

# How to Play ANY Mental Game Over the Net

Concurrently composable secure computation without setup assumptions

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## Abstract

We construct a protocol for general multi-party computation that remains secure even if executed concurrently with multiple copies of itself and of arbitrary other protocols. This is the first such construction that is based on standard cryptographic assumptions and does not require setup conditions such as the existence of a common reference string. Furthermore, our protocol utilizes only a *constant* number of communication rounds and remains secure also with respect to *adaptive* adversaries (without using memory erasures).

The security of our protocol is demonstrated by a simulator with a *quasi-polynomial* simulation overhead, as opposed to the standard notion of polynomial simulation. However, quasi-polynomial simulation still provides sufficient security for almost all applications. Furthermore, it was previously shown that there does not exist such a protocol with polynomial simulation (Lindell, FOCS '03).

**Keywords:** Non-malleable protocols, concurrent composition, multi-party secure computation

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# 1 Introduction

In the 1980’s a sequence of groundbreaking papers [SRA78, SHA79, RAB81, BLU82, GM82, GMR85, GMW86, YAO86] led to the rather amazing result of Goldreich, Micali and Wigderson [GMW87] that it is possible in principle to obtain a secure protocol for essentially *every* cryptographic task one can think of, whether it is secure electronic elections, auctions, privacy-preserving data mining, or poker. That is, [GMW87] gave a compiler that allowed to transform a naive protocol that achieves some task with no security whatsoever (e.g., in the case of elections, a protocol where all parties send their votes to a party  $T$  which counts the votes and announces the results) into a protocol that seemed to obtain the highest level of security one can hope for. That is, their protocol guaranteed that every party or coalition of parties, (even if they cheat and do not follow the protocol), still cannot learn more information or have a larger effect on the outcome than they are entitled to obtain by simply following the rules (e.g., in the example of elections, no party or coalition of parties can vote more than their number or deduce about the other votes more than can be deduced from the publicly announced results).

Although it was always clear that the [GMW87] protocol is far from being practical in terms of the overhead it incurred in computation and communication, it might have seemed initially that there is not much to improve on its *security*. However, with the advent of modern networks, it became clear that this is not the case. This is because while the [GMW87] protocol (and also protocols for simpler tasks such as zero knowledge) guarantees security in the case of an isolated execution, it does not *not* guarantee sufficient security in the increasingly common situation in which parties run the protocol concurrently with other arbitrary network activity, which can include multiple executions of the same protocol and other cryptographic and non-cryptographic protocols. In fact, there are examples of instantiations of [GMW87] and other stand-alone protocols with particular primitives, for which there are known successful *attacks* in the concurrent setting [GK90, FEI90].

Thus, in the 1990’s, researchers began to work on definitions and protocols that are applicable for this “general network” setting. Although, as we elaborate below, this very extensive line of research had many successes, it still fell short of obtaining an analogous result to [GMW87] of a general multi-party computation protocol (or even protocols for specific tasks such as commitment schemes or zero-knowledge proofs) that remains secure in this setting under standard cryptographic assumptions.<sup>1</sup>

**Our results.** In this work we reach this “holy grail:” we obtain protocols that securely realize every functionality in the general network setting, without any setup assumptions, under standard cryptographic assumptions (namely, existence of subexponentially strong hash functions and quasi-polynomially strong trapdoor permutations). There is one caveat in our construction; it was proven by Lindell [LIN03c] (strengthening [CAN00b, CF01, CKL03]) that it is actually *impossible* to obtain such protocols using only polynomial-time simulation. To avoid this impossibility result, while we use the standard ideal vs. real model definition of security, the running time of our ideal-model simulator is not polynomial in the adversary’s running time, but rather *quasi-polynomial*. That is, if the adversary runs in time  $T$ , our simulator runs in time  $2^{(\log T)^c}$  for some constant  $c > 1$ , and hence we can simulate a polynomial-time adversary in quasi-polynomial time, and a subexponential-time

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<sup>1</sup>As we discuss below, this goal was successfully reached in models which assume some setup conditions, such as the existence of a majority of honest parties ([CAN00b], using [RBO89, BOCG93, BOKR94]), or in the CRS model where one assumes the existence a public string that is chosen once and for all by some trusted party [CLOS02]. Furthermore, [PS04] gave a construction achieving this goal under some non-standard computational assumptions.

adversary (with a low enough exponent) in subexponential time. However, as we elaborate below, quasi-polynomial simulation is in fact sufficient for almost all applications of multi-party computation. Indeed, in many of these applications the actual running time of the ideal-model simulator is immaterial, while in most of the others quasi-polynomial simulation will be good enough assuming one makes a sufficiently conservative choice of the security parameter. We stress that all honest parties require only polynomial computation. What we achieve is essentially the best possible given the impossibility results of [LIN03c].

At the heart of our construction is a fully *concurrent* and *non-malleable* zero-knowledge protocol with quasi-polynomial simulation. This protocol has a constant number of rounds and is based on the assumption that there exists a hash function collection that is collision-resistant with respect to  $2^{k^\epsilon}$ -sized circuits (where  $k$  is the security parameter and  $\epsilon > 0$  is some constant). Plugging this protocol into the results of Canetti, Lindell, Ostrovsky, and Sahai [CLOS02], we obtain a *fully concurrent and non-malleable* protocol for computing any polynomial-time functionality under standard assumptions (i.e., existence of quasi-polynomially strong enhanced trapdoor permutations). Furthermore, our protocol utilizes only a *constant* number of communication rounds and remains secure also with respect to *adaptive* adversaries (without using memory erasures). By instantiating this result with particular functionalities, we can obtain many specific corollaries, such as the first concurrently secure electronic auction protocol. Also, combining our result with the results of [BCL+05], we get the first concurrently secure password-based authentication protocol and non-malleable commitment scheme. See Section 2 below for formal statements and more details on our results.

