

Resetable Zero Knowledge in the Bare Public-Key Model under Standard Assumption

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Abstract

In this paper we resolve an open problem regarding resettable zero knowledge in the bare public-key (BPK for short) model: Does there exist constant round resettable zero knowledge argument with concurrent soundness for \mathcal{NP} in BPK model without assuming *sub-exponential hardness*? We give a positive answer to this question by presenting such a protocol for any language in \mathcal{NP} in the bare public-key model assuming only collision-resistant hash functions against *polynomial-time* adversaries.

Key Words. Resetable Zero Knowledge, Concurrent Soundness, Bare Public-Key Model, Resettablely sound Zero Knowledge.

1 Introduction

Zero knowledge (ZK for short) proof, a proof that reveals nothing but the validity of the assertion, is put forward in the seminal paper of Goldwasser, Micali and Rackoff [15]. Since its introduction, especially after the generality demonstrated in [14], ZK proofs have become a fundamental tools in design of some cryptographic protocols. In recent years, the research is moving towards extending the security to cope with some more malicious communication environment. In particular, Dwork et al. [12] introduced the concept of concurrent zero knowledge, and initiate the study of the effect of executing ZK proofs concurrently in some realistic and asynchronous networks like the Internet. Though the concurrent zero knowledge protocols have wide applications, unfortunately, they requires

logarithmic rounds for languages outside \mathcal{BPP} in the plain model for the black-box case [5] and therefore are of round inefficiency. In the Common Reference String model, Damgaard [6] showed that 3-round concurrent zero-knowledge can be achieved efficiently. Surprisingly, using non-black-box technique, Barak [1] constructed a constant round non-black-box bounded concurrent zero knowledge protocol though it is very inefficient.

Motivated by the application in which the prover (such as the user of a smart card) may encounter resetting attack, Canetti et al. [4] introduced the notion of resettable zero knowledge (rZK for short). An rZK formalizes security in a scenario in which the verifier is allowed to reset the prover in the middle of proof to any previous stage. Obviously the notion of resettable zero knowledge is stronger than that of concurrent zero knowledge and therefore we can not construct a constant round black-box rZK protocol in the plain model for non-trivial languages. To get constant round rZK, the work [4] also introduced a very attracting model, the bare public-key model (BPK). In this model, Each verifier deposits a public key pk in a public file and stores the associated secret key sk before any interaction with the prover begins. Note that no protocol needs to be run to publish sk , and no authority needs to check any property of pk . Consequently the BPK model is considered as a very weak set-up assumption compared to previously models such as common reference model and PKI model.

However, as Micali and Reyzin [18] pointed out, the notion of soundness in this model is more subtle. There are four distinct notions of soundness: one time, sequential, concurrent and resettable soundness, each of which implies the previous one. Moreover they also pointed out that there is NO black-box rZK satisfying resettable soundness for non-trivial language and the original rZK arguments in the BPK model of [4] does not seem to be concurrently sound. The 4-round(optimal) rZK arguments with concurrent soundness in the bare public-key model was proposed by Di Crescenzo et al. in [10] and also appeared in [24].

All above rZK arguments in BPK model need some cryptographic primitives secure against sub-exponential time adversaries, which is not a standard assumption in cryptography. Using non-black-box techniques, Barak et al. obtained a constant-round rZK argument of knowledge assuming only collision-free hash functions secure against superpolynomial-time algorithms¹, but their protocol enjoys only sequential soundness. The existence of constant round rZK arguments with concurrent soundness in BPK model under only polynomial-time hardness

¹using idea from [3], this results also holds under standard assumptions that there exist hash functions that are collision-resistant against all polynomial-time adversaries.

assumption is an interesting problem.

Our results. In this paper we resolve the above open problem by presenting a constant-round rZK argument with concurrent soundness in BPK model for \mathcal{NP} under the standard assumptions that there exist hash functions collision-resistant against *polynomial time* adversaries, We note that our protocol is a argument of knowledge and therefore the non-black-box technique is inherently used.

In our protocol, we use the resettable-sound non-black-box zero knowledge argument as a building block in a manner different from that in [2]: instead of using it for the verifier to prove the knowledge of its secret key, the verifier uses it in order to prove that a challenge matches the one he committed to in a previous step. This difference is crucial in the concurrent soundness analysis of our protocol: we just need to simulate *only one execution* among all concurrent executions of the resettable-sound zero knowledge argument for justifying concurrent soundness, instead of simulating all these concurrent executions.

2 Preliminaries

In this section we recall some definitions and tools that will be used later.

In the following we say that function $f(n)$ is negligible if for every polynomial $q(n)$ there exists an N such that for all $n \geq N$, $f(n) \leq 1/q(n)$. We denote by $\delta \leftarrow_R \Delta$ the process of picking a random element δ from Δ .

