIZKs, in turn, are only known to be achievable from Cryptomania [Imp95] primitives such as (enhanced) trapdoor permutations. (See Section 1.2 for details.)

Because of this dichotomy, we consider the setting where the prover is computationally *more powerful* than the simulator/zero knowledge distinguisher. We refer to this setting as the *inefficient prover* setting. This covers both the setting of super-polynomial provers/polynomial adversary, as well as a new fine-grained setting that we consider for the first time (to the best of our knowledge), where the prover is polynomial time and the verifier/simulator/zero knowledge distinguisher are in a lower complexity class, such as  $\text{NC}^1$  (logarithmic depth, polynomial-size circuits with constant fan-in). Our main technical contribution is a new transformation from inefficient prover NIZK in the URS model to inefficient prover ZAPs. A single transformation works both for the unbounded prover and fine-grained settings. Our transformation is obtained via new applications of Nisan-Wigderson *designs*, a combinatorial object originally introduced in the derandomization literature [NW88]. We also show that fine-grained NIZK in the URS model is achievable from worst-case assumptions ( $\oplus L / \text{poly} \not\subseteq \text{NC}^1$ ). Given the well-known construction of unbounded prover NIZK in the URS model from one-way permutations (via the hidden bits model), we obtain (1) super-poly prover ZAPs for AM from Minicrypt assumptions and (2) fine-grained ZAPs for NP from worst-case assumptions.

<sup>4</sup> Throughout this work we make a distinction between common *reference* string denoted as CRS and uniform random string denoted as URS. URS is sometimes referred to common *random* string in literature. We write URS to avoid the confusion and overloading.

<sup>5</sup> Note that recent work on transparent or trustless (succinct) proofs, typically assumes existence of a public random oracle. We will only consider (at most) *short* public random strings in this work.

<sup>6</sup> We understand Minicrypt to be chiefly characterized by the lack of key agreement (KA), and note that one-way permutations (OWP) are separated from KA via the original Impagliazzo and Rudich separation [IR89]. For the same reason, we consider Collision-Resistant Hashing to be in Minicrypt.

*Technical hurdles introduced by inefficient provers.* When dealing with inefficient provers, one must proceed with care, as many “folklore” results no longer hold. We make the following surprising observation (discussed in more detail in Section 1.1): While it is known that NIZKs in the uniform random string (URS) model imply ZAPs for the case of *efficient provers* [DN07], the transformation of [DN07] fails when the NIZK prover is inefficient. Briefly, this occurs because the *reduction* from the zero knowledge of the underlying NIZK to the witness indistinguishability of the ZAP does not have the computational power to run the *honest* prover’s algorithm. Furthermore, as we will discuss in depth in Section 1.1, the honest proofs cannot simply be pre-computed and hardwired into the reduction. Instead, we must develop new techniques for the inefficient prover case.

*Our notions of Zero Knowledge: the “fine-grained” setting.* We introduce fine-grained analogues of zero knowledge and witness indistinguishability. In fine-grained zero knowledge, we are concerned with (very) low complexity verifiers. We wish the honest verifier to have low complexity (we will use  $\text{NC}^1$  as a running example), but we also want to scale down the claim “no additional knowledge” leaked (beyond validity of the statement) to what can be computed in this low complexity class ( $\text{NC}^1$ ). The standard definition of zero knowledge simply requires that real transcripts can be simulated in probabilistic polynomial time. But if the verifier is in  $\text{NC}^1$  the simulation complexity could in fact be substantially larger than that of the verifier, which does not capture the idea that “no additional knowledge” was leaked. While such a notion of simulation is stronger, we only require interactions with malicious verifiers in  $\text{NC}^1$  to be simulatable. Moreover, simulation is only required to be indistinguishable from real to  $\text{NC}^1$  distinguishers. In this sense, our notion of fine-grained zero knowledge is orthogonal to the standard, poly-time zero knowledge.<sup>7</sup> We also define a notion of fine-grained witness indistinguishability, where indistinguishability of interactions is only required to hold for low complexity distinguishers/verifiers.

We note that interactive fine-grained zero knowledge is straightforward to achieve using fine-grained commitments (which follow from the work of [DVV16]) and a commitment-based ZK protocol (e.g. Blum-Hamiltonicity). We therefore focus on fine-grained ZAPs and NIZK.

*NIZK imply ZAPs for inefficient provers.* Our main contribution is to prove that NIZK in the URS model implies ZAPs, even in the case of *inefficient provers*. Specifically, we show the following:

**Theorem 1 (Informal).** *Assuming the existence of an NIZK proof system for a language  $\mathcal{L} \in \text{AM}$  with provers running in time  $T$  in the URS model, there exists a ZAP for  $\mathcal{L}$  with provers running in time  $\text{poly}(T, n)$ , where  $n$  is security parameter.*

Our proof surprisingly leverages a type of *design*—a combinatorial object that was used in the derandomization of BPP by Nisan and Wigderson [NW88]. To the best of our knowledge, this is a novel application of designs to the cryptographic setting.

We also briefly discuss here the notion of a “witness” for an AM language and the meaning of witness indistinguishability. Recall that a language is in AM iff it has an AM protocol (Prover, Verifier) and so AM languages are inherently tied to protocols. Therefore, similarly to tying witnesses for NP languages to a specific verification algorithm, the notion of a “witness” for an AM language will be tied to the protocol.

Specifically, we assume that there is an AM-protocol for a language  $\mathcal{L}$ . Given the first message  $r$  from the verifier, we can consider the Circuit-SAT problem w.r.t. the first message  $r$  and the verifier’s circuit. Specifically, a witness  $w$  is a Prover’s message that causes the verifier to output 1, when the first message  $r$  is fixed. Thus, witness-indistinguishability means that if there are two possible Prover messages  $w_1, w_2$  that

<sup>7</sup> Note that this is very different from other fine-grained flavors of zero knowledge such as “knowledge tightness” or “precise zero knowledge” [GMW91, Gol01, MP06, DG11, DG12] which look for a simulation complexity that is tight to *each* simulator. Under these notions, if a malicious verifier,  $V$ , runs for  $n^{c_V}$  steps, then the interaction with the prover should be simulatable with order  $O(n^{c_V})$  steps. These verifier-by-verifier notions, in some sense, recover fine-grained zero knowledge with respect to  $\text{TIME}(n^c)$  for all  $c$  simultaneously. In this work, we aren’t concerned with such verifier-by-verifier simulation of malicious poly-time verifiers, but instead what can be achieved if one is *only* concerned with (very) simple malicious verifiers (in order to minimize assumptions).

can be sent in response to  $r$  and such that the verifier accepts both, then the transcript of the ZAP should be indistinguishable when the Prover uses witness  $w_1$  or  $w_2$ .

As a concrete example, consider the Goldwasser-Sipser (GS) protocol [?] for proving lower bounds on the size of NP sets. The verifier sends a random hash value and the prover responds with an element in the set that hashes to that value. WI is meaningful if there are multiple elements in the set that hash to the target value, since it guarantees that the verifier cannot distinguish which pre-image was used.<sup>8</sup>

Since it is well-known that NIZK with inefficient provers in the URS model can be constructed from one-way permutations (OWP) (see e.g. [Ps05]), our result immediately yields ZAPs with subexponential provers from the Minicrypt assumption of OWP.

**Theorem 2 (Informal).** *Assuming the existence of one-way permutations, if  $\mathcal{L} \in \text{AM}$  with prover run-time  $T$ , then there exists a ZAP for  $\mathcal{L}$  with prover run-time  $\text{poly}(T, \text{subexp}(n))$ .*

*Extending to the fine-grained setting.* Next, we observe that our same transformation can be applied to obtain *fine-grained* ZAPs from fine-grained NIZK in the URS model. Here, we assume that the prover is polynomial-time, but that the verifier and distinguisher are in a lower complexity class,  $\mathcal{F}$ . We then require that zero knowledge/witness indistinguishability hold against distinguishers from complexity class  $\mathcal{F}$ .

For the proof technique from above to work, we require the class  $\mathcal{F}$  to satisfy some mild compositional requirements, which are, in particular, satisfied by the class  $\text{NC}^1$ .

We thus obtain the following:

**Theorem 3 (Informal).** *Assuming the existence of non-adaptive  $\text{NC}^1$ -fine-grained NIZK proof systems for NP in the URS model, there exist  $\text{NC}^1$ -fine-grained ZAPs for NP.*

We next show how to construct  $\text{NC}^1$ -fine-grained NIZK in the URS model for all of NP, assuming the *worst-case assumption* that  $\oplus L/\text{poly} \not\subseteq \text{NC}^1$ . Our result begins by converting the NIZK construction of [AR16] that works for languages  $\mathcal{L}$  with randomized encodings from the CRS model to the URS model.<sup>9</sup> Since randomized encodings are known for the class  $\oplus L/\text{poly}$ , this yields an NIZK proof system in the URS model (which actually achieves *statistical zero knowledge*). We then introduce a new primitive, which we call a  $\mathcal{G}$ -extractable,  $\mathcal{F}$ -Fine-Grained Commitment. This is a commitment that is perfectly binding, hiding against  $\mathcal{F}$ , but extractable by  $\mathcal{G}$ . We show how to construct  $\oplus L/\text{poly}$ -extractable,  $\text{NC}^1$ -Fine-Grained Commitment under the *worst-case* assumption that  $\oplus L/\text{poly} \not\subseteq \text{NC}^1$  using techniques of [DVV16]. Then, using  $\oplus L/\text{poly}$ -extractable,  $\text{NC}^1$ -Fine-Grained Commitment we show how to bootstrap the NIZK proof system in the URS model for the class  $\oplus L/\text{poly}$  to an  $\mathcal{F}$ -fine-grained NIZK proof system for NP in the URS model. We obtain the following theorem:

**Theorem 4 (Informal).** *Assuming that  $\oplus L/\text{poly} \not\subseteq \text{NC}^1$ , there exist non-adaptive  $\text{NC}^1$ -fine-grained NIZK proof systems for NP in the URS model.*

*Beyond ZAPs.* One reason that ZAPs are a crucial tool in cryptography, is that they can be used as a building block to construct NIWI in the standard (no trusted setup) model under certain types of assumptions that are common in the derandomization literature. Indeed, the seminal work of Barak et al. [BOV07] was the first to establish this connection between derandomization assumptions and NIWI. Furthermore, NIWI in the

<sup>8</sup> We note that the GS protocol is used to prove that MA is contained in AM (by proving that the set of accepting coins of the verifier is sufficiently large). Recall that MA is like NP except the verifier can be randomized. It is not difficult to observe that our notion under the above transformation yields proofs for MA where witnesses that make the randomized verifier accept w.h.p. are indistinguishable.

<sup>9</sup> Recently, [EWT19] constructed one-way permutations in the fine-grained setting. However, their results cannot be extended in straight-forward manner to construct fine-grained NIZKs and therefore are unlikely to lead to simpler constructions without using other techniques. For more discussion on this, we refer the interested readers to Section 1.2.

standard model can be used to construct NIZK with soundness against uniform adversaries in the standard model.

The constructions of NIWI from ZAPs and derandomization techniques go through in the inefficient-prover setting, since parallel repetition of 2-message protocols retains WI even in the inefficient prover setting (though this is not necessarily true for protocols with more than 2-messages).

We are not able to convert NIWI into fully standard NIZK with uniform soundness. The reason is that the transformation from NIWI to NIZK with uniform soundness in the no-CRS model employs the well-known FLS paradigm [FLS99]. In this paradigm, the ZK simulator runs the honest prover with a trapdoor witness. However, in our case, the simulator cannot run the honest prover as it does not have enough computational power. Fortunately, we are able to show that if the simulator is given non-uniform advice that *does not depend on the statement being proved* then the simulator can perfectly simulate the honest prover’s output on the trapdoor witness. Thus, we introduce offline NIZK (oNIZK), which requires existence of a distribution  $\mathcal{D}_{\text{Sim}}$  over small circuit simulators  $\text{Sim}$ , such that for any statement  $x \in \mathcal{L}$ , the distribution over  $(\text{URS}', \pi')$  obtained by drawing  $\text{Sim}$  from  $\mathcal{D}_{\text{Sim}}$  and outputting  $(\text{URS}', \pi') \leftarrow \text{Sim}(x)$  is computationally indistinguishable from honest CRS’s and proofs  $(\text{URS}, \pi)$ . We note that this notion is sufficient for indistinguishability-based applications.

We next state our results for the oNIZK setting:

**Theorem 5 (Informal).** *Assuming the existence of one-way permutations, appropriate derandomization assumptions,<sup>10</sup> and sub-exponentially-hard uniform collision resistant hash functions, then for any constant  $0 < \epsilon < 1$  and constant  $c \geq 1$ , there exist oNIZK in the standard model for NP with honest provers running in uniform time  $2^{n^\epsilon}$  and soundness against uniform adversaries running in time  $2^{n^c}$ , where  $n$  is security parameter.*

**Theorem 6 (Informal).** *Assuming that  $\oplus L / \text{poly} \not\subseteq \text{NC}^1$ , appropriate derandomization assumptions as above, and the existence of uniform collision resistant hash functions, there exist  $\text{NC}^1$ -fine-grained oNIZK in the standard model for NP.*

## 1.1 Technical Overview

*ZAPs from NIZK with inefficient provers.* Let us begin by recapping the construction of ZAPs from a non-adaptive NIZK proof system with an efficient prover in the URS model.