**New technique – “condensed protocols”<sup>2</sup>.** To achieve our result, we introduce a new technique that allows us to take a protocol  $\Pi$  with super-polynomial communication and computation requirements (but polynomial-sized inputs), and “condense” it to obtain a protocol  $\Pi'$  with only polynomial communication and computation requirements, while ensuring that the condensed protocol  $\Pi'$  retains the strong security properties of the super-polynomial protocol  $\Pi$ . Roughly speaking, the initial idea is to replace every super-polynomially long message  $m$  in  $\Pi$  with its short hash  $h(m)$ , and use Universal Arguments [BG01] to prove correctness of the hashed value. This by no means completes our task, as we have two fundamental problems: (1) the hashed messages now contain too little information to allow for the other party to compute a proper response; and (2) even if one had the long message to compute with, the computation time required to compute a response would still be super-polynomial. Solving Problem (1) involves a few technical tricks and is responsible for many of this work’s technical complications. To solve Problem (2), we use the following approach: we “encrypt” all communication in the protocol, and then provide honest parties an “honest backdoor” that allows them to successfully complete the protocol using their private information. In the context of a zero-knowledge proof of the statement  $x \in L$ , this can be done by allowing the prover to prove that *either* the encryption of the super-polynomial protocol  $\Pi$  is accepting, *or* that  $x \in L$  is true. Since the honest prover will have a witness to the truth of  $x \in L$ , it can use this knowledge to quickly (i.e. in polynomial time) prove the statement, without ever actually participating in the super-polynomial protocol. Remarkably, because an adversary can never be sure of which condition actually holds, we are able to argue that such a condensed

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<sup>2</sup>We use quite a few known techniques, and introduce several new techniques as well. We discuss in detail our techniques in Section 3, and so in this paragraph we’ll restrict ourselves to a terse summary of the main new technique introduced.

protocol  $\Pi'$  retains the strong security properties of the super-polynomial protocol  $\Pi$ .

## 1.1 Related Works.

There has been a very large body of research on multi-party secure computation and on composition of cryptographic protocols. In this section we will briefly describe some of the works relevant to our results; we discuss the works relevant to the techniques of this paper in [Section 3](#). See the books by Goldreich [[GOL04](#), [CHAPTER 7](#)] and Lindell [[LIN03B](#)], and the references therein for a more comprehensive review of the literature.

**Secure multi-party computations.** Protocols for secure function evaluation in the stand-alone setting were given by [[YAO86](#), [GMW87](#)]. The latter paper also introduced the paradigm of “forcing” honest but curious behavior using zero-knowledge proofs [[GMR85](#), [GMW87](#)], which has been widely used in many subsequent papers in this area (including the current one). A satisfactory definition of security for such protocols (in the stand-alone setting) was given by [[CAN00A](#)], following [[GL90](#), [MR91](#), [BEA91](#)]. A constant round protocol was given in [[KOS03](#)], and a simpler and improved such protocol was given in [[PAS04](#)].

**Concurrent setting.** Security in the concurrent setting was first considered in the context of zero-knowledge protocols by [[DNS98](#)]. A construction was given in [[RK99](#)], and improvements in the number of rounds were made in [[KP01](#), [PRS92](#)]. Some negative results were given in [[KPR98](#), [ROS00](#), [CKPR01](#)]. The more general setting where the adversary can play *different* roles in each execution (i.e., the person-in-the-middle attack) was first studied by [[DDN91](#)], who gave protocols for commitment and zero knowledge that withstand such an attack in *two* concurrent executions. Constant round protocols were given [[BAR02](#)], and simpler and improved such protocols were given by [[PR05](#)]. Composition with arbitrary other protocols was considered by [[PW00](#), [PSW00](#)]. Security in the most general setting of an arbitrary polynomial number of concurrent executions, in which parties can play different roles and interact in different protocols, was considered by [[CAN00B](#)] who termed such protocols “universally composable” (UC). However, without some setup assumptions, very broad impossibility results were shown to hold for the definition of [[CAN00B](#)] and even significantly relaxed definitions, as long as they require *polynomial-time* simulation [[CAN00B](#), [CF01](#), [CKL03](#), [LIN03C](#), [LIN04](#)].

**Security in relaxed models.** Because of the failure to obtain secure protocols in a model where there are no trusted parties, and parties interact in a fully asynchronous way, there were several works considering more relaxed models. **The CRS model:** Perhaps the most appealing of these models is the *common reference string* (CRS) model, originally introduced in the context of non-interactive zero-knowledge [[BFM88](#)], where the only assumption is that there is a publicly known string that was chosen once and for all by some trusted party. In this model [[CLOS02](#)] gave a construction of multi-party computation protocol satisfying the UC definition [[CAN00B](#)] which implies that it remains secure under general concurrent composition. The main problem with the CRS model is that it places an enormous amount of trust on the party choosing the common string. Indeed, by cheating in choosing this string, this party can completely and undetectably break the security of the [[CLOS02](#)] protocol and of essentially all other protocols in this model. An approach to distributing some of this trust was recently taken by [[BCNP04](#)]. **Honest majority:** Another