The BPK Model. The bare public-key model (BPK model) assumes that:

- A public file F that is a collection of records, each containing a verifier's public key, is available to the prover.
- An (honest) prover P is an interactive deterministic polynomial-time algorithm that is given as inputs a secret parameter 1^n , a n -bit string $x \in L$, an auxiliary input y , a public file F and a random tape r .
- An (honest) verifier V is an interactive deterministic polynomial-time algorithm that works in two stages. In stage one, on input a security parameter 1^n and a random tape w , V generates a key pair (pk, sk) and stores pk in the file F . In stage two, on input sk , an n -bit string x and an random string w , V performs the interactive protocol with a prover, and outputs "accept x " or "reject x ".

Definition 2.1 We say that the protocol $\langle P, V \rangle$ is complete for a language L in \mathcal{NP} , if for all n -bit string $x \in L$ and any witness y such that $(x, y) \in R_L$, here R_L is the relation induced by L , the probability that V interacting with P on input y , outputs "reject x " is negligible in n .

Malicious provers and Its attacks in the BPK model. Let s be a positive polynomial and P^* be a probabilistic polynomial-time algorithm on input 1^n .

P^* is a s -concurrent malicious prover if on input a public key pk of V , performs at most s interactive protocols as following: 1) if P^* is already running $i - 1$ interactive protocols $1 \leq i - 1 \leq s$, it can output a special message "Starting x_i ," to start a new protocol with V on the new statement x_i ; 2) At any point it can output a message for any of its interactive protocols, then immediately receives the verifier's response and continues.

A concurrent attack of a s -concurrent malicious prover P^* is executed in this way: 1) V runs on input 1^n and a random string and then obtains the key pair (pk, sk) ; 2) P^* runs on input 1^n and pk . Whenever P^* starts a new protocol choosing a statement, V is run on inputs the new statement, a new random string and sk .

Definition 2.2 $\langle P, V \rangle$ satisfies concurrent soundness for a language L if for all positive polynomials s , for all s -concurrent malicious prover P^* , the probability that in an execution of concurrent attack, V ever outputs "accept x " for $x \notin L$ is negligible in n .

The notion of resettable zero-knowledge was first introduced in [4]. The notion gives a verifier the ability to rewind the prover to a previous state (after rewinding the prover uses the same random bits), and the malicious verifier can generate an arbitrary file F with several entries, each of them contains a public key generated by the malicious verifier. We refer readers to that paper for intuition of the notion. Here we just give the definition.

Definition 2.3 An interactive argument system $\langle P, V \rangle$ in the BPK model is black-box resettable zero-knowledge if there exists a probabilistic polynomial-time algorithm S such that for any probabilistic polynomial-time algorithm V^* , for any polynomials s, t , for any $x_i \in L$, the length of x_i is n , $i = 1, \dots, s(n)$, V^* runs in at most t steps and the following two distributions are indistinguishable:

1. the view of V^* that generates F with $s(n)$ entries and interacts (even concurrently) a polynomial number of times with each $P(x_i, y_i, j, r_k, F)$ where

y_i is a witness for $x_i \in L$, r_k is a random tape and j is the identity of the session being executed at present for $1 \leq i, j, k \leq s(n)$;

2. the output of S interacting with on input $x_1, \dots, x_{s(n)}$.

Σ -protocols A protocol $\langle P, V \rangle$ is said to be Σ -protocol for a relation R if it is of 3-move form and satisfies following conditions:

1. *Completeness*: for all $(x, y) \in R$, if P has the witness y and follows the protocol, the verifier always accepts.
2. *Special soundness*: Let (a, e, z) be the three messages exchanged by prover P and verifier V . From any statement x and any pair of accepting transcripts (a, e, z) and (a, e', z') where $e \neq e'$, one can efficiently compute y such that $(x, y) \in R$.
3. *Special honest-verifier ZK*: There exists a polynomial simulator M , which on input x and a random e outputs an accepting transcript of form (a, e, z) with the same probability distribution as a transcript between the honest P , V on input x .

Many known efficient protocols, such as those in [16] and [23], are Σ -protocols. Furthermore, there is a Σ -protocol for the language of Hamiltonian Graphs [1], assuming that one-way permutation families exists; if the commitment scheme used by the protocol in [1] is implemented using the scheme in [19] from any pseudo-random generator family, then the assumption can be reduced to the existence of one-way function families, at the cost of adding one preliminary message from the verifier. Note that adding one message does not have any influence on the property of Σ -protocols: assuming the new protocol is of form (f, a, e, z) , given the challenge e , it is easy to indistinguishably generate the real transcript of form (f, a, e, z) ; given two accepting transcripts (f, a, e, z) and (f, a, e', z') , where $e \neq e'$, we can extract a witness easily. We can claim that any language in \mathcal{NP} admits a 4-round Σ -protocol under the existence of any one-way function family (or under an appropriate number-theoretic assumption), or a Σ -protocol under the existence of any one-way permutation family. Though the following OR-proof refers only to 3-round Σ -protocol, readers should keep in mind that the way to construct the OR-proof is also applied to 4-round Σ -protocol.