The public coin verifier sends a random string  $r$ , which is partitioned into  $n'$  sections  $r_1 || \dots || r_{n'}$ . Each  $r_i$  is a bitstring of length  $n$ , where  $n$  is also the bit length of the URS for the underlying NIZK proof system. Upon receiving  $r_1 || \dots || r_{n'}$ , the prover chooses a string  $x \in \{0, 1\}^n$ . For  $i \in [n']$ , the prover then sets  $\text{URS}_i := r_i \oplus x$  and runs the prover of the underlying NIZK proof system on the input statement, witness and  $\text{URS}_i$ , to produce proof  $\pi_i$ . The prover then sends  $x, \pi_1, \dots, \pi_{n'}$  to the verifier. For  $i \in [n']$ , the verifier recomputes  $\text{URS}_i := r_i \oplus x$  and runs the verifier of the underlying NIZK proof system on  $\text{URS}_i, \pi_i$ . If all the proofs accept, then the verifier accepts; otherwise, it rejects.

To prove soundness of the above proof system, a counting argument is employed. Specifically, fix any statement  $\text{st}$  that is not in the language. Since the underlying NIZK is statistically sound, the number of “bad” URS’s for which there exists a proof  $\pi$  that accepts for  $\text{st}$  is small; say the fraction of “bad” URS’s is at most  $1/2$ . This means that for a fixed statement  $\text{st}$  not in the language and a fixed  $x$ , the probability over random choice of  $r_1, \dots, r_{n'}$  that there exists an accepting proof  $\pi_i$  relative to each  $\text{URS}_i, i \in [n']$  is at most  $2^{-n'}$ . Taking a union bound over all possible choices for  $x$ , we have that for a fixed  $\text{st}$ , the probability over choice of  $r_1, \dots, r_{n'}$  that there *exists* an  $x$  of length  $n$  for which there exists an accepting proof relative to each  $\text{URS}_i, i \in [n']$  is at most  $2^{n-n'}$ . Setting  $n' = 2n$  provides us with negligible statistical soundness in  $n$ .

On the other hand, to prove witness indistinguishability, one proceeds via a hybrid argument. In the original hybrid, witness  $w_1$  is used for each of the  $n'$  number of honestly generated proofs  $\pi_1, \dots, \pi_{n'}$ . In the

<sup>10</sup> Specifically, the existence of efficient 1/2-hitting set generators (HSG) against co-nondeterministic uniform algorithms [BOV07].

final hybrid, witness  $w_2$  is used for each of the  $n'$  number of honestly generated proofs  $\pi_1, \dots, \pi_{n'}$ . In each intermediate hybrid, we switch from honestly generating a proof using  $w_1$  to using  $w_2$ . Indistinguishability of intermediate hybrids is proved by showing that an efficient distinguisher between the hybrids implies an efficient distinguisher between real and simulated proofs of the underlying NIZK system. Specifically, a *reduction* is constructed as follows: Given the verifier's string  $r = r_1 || \dots || r_{n'}$  and a real or simulated URS/proof pair  $(\text{URS}^*, \pi^*)$ , the reduction sets  $x$  such that  $\text{URS}_i = x \oplus r_i = \text{URS}^*$ . The reduction then runs the honest prover with  $w_2$  for the first  $i - 1$  proofs, runs the honest prover with  $w_1$  for the last  $n' - i$  proofs, and embeds  $\pi^*$  in the  $i$ -th location. The reduction then applies the distinguisher between Hybrids  $i - 1$  and  $i$  to the resulting transcript, and outputs whatever it does. Since a distinguisher between Hybrids  $i - 1$  and  $i$  must either distinguish the above when  $(\text{URS}^*, \pi^*)$  were generated using the honest prover and  $w_1$  versus using the simulator or when  $(\text{URS}^*, \pi^*)$  were generated using the honest prover and  $w_2$  versus using the simulator, the above reduction succeeds in one of those cases. If one of the cases succeeds, we obtain a contradiction to the zero knowledge property.

Note that for the soundness argument for the ZAP, soundness against unbounded provers in the underlying NIZK is crucial since we use a counting argument based on the number of “bad” URS's for which there exists an accepting proof of the false statement. Furthermore, the fact that the prover in the underlying NIZK is *efficient* is crucial for the witness indistinguishability argument. The reason can be seen from the sketch of the hybrid argument above. Specifically, we will have a hybrid in which we reduce to the zero knowledge of the underlying NIZK (note that the zero knowledge must always be *computational*, since we require the soundness to be statistical). This means that existence of a distinguisher for consecutive hybrids must imply a ZK distinguisher, and the ZK distinguisher that is constructed, given an efficient distinguisher for consecutive hybrids, must be efficient. But in the approach outlined above, to generate the correct hybrid distributions for the efficient distinguisher, we must run the honest prover with witness  $w_2$  for the first  $i - 1$  number of proofs and run the honest prover with witness  $w_1$  for the last  $n' - i$  number of proofs. This cannot be done efficiently if the honest prover is inefficient. An immediate thought would be to use non-uniform advice to hardcode all the proofs except the  $i$ -th proof into the ZK distinguisher. However, this does not work because  $\text{URS}_{i'}$  for  $i' \neq i$  depends on  $\text{URS}^*$ , which is part of the input to the ZK distinguisher. Specifically, on input  $(\text{URS}^*, \pi^*)$ ,  $x$  is set to  $\text{URS}^* \oplus r_i$  and only once  $x$  is fixed do we learn  $\text{URS}_{i'} := r_{i'} \oplus x$  for  $i' \neq i$ . So we cannot know the URS's  $\text{URS}_{i'}, i' \neq i$  ahead of time. In this case, we cannot hope to hardcode the proofs  $\pi_{i'}$  as non-uniform advice.

We will resolve this issue and show that non-uniform advice *can* help in our setting, by allowing limited pairwise dependency across the URS's, instead of imposing pairwise independence. Specifically, our construction leverages the notion of a *design*, introduced by Nisan and Wigderson in their seminal work [NW88]. A *design* with parameters  $(l, n, c, n')$  is a set of  $n'$  number of sets  $\mathcal{S}_1, \dots, \mathcal{S}_{n'}$ , where each  $\mathcal{S}_i, i \in [n']$  is a subset of  $[l]$  and has size  $|\mathcal{S}_i| = n$ . Moreover for every pair  $i, j \in [n'], i \neq j$ , it holds that  $|\mathcal{S}_i \cap \mathcal{S}_j| \leq c$ . It is known how to construct designs with  $l = n^2$ , constant  $c$  and  $n' := n^c$  (see e.g. [NW88]). Let us see how a design with parameters  $(l = n^2, n, c = 3, n' = n^3)$  can be used to resolve our problems above. Upon receiving string  $r = r_1 || \dots || r_{n'}$  from the verifier, we now allow the prover to choose a bit string  $x = [x_j]_{j \in [l]}$  of length  $l$ .  $\text{URS}_i$  is then defined as  $r_i \oplus [x_j]_{j \in \mathcal{S}_i}$ , where  $[x_j]_{j \in \mathcal{S}}$  for a set  $\mathcal{S} \subseteq [l]$  denotes the substring of  $x$  corresponding to the positions  $j \in \mathcal{S}$  and  $\mathcal{S}_i$  is the corresponding set in the design. Now, soundness is ensured by the same argument as above (i.e. via a union bound), since  $2^{-n'} \cdot 2^l = 2^{-n^3} \cdot 2^{n^2} = 2^{-n^3+n^2}$  is negligible in  $n$ . Furthermore, since for each pair  $i, j \in [n'], i \neq j$ , it holds that  $|\mathcal{S}_i \cap \mathcal{S}_j| \leq 3$ , we can use the following proof strategy to argue indistinguishability of consecutive hybrids: In the  $i$ -th hybrid, we fix the string  $[x_j]_{j \notin \mathcal{S}_i}$  at random. We then generate  $n' - 1$  truth tables with constant input length. The input to the  $i'$ -th truth table ( $i' \in [n'], i' \neq i$ ) will be at most 3 bits, corresponding to  $[x_j]_{j \in \mathcal{S}_{i'} \cap \mathcal{S}_i}$ . For  $i' < i$ , the output of the truth table  $T_{i'}$  will be a proof  $\pi_{i'}$  that is honestly computed using witness  $w_2$  and  $\text{URS}_{i'} = [x_j]_{j \in \mathcal{S}_{i'}}$ . For  $i' > i$ , the output of the truth table  $T_{i'}$  will be a proof  $\pi_{i'}$  that is honestly computed using witness  $w_1$  and  $\text{URS}_{i'} = [x_j]_{j \in \mathcal{S}_{i'}}$ . Note that since everything is fixed (including all the bits of  $[x_j]_{j \in \mathcal{S}_{i'}}$ , except for  $[x_j]_{j \in \mathcal{S}_{i'} \cap \mathcal{S}_i}$ ), each truth table can be computed by an  $NC^0$  circuit.

Now, given a real or simulated URS/proof pair  $(\text{URS}^*, \pi^*)$ , the reduction will set  $[x_j]_{j \in \mathcal{S}_i}$  such that  $\text{URS}_i = [x_j]_{j \in \mathcal{S}_i} \oplus r_i = \text{URS}^*$ . The reduction will then use the truth table  $T_{i'}$  to generate proof  $\pi_{i'}$  for  $i' \neq i$ ,

and will embed  $\pi^*$  in the  $i$ -th location. The reduction will then evaluate the distinguisher  $D$  (represented as a poly-sized circuit) on the resulting transcript and output whatever it outputs. Note that the reduction can now be represented as a poly-sized circuit and note that it outputs exactly the correct distribution to the distinguisher. Thus, an efficient distinguisher for intermediate hybrids yields a poly-sized circuit that breaks the zero knowledge property of the underlying NIZK, resulting in contradiction.

*Fine-Grained ZAPs.* As discussed previously, fine-grained ZAPs relative to a class  $\mathcal{F}$  are ZAPs that have a poly-time prover and provide witness indistinguishability against class  $\mathcal{F}$  that is conjectured to not contain  $P$ . The same difficulty of converting a single-theorem fine-grained NIZK in the common random string model into a ZAP arises as above. Luckily, if circuits  $f \in \mathcal{F}$  composed with  $\text{NC}^0$  circuits are also in  $\mathcal{F}$ , then the same proof as above can work (since the reduction sketched above can be implemented with a  $\text{NC}^0$  circuit). Thus, given a non-adaptive, fine-grained NIZK in the URS model against  $\text{NC}^1$ , we obtain a fine-grained ZAP relative to  $\text{NC}^1$ .

*Fine-Grained NIZK in uniform random string (URS) model.* We first modify a construction of [AR16] in the CRS model to yield a construction in the URS model. This is done by observing that a random string is a good CRS for the construction of [IK00] with probability  $1/2$  (which follows from the fact that randomized encodings of [IK00] are “balanced”). We then construct a URS by sampling many reference strings at random, and having the prover either prove that the reference string is invalid or provide a proof of the statement relative to the reference string. Note that this yields a construction with a poly-time prover and provides *statistical*-zero knowledge as well as soundness against unbounded provers. However, this construction only allows proving statements for languages that have randomized encodings (such as languages in  $\oplus L/\text{poly}$ ). We would like to obtain a proof system for all languages in  $\text{NP}$ , while sacrificing the statistical zero knowledge property and obtaining a fine-grained NIZK with poly-time prover against the class  $\text{NC}^1$ . It turns out that to obtain this, we can use the fact that, assuming  $\oplus L/\text{poly} \neq \text{NC}^1$ , there exist “commitments” with the following properties: (1) Commitments can be constructed in the class  $\text{NC}^1$ . (2) Given a commitment, extracting the committed value can be performed in the class  $\oplus L/\text{poly}$  (i.e. the decision problem  $\mathcal{L}_{det}$  which, given a commitment  $com$  outputs 1 if it is a commitment to 1 is in  $\oplus L/\text{poly}$ ). (3) Commitments are hiding against a  $\text{NC}^1$  adversary. Such commitments can be easily constructed by computing the randomized encoding of a “canonical” 0 (resp. 1) input to commit to 0 (resp. 1). Now, using the fact that  $\oplus L/\text{poly}$  is closed under negation, disjunction and conjunction (see [BG99]), we can use the statistical-zero knowledge NIZK in the URS model for languages in  $\oplus L/\text{poly}$  to obtain a fine-grained NIZK in the URS model against  $\text{NC}^1$  for all of  $\text{NP}$  as follows: Given a circuit-SAT instance  $\mathcal{C}$ , where  $\mathcal{C}$  is a circuit consisting of NAND gates and we assume that it has  $z$  wires. the prover will commit to the values of all the wires of  $\mathcal{C}$  for some satisfying assignment. This commitment will be performed using the “commitment” scheme described above. The prover will then prove that the sequence of “commitments”  $com_1, \dots, com_z$  is in the language  $\mathcal{L}_{\mathcal{C}}$ , where  $com_z \in \mathcal{L}_{det}$ , and for each NAND gate, with input wires  $i, j$  and output wire  $k$ ,  $com_i, com_j, com_k$  are commitments to valid inputs/outputs for a NAND gate (i.e.  $(com_i, com_j, com_k) \in \mathcal{L}_{gate}$ ). Since  $\mathcal{L}_{\mathcal{C}}$  will consist of negation/conjunction/disjunction of languages in  $\oplus L/\text{poly}$  and since  $\oplus L/\text{poly}$  is closed under negation/conjunction/disjunction, we have that  $\mathcal{L}_{\mathcal{C}} \in \oplus L/\text{poly}$ . Moreover, given  $com_1, \dots, com_z$ , we can simulate a proof in  $\text{NC}^1$  (using the simulator for the NIZK for languages in  $\oplus L/\text{poly}$ ), indicating that the NIZK provides zero knowledge against  $\text{NC}^1$ .