assumption which was used to construct such protocols is the existence of a majority of honest parties [BOGW88, RBO89, CAN00B]. However, this assumption seems to be less reasonable in a general network setting such as the Internet, and in particular does not allow for 2-party protocols or subprotocols. **Timing assumptions:** Yet another assumption that was used is the *timing model* [DNS98], in which one assumes that all the parties have clocks with some bounds on the drift between the clocks and on the time to transmit a message across the network. [DNS98] gave a concurrent zero-knowledge proof system in this model. Recently, [KLP05] gave a multi-party computation protocol for this setting that remains secure under general concurrent composition. The main problem with the protocol of [KLP05] (and all other protocols in the timing model such as [DNS98, Gol02]) is that they require that *every* message in *every* protocol running in the network will be delayed by amount of time that is larger than the latency of the slowest link in the network. Thus, such protocols do not seem suitable for a heterogeneous network in which some parties have significantly faster connections than other parties. **Bounded concurrency:** Yet another assumption, introduced in the context of zero knowledge in [BAR01] and extended to the general case in [LIN03A], is that there is a fixed known polynomial upper-bound  $M$  on length of *all* the communication throughout the entire network. [LIN03A], later improved by [PR03, PAS04, PR05], gave constructions for multi-party computation protocols that remain secure under general composition using this assumption. However, these protocols use computation and communication that is *larger* than  $M$ , and this was shown to be necessary by [LIN03A]. Hence, while bounded-concurrent protocols can be sometimes very useful tools in other constructions (and indeed we use techniques from [PAS04, PR05] in this paper), they do not seem suitable as a solution for obtaining secure computation in the general network setting.

**Relaxed security in the standard model.** Another approach, which is the one taken in this work, is not to make stronger assumptions on the network or trust, but rather achieve a weaker notion of security. **Super-polynomial simulation:** One natural relaxation (which is the one considered in this work) is to allow the ideal-model simulator to run in time which not a polynomial in the running time of the adversary but rather some super-polynomial (e.g., quasi-polynomial) function in this time. As we elaborate below in Section 2.1, super-polynomial simulation provides sufficient security for almost all applications of multi-party computation. This notion was implicit in some works (e.g., [CGGM00]) but was first explicitly put forward in [PAS03], in the context of zero-knowledge. While allowing super-polynomial simulation makes constructing concurrent zero-knowledge protocols much easier [PAS04],<sup>3</sup> it did not seem to be so helpful in constructing *non-malleable* protocols. Also, super-polynomial simulation seemed to ruin the most attractive feature of the UC framework of [CAN00B], namely the UC composition theorem. Thus, it might have seemed initially that it will be possible to generalize the extensive impossibility results of [CAN00B, CF01, CKL03, LIN03c, LIN04] to rule out even super-polynomial simulation. **The PS paper:** The first *positive* result in this direction was given by Prabhakaran and Sahai [PS04]. They gave a construction of a fully concurrent and non-malleable multi-party computation protocol in the general-network setting, but they required new (quite unstudied and non-standard) computational assumptions. Since the previous negative results were often interpreted that one must either use setup assumptions, or give up on ideal-model simulation-based security, [PS04] offered the exciting possibility of obtaining secure protocols without giving up either. However, the weak point of [PS04]

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<sup>3</sup>We note that [RK99] also claim that a constant round version of their protocol can be simulated in quasi-polynomial time, although we are not aware of a proof of this statement.

is the computational assumption used, which essentially assumes that there exists a cryptographic hash function (not a collection of functions) that is a non-malleable commitment scheme. While, unlike the Random Oracle Model [BR93], the assumptions of [PS04] are valid and well-defined mathematical assumptions, they are not well-studied, and seem to be difficult to analyze because of their complexity. On a more technical level, although [PS04] tackles some major technical difficulties such as getting UC composition to work in this setting, they essentially do not tackle non-malleability from a technical standpoint, and instead assume it to be present in the hash function. The current work can be seen as subsuming the result of [PS04] by obtaining it under standard assumptions<sup>4</sup>. **Other relaxed security notions:** There are other security definitions for particular cryptographic tasks which are outside of the ideal-model simulation paradigm. However, to the best of our knowledge, under standard assumptions, all such definitions are weaker than the ideal-model simulation, and (assuming one uses a conservative enough security parameter), this holds even if the simulator runs in quasi-polynomial time.

## 1.2 Overview of this paper.

In Section 2 we discuss the definitions and model we use, state our results, and elaborate on why these results provide a meaningful notion of security. In Section 3 we give an overview of our techniques. The main component we construct— a fully concurrent and non-malleable zero-knowledge protocol— is Protocol 3.1 (outlined in Page 16). A detailed description of the protocol is given in Section 4, with the simulation soundness property proven in Section 5. The construction of a general multi-party protocol from the zero-knowledge protocol (using the results of [CLOS02]) is described in Section 6.