Interestingly, Σ -protocols can be composed to proving the OR of atomic statements, as shown in [8, 7]. Specifically, given two protocols Σ_0, Σ_1 for two relationships R_0, R_1 , respectively, we can construct a Σ_{OR} -protocol for the following

relationship efficiently: $R_{OR} = ((x_0, x_1), y) : (x_0, y) \in R_{0or}(x_1, y) \in R_1$, as follows. Let $(x_b, y) \in R_b$ and y is the private input of P . P computes a_b according the protocol Σ_b using (x_b, y) . P chooses e_{1-b} and feeds the simulator M guaranteed by Σ_{1-b} with e_{1-b}, x_{1-b} , runs it and gets the output $(a_{1-b}, e_{1-b}, z_{1-b})$. P sends a_b, a_{1-b} to V in first step. In second step, V picks $e \leftarrow_R \mathbb{Z}_q$ and sends it to P . Last, P sets $e_b = e \oplus e_{1-b}$, and computes the last message z_b to the challenge e_b using x_b, y as witness according the protocol Σ_b . P sends e_b, e_{1-b}, z_b and e_{1-b}, z_{1-b} to V . V checks $e = e_b \oplus e_{1-b}$, and the two transcripts (a_b, e_b, z_b) and $(a_{1-b}, e_{1-b}, z_{1-b})$ are accepting. The resulting protocol turns out to be witness indistinguishable: the verifier can not tell which witness the prover used from a transcript of a session.

In our rZK argument, the verifier uses a 3-round Witness Indistinguishable Proof of Knowledge to prove knowledge of one of the two secret keys associating with his public key. As required in [11], we need a *partial-witness-independence* property from above proof of knowledge: the message sent at its first round should have distribution independent from any witness for the statement to be proved. We can obtain such a protocol using [23] [8].

Commitment scheme. A commitment scheme is a two-phase (committing phase and opening phase) two-party (a sender S and a receiver R) protocol which has following properties: 1) *hiding*: two commitments (here we view a commitment as a variable indexed by the value that the sender committed to) are computationally distinguishable for every probabilistic polynomial-time (possibly malicious) R^* ; 2) *Binding*: after sent the commitment to a value m , any probabilistic polynomial-time (possibly malicious) sender S^* cannot open this commitment to another value $m' \neq m$ except with negligible probability. Under the assumption of existence of any one-way function families (using the scheme from [19] and the result from [17]) or under number-theoretic assumptions (e.g., the scheme from [21]), we can construct a schemes in which the first phase consists of 2 messages. Assuming the existence of one-way permutation families, a well-known non-interactive (in committing phase) construction of a commitment scheme (see, e.g. [13]) can be given.

A *statistically-binding commitment scheme (with computational hiding)* is a commitment scheme except with a stronger requirement on binding property: for all powerful sender S^* (without running time restriction), it cannot open a valid commitment to two different values except with exponentially small probability. We refer readers to [13, 19] for the details for constructing statistically-binding commitments.

A *perfect-hiding commitment scheme (with computational binding)* is the one except with a stronger requirement on hiding property: the distribution of the commitments is indistinguishable for all powerful receiver R^* . As far as we know, all perfect-hiding commitment scheme requires interaction (see also [21, 20]) in the committing phase.

Definition 2.4 [13]. Let $d, r : N \rightarrow N$. we say that

$$\{f_s : \{0, 1\}^{d(|s|)} \rightarrow \{0, 1\}^{r(|s|)}\}_{s \in \{0, 1\}^*}$$

is an *pseudorandom function ensemble* if the following two conditions hold:

1. *Efficient evaluation:* There exists a polynomial-time algorithm that on input s and $x \in \{0, 1\}^{d(|s|)}$ returns $f_s(x)$;
2. *Pseudorandomness:* for every probabilistic polynomial-time oracle machine M , every polynomial $p(\cdot)$, and all sufficient large n 's,

$$|[\Pr[M^{F_n}(1^n) = 1] - \Pr[M^{H_n}(1^n) = 1]]| < 1/p(n)$$

where F_n is a random variable uniformly distributed over the multi-set $\{f_s\}_{s \in \{0, 1\}^n}$, and H_n is uniformly distributed among all functions mapping $d(n)$ -bit-long strings to $r(n)$ -bit-long strings.

3 A Simple Observation on Resetably-sound Zero Knowledge Arguments

resetably-sound zero knowledge argument is a zero knowledge argument with stronger soundness: for all probabilistic polynomial-time prover P^* , even P^* is allowed to reset the verifier V to previous state (after resetting the verifier V uses the same random tape), the probability that P^* make V accept a false statement $x \notin L$ is negligible.

In [2] Barak et al. transform a constant round public-coin zero knowledge argument $\langle P, V \rangle$ for a \mathcal{NP} language L into a constant round resetably-sound zero knowledge argument $\langle P, W \rangle$ for L as follows: equip W with a collection of pseudorandom functions, and then let W emulate V except that it generate the current round message by applying a pseudorandom function to the transcript so far.