## 1.2 Related Work

*Zero Knowledge* Zero knowledge (ZK) proofs were introduced by Goldwasser, Micali, and Rackoff [GMR89]. Since its introduction, ZK proof systems and its variants have been studied with great interest. Some of the notable results related to ZK proofs are – [GMW91] which showed ZK proofs exist for all languages in  $\text{NP}$ , and [GO94] which showed that interaction is crucial for achieving zero knowledge property in case of non-trivial languages. Specifically, [GO94] showed that if for language  $\mathcal{L}$ , 2-message ZK proof system exists then  $\mathcal{L} \in \text{BPP}$ . The research aimed at minimizing the interaction has since relied on

either constructing Non-Interactive Zero Knowledge proof systems (NIZKs) with the help of trusted setup assumptions such as uniform random string (URS) [BFM88] or constructing non-interactive protocols with weaker security guarantees such as *non-interactive witness indistinguishability* (NIWI). Intuitively, witness indistinguishability ensures that the verifier does not learn which witness (out of multiple valid witnesses) is used by the prover to generate the proof. Dwork and Naor [DN07] showed introduced two-message, witness indistinguishable proof systems (ZAPs) and showed that ZAPs (in a no-CRS model) are equivalent to NIZKs in uniform *random* string (URS) model.

*Zero Knowledge Primitives and Underlying Assumptions* Blum et al. [BFM88], gave the first construction of NIZK in CRS model from number-theoretic assumptions (e.g. quadratic residuosity). Since then, NIZKs have been constructed in URS model from one-way permutations and certified trapdoor permutations [FLS99], whereas Lapidot and Shamir [LS91], constructed publicly verifiable NIZK from one-way permutations in URS model, Groth et al. [GOS06] constructed NIZK from DLIN assumption in URS model. Recently, Peikert and Shiehian [PS19] constructed NIZK from LWE assumption in URS model.

NIZKs have also been studied in other models [BG03, CV07, CCKV08], and models which consider preprocessing along with other assumptions such as one-way encryption schemes exist [DMP90], lattices (LWE) [KW18], and DDH/CDH [KNYY19]. Few of the other works on NIZKs include [BY96, Ps05, GS08, BL18, CCH<sup>+</sup>19, GJS19, ADKL19]. For more details on NIZK related research, we refer the interested readers to [WW14]

We now present an overview of research related to ZAP and NIWI systems. The notion of witness indistinguishable proofs was introduced by [FS90]. As discussed earlier, Dwork and Naor [DN07] introduced ZAP (two-message, witness indistinguishable proofs) and presented a construction in plain (no-CRS) model assuming the existence of certified trapdoor permutations. Barak et al. [BOV07] gave a construction of NIWI based on derandomization assumptions and certified trapdoor permutations (by derandomizing the verifier of [DN07] construction). Groth et al. [GOS12] constructed first non-interactive ZAP from DLIN assumption, whereas Bitansky and Paneth [BP15] showed a construction of ZAP based on indistinguishably obfuscation (iO) and one-way functions, and NIWI from iO and one-way permutations. Recently ZAP were constructed assuming quasi-polynomial hardness of DDH [JKKR17, KKS18], and quasi-polynomial hardness of LWE [BFJ<sup>+</sup>19, JJ19].

*Fine-Grained Cryptography* Fine-grained cryptography refers to construction of primitives which provide security guarantees against adversaries with sharper complexity bounds than simply “polynomial time.” Both adversaries with *specific* polynomial runtime bounds (e.g.  $\text{TIME}[O(n^2)]$ ) and adversaries with *specific* parallel-time complexity (e.g.  $\text{NC}^1$ ) have been considered under this moniker in the literature. In [DVV16] Degwekar et al. constructed primitives like one-way functions, pseudo-random generators, collision-resistant hash functions and public key encryption schemes based on well-studied complexity theoretic assumptions. Ball et al. [BRSV17, BRSV18] worst-case to average-case reduction for different type of fine-grained hardness problems and then extended their work to construct Proofs of Work. Campanelli and Gennaro [CG18] initiated the study of fine-grained secure computation by constructing a verifiable computation protocol secure against  $\text{NC}^1$  adversaries based on worst-case assumptions. LaVigne et al. [LLW19] constructed a fine-grained key-exchange protocol.

*Comparison with Egashira et al. [EWT19]* Recently, Egashira et al. [EWT19] constructed one-way permutations, hash-proof systems, and trapdoor one-way functions, all of which can be computed in  $\text{NC}^1$  and are secure against adversaries in  $\text{NC}^1$ , from the same assumptions that are considered in this work ( $\oplus L / \text{poly} \not\subseteq \text{NC}^1$ ). Their results do not directly extend to construct  $\text{NC}^1$ -fine-grained NIZK systems in the URS model, as (1) to the best of our knowledge it is not known how to construct NIZK in URS model from trapdoor one-way functions, and (2) their one-way permutation does not directly allow instantiation of the hidden bits model [FLS99], which could then be used to construct  $\text{NC}^1$ -fine-grained NIZK in the URS model. Specifically, the domain/range of their OWP includes only full rank matrices and does not include *all* strings of a given length. Furthermore, whether a given string is contained in the domain/range cannot



be determined by a  $\text{NC}^1$  circuit (assuming  $\oplus L / \text{poly} \not\subseteq \text{NC}^1$ ) and strings that are not in the range can have more than one pre-image. This means that to implement the hidden bits model, a prover would need to prove that a string is or is not contained in the domain/range, without compromising the one-wayness of unopened bits, which would itself require a  $\text{NC}^1$ -fine-grained NIZK proof system in the URS model. In contrast, our construction of  $\text{NC}^1$ -fine-grained NIZK in the URS model is direct and does not require fine-grained OWP nor implementing a fine-grained hidden bits model.

## Organization

The paper is organized as follows: We present preliminaries and definitions related to NIZK and ZAPs in Section 2. Section 3, presents a construction of inefficient-prover ZAPs from inefficient-prover NIZK. The constructions of NIZK in the fine-grained setting are presented in Section 5. The applications of inefficient-prover ZAPs to obtain oNIZK with uniform soundness (in the super-polynomial and fine-grained settings) are presented in Sections 4 and 5.6.

## 2 Definitions

**Definition 1.** Let  $\mathcal{F} = \{\mathcal{F}_n\}_{n \in \mathbb{N}}$  be a class of circuits parameterized by  $n$  with input length  $\ell(n)$ . We say that two distribution ensembles  $\{\mathcal{D}_n^0\}_{n \in \mathbb{N}}, \{\mathcal{D}_n^1\}_{n \in \mathbb{N}}$ , with support  $\{0, 1\}^{\ell(n)}$ , are indistinguishable by  $\mathcal{F}$  if

$$\max_{f_n \in \mathcal{F}_n} |\Pr[f_n(x) = 1 \mid x \sim \mathcal{D}_n^0] - \Pr[f_n(x) = 1 \mid x \sim \mathcal{D}_n^1]| \leq \text{negl}(n).$$

**Definition 2 (Fine-Grained Pseudorandom Generator (PRG) [DVV16]).** Let  $\mathcal{H} = \{h_n : \{0, 1\}^n \rightarrow \{0, 1\}^{\ell(n)}\}$  be a function family.  $\mathcal{H}$  is a  $\mathcal{F}$ -fine-grained-pseudorandom generator (PRG) if<sup>11</sup> :

- **Computability:** For each  $n$ ,  $h_n$  is deterministic.
- **Expansion:**  $\ell(n) > n$  for all  $n$ .
- **Pseudorandomness:** For any  $F = \{f_n : \{0, 1\}^{\ell(n)} \rightarrow \{0, 1\}\} \in \mathcal{F}$ , and for all  $n \in \mathbb{N}$ :

$$\left| \Pr_{x \leftarrow U_n} [f_n(h_n(x)) = 1] - \Pr_{x' \leftarrow U_{\ell(n)}} [f_n(x') = 1] \right| \leq \text{negl}(n)$$

**Definition 3 ( $\mathcal{G}$ -Extractable,  $\mathcal{F}$ -Fine-Grained Commitment Scheme).** A commitment scheme comprising of three algorithms (Commit, Open, Extract) is called  $\mathcal{G}$ -Extractable,  $\mathcal{F}$ -Fine-Grained Commitment Scheme if the following hold:

- Commit  $\in \mathcal{F}$  and Open  $\in \mathcal{F}$  for class  $\mathcal{F}$ .
- **Correctness:** For all  $n \in \mathbb{N}$  and for  $b \in \{0, 1\}$ :

$$\Pr[(com, d) \leftarrow \text{Commit}(1^n, b) : \text{Open}(com, d) = b] = 1$$

- **Perfect Binding:** There does not exist a tuple  $(com, d, d')$  such that

$$\text{Open}(com, d) = 0 \wedge \text{Open}(com, d') = 1.$$

- **$\mathcal{F}$ -Hiding:** For any Open\*  $\in \mathcal{F}$ ,

$$\left| \Pr_{b \leftarrow \{0, 1\}} [(com, d) \leftarrow \text{Commit}(1^n, b) : \text{Open}^*(c) = b] - \frac{1}{2} \right| \leq \text{negl}(n)$$

- **$\mathcal{G}$ -Extractability:** There exists Extract  $\in \mathcal{G}$  such that for any string  $com$ ,

$$\text{Extract}(com) = b \text{ iff } \exists d \text{ s.t. } \text{Open}(com, d) = b.$$

An  $\mathcal{F}$ -Fine-Grained Commitment Scheme is the same as the above definition, but does not enjoy the  $\mathcal{G}$ -Extractability property.

<sup>11</sup> Note that unlike the definition of [DVV16], our notion  $\mathcal{F}$ -PRG means  $\mathcal{H}$  is secure against adversaries in class  $\mathcal{F}$ . Whereas, [DVV16] use notation  $\mathcal{F}$ -PRG to indicate that PRG  $\mathcal{H}$  can be computed in class  $\mathcal{F}$ .

## 2.1 NIZK and Fine-Grained NIZK in the URS Model

**Definition 4 (Non-Interactive Proofs in the URS Model).** A pair of algorithms (Prover, Verifier) is called a non-interactive proof system in the URS model for a language  $\mathcal{L}$  if the algorithm Verifier is deterministic polynomial-time, there exists a polynomial  $p(\cdot)$  and a negligible function  $\mu(\cdot)$  such that the following two conditions hold:

– **Completeness:** For every  $x \in \mathcal{L}$

$$\Pr[\text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi \leftarrow \text{Prover}(x, \text{URS}) : \text{Verifier}(x, \text{URS}, \pi) = 1] \geq 1 - \mu(|x|).$$

– **Soundness:** For every  $x \notin \mathcal{L}$ , every algorithm  $P^*$

$$\Pr[\text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi' \leftarrow P^*(x, \text{URS}) : \text{Verifier}(x, \text{URS}, \pi') = 1] \leq \mu(|x|).$$

**Definition 5 (Non-Interactive Zero-Knowledge with Offline Simulation (oNIZK) in the URS Model).** Let (Prover, Verifier) be a non-interactive proof system in the URS model for the language  $\mathcal{L}$ . We say that (Prover, Verifier) is non-adaptively zero-knowledge with offline simulation in the URS model if there exists a distribution  $\mathcal{D}_{\text{Sim}}$  over polynomial-sized circuits Sim such that the following two distribution ensembles are computationally indistinguishable by polynomial-sized circuits (when the distinguishing gap is a function of  $|x|$ )

$$\begin{aligned} & \{(\text{URS}, \pi) : \text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi \leftarrow \text{Prover}(\text{URS}, x)\}_{x \in \mathcal{L}} \\ & \{(\text{URS}', \pi') \leftarrow \text{Sim}(x) : \text{Sim} \leftarrow \mathcal{D}_{\text{Sim}}\}_{x \in \mathcal{L}}. \end{aligned}$$

A useful property of oNIZK is the following: Let  $\mathcal{D}_{\text{yes}}$  be a distribution over statements  $x \in \mathcal{L}$  and let  $\mathcal{D}_{\text{no}}$  be a distribution over statements  $x \in \bar{\mathcal{L}}$ . If  $\mathcal{D}_{\text{yes}}$  and  $\mathcal{D}_{\text{no}}$  are computationally indistinguishable by polynomial-sized circuits then the following two distribution ensembles are computationally indistinguishable by polynomial-sized circuits (when the distinguishing gap is a function of  $|x|$ )

$$\begin{aligned} & \{(x, (\text{URS}, \pi) \leftarrow \text{Sim}(x)) : \text{Sim} \leftarrow \mathcal{D}_{\text{Sim}}, x \leftarrow \mathcal{D}_{\text{yes}}\} \\ & \{(x', (\text{URS}', \pi') \leftarrow \text{Sim}(x')) : \text{Sim} \leftarrow \mathcal{D}_{\text{Sim}}, x' \leftarrow \mathcal{D}_{\text{no}}\}. \end{aligned}$$

The above allows a typical usage of oNIZK in hybrid style proofs: In the first hybrid, one can leave the statement the same and switch from proofs generated by the honest prover to proofs generated by the simulator, in the second step, one can switch the statement from a true statement to a false statement.

**Relation to Zero Knowledge Notions in the Literature.** We next discuss the relationship between Definition 5 and the notions of *witness hiding* (WH) and *weak zero knowledge* (WZK).

First, we show that Definition 5 in fact implies *witness hiding* (WH).