## 2 Model, Results, Meaning

The network model we consider is the same one as in [CAN00A, CAN00B, LIN03c]. There is a network of point-to-point channels between a set of parties. Each party has a string that uniquely identifies it (which we call the party’s ID). The parties do not need to be aware of each other’s existence. An adversary can do the following: (1) Control some of the parties (such parties are said to be “corrupted”), (2) create new parties dynamically, (3) view all messages submitted on the network, and (4) fully control the scheduling of these messages. We denote the strategy that an honest party  $P_i$  uses as  $\pi_i$ . This strategy models all the activity of  $P_i$ , including all protocols<sup>5</sup>, cryptographic or non-cryptographic, that are executed sequentially or concurrently by  $P_i$ . We denote the collection of all these strategies for all parties by  $\pi$ . We note that in this model the adversary can control all scheduling of messages to honest parties, and hence can indefinitely postpone the delivery of messages to any honest party. Thus this work (as is the case with [CLOS02] and with [GMW87] in the

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<sup>4</sup>Prabhakaran and Sahai [PS04], aside from obtaining their result on secure multiparty computation, also put forward a new framework for security definitions. This is something we do not do in this paper. Our result can be seen as holding within the “Angel” definitional framework of [PS04]. However, for the sake of being as self-contained as possible, we instead prove our result directly in the context of the definitions of [CAN00B]. We also note that recently [MMY05] gave a different construction in the [PS04] model, which is based on different non-standard assumptions of a more number-theoretic nature (they assume some non-malleability of the discrete log problem).

<sup>5</sup>We note that another equivalent way to model this, following [CAN00B], is to have a special adversarial entity called an *environment* that models all other protocols happening in the system, other than the one being analyzed. We follow this modeling in the detailed description of our protocol.



non honest-majority case) does not guarantee security against denial of service attacks or provide the related guarantee of fairness [GL90].

If  $\mathcal{F}$  is some (possibly probabilistic, stateful) functionality, then the  $\mathcal{F}$ -hybrid model is the same model augmented by an additional trusted party that computes  $\mathcal{F}$ . We say that a protocol  $\rho$  *securely computes  $\mathcal{F}$  with polynomial simulation* if the following holds: for every polynomial-sized adversary  $\text{Adv}$  there exists an polynomial-sized adversary  $\text{Adv}'$  in the  $\mathcal{F}$ -hybrid model such that if  $\pi$  is an honest parties strategy that includes calls to  $\rho$  as a subroutine, then the view of  $\text{Adv}$  when interacting with  $\pi$  is indistinguishable from the view of  $\text{Adv}'$  when interacting with  $\pi'$ , where  $\pi'$  is obtained from  $\pi$  by replacing all calls to the  $\rho$  subroutine with calls to the ideal function  $\mathcal{F}$ . We say that  $\rho$  *securely computes  $\mathcal{F}$  with quasi-polynomial simulation* if  $\text{Adv}'$  is allowed to be of quasi-polynomial (i.e.,  $k^{\log^{O(1)} k}$ ) size.

## 2.1 Why is quasi-polynomial simulation meaningful?

Quasi-polynomial simulation is certainly quantitatively *worse* than polynomial simulation, just as  $T^{10}$ -time simulation of a time  $T$  adversary is worse than  $T^2$ -time simulation. However, the question is what is the *qualitative* difference between polynomial and quasi-polynomial simulation.

The essential difference (which is indeed the reason we bypass all the known impossibility results) between super-polynomial simulation and polynomial simulation is that the time we allow for simulation in the ideal model is larger than the time that is considered as an efficient adversary strategy in the real model. This is certainly philosophical troubling, as the principle behind the paradigm of simulation is that (\*) “whatever the adversary could have obtained in the real model, she could have obtained in the ideal model”. However, simulation is almost never a *goal* in itself, but is usually a *tool* to prove security.<sup>6</sup> Thus, the usual reasoning for security continues the above argument (\*) and says that “since in the ideal model the adversary could not have caused any inadmissible damage, the protocol is secure even in the real model”. The ideal model is much simpler, and hence in many cases it can be shown that even an *computationally unbounded* adversary cannot cause any damage in this model. Furthermore, even in the other cases, it is usually easy to ensure that even a quasi-polynomial time adversary cannot cause damage by simply choosing a more conservative security parameter.

**Interaction with other protocols.** While the above reasoning suggests that there does not seem to be a qualitative difference between the security ensured by polynomial and quasi-polynomial simulation in the stand-alone setting, one may worry that there might be such a difference in the general concurrent settings. The reason is that in the concurrent setting the protocol might be run concurrently with other cryptographic and non-cryptographic protocols, that are not aware of the protocol, and might not be secure against quasi-polynomial adversaries. Indeed, under standard assumptions, it is not hard to come up with a protocol that cannot be broken in time  $T$  but *can* be broken using quasi-polynomial in  $T$  steps.<sup>7</sup> Our proof does not guarantee the security of such protocols when concurrently executed with our protocol. However, note that it also possible to come up with protocols that cannot be broken in time  $T$  but can be broken in time  $T^3$ . (In fact,

<sup>6</sup>The only application where simulation is itself a goal that we are aware of is *deniability* [CDNO97, Nao02]. However, deniability is a delicate property that is hard even to define in the general concurrent network setting, and previous works in this area such as [CLOS02] also fail to achieve deniability, even when using setup assumptions.

<sup>7</sup>In fact, our protocol has this property, which is why it requires a highly non-trivial proof to show that it preserves soundness under concurrent composition.

such protocols may be common due to the tendency of practitioners to instantiate cryptographic protocols with the absolutely smallest key size that has not yet been broken.) Thus, in our opinion also in the general concurrent case, quasi-polynomial simulation offers *quantitatively* rather than *qualitatively* lower security.