We will use a resettably-sound zero knowledge argument as a building block in which the verifier proves to the prover that a challenge matches the one that he have committed to in previous stage. The simulation for such sub-protocols plays a important role in our security reduction, but there is a subtlety in the simulation itself. In the scenario considered in this paper, in which the prover (i.e., the verifier in the underlying sub-protocol) can interact with many copies of the verifier and schedule all sessions at its wish, the simulation seems problematic because we do not know how to simulate all the concurrent executions of the Barak’s protocol described below ²(therefore the resettably-sound zero knowledge argument). However, fortunately, it is not necessary to simulate all the concurrent executions of the underlying resettably-sound zero knowledge argument. Indeed, in order to justify concurrent soundness, we just need to simulate *only one execution* among all concurrent executions of the resettably-sound zero knowledge argument. We call this property *one-many simulatability*. We note that Pass and Rosen [22] made a similar observation (in a different context) that enables the analysis of concurrent non-malleability of their commitment scheme.

Now we recall the Barak’s constant round public-coin zero knowledge argument [1], and show this protocol satisfies *one-many simulatability*, and then so does the resettably-sound zero knowledge argument transformed from it.

Informally, Barak’s protocol for a \mathcal{NP} language L consists of two subprotocol: a general protocol and a WI universal argument. An real execution of the general protocol generates an instance that is unlikely in some properly defined language, and in the WI universal argument the prover proves that the statement $x \in L$ or the instance generated above is in the properly defined language. Let n be security parameter and $\{\mathcal{H}_n\}_{n \in \mathbb{N}}$ be a collection of hash functions where a hash function $h \in \mathcal{H}_n$ maps $\{0, 1\}^*$ to $\{0, 1\}^n$, and let \mathbf{C} be a statistically binding commitment scheme. We define a language Λ as follows. We say a triplet $(h, c, r) \in \mathcal{H}_n \times \{0, 1\}^n \times \{0, 1\}^n$ is in Λ , if there exist a program Π and a string $s \in \{0, 1\}^{\text{poly}(n)}$ such that $z = \mathbf{C}(h(\Pi), s)$ and $\Pi(z) = r$ within superpolynomial time (i.e., $n^{\omega(1)}$).

The Barak’s Protocol [1]

Common input: an instance $x \in L$ ($|x| = n$)

²Barak also presented a constant round bounded concurrent ZK arguments, hence we can obtain a constant round resettably-sound bounded concurrent ZK argument by applying the same transformation technique to the bounded concurrent ZK argument. We stress that in this paper we do not require the bounded concurrent zero knowledge property to hold for the resettably-sound ZK argument.

Prover's private input: the witness w such that $(x, w) \in R_L$

$V \rightarrow P$: Send $h \leftarrow_R \mathcal{H}_n$;

$P \rightarrow V$: Pick $s \leftarrow_R \{0, 1\}^{\text{poly}(n)}$ and Send $c = \mathbf{C}(h(0^{3n}, s))$;

$V \rightarrow P$: Send $r \leftarrow_R \{0, 1\}^n$;

$P \Leftrightarrow V$: A WI universal argument in which P proves $x \in L$ or $(h, c, r) \in \Lambda$.

Fact 1. The Barak's protocol enjoys *one-many simulatability*. That is, For every malicious probabilistic polynomial time algorithm V^* that interacts with (arbitrary) polynomial s copies of P on true statements $\{x_i\}, 1 \leq i \leq s$, and for every $j \in \{1, 2, \dots, s\}$, there exists a probabilistic polynomial time algorithm \mathbf{S} , takes V^* and all witness but the one for x_j , such that the output of $\mathbf{S}(V^*, \{(x_i, w_i)\}_{1 \leq i \leq s, i \neq j}, x_j)$ (where $(x_i, w_i) \in R_L$) and the view of V^* are indistinguishable.

We can construct a simulator $\mathbf{S} = (\mathbf{S}_{real}, \mathbf{S}_j)$ as follows: \mathbf{S}_{real} , taking as inputs $\{(x_i, w_i)\}_{1 \leq i \leq s, i \neq j}$, does exactly what the honest provers do on these statements and outputs the transcript of all but the j th sessions (in j th session $x_j \in L$ is to be proven), and \mathbf{S}_j acts the same as the simulator associated with Barak's protocol in the session in which $x_j \in L$ is to be proven, except that when \mathbf{S}_j is required to send a commitment value (the second round message in Barak's protocol), it commit to the hash value of the **joint** residual code of V^* and \mathbf{S}_{real} at this point instead of committing to the hash value of the residual code of V^* (that is, we treat \mathbf{S}_{real} as a subroutine of V^* , and it interacts with V^* internally). We note that the next message of the joint residual code of V^* and \mathbf{S}_{real} is only determined by the commitment message from \mathbf{S}_j , so as showed in [1], \mathbf{S}_j works. On the other hand, the \mathbf{S}_{real} 's behavior is identical to the honest provers. Thus, the whole simulator \mathbf{S} satisfies our requirement.