Let  $\mathcal{D}$  be a distribution over statements  $x \in \mathcal{L}$ . Assume that  $\mathcal{L}$  has witness relation  $\mathcal{R}$ , computable by a poly-size circuit, such that  $x \in \mathcal{L}$  if and only if there exists a witness  $w$  such that  $(x, w) \in \mathcal{R}$ . We wish to show that if for all polynomial sized circuits  $C$ ,

$$\Pr_{x \sim \mathcal{D}}[\mathcal{R}(x, C(x)) = 1] \leq \text{negl}(|x|).$$

Then for all polynomial sized circuits  $C'$

$$\Pr_{x \sim \mathcal{D}}[\mathcal{R}(x, C'(x, \text{URS}, \pi)) = 1 : \text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi \leftarrow \text{Prover}(\text{URS}, x)] \leq \text{negl}(|x|).$$

Towards contradiction, assume that there exists a polynomial sized circuit  $C'$  such that

$$\Pr_{x \sim \mathcal{D}}[\mathcal{R}(x, C'(x, \text{URS}, \pi)) = 1 : \text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi \leftarrow \text{Prover}(\text{URS}, x)] \geq \mu(|x|),$$

where  $\mu(\cdot)$  is non-negligible. Consider the following poly-size distinguisher  $D$ : On input  $(\text{URS}, \pi)$  and implicit  $x$ , run  $C'(x, \text{URS}, \pi)$  and obtain  $w$ . If  $R(x, w) = 1$  output 1. Otherwise, output 0. Then we have that

$$\Pr_{x \sim \mathcal{D}} [D(\text{URS}, \pi) = 1 : \text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi \leftarrow \text{Prover}(\text{URS}, x)] \geq \mu(|x|).$$

By the above zero knowledge property (Def. 5), we have that

$$\Pr_{x \sim \mathcal{D}, \text{Sim} \sim \mathcal{D}_{\text{Sim}}} [D(\text{URS}', \pi') = 1 : (\text{URS}', \pi') \leftarrow \text{Sim}(x)] \geq \mu'(|x|),$$

where  $\mu'$  is non-negligible. But this implies that

$$\Pr_{x \sim \mathcal{D}, \text{Sim} \sim \mathcal{D}_{\text{Sim}}} [R(x, C'(x, \text{Sim}(x))) = 1] \geq \mu'(|x|),$$

and equivalently, that

$$\mathbb{E}_{x \sim \mathcal{D}, \text{Sim} \sim \mathcal{D}_{\text{Sim}}} [R(x, C'(x, \text{Sim}(x)))] \geq \mu'(|x|).$$

This, in turn, implies that there exists some  $\text{Sim}$  in the support of  $\mathcal{D}_{\text{Sim}}$  such that

$$\Pr_{x \sim \mathcal{D}} [R(x, C'(x, \text{Sim}(x))) = 1] \geq \mu'(|x|).$$

But the above implies a poly-sized circuit  $C$  (corresponding to  $C'$  composed with  $\text{Sim}$ ) such that  $\Pr_{x \sim \mathcal{D}} [R(x, C(x)) = 1]$  is non-negligible, which is a contradiction to the hardness of distribution  $\mathcal{D}$  over language  $\mathcal{L}$ .

Recall that Weak Zero Knowledge (WZK) defined in ([DNRS99]), allows the simulator  $\text{Sim}$  to depend on the zero knowledge distinguisher  $D$ . Weak zero knowledge is known to be sufficient to argue security in For any cryptographic protocol that only aims to achieve indistinguishability-based security, weak zero knowledge is known to be sufficient, since the security reduction has access to an efficient distinguisher [JKKR17].

We also show that Definition 5 implies Weak Zero Knowledge (WZK) with an inverse-polynomial bound on distinguishing advantage. (This follows more or less directly from Lipton and Young's sparse min-max theorem [LY94], but we give full details here for completeness.)

Fix any distinguisher  $A$ ,  $\epsilon(n) = 1/n^c$  for some  $c$ , and define

$$\begin{aligned} D_x^{\text{P}} &:= \{(\text{URS}, \pi, x) : \text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi \leftarrow \text{P}(\text{URS}, x)\} \\ D_x^{\text{Sim}} &:= \{(\text{URS}', \pi', x) \leftarrow \text{Sim}(x), \forall \text{Sim} \in \text{Supp}(\mathcal{D}_{\text{Sim}})\} \end{aligned}$$

Consider  $\text{Sim}'$ , and corresponding distributions  $\mathcal{D}_x^{\text{Sim}'}$ , that works by sampling  $k \geq \frac{2n + \ln(2)}{2\epsilon(n)^2}$  i.i.d. samples  $\text{Sim}_1, \dots, \text{Sim}_k \leftarrow \mathcal{D}_{\text{Sim}}$ , before selecting a  $\text{Sim}_{i^*}$  uniformly at random from  $\{\text{Sim}_i\}_{i=1}^k$  and evaluating it on  $x$ .

Notice that by Chernoff/Hoeffding

$$\Pr_{(\text{Sim}_1, \dots, \text{Sim}_k) \leftarrow \mathcal{D}_{\text{Sim}'}} \left[ \left| \sum_{i=1}^k \frac{\mathbb{E}[A(D_x^{\text{Sim}_i})]}{k} - \mathbb{E}[A(D_x^{\text{Sim}'})] \right| > \epsilon \right] < 2e^{-2k\epsilon(n)^2} \leq 2^{-2n}$$

Additionally, for any fixed  $i \in [k]$  we have

$$\mathbb{E}_{\text{Sim}_1, \dots, \text{Sim}_k \leftarrow \mathcal{D}_{\text{Sim}'}} [A(D_x^{\text{Sim}_i})] = \mathbb{E}_{\text{Sim} \leftarrow \mathcal{D}_{\text{Sim}}} [A(D_x^{\text{Sim}})].$$

It follows that

$$\mathbb{E}_{\substack{i^* \leftarrow [k], \\ \text{Sim}_1, \dots, \text{Sim}_k \leftarrow \mathcal{D}_{\text{Sim}'}}} [A(D_x^{\text{Sim}_{i^*}})] = \mathbb{E}_{\text{Sim} \leftarrow \mathcal{D}_{\text{Sim}}} [A(D_x^{\text{Sim}})].$$

Thus by the triangle inequality we have that with probability at least  $1 - 2^{-2n}$  over the choice of  $S \leftarrow \mathcal{D}_{\text{Sim}'}$ , for any  $x$

$$\begin{aligned}
|\mathbb{E}[A(D_x^S)] - \mathbb{E}[A(D_x^P)]| &= |\mathbb{E}[A(D_x^S)] \\
&\quad - (\mathbb{E}_{\substack{i^* \leftarrow [k], \\ \text{Sim}_1, \dots, \text{Sim}_k \leftarrow \mathcal{D}_{\text{Sim}'}}} [A(D_x^{\text{Sim}_{i^*}})] - \mathbb{E}_{\text{Sim} \leftarrow \mathcal{D}_{\text{Sim}}} [A(D_x^{\text{Sim}})]) \\
&\quad - \mathbb{E}[A(D_x^P)]| \\
&\leq |\mathbb{E}[A(D_x^S)] - \mathbb{E}_{i^* \leftarrow [k], \text{Sim}_1, \dots, \text{Sim}_k \leftarrow \mathcal{D}_{\text{Sim}'}} [A(D_x^{\text{Sim}_{i^*}})]| \\
&\quad + |\mathbb{E}_{\text{Sim} \leftarrow \mathcal{D}_{\text{Sim}}} [A(D_x^{\text{Sim}})] - \mathbb{E}[A(D_x^P)]| \\
&\leq \epsilon(n) + \eta(n)
\end{aligned}$$

So, for all  $x$  we have that  $\Pr[|\mathbb{E}[A(D_x^S)] - \mathbb{E}[A(D_x^P)]| > \epsilon + \eta] < 2^{-2n}$ . It follows that

$$\begin{aligned}
\Pr[\exists x : |\mathbb{E}[A(D_x^S)] - \mathbb{E}[A(D_x^P)]| > \epsilon + \eta] &\leq \sum_x \Pr[|\mathbb{E}[A(D_x^S)] - \mathbb{E}[A(D_x^P)]| > \epsilon + \eta] \\
&< \frac{2^n}{2^{2n}} = 2^{-n}.
\end{aligned}$$

So,  $\Pr[\forall x : |\mathbb{E}[A(D_x^S)] - \mathbb{E}[A(D_x^P)]| \leq \epsilon + \eta] > 1 - 2^{-n}$ . In other words, the probability  $A$  has advantage at most  $\epsilon + \eta$  (on any  $x$ ) is bounded away from zero. By an averaging argument, it follows that there must exist some *fixed* choice of  $\text{Sim}_1, \dots, \text{Sim}_k$  that satisfies this bound on distinguishing advantage for  $A$ .

**Definition 6 (Fine-Grained Non-Interactive Proofs in the URS Model).** *A pair of algorithms (Prover, Verifier) is called a  $\mathcal{F}$ -fine-grained non-interactive proof system in the URS model for a language  $\mathcal{L}$  if the algorithm Prover is polynomial-time, (uniformly generated)  $\text{Verifier} \in \mathcal{F}_{|x|}$  (Verifier can be uniformly generated), there exists a polynomial  $p(\cdot)$  and a negligible function  $\mu(\cdot)$  such that the following two conditions hold:*

– **Completeness:** For every  $x \in \mathcal{L}$

$$\Pr[\text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi \leftarrow \text{Prover}(x, \text{URS}) : \text{Verifier}(x, \text{URS}, \pi) = 1] \geq 1 - \mu(|x|).$$

– **Soundness:** For every  $x \notin \mathcal{L}$ , every algorithm  $P^*$

$$\Pr[\text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi' \leftarrow P^*(x, \text{URS}) : \text{Verifier}(x, \text{URS}, \pi') = 1] \leq \mu(|x|).$$

**Definition 7 (Fine-Grained Non-Interactive Zero-Knowledge in the URS Model).** *Let (Prover, Verifier) be a  $\mathcal{F}$ -fine-grained non-interactive proof system in the URS model for the language  $\mathcal{L}$ . We say that (Prover, Verifier) is a  $\mathcal{F}$ -fine-grained non-adaptively zero-knowledge in the URS model if there exists a randomized circuit  $\text{Sim}$  in  $\mathcal{F}$  such that the following two distribution ensembles are computationally indistinguishable by circuits in  $\mathcal{F}$  (when the distinguishing gap is a function of  $|x|$ )*

$$\begin{aligned}
&\{(\text{URS}, \pi) : \text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi \leftarrow \text{Prover}(\text{URS}, x)\}_{x \in \mathcal{L}} \\
&\{(\text{URS}', \pi') \leftarrow \text{Sim}(x)\}_{x \in \mathcal{L}}.
\end{aligned}$$

We say that a fine-grained non-interactive proof system in the URS model is a *statistical NIZK* protocol (or alternatively *achieves statistical zero knowledge*) if the above distribution ensembles are statistically close.

**Definition 8 (Fine-Grained Non-Interactive Zero-Knowledge with Offline Simulation (oNIZK) in the URS Model).** *Let (Prover, Verifier) be a  $\mathcal{F}$ -fine-grained non-interactive proof system in the URS model for the language  $\mathcal{L}$ . We say that (Prover, Verifier) is a  $\mathcal{F}$ -fine-grained non-adaptively zero-knowledge with offline simulation in the URS model if there exists a distribution  $\mathcal{D}_{\text{Sim}}$  over circuits in  $\mathcal{F}$  such that*

the following two distribution ensembles are computationally indistinguishable by circuits in  $\mathcal{F}$  (when the distinguishing gap is a function of  $|x|$ )

$$\begin{aligned} & \{(\text{URS}, \pi) : \text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi \leftarrow \text{Prover}(\text{URS}, x)\}_{x \in \mathcal{L}} \\ & \{(\text{URS}', \pi') \leftarrow \text{Sim}(x) : \text{Sim} \leftarrow \mathcal{D}_{\text{Sim}}\}_{x \in \mathcal{L}}. \end{aligned}$$

Note that by the same argument as above, our fine-grained NIZK definition (for  $\mathcal{F} = \text{NC}^1$ ) implies witness hiding and weak zero knowledge with inverse-polynomial distinguishing advantage. Specifically, for the witness hiding case: Let  $\mathcal{D}$  be a distribution over statements  $x \in \mathcal{L}$ . Assume that  $\mathcal{L}$  has witness relation  $\mathcal{R}$  such that  $x \in \mathcal{L}$  if and only if there exists a witness  $w$  such that  $(x, w) \in \mathcal{R}$ . Note that WLOG we can assume that  $\mathcal{R} \in \text{NC}^1$ . Assume that for all circuits  $C \in \text{NC}^1$ ,

$$\Pr_{x \sim \mathcal{D}} [R(x, C(x)) = 1] \leq \text{negl}(|x|).$$

Then we have that for all circuits  $C' \in \text{NC}^1$

$$\Pr_{x \sim \mathcal{D}} [R(x, C'(x, \text{URS}, \pi)) = 1 : \text{URS} \leftarrow \{0, 1\}^{p(|x|)}; \pi \leftarrow \text{Prover}(\text{URS}, x)] \leq \text{negl}(|x|).$$

## 2.2 Witness Indistinguishability and Fine-Grained Witness Indistinguishability

**Definition 9 (Witness Indistinguishability).** A proof system  $\langle \text{Prover}, \text{Verifier} \rangle$  for a language  $\mathcal{L}$  is witness-indistinguishable if for any polynomial time  $V^*$ , for all  $x \in \mathcal{L}$ , for all  $w_1, w_2 \in w(x)$ , and for all auxiliary inputs  $z$  to  $V^*$ , the distribution on the views of  $V^*$  following an execution  $\langle \text{Prover}, \text{Verifier} \rangle(x, w_1, z)$  is indistinguishable from the distribution on the views of  $V^*$  following an execution  $\langle \text{Prover}, \text{Verifier} \rangle(x, w_2, z)$  to a non-uniform probabilistic polynomial-time distinguisher receiving one of the above transcripts as well as  $(x, w_1, w_2, z)$ .