**Affect of simulation overhead on other protocols.** In general, simulation always has an overhead, and super-polynomial simulation has a larger overhead. Let us elaborate on what we mean by considering a more concrete notion of security. Let  $T$  be some conservative upper bound on the resources available to the adversary (e.g., today it seems that one can let  $T = 2^{60}$ ). Now, suppose that we have a stand-alone secure protocol  $\Pi$ , and we instantiate it with the smallest (and hence most efficient) security parameter, namely the parameter that guarantees us security against time  $T$  adversaries.<sup>8</sup> Suppose further that we enjoy some setup conditions (such as availability of a trusted common reference string) and we want to use a protocol  $\Pi'$  which is general-concurrent secure with *polynomial* simulation such as [CLOS02] to be executed concurrently with  $\Pi$ . Then, to argue that  $\Pi$  remains secure in this setting we'll need to make sure that it is secure not just for  $T$ -time adversaries but also for  $T^c$ -time adversaries, for some constant  $c > 1$ . Therefore, we will need to increase the security parameter of  $\Pi$ . If the security of  $\Pi$  is exponential or subexponential in its security parameter this means that we will need to increase the security parameter of  $\Pi$  by a constant multiplicative factor, and hence (since  $\Pi$  runs in time polynomial in its security parameter) suffer a constant factor decrease in the efficiency of  $\Pi$ . Now, if we don't have such trusted setup conditions, and we want to use the protocol of this paper which has *quasi-polynomial* simulation, then we will need to increase the security of  $\Pi$  from  $T$  to  $2^{(\log T)^c}$ . This means that we will need to increase the security parameter of  $\Pi$  by a polynomial amount and hence suffer a polynomial decrease in efficiency. We remark that under stronger but reasonable assumptions, (namely existence of *exponentially* rather than sub-exponentially collision-resistant hash functions) we can make this polynomial loss in efficiency “almost linear” (e.g., a function of the form  $k^{1+o(1)}$ ).

## 2.2 Our Results.

We consider the zero-knowledge ideal functionality  $\mathcal{F}_{\text{ZK}}$  (for an NP-complete problem such as SAT) which gets as input from party  $P_i$  two strings  $y$  and  $w$  and the identity of a party  $P_j$ , and sends to  $P_j$  the tuple  $(\text{ZK}, P_i, P_j, y)$  if  $w$  is a satisfying assignment for the formula  $y$ , and does nothing otherwise.

Our main result is a construction of a protocol for securely implementing the  $\mathcal{F}_{\text{ZK}}$  functionality under general composition. Namely, we prove the following theorem:

**Theorem 2.1** (General-concurrent zero knowledge). *Suppose that there exists a hash function collection that is collision resistant for  $2^{k^\epsilon}$ -sized adversaries (where  $\epsilon > 0$  is a constant and  $k$  denote the collection's security parameter). Then, there exists a protocol that securely realizes the  $\mathcal{F}_{\text{ZK}}$  functionality with quasi-polynomial simulation.*

Canetti *et al.* [CLOS02] showed how to securely compute *any* functionality in the  $\mathcal{F}_{\text{ZK}}$ -hybrid model. Thus, by observing that their results “scale up” and hold in our model, and by plugging in [Theorem 2.1](#), we obtain the following result:

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<sup>8</sup>We ignore here the issue that one has to be actually more conservative since we don't really know the security of the primitives we use. This issue seems orthogonal to the issue of polynomial vs. super-polynomial simulation.

**Theorem 2.2** (General-concurrent secure function evaluation). *Suppose that there exists a hash function collection that is collision-resistant for  $2^{k^\epsilon}$ -sized adversaries (where  $\epsilon > 0$  is a constant and  $k$  denote the collection’s security parameter). Then, there exists  $c = c(\epsilon)$  such that if there is a collection of enhanced trapdoor permutations which is secure for  $k^{\log^c k}$ -sized adversaries then for every (possibly probabilistic) polynomial-time functionality  $\mathcal{F}$ , there is a protocol  $\rho_{\mathcal{F}}$  that securely realizes  $\mathcal{F}$  with quasi-polynomial simulation.*

We remark that there are several applications that can be obtained by simply instantiating this result with the appropriate functionalities. Among them are the first constructions for concurrently-secure auctions, password-based key-exchange protocols, and non-malleable commitments (the latter two require using the results of [BCL+05] to obtain security in the unauthenticated model). We defer these applications for a later version of this work.

### 3 Overview of Our Techniques.

In this section we provide an rough overview of our approach to obtaining a zero-knowledge protocol that is secure under general concurrent composition. That is, we describe our approach to proving [Theorem 2.1](#). We start by briefly describing some of the primitives and tools we use. We then present how one can obtain such a protocol by combining two different approaches that fail with some new techniques and tricks. We warn the reader that this description is missing a few important subtleties and issues that make the our actual construction and proof more complicated. Because of these subtleties, our actual construction ([Protocol 3.1](#)) does not exactly follow the approach illustrated in this section, but follows a more “low level” approach.

#### 3.1 Preliminaries.

We will use the following primitives and sub protocols. Because this is an overview section, we describe the primitives in an informal way, and also present each primitive in its simplest variant, even if this variant requires stronger assumptions than the ones stated in [Theorem 2.1](#). We will use the following primitives:

**Commitment schemes.** A non-interactive perfectly binding and computationally hiding commitment scheme  $\text{Com}$  [BLU82, NAO89].