When we transform a constant round public-coin zero knowledge argument into a resettably-sound zero knowledge argument, the transformation itself does not influence the simulatability (zero knowledge) of the latter argument because the zero knowledge requirement does not refer to the honest verifier (as pointed out in [2]). Thus, the same simulator described above also works for the resettably-sound zero knowledge argument in concurrent settings. So we have

Fact 2. The resettably-sound zero knowledge arguments in [2] enjoy *one-many simulatability*.

4 rZK Argument with Concurrent Soundness for \mathcal{NP} in the BPK model Under Standard Assumption

In this section we present a constant-round rZK argument with concurrent soundness in the BPK model for all \mathcal{NP} language without assuming any subexponential hardness.

For the sake of readability, we give some intuition before describe the protocol formally.

We construct the argument in the following way: build a concurrent zero knowledge argument with concurrent soundness and then transform this argument to a resettable zero knowledge argument with concurrent soundness. Concurrent zero knowledge with concurrent soundness was presented in [11] under standard assumption (without using "complexity leveraging"). For the sake of simplification, we modify the *flawed* construction presented in [26] to get concurrent zero knowledge argument with concurrent soundness. Considering the following two-phase argument in BPK model: Let n be the security parameter, and f be a one way function that maps $\{0, 1\}^{\kappa(n)}$ to $\{0, 1\}^n$ for some function $\kappa : \mathbb{N} \rightarrow \mathbb{N}$. The verifier chooses two random numbers $x_0, x_1 \in \{0, 1\}^{\kappa(n)}$, computes $y_0 = f(x_0)$, $y_1 = f(x_1)$ then publishes y_0, y_1 as he public key and keep x_0 or x_1 secret. In phase one of the argument, the verifier proves to the prover that he knows one of x_0, x_1 using a *partial-witness-independently* Witness Indistinguishable Proof of Knowledge protocol Π_v . In phase two, the prover proves that the statement to be proven is true or he knows one of preimages of y_0 and y_1 via a witness indistinguishable argument of knowledge protocol Π_p . Note that In phase two we use *argument* of knowledge, this means we restrict the prover to be a probabilistic polynomial-time algorithm, and therefore our whole protocol is an argument (not a proof).

Though the above two-phase argument does not enjoy concurrent soundness [11], it is still a good start point and We can use the same technique in [11] in spirit to fix the flaw: in phase two, the prover uses a commitment scheme³ COM_1 to compute a commitments to a random strings s , $c = \text{COM}_1(s, r)$ (r is a random string needed in the commitment scheme), and then the prover prove that the statement to be proven is true or he committed to a preimage of y_0 or y_1 . We can

³In contrast to [11], we proved that computational binding commitment scheme suffices to achieve concurrent soundness. In fact, the statistically binding commitment scheme in [11] could also be replaced with computational binding one without violating the concurrent soundness.

prove that the modified argument is concurrent zero knowledge argument with concurrent soundness using technique similar to that in [11].

Given the above (modified) concurrent zero knowledge argument with concurrent soundness, we can transform it to resettable zero knowledge argument with concurrent soundness in this way: 1) using a statistically-binding commitment scheme COM_0 , the verifier computes a commitment $c_e = \text{COM}_0(e, r_e)$ (r_e is a random string needed in the scheme) to a random string e in the phase one, and then he sends e (note that the verifier does not send r_e , namely, it does not open the commitment c_e) as the second message (i.e the challenge) of Π_p and prove that e is the string he committed to in the first phase using resettably sound zero knowledge argument; 2) equipping the prover with a pseudorandom function, whenever the random bits is needed in a execution, the prover applied the pseudorandom function to what he have seen so far to generate random bits.

Let's Consider concurrent soundness of the above protocol. Imagine that a malicious prover convince a honest verifier of a false statement on a session (we call it a cheating session) in an execution of concurrent attack with high probability. Then we can use this session to break some hardness assumption: after the first run of this session, we rewind it to the point where the verifier is required to send a challenge and chooses an arbitrary challenge and run the simulator for this underlying resettably-sound zero knowledge proof. At the end of the second run of this session, we will extract one of preimages of y_0 and y_1 from the two different transcripts, and this contradicts either the witness indistinguishability of Π_v or the binding property of the commitment scheme COM_1 . Note that in the above reduction we just need to simulate the single execution of the resettably-sound zero knowledge argument in that cheating session, and do not care about other sessions that initiated by the malicious prover (in other sessions we play the role of honest verifier). We have showed the simulation in this special concurrent setting can be done in a simple way in last section.

The Protocol (rZK argument with concurrent soundness in BPK model)

Let $\{prf_r : \{0, 1\}^* \rightarrow \{0, 1\}^{d(n)}\}_{r \in \{0, 1\}^n}$ be a pseudorandom function ensembles, where d is a polynomial function, COM_0 be a *statistically-binding* commitment scheme, and let COM_1 be a general commitment scheme (can be either statistically-binding or computational-binding⁴). Without loss of generality, we assume both the preimage size of the one-way function f and the message size of COM_1 equal n .