**Definition 10 ( $\mathcal{F}$ -fine-grained Witness Indistinguishability).** A proof system  $\langle \text{Prover}, \text{Verifier} \rangle$  for a language  $\mathcal{L}$  is  $\mathcal{F}$ -fine-grained witness-indistinguishable if  $\text{Prover}$  is polynomial-time,  $\text{Verifier}$  is in the class  $\mathcal{F}$  and for any  $V^* \in \mathcal{F}$ , for all  $x \in \mathcal{L}$ , for all  $w_1, w_2 \in w(x)$ , and for all auxiliary inputs  $z$  to  $V^*$ , the distribution on the views of  $V^*$  following an execution  $\langle \text{Prover}, \text{Verifier} \rangle(x, w_1, z)$  is indistinguishable from the distribution on the views of  $V^*$  following an execution  $\langle \text{Prover}, \text{Verifier} \rangle(x, w_2, z)$  to a non-uniform distinguisher in class  $\mathcal{F}$  receiving one of the above transcripts as well as  $(x, w_1, w_2, z)$ .

## 2.3 ZAPs and Fine-Grained ZAPs

**Definition 11 (ZAP).** A ZAP is a 2-round (2-message) protocol for proving membership of  $x \in \mathcal{L}$ , where  $\mathcal{L}$  is a language in NP. Let the first-round (verifier to prover) message be denoted  $\rho$  and the second-round (prover to verifier) response be denoted  $\pi$  satisfying the following conditions:

- **Public Coins:** There is a polynomial  $p(\cdot)$  such that the first round messages form a distribution on strings of length  $p(|x|)$ . The verifier's decision whether to accept or reject is a polynomial time function of  $x, \rho$ , and  $\pi$  only.
- **Completeness:** Given  $x$ , a witness  $w \in w(x)$ , and a first-round  $\rho$ , the prover generates a proof  $\pi$  that will be accepted by the verifier with overwhelming probability over the choices made by the prover and the verifier.
- **Soundness:** With overwhelming probability over the choice of  $\rho$ , there exists no  $x' \notin \mathcal{L}$  and second round message  $\pi$  such that the verifier accepts  $(x', \rho, \pi)$ .
- **Witness-Indistinguishability:** Let  $w, w' \in w(x)$  for  $x \in \mathcal{L}$ . Then  $\forall \rho$ , the distribution on  $\pi$  when the prover has input  $(x, w)$  and the distribution on  $\pi$  when the prover has input  $(x, w')$  are nonuniform probabilistic polynomial time (in  $|x|$ ) indistinguishable, even given both witnesses  $w, w'$ .

**Definition 12 ( $\mathcal{F}$ -fine-grained ZAP).** A  $\mathcal{F}$ -fine-grained ZAP is a 2-round (2-message) protocol for proving membership of  $x \in \mathcal{L}$ , where  $\mathcal{L}$  is a language in NP. Let the first-round (verifier to prover) message be denoted  $\rho$  and the second-round (prover to verifier) response be denoted  $\pi$  satisfying the following conditions:

- **Public Coins and Fine-Grained Verifier:** There is a polynomial  $p(\cdot)$  such that the first round messages form a distribution on strings of length  $p(|x|)$ . The verifier’s decision whether to accept or reject is a function of  $x, \rho$ , and  $\pi$  only, and is contained in  $\mathcal{F}_{|x|}$ .
- **Completeness:** Given  $x$ , a witness  $w \in w(x)$ , and a first-round  $\rho$ , the prover, running in time polynomial in  $|x|$ , can generate a proof  $\pi$  that will be accepted by the verifier with overwhelming probability over the choices made by the prover and the verifier.
- **Soundness:** With overwhelming probability over the choice of  $\rho$ , there exists no  $x' \notin \mathcal{L}$  and second round message  $\pi$  such that the verifier accepts  $(x', \rho, \pi)$ .
- **$\mathcal{F}$ -fine-grained Witness-Indistinguishability:** Let  $w, w' \in w(x)$  for  $x \in L$ . Then  $\forall \rho$ , the distribution on  $\pi$  when the prover has input  $(x, w)$  and the distribution on  $\pi$  when the prover has input  $(x, w')$  are indistinguishable to nonuniform algorithms in the class  $\mathcal{F}_{|x|}$ , even given both witnesses  $w, w'$ .

## 2.4 NIWI and Fine-Grained NIWI

**Definition 13 (NIWI).** A NIWI is a non-interactive protocol for proving membership of  $x \in \mathcal{L}$ , where  $\mathcal{L}$  is a language in NP. A single message  $\pi$  is sent from the prover to the verifier.

- **Efficient Verifier:** The verifier’s decision whether to accept or reject is a polynomial time function of  $x$  and  $\pi$  only.
- **Completeness:** Given  $x$  and a witness  $w \in w(x)$ , the prover generates a proof  $\pi$  that will be accepted by the verifier.
- **Soundness:** There exists no  $x' \notin \mathcal{L}$  and message  $\pi$  such that the verifier accepts  $(x', \pi)$ .
- **Witness-Indistinguishability:** Let  $w, w' \in w(x)$  for  $x \in L$ . Then the distribution on  $\pi$  when the prover has input  $(x, w)$  and the distribution on  $\pi$  when the prover has input  $(x, w')$  are nonuniform probabilistic polynomial time (in  $|x|$ ) indistinguishable, even given both witnesses  $w, w'$ .

**Definition 14 ( $\mathcal{F}$ -fine-grained NIWI).** A  $\mathcal{F}$ -fine-grained NIWI is a non-interactive protocol for proving membership of  $x \in \mathcal{L}$ , where  $\mathcal{L}$  is a language in NP. A single message  $\pi$  is sent from the prover to the verifier.

- **Fine-Grained Verifier:** The verifier’s decision whether to accept or reject is a function of the statement  $x$  and proof  $\pi$  only, and the verifier’s circuit is contained in  $\mathcal{F}_{|x|}$ .
- **Completeness:** Given  $x$ , and a witness  $w \in w(x)$  the prover, running in time polynomial in  $|x|$ , can generate a proof  $\pi$  that will be accepted by the verifier with overwhelming probability over the choices made by the prover and the verifier.
- **Soundness:** There exists no  $x' \notin \mathcal{L}$  and message  $\pi$  such that the verifier accepts  $(x', \pi)$ .
- **$\mathcal{F}$ -fine-grained Witness-Indistinguishability:** Let  $w, w' \in w(x)$  for  $x \in L$ . Then the distribution on  $\pi$  when the prover has input  $(x, w)$  and the distribution on  $\pi$  when the prover has input  $(x, w')$  are indistinguishable by the class  $\mathcal{F} := \{\mathcal{F}_{|x|}\}_{|x| \in \mathbb{N}}$ , even given both witnesses  $w, w'$ .

## 2.5 NIZK and Fine-Grained NIZK without CRS and with uniform soundness

**Definition 15 (Non-Interactive Proofs with uniform soundness).** A pair of algorithms (Prover, Verifier) is called a non-interactive proof system with uniform soundness  $T := T(|x|)$ , for a language  $\mathcal{L}$  if the algorithm Verifier is deterministic polynomial-time, there exists a polynomial  $p(\cdot)$  and a negligible function  $\mu(\cdot)$  such that the following two conditions hold:

- **Completeness:** For every  $x \in \mathcal{L}$

$$\Pr[\pi \leftarrow \text{Prover}(x) : \text{Verifier}(x, \pi) = 1] \geq 1 - \mu(|x|).$$

- **Soundness:** For every  $x \notin \mathcal{L}$ , every algorithm  $P^*$  running in uniform time  $T$ ,

$$\Pr[\pi' \leftarrow P^*(x) : \text{Verifier}(x, \pi') = 1] \leq \mu(|x|).$$

**Definition 16 (Non-Interactive Zero-Knowledge with Offline Simulation (oNIZK) in the standard model with uniform soundness).** Let  $(\text{Prover}, \text{Verifier})$  be a non-interactive proof system with uniform soundness  $T := T(|x|)$  for the language  $\mathcal{L}$ . We say that  $(\text{Prover}, \text{Verifier})$  is zero-knowledge with offline simulation if there exists a distribution  $\mathcal{D}_{\text{Sim}}$  over polynomial-sized circuits  $\text{Sim}$  such that the following two distribution ensembles are computationally indistinguishable by polynomial-sized circuits (when the distinguishing gap is a function of  $|x|$ )

$$\begin{aligned} & \{\pi \leftarrow \text{Prover}(x)\}_{x \in \mathcal{L}} \\ & \{\pi' \leftarrow \text{Sim}(x) : \text{Sim} \leftarrow \mathcal{D}_{\text{Sim}}\}_{x \in \mathcal{L}}. \end{aligned}$$

As discussed previously, our NIZK definition above implies witness hiding, via the same argument.

**Definition 17 (Fine-Grained Non-Interactive Proofs with uniform soundness).** A pair of algorithms  $(\text{Prover}, \text{Verifier})$  is called a  $\mathcal{F}$ -fine-grained non-interactive proof system with uniform soundness for a language  $\mathcal{L}$  if the algorithm  $\text{Prover}$  is polynomial-time, (uniformly generated)  $\text{Verifier} \in \mathcal{F}_{|x|}$ , there exists a polynomial  $p(\cdot)$  and a negligible function  $\mu(\cdot)$  such that the following two conditions hold:

- **Completeness:** For every  $x \in \mathcal{L}$

$$\Pr[\pi \leftarrow \text{Prover}(x, \text{URS}) : \text{Verifier}(x, \pi) = 1] \geq 1 - \mu(|x|).$$

- **Soundness:** For every  $x \notin \mathcal{L}$ , every uniform, PPT algorithm  $P^*$

$$\Pr[\pi' \leftarrow P^*(x) : \text{Verifier}(x, \pi') = 1] \leq \mu(|x|).$$

**Definition 18 (Fine-Grained Non-Interactive Zero-Knowledge with Offline Simulation (oNIZK) in the standard model with uniform soundness).** Let  $(\text{Prover}, \text{Verifier})$  be a  $\mathcal{F}$ -fine-grained non-interactive proof system with uniform soundness for the language  $\mathcal{L}$ . We say that  $(\text{Prover}, \text{Verifier})$  is  $\mathcal{F}$ -fine-grained zero-knowledge with offline simulation if there exists a distribution  $\mathcal{D}_{\text{Sim}}$  over circuits in  $\mathcal{F}$  such that the following two distribution ensembles are computationally indistinguishable by circuits in  $\mathcal{F}$  (when the distinguishing gap is a function of  $|x|$ )

$$\begin{aligned} & \{\pi \leftarrow \text{Prover}(x)\}_{x \in \mathcal{L}} \\ & \{\pi' \leftarrow \text{Sim}(x) : \text{Sim} \leftarrow \mathcal{D}_{\text{Sim}}\}_{x \in \mathcal{L}}. \end{aligned}$$

As discussed previously, our fine-grained NIZK definition above implies witness hiding, via the same argument.

### 3 ZAPs from NIZK

For our construction of ZAPs from oNIZK in the URS model, we will require a certain type of *design*, defined next and first used by Nisan and Wigderson in their derandomization of BPP [NW88].

**Definition 19 (Design).** A  $(l, n', n, c)$ -design consists of sets  $\mathcal{S}_1, \dots, \mathcal{S}_{n'} \subseteq [l]$  such that the following hold:

- For each  $i \in [n']$ ,  $|\mathcal{S}_i| = n$ ,
- For each  $i, i'$  s.t.  $i \neq i'$ ,  $|\mathcal{S}_i \cap \mathcal{S}_{i'}| \leq c$ .

$(l, n', n, c)$  designs are known to exist for  $l := n^2$ , constant  $c \in \mathbb{N}$ , and  $n' := n^c$  [NW88].

Let  $\Pi = (\text{Prover}^{\text{NIZK}}, \text{Verifier}^{\text{NIZK}})$  be a non-adaptive oNIZK in the URS model with inefficient prover for language  $\mathcal{L}$  that has soundness  $1/2$  or better. Let sets  $\mathcal{S}_1, \dots, \mathcal{S}_{n'} \subseteq [l]$  form a  $(l, n', n, c)$ -design, where  $l := n^2$ ,  $c := 3$ , and  $n' := n^3$ .

**Verifier's First Round Message:** Recall that in the first round of a ZAP, the Verifier sends a random string  $r$  to the Prover.

**Prover Algorithm:** On input statement  $\text{st} \in \mathcal{L}$ , witness  $w$ , and random string  $r = r_1 || \dots || r_{n'}$  from the Verifier:

1. Choose bits  $[x_j]_{j \in [l]}$  at random. For a set  $\mathcal{S} \subseteq [l]$ , let  $[x_j]_{j \in \mathcal{S}}$  denote the substring of  $[x_1, \dots, x_l]$  corresponding to indices in set  $\mathcal{S}$ .
2. For each  $i \in [n']$ , let  $\text{URS}_i = r_i \oplus [x_j]_{j \in \mathcal{S}_i}$ , where each  $r_i$  has length  $n$  and each  $|\mathcal{S}_i| = n$  (recall that the sets  $\mathcal{S}_i$  are the sets of the design).
3. For  $i \in [n']$ , run  $\text{Prover}^{\text{NIZK}}$  on input  $\text{URS}_i$  and witness  $w$ , outputting proof  $\pi_i$ .
4. Output  $[\pi_i]_{i \in [n']}$  along with  $[x_1, \dots, x_l]$ .