**Zero-Knowledge proofs of knowledge.** A constant-round zero-knowledge proof/argument of knowledge for NP [FS89, GK96]. We will also sometimes use the weaker notion of a *witness indistinguishable* proof, which we denote by WIP [FS90]. We note that witness-indistinguishability, unlike zero-knowledge, is closed under concurrent composition. Indeed, under some strong but reasonable assumptions it is even possible to have two-message or even one-message WI proofs, which are trivially closed under concurrent composition [DN00, BOV03].

**Collision resistant hash functions.** A collection  $\text{Hash}$  of functions that map arbitrarily long strings into polynomial-sized strings such that it is hard given a random  $h \in \text{Hash}$  to find  $x, y$  such that  $h(x) = h(y)$ . We note that by combining a hash function with a commitment scheme we can obtain a commitment scheme that allows us to commit to messages of unbounded size.<sup>9</sup>

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<sup>9</sup>We ignore here the issue of who gets to choose the hash function – the sender or the receiver. Although intuitively it seems that the receiver should choose the hash function, it turns out that in some cases we actually want the sender

**Universal arguments.** A constant-round public-coin argument of knowledge for  $\mathbf{Ntime}(T)$  for a *super-polynomial* function  $T(\cdot)$  (e.g.,  $T(k) = k^{\log k}$ ). Universal arguments were first constructed by [KIL92], with improved analysis in [Mic94] and [BG01] (with the latter work showing they are a proof of knowledge). We'll also use constructions of universal arguments that are *zero knowledge* and *witness indistinguishable* [KIL92, BG01, BAR04]. Universal arguments have the property that the total communication and running time of the verifier is always polynomial, even if the statement proven is not in  $\mathbf{NP}$ . Furthermore, the running time of the prover is polynomial in the time to actually verify the instance being proven. For example, if  $L \in \mathbf{NP}$  and  $L' \in \mathbf{Ntime}(k^{\log k})$  and one is proving using universal arguments that  $x \in L \cup L'$  then if  $x$  is in fact in  $L$  and the prover is given a witness to this fact, then the prover can execute the proof in polynomial time.

**Knowledge commitments.** We denote by  $\mathbf{KCom}$  the protocol in which a sender commits to a string  $x$  using  $\mathbf{Com}(\cdot)$  and then proves knowledge of the committed string using a zero-knowledge proof of knowledge. We denote by  $\mathbf{UAKCom}$  the same protocol in which the sender commits to  $h(x)$  and proves knowledge of  $x$  using a zero-knowledge universal argument.

**Weak commitments.** We denote by  $\mathbf{Com}_{\text{weak}}$  a commitment scheme that can be completely broken in time that is smaller than the time to violate the security of all the other primitives we use. Such a commitment scheme can be constructed under our assumptions using the complexity leveraging technique of [CGGM00].

**Brute force breaking opportunity.** We denote by  $\mathbf{BFOP}$  the protocol in which a verifier sends  $\mathbf{Com}_{\text{weak}}(r)$  and then the prover sends  $\mathbf{KCom}(r')$  for some string  $r'$ . We say that the prover *broke* this instance if  $r' = r$ . Note that this protocol can be broken by breaking  $\mathbf{Com}_{\text{weak}}$ . Similar tricks were used in several previous works such as [CGGM00, Pas03].

### 3.2 First Attempt: The Brute Force Protocol

Recall that we're trying to prove [Theorem 2.1](#) by constructing a general-concurrent secure zero-knowledge argument. Here's a naive attempt at such a protocol, which we denote by  $\Pi_{\mathbf{BF}}$ : let  $L$  be an  $\mathbf{NP}$ -language with a corresponding relation  $R$ . To prove that  $x \in L$ , given  $w$  such that  $(x, w) \in R$ , the prover and verifier interacts as follows:

1. Prover sends  $\mathbf{Com}_{\text{weak}}(w)$  to the verifier.
2. Prover and verifier interact in a brute-force breaking opportunity  $\mathbf{BFOP}$ .
3. Prover proves to verifier in  $\mathbf{WI}$  that it either committed to the witness in the first step or that it broke the  $\mathbf{BFOP}$  in the second step.

It is not hard to verify that this protocol satisfies completeness and soundness. In fact, in a *real* concurrent interaction, whenever the verifier is honest, the probability that it accepts a proof without the weak commitment actually containing a witness is negligible. There is a natural straight-line black-box simulator for  $\Pi_{\mathbf{BF}}$ : when simulating an interaction in which the adversary is

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to choose it. For the sake of this overview, the reader can assume that each party chooses its own hash function and then they use the function that on input  $x$  returns the concatenation of both functions applied to  $x$ . This function is guaranteed to be collision resistant if one of the parties is honest.

a verifier, the simulator commits to  $0^k$  instead of to the witness, and then breaks BFOP and uses this fact to run the WI proof of Step 3. It is not hard to prove that the simulator’s output is indeed indistinguishable from a real execution<sup>10</sup>.

When simulating an interaction in which the adversary is the prover, the simulator will attempt to extract a witness by breaking the weak commitment sent by the adversary. However, in this case, we are not sure that it will succeed. The property we’re looking for, that even during the simulation the adversary’s proof must contain a real witness, is called *simulation soundness* [SAH99], and this property lies at the heart of constructing non-malleable zero-knowledge protocols. Unfortunately, it can be shown that protocol  $\Pi_{\text{BF}}$  does *not* satisfy this property (i.e., there is a known attacking strategy on instantiations of  $\Pi_{\text{BF}}$  with particular primitives).