⁴If the computational-binding scheme satisfies perfect-hiding, then this scheme requires stronger assumption, see also [21, 20]

Common input: the public file F , n -bit string $x \in L$, an index i that specifies the i -th entry $pk_i = (f, y_0, y_1)$ (f is a one-way function) of F .

P 's Private input: a witness w for $x \in L$, and a fixed random string $(r_1, r_2) \in \{0, 1\}^{2n}$.

V 's Private input: a secret key α ($y_0 = f(\alpha)$ or $y_1 = f(\alpha)$).

Phase 1: V Proves Knowledge of α and Sends a Committed Challenge to P .

1. V and P runs the 3-round *partial-witness-independently* witness indistinguishable protocol (Σ_{OR} -protocol) Π_v in which V prove knowledge of α that is one of the two preimages of y_0 and y_1 . the randomness bits used by P equals r_1 ;
2. V computes $c_e = \mathbf{COM}_0(e, r_e)$ for a random e (r_e is a random string needed in the scheme), and sends c_e to P .

Phase 2: P Proves $x \in L$.

1. P checks the transcript of Π_v is accepting. if so, go to the following step.
2. P chooses a random string $s, |s| = n$, and compute $c = \mathbf{COM}_1(s, r_s)$ by picking a randomness r_s ; P forms a new relation $R' = \{(x, y_0, y_1, c, w') \mid (x, w') \in R_L \vee (w' = (w'', r_{w''}) \wedge y_0 = f(w'') \wedge c = \mathbf{COM}_1(w'', r_{w''})) \vee (w' = (w'', r_{w''}) \wedge y_1 = f(w'') \wedge c = \mathbf{COM}_1(w'', r_{w''}))\}$; P invokes the 3-round witness indistinguishable argument of knowledge (Σ_{OR} -protocol) Π_p in which P prove knowledge of w' such that $(x, y_0, y_1, c; w') \in R'$, computes and sends the first message a of Π_p .
All randomness bits used in this step is obtained by applying the pseudo-random function prf_{r_2} to what P have seen so far, including the common inputs, the private inputs and all messages sent by both parties so far.
3. V sends e to P , and execute a resettably sound zero knowledge argument with P in which V proves to P that $\exists r_e$ s.t. $c_e = \mathbf{COM}_0(e, r_e)$. Note that the subprotocol will costs several (constant) rounds. Again, the randomness used by P is generated by applying the pseudorandom function prf_{r_2} to what P have seen so far.
4. P checks the transcript of resettably sound zero knowledge argument is accepting. if so, P computes the last message z of Π_p and sends it to V .
5. V accepts if only if (a, e, z) is accepting transcript of Π_p .

Theorem 1. Let L be a language in \mathcal{NP} , If there exists hash functions collision-resistant against any polynomial time adversary, then there exists a constant round rZK argument with concurrent soundness for L in BPK model.

Remark on complexity assumption. We prove this theorem by showing the protocol described above is a rZK argument with concurrent soundness. Indeed, our protocol requires collision-resistant hash functions and one-way *permutations*, this is because the 3-round Σ -protocol (therefore Σ_{OR} -protocol) for \mathcal{NP} assumes one-way permutations and the resettably sound zero knowledge argument assumes collision-resistant hash functions. However, we can build 4-round Σ -protocol (therefore Σ_{OR} -protocol) for \mathcal{NP} assuming existence of one-way functions by adding one message (see also discussions on Σ -protocol in section 2), and our security analysis can be also applied to this variant. We also note that collision-resistant hash functions implies one-way functions which suffices to build statistically-binding commitment scheme [19](therefore computational-binding scheme), thus, if we proved our protocol is a rZK argument with concurrent soundness, then we get theorem 1. Here we adopt the 3-round Σ_{OR} -protocol just for the sake of simplicity.

Proof. Completeness. Straightforward.

Resettable (*black-box*) Zero Knowledge. The analysis is very similar to the analysis presented in [4, 10]. Here we omit the tedious proof and just provide some intuition. As usual, we can construct a simulator \mathbf{Sim} that extracts all secret keys corresponding to those public keys registered by the malicious verifier from Π_v and then uses them as witness in executions of Π_p , and \mathbf{Sim} can complete the simulation in expected polynomial time. We first note that when a malicious verifier resets a an honest prover, it can not send two different challenge for a fixed commitment sent in Phase 1 to the latter because of statistically-binding property of \mathbf{COM}_0 and resettable soundness of the underlying sub-protocol used by the verifier to prove the challenge matches the value it has committed to in Phase 1. To prove the property of rZK, we need to show that the output of \mathbf{Sim} is indistinguishable from the real interactions. This can be done by constructing a non-uniform hybrid simulator \mathbf{HSim} and showing the output of \mathbf{HSim} is indistinguishable from both the output of \mathbf{Sim} and the real interaction. \mathbf{HSim} runs as follows. Taking as inputs all these secret keys and all the witnesses of statements in interactions, \mathbf{HSim} computes commitments exactly as \mathbf{Sim} does but executes Π_p using the same witness of the statement used by the honest prover. It is easy to see that the output of the hybrid simulator is indistinguishable from both the transcripts of real interactions (because of the computational-hiding property of

COM_1) and the output of Sim (because of the witness indistinguishability of Π_p), therefore, we proved the the output of Sim is indistinguishable form the real interactions.