**Verifier's Algorithm after the Second Round:** Recall that the Verifier's first message is denoted  $r$  and that the verifier gets input statement  $\text{st}$ . After observing the Prover's message consisting of  $[\pi_i]_{i \in [n']}$ ,  $[x_1, \dots, x_l]$ , the Verifier does the following:

1. For  $i \in [n']$ , set  $\text{URS}_i = r_i \oplus [x_j]_{j \in \mathcal{S}_i}$ .
2. For  $i \in [n']$ , verify proof  $\pi_i$  relative to  $\text{URS}_i$  by running the verifier  $\text{Verifier}^{\text{NIZK}}$ .
3. If all checks accept, then accept. Otherwise reject.

**Theorem 7.** *Assume  $\Pi = (\text{Prover}^{\text{NIZK}}, \text{Verifier}^{\text{NIZK}})$  is a non-adaptive oNIZK proof system for language  $\mathcal{L}$  with an inefficient prover in the URS model. Then the above construction is a ZAP for language  $\mathcal{L}$  with an inefficient prover.*

*Soundness Proof:* We say that a URS is “bad” relative to a statement  $\text{st} \notin \mathcal{L}$  that is not in the language, if there exists an accepting proof relative to that URS (recall that the verifier is deterministic). For statement  $\text{st} \notin \mathcal{L}$  and fixed  $[x_j]_{j \in [l]}$ , the probability over choice of  $r$  that every  $\text{URS}_i$ ,  $i \in [n']$  is bad is at most  $2^{-n'}$ . Since there are at most  $2^l$  choices for  $[x_j]_{j \in [l]}$  (where  $l := n^2$ ), the probability over random choice of  $r$  that there exists a setting of  $[x_j]_{j \in [l]}$  such that each  $\text{URS}_i$  is bad is at most  $2^{n^2} \cdot 2^{-n'}$ . Since we have set  $n' := n^3$ , we have that that  $2^{n^2} \cdot 2^{-n'} = 2^{-n^3+n^2}$  is negligible.

*Witness Indistinguishability Proof:* We consider the following distributions:

**Hybrid  $H^{w_1}$ :** This is the real world distribution with statement  $\text{st}$  and witness  $w_1$ .

**Hybrid  $H^{w_2}$ :** This is the real world distribution with statement  $\text{st}$  and witness  $w_2$ .

To prove WI, we must show that for every malicious verifier  $V^*$ .

$$H^{w_1} \approx H^{w_2}.$$

Towards this goal, we define the following sequences of hybrid distributions:

**Hybrid  $H^{i, w_1, w_2}$ , for  $i \in [n']$ :** Proofs with  $\text{URS}_{i'}$  for  $i' \leq i$  are honest proofs using  $w_2$ . Proofs with  $\text{URS}_{i'}$  for  $i' > i$  are honest proofs using  $w_1$ .

Note that  $H^{w_1} = H^{0, w_1, w_2}$  and  $H^{w_2} = H^{n', w_1, w_2}$ .

*Claim.* For  $i \in [n']$ ,

$$H^{i-1, w_1, w_2} \approx H^{i, w_1, w_2}.$$



*Proof.* Consider the distribution  $H^{*,i,w_1,w_2}(\text{URS}^*, \pi^*)$ , where a draw from the distribution is defined as follows:

- Run  $V^*$  to produce  $r = r^1 || \dots || r^{n'}$ , sample  $[x_j]_{j \in [l] \setminus \mathcal{S}_i}$
- Set  $[x_j]_{j \in \mathcal{S}_i} := \text{URS}^* \oplus r^i$ .
- Set  $\pi_i := \pi^*$ .
- For each  $i' \in [i-1]$ , run the honest prover  $\text{Prover}^{\text{NIZK}}$  on witness  $w_2$  and  $\text{URS}_{i'} = r^{i'} \oplus [x_j]_{j \in \mathcal{S}_{i'}}$  to obtain proof  $\pi_{i'}$ .
- For each  $i' \in \{i+1, \dots, n'\}$ , run the honest prover  $\text{Prover}^{\text{NIZK}}$  on witness  $w_1$  and  $\text{URS}_{i'} = r^{i'} \oplus [x_j]_{j \in \mathcal{S}_{i'}}$  to obtain proof  $\pi_{i'}$ .
- Output  $[\pi_{i'}]_{i' \in [n']}$  and  $x := [x_j]_{j \in [l]}$ .

Note that when  $(\text{URS}^* = \text{URS}_{\text{honest}}, \pi^* = \pi_{w_1})$  (resp.  $(\text{URS}^* = \text{URS}_{\text{honest}}, \pi^* = \pi_{w_2})$ ) are generated as honest CRS/proofs with witness  $w_1$  (resp.  $w_2$ ), then  $H^{*,i,w_1,w_2}(\text{URS}_{\text{honest}}, \pi_{w_1})$  (resp.  $H^{*,i,w_1,w_2}(\text{URS}_{\text{honest}}, \pi_{w_2})$ ) is equivalent to  $H^{i-1,w_1,w_2}$  (resp.  $H^{i,w_1,w_2}$ ). We must also have that  $H^{*,i,w_1,w_2}(\text{URS}_{\text{honest}}, \pi_{w_1})$  (resp.  $H^{*,i,w_1,w_2}(\text{URS}_{\text{honest}}, \pi_{w_2})$ ) is indistinguishable from  $H^{*,i,w_1,w_2}(\text{URS}_{\text{Sim}}, \pi_{\text{Sim}})$  (where  $\text{URS}_{\text{Sim}}, \pi_{\text{Sim}}$  are generated by drawing a simulator from the oNIZK distribution and obtaining its output), since otherwise we obtain a non-uniform PPT adversary that breaks the zero knowledge of the underlying NIZK proof system. We will elaborate on how this indistinguishability is proved below. Assuming that this is the case, we conclude that  $H^{i-1,w_1,w_2}$  and  $H^{i,w_1,w_2}$  are indistinguishable, which completes the proof.

We now show that  $H^{*,i,w_1,w_2}(\text{URS}_{\text{honest}}, \pi_{w_1})$  (resp.  $H^{*,i,w_1,w_2}(\text{URS}_{\text{honest}}, \pi_{w_2})$ ) is indistinguishable from  $H^{*,i,w_1,w_2}(\text{URS}_{\text{Sim}}, \pi_{\text{Sim}})$  (where  $\text{URS}_{\text{Sim}}, \pi_{\text{Sim}}$  are generated by drawing a simulator from the oNIZK distribution and obtaining its output). Towards contradiction, assume the existence of non-uniform PPT verifier  $V^*$  and non-uniform PPT distinguisher  $D$  distinguishing  $H^{*,i,w_1,w_2}(\text{URS}_{\text{honest}}, \pi_{w_1})$  (resp.  $H^{*,i,w_1,w_2}(\text{URS}_{\text{honest}}, \pi_{w_2})$ ) from  $H^{*,i,w_1,w_2}(\text{URS}_{\text{Sim}}, \pi_{\text{Sim}})$ . Using  $V^*, D$  as above, we construct the following distribution over poly-sized circuits that receive as input  $(\text{URS}^*, \pi^*)$ :

- Run  $V^*$  to produce  $r = r^1 || \dots || r^{n'}$ , sample  $[x_j]_{j \in [l] \setminus \mathcal{S}_i}$  uniformly at random as well as any auxiliary state  $\text{state}_{V^*}$ , which will be used by the distinguishing circuit  $D$ .
- **Hardwired values:**
  1. Statement  $s$  and witnesses  $w_1, w_2$ .
  2. Auxiliary state  $\text{state}_{V^*}$ .
  3.  $r = r^1 || \dots || r^{n'}$ ,  $[x_j]_{j \in [l] \setminus \mathcal{S}_i}$ .
  4. For each  $i' \in [i]$ , hardwire truthtable  $T_{i'}$  that takes as input  $[x_j]_{j \in \mathcal{S}_i \cap \mathcal{S}_{i'}}$  (at most 3 input bits) and outputs  $\text{URS}_{i'} = r^{i'} \oplus [x_j]_{j \in \mathcal{S}_{i'}}$ , and proof  $\pi_{i'}$  honestly computed with statement  $\text{st}$  and witness  $w_2$ .
  5. For each  $i' \in \{i+1, \dots, n'\}$ , hardwire truthtable  $T_{i'}$  that takes as input  $[x_j]_{j \in \mathcal{S}_i \cap \mathcal{S}_{i'}}$  and outputs  $\text{URS}_{i'} = r^{i'} \oplus [x_j]_{j \in \mathcal{S}_{i'}}$ , and proof  $\pi_{i'}$  honestly computed with statement  $\text{st}$  and witness  $w_1$ .
- **Circuit Evaluation:** On input  $(\text{URS}^*, \pi^*)$ , do the following:
  - **Embed  $(\text{URS}^*, \pi^*)$ :** Set  $[x_j]_{j \in \mathcal{S}_i} := r^i \oplus \text{URS}^*$ . Set  $\pi_i := \pi^*$ .
  - **Compute Honest Proofs:** Use the truthtables to compute  $\text{URS}_{i'}$  and  $\pi_{i'}$  for all  $i' \neq i$ , where the  $i'$ -th truthtable  $T_{i'}$  takes input  $[x_j]_{j \in \mathcal{S}_i \cap \mathcal{S}_{i'}}$ .
  - **Output of Prover:** Combine the above two steps to obtain the Prover's message:  $([\pi_{i'}]_{i' \in [n']}, x := [x_j]_{j \in [l]})$ .
  - **Application of Distinguisher:** Apply  $D$  (which may require  $\text{state}_{V^*}$  as auxiliary input) to the transcript and output  $D(r, [\pi_{i'}]_{i' \in [n']}, x := [x_j]_{j \in [l]})$ .

Note that since each of the truth tables  $T_{i'}$  takes a constant number of input bits, and since all the truth tables can be evaluated in parallel, the above is a distribution over circuits corresponding to a (non-uniform)  $\text{NC}^0$  circuit composed with the distinguisher  $D$ . When  $D$  is a poly-sized circuit, the resulting circuit drawn from the distribution is poly-sized. Moreover, the expected distinguishing probability of a circuit drawn from the above distribution is exactly equal to  $D$ 's distinguishing probability (which is assumed to be non-negligible). But this contradicts the the zero knowledge property of the underlying oNIZK.

Note the same proof as above holds for the case of  $\mathcal{F}$ -fine-grained oNIZK, as long as the distribution defined above is a distribution over circuits contained in  $\mathcal{F}$ , whenever  $D$  is contained in  $\mathcal{F}$ . This holds when instantiating  $\mathcal{F}$  with the class non-uniform  $\text{NC}^1$  since, as discussed above, the depth of “Embed” + “Compute Honest Proofs” + “Output of Prover” is constant. So if the depth of  $D$  in the “Application of Distinguisher” is logarithmic, then the depth of the entire “Circuit Evaluation” is logarithmic. We therefore obtain the following theorem:

**Theorem 8.** *Assume  $\Pi = (\text{Prover}^{\text{NIZK}}, \text{Verifier}^{\text{NIZK}})$  is a  $\text{NC}^1$ -fine-grained, non-adaptive oNIZK proof system in the URS model. Then the above construction is a  $\text{NC}^1$ -fine-grained ZAP.*

## 4 ZAPs, NIWI and oNIZK for AM or NP with Polynomial Security

Using Theorem 7 and the fact that non-adaptive (standard) NIZK with unbounded provers in the URS model for AM can be constructed from one-way permutations, we obtain:

**Theorem 9 (Informal).** *Assuming the existence of one-way permutations, there exist NIWI for AM with inefficient provers.*

Using known results [BOV03, BOV07] on transformation of ZAPs to NIWI proof systems via the derandomization assumption of the existence of hitting set generators (HSG) against co-nondeterministic uniform algorithms, we obtain:

**Theorem 10 (Informal).** *Assuming the existence of one-way permutations and efficient 1/2-HSG against co-nondeterministic uniform algorithms, there exist NIWI for NP with inefficient provers.*

Finally, we observe that the only non-polynomial-time computations performed by the NIWI prover are inversions of OWP, and that the hardness of the OWP is tunable to any  $2^{n^\epsilon}$  for any constant  $0 < \epsilon < 1$ , since the input length of the OWP is independent of all other parameters. Therefore, we can use known techniques to obtain oNIZK in the standard model that guarantees soundness against uniform adversaries. Specifically, the soundness against uniform adversaries comes from the hardness of finding a collision in a keyless collision resistant hash function. Assuming subexponential hardness of such collision resistant hash functions, we can tune the hardness of finding such a collision to be any  $2^{n^c}$ , for any constant  $c$ . We therefore obtain the following:

**Theorem 11 (Informal).** *Assuming the existence of one-way permutations, efficient 1/2-HSG against co-nondeterministic uniform algorithms, and subexponentially-hard uniform collision resistant hash functions, then for any constant  $0 < \epsilon < 1$  and constant  $c \geq 1$ , there exist oNIZK in the standard model for NP with honest provers running in uniform time  $2^{n^\epsilon}$  and soundness against uniform adversaries running in time  $2^{n^c}$ , where  $n$  is security parameter.*

## 5 Fine-Grained NIZK and ZAPs for NP

This section is chiefly devoted to constructing an  $\text{NC}^1$ -fine-grained zero-knowledge non-interactive proofs for NP. Our general approach is bootstrap a *statistical* NIZK just for languages in  $\oplus\text{L}/\text{poly}$  to a fine-grained NIZK for all of NP.