### 3.3 Second Attempt: The Condensed Protocol

The problem with the first attempt was that that protocol did not satisfy simulation soundness / non-malleability (it is essentially the same property). There are very few simulation-sound zero-knowledge protocols without setup assumptions [DDN91, BAR02, PAS04, PR05] and most of these are only analyzed in the scenario where there are only two executions occurring concurrently: one in which the adversary is the verifier and another in which the adversary is the prover. However, it was observed in [BCL+05] that using similar ideas to [PR05], it is possible to convert the protocol of [PAS04] to a protocol that remains simulation-sound even when the adversary interacts not just in two executions but in  $k$  executions – playing the role of prover in some, and playing the role of verifier in others. Here,  $k$  is the security parameter.<sup>11</sup> We denote this protocol by **bgcZK** (for bounded general-concurrent zero knowledge).

**A strange idea.** This leads us to the following strange idea - why don’t we try to use Protocol **bgcZK**, but set the security parameter to *super-polynomial* size? Unfortunately there is a good reason cryptographers do not set the security parameter to super-polynomial values: because this yields a protocol with super-polynomial communication and computation even for the honest parties. Can we overcome this difficulty? We do have a way to compress at least the communication, using hash functions combined with universal arguments. That is, we define  $\Pi_{\text{condensed}}$  to be the protocol that is the result of executing **bgcZK** with security parameter  $k^{\log k}$  (where  $k$  is our “true” security parameter), but replacing each message  $m$  in **bgcZK**( $k^{\log k}$ ) which is of super-polynomial size with  $h(m)$  followed by a universal argument proving knowledge of  $m$ . Now, it is not at all clear that this protocol makes sense, because if a party needs to change its action in **bgcZK**( $k^{\log k}$ ) according to the contents of a super-polynomially sized message  $m$ , then during an interaction in  $\Pi_{\text{condensed}}$ , this party won’t be able to recover  $m$  regardless of its computation powers (indeed, the polynomial-sized transcript simply does not contain enough information about  $m$ ).

Thus we are left with two problems: **(1)**  $\Pi_{\text{condensed}}$  is not a valid protocol since the parties need to run in super-polynomial time, if they can work at all *and* **(2)** Even though  $k^{\log k}$  concurrent sessions

<sup>10</sup>Thus, the protocol  $\Pi_{\text{BF}}$  is a concurrent zero knowledge protocol with quasi-polynomial simulation. But note that we need more than just concurrent zero knowledge, because the adversary can also play the role of prover.

<sup>11</sup>[PAS04] already gave a simulation-sound zero-knowledge satisfying this property assuming the ID’s of each party come from a polynomial-sized domain. [PR05] showed how one can convert this protocol to a standard simulation-sound protocol by having a party with ID  $\alpha = \alpha_1, \dots, \alpha_k$  run  $k$  parallel executions of [PAS04]’s protocol using the ID  $\langle i, \alpha_i \rangle$  for the  $i^{\text{th}}$  execution. [BCL+05] observed that if one first encodes the ID using an error-correcting code with  $\text{poly}(k)$  alphabet-size and relative distance larger than  $1 - 1/k$  then the [PR05] protocol actually handles  $k$  concurrent sessions. In the full protocol we actually use a different trick, based on signature schemes.

of  $\text{bgcZK}(k^{\log k})$  can be simulated, that does not mean that the same holds for  $\Pi_{\text{condensed}}$ , since now the simulator needs to *rewind* to extract the long messages sent and rewinding in a concurrent setting is notoriously problematic. Both problems are rather serious but can be resolved by moving to a third protocol that tries to combine the good properties of  $\Pi_{\text{BF}}$  and  $\Pi_{\text{condensed}}$ .

### 3.4 The Combined Protocol: Two Protocols with Two Simulators.

We now present our third protocol, which will actually be (almost) a concurrently simulation-sound zero-knowledge protocol.<sup>12</sup> The idea is the following: we will run both  $\Pi_{\text{BF}}$  and  $\Pi_{\text{condensed}}$ , but we'll run  $\Pi_{\text{condensed}}$  in an “encrypted” form, that is replacing every message  $m$  of  $\text{bgcZK}$  by  $\text{KCom}(m)$  if  $m$  is of polynomial size and  $\text{UAKCom}(m)$  if  $m$  is of super-polynomial size. At the end, we will prove in a witness indistinguishable way that one of these protocols succeeded. That is, our combined protocol, which we denote by  $\Pi_{\text{combined}}$  will operate as follows, when proving  $x \in L$  with  $w$  a witness for  $x$ :

1. Prover sends to verifier  $\text{Com}_{\text{weak}}(w)$ .
2. Prover and verifier engage in a brute-force breaking opportunity BFOP.
3. Prover and verifier engage in “encrypted and condensed” version of  $\text{bgcZK}(k^{\log k})$ : any message  $m$  is replaced with  $\text{KCom}(m)$  if  $m$  is polynomial size and  $\text{UAKCom}(m)$  if  $m$  is of super-polynomial size.
4. Prover and verifier engage in a witness indistinguishable universal argument that *either*:
  - (a) the commitment in Step 1 is indeed a witness *or*
  - (b) prover broke BFOP *or*
  - (c) there exists a transcript for  $\text{bgcZK}(k^{\log k})$  that the honest verifier of that protocol accepts, and this transcript is consistent with the “encrypted condensed” transcript of Step 2.