Concurrent Soundness. Proof proceeds by contradiction.

Assume that the protocol does not satisfy the concurrent soundness property, thus there is a s -concurrently malicious prover P^* , concurrently interacting with V , makes the verifier accept a false statement $x \notin L$ in j th session with non-negligible probability p .

We now construct an algorithm \mathbf{B} that takes the code (with randomness hardwired in) of P^* as input and breaks the one-wayness of f with non-negligible probability.

\mathbf{B} runs as follows. On input the challenge f, y (i.e., given description of one-way function, \mathbf{B} finds the preimage of y), \mathbf{B} randomly chooses $\alpha \in \{0, 1\}^n$, $b \in \{0, 1\}$, and guess a session number $j \in \{1, \dots, s\}$ (guess a session in which P^* will cheat the verifier successfully on a false statement x . Note that the event that this guess is correct happens with probability $1/s$), then B registers $pk = (f, y_0, y_1)$ as the public key, where $y_b = f(\alpha)$, $y_{1-b} = y$. For convenience we let $x_b = \alpha$, and denote by x_{1-b} one of preimages of y_{1-b} ($y_{1-b} = y = f(x_{1-b})$). Our goal is to find one preimage of y_{1-b} .

We write \mathbf{B} as $\mathbf{B} = (\mathbf{B}_{real}, \mathbf{B}_j)$. \mathbf{B} interacts with P^* as honest verifier (note that \mathbf{B} knows the secret key α corresponding the public key pk) for all but j th session. Specifically, \mathbf{B} employs the following extraction strategy:

1. \mathbf{B} acts as the honest verifier in this stage. That is, it completes Π_v using $\alpha = x_b$ as secret key, and commits to e , $c_e = \text{COM}_0(e, r_e)$ in phase 1 then runs resettably sound ZK argument in Phase 2 using e, r_e as the witness. In particular, \mathbf{B} uses \mathbf{B}_j to play the role of verifier in the j th session, and uses \mathbf{B}_{real} to play the role of verifier in all other sessions. At the end of j th session, if B gets an accepting transcript (a, e, z) of Π_p , it enters the following rewinding stage; otherwise, B halts and output " \perp "
2. \mathbf{B}_j rewind P^* to the point of beginning of step 3 in Phase 2 in j th session, it chooses a random string $e' \neq e$ and simulates the underlying resettably sound ZK argument in the same way showed in section 3: it commits to the hash value of the joint residual code of P^* and \mathbf{B}_{real} in the second round of the resettably sound ZK argument (note this subprotocol is transformed from Barak's protocol) and uses them as the witness to complete the proof for the following *false* statement: $\exists r_e$ s.t. $c_e = \text{COM}_0(e', r_e)$. If this

rewinds incurs some other rewinds on other sessions, \mathbf{B}_{real} always acts as an honest verifier. When \mathbf{B} get another accepting transcript (a, e', z') of Π_p at step 5 in Phase 2 in j th session, it halts, computes the witness from the two transcripts and outputs it, otherwise, \mathbf{B} plays step 3 in j th session again.

We denote this extraction with *Extra*.

We first note that \mathbf{B} 's simulation of P^* 's view only differs from P^* 's view in real interaction with an honest verifier in the following: In the second run of Π_p in j th session \mathbf{B} proves a *false* statement to P^* via the resettably sound zero knowledge argument instead of executing this sub-protocol honestly. We will show that this difference is computationally indistinguishable by P^* using the technique presented in the analysis of resettable zero knowledge property, or otherwise we can use P^* to violate the zero knowledge property of the underlying resettably sound zero knowledge argument or the statistically-binding property of the commitment scheme COM_0 . We also note that if the simulation is successful, \mathbf{B} gets an accepting transcript of Π_p in stage 1 with probability negligibly close to p , and once \mathbf{B} enters the rewinding stage (stage 2) it will obtain another accepting transcript in expected polynomial time because p is non-negligible. In another words, \mathbf{B} can outputs a valid witness with probability negligibly close to p in the above extraction.

Now assume \mathbf{B} outputs a valid witness w' such that $(x, y_0, y_1, c, w') \in R'$, furthermore, the witness w' must satisfy $w' = (w'', r_{w''})$ and $y_b = f(w'')$ or $y_{1-b} = f(w'')$ because $x \notin L$. If $y_{1-b} = f(w'')$, we break the one-way assumption of f (find the one preimage of y_{1-b}), otherwise(i.e., w'' satisfies $y_b = f(w'')$), we fails. Next we claim \mathbf{B} succeed in breaking the one-way assumption of f with non-negligible probability.