The NISZK protocol we bootstrap is a variant of NISZK protocol from [AR16], in turn constructed from the randomized encodings of [IK00, IK02], adapted to work in the URS setting. Next we repurpose the randomized encodings to construct a perfectly binding commitment scheme which is (a) hiding for  $\text{NC}^1$ , yet (b) extractable in  $\oplus\text{L}/\text{poly}$ . Finally, to prove a circuit is satisfiable, the prover simply commits to a witness and the ensuing circuit evaluation and appends a NISZK that the commitments indeed open to a satisfying evaluation (which, when using such a special commitment scheme, is a  $\oplus\text{L}/\text{poly}$  statement).

The fine-grained ZAP follows from the fine-grained NIZK by Theorem 8.

## 5.1 Background on Randomized Encodings of [IK00, IK02]

We begin by reviewing some of the ingredients we require from the work of Ishai and Kushilevitz [IK00, IK02]. Our exposition in this subsection follows that of [App14].

Let  $BP = (G, \phi, s, t)$  be a mod-2 BP of size  $\ell$ , computing a Boolean function  $f : \{0, 1\}^n \rightarrow \{0, 1\}$ ; that is,  $f(x) = 1$  if and only if the number of paths from  $s$  to  $t$  in  $G_x$  equals 1 modulo 2, where  $G_x$  is the subgraph of  $G$  specified momentarily. Fix some topological ordering of the vertices of  $G$ , where the source vertex  $s$  is labeled 1 and the terminal vertex  $t$  is labeled  $\ell$ .

Let  $A(x)$  be the  $\ell \times \ell$  adjacency matrix of  $G_x$  viewed as a formal matrix whose entries are degree-1 polynomials in the input variables,  $x_1, \dots, x_n = x$ . Specifically, the  $(i, j)$  entry of  $A(x)$  contains the value of  $\phi_{i,j}(x)$ , where  $\phi_{i,j}(x)$  is equal to either a constant function 1 or some literal, such as  $x_k$  or  $\bar{x}_k$ . We constrain  $\phi$  such that if  $(i, j)$  is not an edge, the entry is necessarily 0. Define  $L(x)$  as the submatrix of  $A(x) - I$  obtained by deleting column  $s$  and row  $t$  (i.e., the first column and the last row). As before, each entry of  $L(x)$  is a degree-1 polynomial in a single input variable  $x_i$ ; moreover,  $L(x)$  contains the constant  $-1 = 1 \pmod 2$  in each entry of its second diagonal (the one below the main diagonal) and the constant 0 below this diagonal (see Figure 5.1).

$$\begin{pmatrix} 1 & r_1^{(1)} & r_2^{(1)} & \cdots & r_{\ell-2}^{(1)} \\ 0 & 1 & \cdot & \cdot & \cdot \\ 0 & 0 & 1 & \cdot & \cdot \\ 0 & 0 & 0 & 1 & \cdot \\ 0 & 0 & 0 & 0 & 1 & r_{\binom{\ell-1}{2}}^{(1)} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \phi_{1,2}(x) & \phi_{1,3}(x) & \cdot & \cdot & \cdot & \phi_{1,\ell}(x) \\ 1 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 1 & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 1 & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 1 & \cdot & \cdot \\ 0 & 0 & 0 & 0 & 1 & \cdot \\ 0 & 0 & 0 & 0 & 0 & 1 & \phi_{\ell-1,\ell}(x) \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & r_1^{(2)} \\ 0 & 1 & 0 & 0 & 0 & r_2^{(2)} \\ 0 & 0 & 1 & 0 & 0 & \cdot \\ 0 & 0 & 0 & 1 & 0 & \cdot \\ 0 & 0 & 0 & 0 & 1 & r_{\ell-2}^{(2)} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

**Fig. 5.1.** The matrices  $R_1(r^{(1)})$ ,  $A(x)$ , and  $R_2(r^{(2)})$ .

Let  $r^{(1)}$  and  $r^{(2)}$  be vectors of  $\mathbb{F}_2$  of length  $\sum_{i=1}^{\ell-2} i = \binom{\ell-1}{2}$  and  $\ell - 2$ , respectively. Let  $R_1(r^{(1)})$  be an  $(\ell - 1) \times (\ell - 1)$  matrix with 1's on the main diagonal, 0's below it, and  $r^{(1)}$ 's elements in the remaining  $\binom{\ell-1}{2}$  entries above the diagonal (a unique element of  $r^{(1)}$  is assigned to each matrix entry). Let  $R_2(r^{(2)})$  be an  $(\ell - 1) \times (\ell - 1)$  matrix with 1's on the main diagonal,  $r^{(2)}$ 's elements in the rightmost column, and 0's in each of the remaining entries (see Figure 5.1).

We will also need the following facts. Note that in all that follows, we consider all arithmetic over  $\mathbb{F}_2$ , including determinants.

**Fact 1** ([App14]) *Let  $M, M'$  be  $(\ell - 1) \times (\ell - 1)$  matrices that contain the constant  $-1 = 1 \pmod 2$  in each entry of their second diagonal and the constant 0 below this diagonal. Then,  $\det(M) = \det(M')$  if and only if there exist  $r^{(1)}$  and  $r^{(2)}$  such that  $R_1(r^{(1)})MR_2(r^{(2)}) = M'$ .*

**Lemma 1** ([App14]). *Let BP be a mod-2 branching program computing the Boolean function  $f$ . Define a function  $\hat{f}(x, (r^{(1)}, r^{(2)})) := R_1(r^{(1)})L(x)R_2(r^{(2)})$ . Then  $\hat{f}$  is a perfect randomized encoding of  $f$ .*

Define  $M_0$  and  $M_1$  as matrices that are all 0 except for the lower diagonal which is 1, and the top right entry which is 1 in the case of  $M_1$  (and 0 in the case of  $M_0$ ).

$$M_0 := \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix} \quad M_1 := \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

**Lemma 2.** Assuming  $\oplus L/\text{poly} \not\subseteq \text{NC}^1$ , the distributions  $R_1(r^{(1)})M_0R_2(r^{(2)})$  and  $R_1(r^{(1)})M_1R_2(r^{(2)})$  cannot be distinguished by  $\text{NC}^1$  circuits, where  $r^{(1)}, r^{(2)}$  are chosen at random.

## 5.2 Statistical NIZK protocol in the URS model for $\oplus L/\text{poly}$

Due to properties of the randomized encoding construction of [IK00], we can construct a statistical NIZK protocol in the uniform *random* string (URS) model for languages in  $\oplus L/\text{poly}$ . Our protocol is heavily based on the protocol of Applebaum and Raykov [AR16], which gave a NISZK construction in the common *reference* string (CRS) model for languages that have (statistical) randomized encodings. Our protocol is described next:

- **URS Generation:** The URS consists of  $\lambda$  random strings, each from  $\{0, 1\}^t = \{0, 1\}^{\binom{\ell-1}{2} + \ell - 1}$ .
- **Prover:** On input statement matrix  $M = L(x)$  (as defined in Section 5.1), the prover does the following:
  1. For  $i \in [\lambda]$ , use the  $i$ -th block of  $t$  bits to populate the upper-triangular entries of a matrix  $M'_i$  that has  $-1$ 's on its second diagonal and  $0$ 's below it.
  2. For  $i \in [\lambda]$ , if  $\det(M'_i) = 0$ , reveal  $r_i^{(1)}, r_i^{(2)}$  of the correct form such that  $R_1(r_i^{(1)})M_0R_2(r_i^{(2)}) = M'_i$ , where  $M_0$  is a determinant 0 matrix of “canonical form.” Otherwise, reveal  $r^{(1)}, r^{(2)}$  of the correct form, such that  $R_1(r_i^{(1)})MR_2(r_i^{(2)}) = M'_i$ .
  3. Output  $\pi = [(r_i^{(1)}, r_i^{(2)})]_{i \in [\lambda]}$ .
- **Verifier:** On input (URS,  $M, \pi = [(r_i^{(1)}, r_i^{(2)})]_{i \in [\lambda]}$ ), the verifier checks that for all  $i \in [\lambda]$ , either  $M'_i = R_1(r_i^{(1)})M_0R_2(r_i^{(2)})$  or  $M'_i = R_1(r_i^{(1)})MR_2(r_i^{(2)})$ .

**Lemma 3.** The protocol above is a NIZK proof system with statistical soundness and statistical zero knowledge in the URS for languages  $\mathcal{L} \in \oplus L/\text{poly}$ . Moreover, the NIZK simulator can be instantiated by sampling a  $\text{NC}^1$  circuit  $\text{Sim}$  from an efficiently samplable distribution  $\mathcal{D}_{\text{Sim}}$ .

The only way that soundness fails, is if all  $\lambda$  instances  $M'_i$  obtained from the URS have determinant 0. This occurs with probability at most  $2^{-\lambda}$ , due to the fact that the randomized encodings of [IK00] are “balanced” (i.e. an equal number of strings correspond to an encoding of 0 vs. 1).

**Statistical Zero knowledge.** We define the following randomized circuit  $\text{Sim} \in \text{NC}^1$ .  $\text{Sim}$  takes as input the instance, represented by  $M$ , and a sufficiently long string of random coins and does as follows:

- Sample a random set  $\mathcal{S} \subseteq [\lambda]$  of indices, where each  $i \in [\lambda]$  is placed in  $\mathcal{S}$  with independent probability  $1/2$ .
- Sample random bitstrings  $(r_i^{(1)}, r_i^{(2)})$  of the correct length for  $i \in [\lambda]$ .
- For  $i \in \mathcal{S}$ ,  $\text{Sim}$  sets the corresponding  $t$  bit string of the URS to consist of the entries of  $R_1(r_i^{(1)})M_0R_2(r_i^{(2)})$  and reveals  $(r_i^{(1)}, r_i^{(2)})$ .
- For  $i \notin \mathcal{S}$ ,  $\text{Sim}$  sets the corresponding  $t$  bit string of the URS to consist of the entries of  $R_1(r_i^{(1)})MR_2(r_i^{(2)})$  and reveals  $(r_i^{(1)}, r_i^{(2)})$ .

## 5.3 $\mathcal{G}$ -extractable, $\mathcal{F}$ -Fine-Grained Commitments for $\text{NC}^1$

$\mathcal{G}$ -extractable,  $\mathcal{F}$ -Fine-Grained Commitments are commitments that are perfectly binding and have the following properties (see also Definition 3 for a formal description):

- The commitments can be computed and opened in class  $\mathcal{F}$ .
- Given a commitment, the committed value can be extracted in class  $\mathcal{G}$ .
- The hiding property of the commitment holds against adversaries in class  $\mathcal{F}$ .

For our purposes, we will consider  $\mathcal{G}$  to be the class  $\oplus L/\text{poly}$  and the class  $\mathcal{F}$  to be the class  $\text{NC}^1$ .

Define the following languages  $\mathcal{L}_{det}, \overline{\mathcal{L}_{det}}$ .  $\mathcal{L}_{det}$  is the set of  $\ell - 1 \times \ell - 1$  matrices  $M$  with  $-1$  on the second diagonal,  $0$ 's below the second diagonal,  $0$  or  $1$  elements on the diagonal and above such that  $M$  has determinant  $1$  over  $\mathbb{F}_2$ .  $\overline{\mathcal{L}_{det}}$  is the set of  $\ell - 1 \times \ell - 1$  matrices  $M$  with  $-1$  on the second diagonal,  $0$ 's below the second diagonal,  $0$  or  $1$  elements on the diagonal and above such that  $M$  has determinant  $0$  over  $\mathbb{F}_2$ .

**Lemma 4.** *The languages  $\mathcal{L}_{det}$  and  $\overline{\mathcal{L}_{det}}$  are contained in  $\oplus L/\text{poly}$ .*

Toda [Tod84] showed that the determinant is complete for  $\#L$  by demonstrating  $\text{NC}^1$ -computable projection from the determinant to counting paths in acyclic graphs. It follows that evaluating the determinant in  $\mathbb{F}_2$  can be done in  $\oplus L/\text{poly}$ .

*Construction of  $\oplus L/\text{poly}$ -extractable,  $\text{NC}^1$ -Fine-Grained Commitment Scheme:* To commit to a  $1$ , choose random  $(r^{(1)}, r^{(2)})$  of appropriate length and output  $R_1(r^{(1)})M_0R_2(r^{(2)})$ . To commit to a  $0$ , choose random  $(r^{(1)}, r^{(2)})$  of appropriate length and output  $R_1(r^{(1)})M_1R_2(r^{(2)})$ .

The required properties of the  $\oplus L/\text{poly}$ -extractable,  $\text{NC}^1$ -Fine-Grained Commitment Scheme follow from Lemma 4 and from the assumption that  $\oplus L/\text{poly} \not\subseteq \text{NC}^1$ , as shown by [DVV16].

#### 5.4 $\text{NC}^1$ -Fine-Grained NIZK for Circuit SAT

Assume  $\mathcal{C}$  is represented as a circuit consisting of NAND gates and assume it has  $z$  number of wires. The value of each wire is committed (using the  $\oplus L/\text{poly}$ -extractable,  $\text{NC}^1$ -fine-grained commitment scheme from the previous section) as  $com_1, \dots, com_z$ . Recall that  $com_i$  commits to  $1$  iff  $com_i \in \mathcal{L}_{det}$  and  $com_i$  commits to  $0$  iff  $com_i \in \overline{\mathcal{L}_{det}}$ . Additionally, recall that  $\mathcal{L}_{det}$  (and therefore also  $\overline{\mathcal{L}_{det}}$ ) is contained in  $\oplus L/\text{poly}$ . The language  $\mathcal{L}_{\mathcal{C}}$  consists of strings  $com_1, \dots, com_z$  which satisfy all of the following:

- $com_z \in \mathcal{L}_{det}$
- For each gate  $G_\ell$  with with input wires  $i, j$  and output wire  $k$ :

$$\begin{aligned} & (com_i \in \overline{\mathcal{L}_{det}} \wedge com_k \in \mathcal{L}_{det}) \vee (com_j \in \overline{\mathcal{L}_{det}} \wedge com_k \in \mathcal{L}_{det}) \vee \\ & (com_i \in \mathcal{L}_{det} \wedge com_j \in \mathcal{L}_{det} \wedge com_k \in \overline{\mathcal{L}_{det}}). \end{aligned}$$

We denote this as  $(com_i, com_j, com_k) \in \mathcal{L}_{gate}$ .

Due to closure of  $\oplus L/\text{poly}$  w.r.t. negation, conjunction and disjunction [BG99], we have that  $\mathcal{L}_{\mathcal{C}} \in \oplus L/\text{poly}$ .

*Construction of  $\text{NC}^1$ -Fine-Grained NIZK for Circuit SAT.* Given a circuit-SAT instance with circuit  $C$ , commit to the witness  $w$  using the above type of commitment (i.e. the witness corresponds to the values of all wires in the circuit  $C$  and the commitment is a wire-by-wire commitment to those values as above). We have shown above that the following language  $\mathcal{L}_{\mathcal{C}}$  is then in  $\oplus L/\text{poly}$   $\mathcal{L}_{\mathcal{C}} : \{(com_1, \dots, com_z) : com_1, \dots, com_z \text{ are commitments to } w = w_1, \dots, w_z \text{ and } w \text{ is a circuit-SAT witness for } C\}$ .

Now, applying the argument system from before to proving statement  $(com_1, \dots, com_z)$  is contained in language  $\mathcal{L}_{\mathcal{C}}$  yields a fine-grained NIZK in the URS model for circuit SAT.

In more detail, the construction proceeds as follows: The Prover commits to witness  $w = w_1, \dots, w_z$  using a  $\oplus L/\text{poly}$ -extractable,  $\text{NC}^1$ -Fine-Grained Commitment Scheme, yielding  $(com_1, \dots, com_z)$ . The Prover then runs the statistical NIZK protocol given above in Section 5.2 to prove that  $(com_1, \dots, com_z) \in \mathcal{L}_{\mathcal{C}}$ .

**Theorem 12.** *The construction above is a  $\text{NC}^1$ -fine-grained NIZK proof system for the circuit SAT language.*

Note that the above implies a  $\text{NC}^1$ -fine-grained NIZK proof system for all of NP. This is because given an NP language,  $L$ , with a canonical polynomial size verification circuit  $V(x, w)$ , the prover can simply prove that the circuit  $V_x(\cdot) := V(x, \cdot)$  is satisfiable. Because each bit of  $V_x$  is computable in  $\text{NC}^0$ , the NIZK verifier can generate  $V_x$  independently of the prover.

To argue zero knowledge of the NIZK against a  $\text{NC}^1$  distinguisher, we define the following randomized circuit  $\text{Sim}' \in \text{NC}^1$ .  $\text{Sim}'$  takes as input the instance, represented by NAND circuit  $\mathcal{C}$  consisting of  $z$  number of wires, and a sufficiently long string of random coins and does as follows:

- Generate  $z$  commitments to garbage  $(com_1, \dots, com_z)$ .
- Let  $\text{Sim}$  be the zero knowledge simulator defined in Section 5.2 for languages in  $\oplus L/\text{poly}$ .
- $\text{Sim}'$  runs the simulator  $\text{Sim}$  on input statement  $(com_1, \dots, com_z)$  and language  $\mathcal{L}_{\mathcal{C}}$ .
- $\text{Sim}'$  outputs whatever  $\text{Sim}$  outputs.

Note that  $\text{Sim}' \in \text{NC}^1$ , since  $\text{Sim} \in \text{NC}^1$ . If a  $\text{NC}^1$  adversary can distinguish simulated and real proofs, then we can use the adversary to break the hiding property of the  $\oplus L/\text{poly}$ -extractable,  $\text{NC}^1$ -Fine-Grained Commitment Scheme, a contradiction.

We now present an alternative construction of  $\text{NC}^1$ -fine-grained NIZK in the URS model, which will be needed to construct  $\text{NC}^1$ -fine-grained oNIZK with uniform soundness in the standard model.

*Alternative Construction.* The following alternative construction of a  $\text{NC}^1$ -fine-grained NIZK proof system for the Circuit SAT language will be useful for some of our applications. In the alternate construction, the Prover still produces a single set of commitments  $(com_1, \dots, com_z)$  to the wire values of the circuit  $\mathcal{C}$ , but we include a separate URS for proving that the satisfying assignment is valid for each individual gate. Details follow.

Given a circuit  $\mathcal{C}$  with  $t$  gates and a common random string split into  $t + 1$  sections  $\text{URS}_0, \dots, \text{URS}_t$ , witness  $w = w_1, \dots, w_z$  (which consists of the values of each of the  $z$  wires of  $\mathcal{C}$  corresponding to a satisfying assignment). The Prover does as follows: Commit to the values of the wires, using the  $\oplus L/\text{poly}$ -extractable,  $\text{NC}^1$ -Fine-Grained Commitment Scheme, producing commitments  $com_1, \dots, com_z$ . Use  $\text{URS}_0$  to prove that  $com_z \in \mathcal{L}_{det}$ . For the  $\ell$ -th gate, with input wires  $i, j$  and output wire  $k$ , use  $\text{URS}_\ell$  to prove that  $(com_i, com_j, com_k) \in \mathcal{L}_{gate}$ . Note that  $\mathcal{L}_{det}$  and  $\mathcal{L}_{gate}$  are both contained in  $\oplus L/\text{poly}$ . Therefore, to prove each of the  $z + 1$  statements, the NIZK in the URS model given in Section 5.2 can be used.

The simulator  $\text{Sim}'$  is almost exactly as above: On input circuit  $\mathcal{C}$ ,  $\text{Sim}'$  still proceeds by randomly generating a commitments  $(com_1, \dots, com_z)$  to garbage. We also now will now invoke the simulator  $\text{Sim} \in \text{NC}^1$  given in Section 5.2,  $\text{Sim}'$  now has  $z + 1$  number of statements to be proven about different subsets of the commitments  $(com_1, \dots, com_z)$ , each proof with a separate URS. In parallel for the  $z + 1$  statements,  $\text{Sim}'$  invokes  $\text{Sim}$  with the corresponding  $i$ -th statement. Each invocation of  $\text{Sim}$  outputs a  $\text{URS}_i$  and a proof  $\pi_i$ .  $\text{Sim}'$  then concatenates the URS's and proofs and outputs the result as the final simulated URS and proof.

Since  $\text{Sim}' \in \text{NC}^1$ , if a  $\text{NC}^1$  adversary can distinguish simulated and real proofs, then we can use the adversary to break the hiding property of the  $\oplus L/\text{poly}$ -extractable,  $\text{NC}^1$ -fine-grained commitment scheme, a contradiction.

## 5.5 $\text{NC}^1$ -Fine-Grained ZAPs for Circuit SAT

We use the construction above together with Theorem 8 to obtain the following:

**Theorem 13.** *Assuming that  $\oplus L/\text{poly} \not\subseteq \text{NC}^1$ , there exist  $\text{NC}^1$ -fine-grained ZAPs for NP.*

## 5.6 $\text{NC}^1$ -Fine-Grained NIWI for NP

We use the transformation of Barak et al. [BOV03, BOV07] from ZAPs to NIWI, that relies on the existence of hitting set generators (HSG) against co-nondeterministic uniform algorithms. Note that this transformation retains statistical soundness (due to the properties of the HSG) and retains its witness indistinguishability against  $\text{NC}^1$  adversaries. However, the verifier may no longer be in  $\text{NC}^1$ , since the verifier must evaluate the HSG in order to check that the prover is using the correct URS for each of the sub-proofs. To remedy this situation, the prover evaluates the HSG and then sends a tableau of the computation (which can be verified in  $\text{AC}^0$ ) to the verifier, who can then verify that the URS being used is indeed consistent with the output of the HSG.

**Theorem 14.** *Assuming that  $\oplus L/\text{poly} \not\subseteq \text{NC}^1$ , the existence of efficient 1/2-HSG against co-nondeterministic uniform algorithms, there exist  $\text{NC}^1$ -fine-grained NIWI for NP.*

## 5.7 $\text{NC}^1$ -Fine-Grained oNIZK with uniform soundness

We now assume existence of a uniform collision resistant hash function  $h$ . Let  $\mathcal{C}_h$  be the circuit that takes two inputs  $x_1, x_2$  and outputs 1 if  $x_1 \neq x_2$  and  $h(x_1) = h(x_2)$ . On input circuit SAT circuit  $\mathcal{C}$ , the prover now proves circuit satisfiability of the circuit  $\mathcal{C}'$ , where  $\mathcal{C}'$  is defined as follows:  $\mathcal{C}'$  takes public input  $\text{desc}(\mathcal{C})$ , which is a description of the circuit  $\mathcal{C}$ , and private input  $x$ .  $\mathcal{C}'$  outputs 1 on input  $(\text{desc}(\mathcal{C}), x)$  if and only if  $x$  is a satisfying assignment for  $\mathcal{C}$  or  $x$  is a satisfying assignment for  $\mathcal{C}_h$ . Note that  $\mathcal{C}'$  is a  $\text{NC}^1$  circuit.

On input statement  $\mathcal{C}$ , the Prover uses the NIWI based on the alternate construction of the  $\text{NC}^1$ -fine-grained NIZK proof system with statistical soundness for the Circuit SAT language to prove that (1)  $(\text{com}_1, \dots, \text{com}_z)$  is a satisfying assignment for  $\mathcal{C}'$  and (2) The commitments corresponding to the public input decommit to values that are consistent with  $\text{desc}(\mathcal{C})$ .

The verifier runs the verifier of the NIWI to verify the proof for the statements (1) and (2) above.

To prove zero knowledge with offline simulation (oNIZK), we must show a distribution  $\mathcal{D}_{\text{Sim}}$  over  $\text{NC}^1$  circuits such that a circuit drawn from this distribution, evaluated on input statement  $\mathcal{C}$  produces a distribution over proofs that is indistinguishable from real proofs for a  $\text{NC}^1$  circuit.

A draw from  $\mathcal{D}_{\text{Sim}}$  is defined as follows:

- Sample colliding inputs  $x_1, x_2$  for  $h$ .
- For each wire  $i$  of  $\mathcal{C}'$ , sample a commitment to 0 and a commitment to 1:  $(\text{com}_i^0, \text{com}_i^1)$ .
- For each public wire  $i$  of  $\mathcal{C}'$ , compute honest proofs  $\pi_{in,i}^0, \pi_{in,i}^1$  proving that  $\text{com}_i^0 \in \overline{\mathcal{L}_{det}}$  and that  $\text{com}_i^1 \in \mathcal{L}_{det}$ , respectively.
- For the output wire  $z$  of  $\mathcal{C}'$ , compute an honest proof  $\pi_{out}$  that  $\text{com}_z^1 \in \mathcal{L}_{det}$ .
- For each gate with input wires  $i, j$  and output wire  $k$  of  $\mathcal{C}'$ , compute 4 honest proofs  $[\pi_{gate,i,j,k}^{b_1,b_2}]_{b_1,b_2 \in \{0,1\}}$  proving that  $\text{com}_i^{b_1}, \text{com}_j^{b_2}, \text{com}_k^{1-b_1 \wedge b_2} \in \mathcal{L}_{gate}$ , for  $b_1, b_2 \in \{0,1\}$ .
- **Hardwired Values:** A satisfying assignment  $y$  (using colliding inputs  $x_1, x_2$ ) for  $\mathcal{C}_h$  and  $[\text{com}_i^0, \text{com}_i^1]_{i \in [z]}$ ,  $(\pi_{in,i}^0, \pi_{in,i}^1), \pi_{out}, [\pi_{gate,i,j,k}^{b_1,b_2}]_{i,j,k,b_1,b_2}$ .
- **Circuit Evaluation:** On input  $\text{desc}(\mathcal{C})$ , choose the appropriate public inputs corresponding to that input. Additionally, chose the private inputs corresponding to the satisfying assignment  $y$ . Let  $b_{in}(i)$  denote the value of the  $i$ -th public input wire. Assume there are a total of  $z'$  input wires. Using these, compute the values of all wires of  $\mathcal{C}'$  (this can be done in  $\text{NC}^1$ , since  $\mathcal{C}'$  is a  $\text{NC}^1$  circuit). Let  $b(i)$  denote the value of the  $i$ -th wire of  $\mathcal{C}'$ . Output commitments  $[\text{com}_i^{b(j)}]_{i \in [z]}$  and proofs  $[\pi_{in,i}^{b_{in}(i)}]_{i \in [z']}$ ,  $[\pi_{gate,i,j,k}^{b(i),b(j)}]_{i,j,k}$ .

Note that the outputted distribution is identical to an honest proof with witness corresponding to a satisfying assignment of  $\mathcal{C}_h$ . Thus, by the witness indistinguishability property of the proof system, the simulated proof is indistinguishable from the real proof.

Moreover, note that by the collision resistance of  $h$ , soundness still holds against uniform, poly-time provers.

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