Assume otherwise, with at most a negligible probability q , \mathbf{B} outputs one preimage of y_{1-b} . Then We can construct a non-uniform algorithm \mathbf{B}' (incorporating the code of P^*)to break the witness indistinguishability of Π_v or the computational binding of the commitment scheme COM_1 .

The non-uniform algorithm \mathbf{B}' takes as auxiliary input (y_0, y_1, x_0, x_1) (with input both secret keys) and interacts with P^* under the public key (y_0, y_1) . It performs the following experiment:

1. *Simulation (until \mathbf{B}' receives the first message a of Π_p in j th session).* \mathbf{B}' acts exactly as the \mathbf{B} . Without loss of generality, let \mathbf{B}' uses x_0 as witness in all executions of Π_v that completed before step 2 in Phase 2 of the j th session. Once \mathbf{B}' receives the first message a of Π_p in j th session, it splits this experiment and continues independently in following games:

2. *Extracting Game 0.* \mathbf{B}' continues the above simulation and uses the same extraction strategy of \mathbf{B} . In particular, it runs as follows. 1) continuing to simulate: \mathbf{B} uses x_0 as witness in all executions of Π_v that take place during this game; 2) extracting: if \mathbf{B} obtained an accepting transcript (a, e_0, z_0) at the end of the first run of Π_p in j th session, it rewinds to the point of beginning of step 3 in Phase 2 in j th session and replays this round by sending another random challenge $e' \neq e$ until he gets another accepting transcript (a, e'_0, z'_0) of Π_p , and then \mathbf{B} outputs a valid witness, otherwise outputs " \perp ".
3. *Extracting Game 1:* \mathbf{B}' repeats Extracting Game 0 but \mathbf{B}' uses x_1 as witness in all executions of Π_v during this game (i.e., those executions of Π_v completed after the step 2 in Phase 2 in the j th session). At the end of this game, \mathbf{B}' either obtains two accepting transcripts $(a, e_1, z_1), (a, e'_1, z'_1)$ and outputs a valid witness, or outputs " \perp ". Note that an execution of Π_v that takes place during this game means at least the last (third) message of Π_v in that execution has not yet been sent before step 2 in Phase 2 in j th session. Since the Π_v is *partial-witness-independent* Σ -protocol (so we can decide to use which witness at the last (third) step of Π_v), \mathbf{B}' can choose witness at its desire to complete that execution of Π_v after the step 2 in Phase 2 in the j th session.

We denote by EXP_0 the *Simulation* in stage 1 described above with its first continuation *Extracting Game 0*, similarly, denote by EXP_1 the same *Simulation* with its second continuation *Extracting Game 1*.

Note that the P^* 's view in EXP_0 is identical to its view in *EXTRA* in which \mathbf{B} uses x_0 ($b = 0$) as witness in all executions of Π_v , so the outputs of \mathbf{B}' at the end of EXP_0 is identical to the outputs of \mathbf{B} taking x_0 as the secret key in *EXTRA*, that is, with non-negligible probability p \mathbf{B}' outputs one preimage of y_0 ; and with negligible probability q it outputs one preimage of y_1 .

Consider \mathbf{B}' 's behavior in *EXTRA* when it uses x_1 ($b = 1$) as the secret key. The behavior of \mathbf{B} only differs from the behavior of \mathbf{B}' in EXP_1 in those executions of Π_v that completed before the step 2 in Phase 2 in the j th session: \mathbf{B}' uses x_0 as witness in all those executions, while \mathbf{B} uses x_1 as witness. However, the P^* cannot tell these apart because Π_v is witness indistinguishable and all those executions of Π_v have not been rewound during both *EXTRA* and EXP_1 (note that \mathbf{B}' does not rewind past the the step 2 in Phase 2 in the j th session in the whole experiment). Thus, we can claim that at the end of EXP_1 , \mathbf{B}' outputs one preimage

of y_1 with probability negligibly close to p ; and it outputs one preimage of y_0 with probability negligibly close to q .

In the above experiment conducted by **B**, the first message a sent by P^* in the j th session contains a commitment c and this message a (therefore c) remains unchanged during the above whole experiment. Clearly, with probability negligibly close to p^2 (note that q is negligible), **B'** will output two valid witness $w'_0 = (w_0'', r_{w_0''})$ and $w'_1 = (w_1'', r_{w_1''})$ (note that $w_0'' \neq w_1''$ except for a very small probability) from the above two games such that the following holds: $y_0 = f(w_0'')$, $y_1 = f(w_1'')$, $c = \text{COM}_1(w_0'', r_{w_0''})$ and $c = \text{COM}_1(w_1'', r_{w_1''})$. This contradicts the computational-binding property of the scheme COM_1 .

In sum, we proved that if COM_1 enjoys computational-binding and Π_v is witness indistinguishable protocol with *partial-witness-independence* property, then **B** succeeds in breaking the one-wayness of f with non-negligible probability. In another words, if the one-way assumption on f holds, it is infeasible for P^* to cheat an honest verifier in concurrent settings with non-negligible probability. \square

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