**What is this good for?** First of all note that, unlike  $\Pi_{\text{condensed}}$ , in  $\Pi_{\text{combined}}$  both parties can be implemented using only polynomial time computation, and so at least we got rid of one of our problems. Like  $\Pi_{\text{BF}}$ , Protocol  $\Pi_{\text{combined}}$  has a simple straight-line black-box simulator. However, our intention is that unlike in the case  $\Pi_{\text{BF}}$  this simulator will enjoy the simulation soundness property and furthermore that we will be able to prove that this is the case. Our idea is to prove simulation soundness using what we call a *virtual simulator*. The virtual simulator will have two properties: **(1)** it will satisfy the simulation-soundness property and **(2)** it will be *strongly indistinguishable* from the output of the straight-line simulator, in the sense that it will be indistinguishable *even for algorithms with enough running time to break  $\text{Com}_{\text{weak}}$* . These two properties together will imply that our straight-line simulator must also satisfy the simulation soundness requirement.

**Why do we need the straight-line simulator?** If the virtual simulator already satisfies the simulation soundness condition, why do we need to use the straight-line simulator at all? The reason is that the virtual simulator will actually use the *witness* as part of its input. This is OK since the virtual simulator is not the “real” simulator and is only used as part of the security proof. Note that it is not at all clear that using the witness helps the virtual simulator as we can't commit to the witness in Step 1 without destroying the strong indistinguishability property.

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<sup>12</sup>The qualifier “almost” is because there are still some subtleties that we ignore here. Some of these are discussed below, while others are only handled in the full proof presented in the later sections.



**The operation of the virtual simulator.** The virtual simulator will try to run the simulator of the protocol  $\text{bgcZK}(k^{\log k})$ , which does enjoy the simulation-soundness property. The question is how do we solve our second problem above – namely, how do we use the simulator of  $\text{bgcZK}(k^{\log k})$  when we are unable to rewind in a concurrent setting. The trick is that we *are* able to rewind using the *witnesses*. That is, in order to produce the auxiliary sessions we need for rewinding we actually use the witness to perform a straight-line simulation. The reason we can get away with using the witness in these auxiliary sessions is that the auxiliary sessions don’t need to be strongly indistinguishable from the main simulation, but rather only need to be indistinguishable “enough” to ensure successful extraction. The reason we can’t use the breaking opportunity is that in order to ensure the simulation soundness we need to make sure that the running time of the virtual simulator is less even than the time to break  $\text{Com}_{\text{weak}}$ .

### 3.5 Some issues and subtleties.

**Witness-based continuation:** To actually implement this idea, we need to make sure that regardless at which point we are in the simulation, we can always continue in a straight-line fashion using the witness alone, without requiring the internal state of any of the parties. Toward this end, we use a compiler, which we call a *witness-based-continuation (WBC) compiler* that transforms the protocol to a protocol that satisfies this property. Loosely speaking, we first make sure that the only prover messages that unavoidably depend on internal state are the last messages sent in some proof system used as a sub-protocol. We then change the prover to have these messages not sent in the clear but rather in a weak commitment, along with a weak commitment to a string  $w'$  and a WI proof that either the committed message causes the verifier to accept or  $w'$  is a witness.<sup>13</sup>

**“Forcing” scheduling constraints on adversary:** Another point is that when we transformed  $\text{bgcZK}$  into its condensed version, we converted each message into an interactive universal argument, thus ruining the “atomicity” of individual messages. The security proof of  $\text{bgcZK}$  actually relies on this atomicity and hence we need to do something to restore it. Our solution is to use brute force breaking opportunities as “buffers” between individual messages. It turns out that if during a session in which the adversary is a verifier, it schedules the universal arguments for two messages during the same time as it schedules the universal argument for a single message in the session where it is a prover, then in this case it is actually “safe” for the virtual simulator to break the BFOP (even though this requires more running time than the virtual simulator is officially “allowed”). Thus, we can use the straight-line simulator in the cases where the adversary’s scheduling violates the atomicity condition.

### 3.6 Guide to the actual protocol and proof.

Our general-concurrent zero knowledge argument scheme is [Protocol 3.1](#) (Page 16). This protocol follows broadly the approach sketched above, but its analysis and design are more “low level”. That is, instead of combining “generic” components such as  $\Pi_{\text{BF}}$  and  $\text{bgcZK}$  and proving something about the composition of any two such components, we use the ideas behind  $\Pi_{\text{BF}}$  and  $\text{bgcZK}$  to construct our protocol which we then analyze. The reason is that there are some subtleties, especially involving the ability of the adversary to dynamically schedule messages and choose the statements

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<sup>13</sup>We use a variant of this compiler with trapdoor commitments a la [FS89, CLOS02] to obtain security with respect to *adaptive* adversaries.

to be proven, that make the low level approach preferable. Some points in which we deviate from the description above include using more complexity levels than just two, and using verification keys of digital signatures to avoid issues with dynamically chosen statements.

Under our assumptions we have for every constant  $i$  a super-polynomial function  $T_i(k)$  such that, by using an appropriately scaled security parameter, we can get a variant of each of the primitives above that is secure against  $T_i(k)$ -sized adversaries but completely broken by  $T_{i+0.1}(k)$ -sized adversaries. We use a subscript  $i$  to denote such primitives. A full description of this protocol and its analysis can be found in the following sections.



<p><b>Public input:</b> <math>1^k</math>: security parameter , <math>x \in \{0, 1\}^{\ell_{\text{stmt}}}</math> (statement to be proved is “<math>x \in L</math>”)  <b>Prover’s auxiliary input:</b> <math>w \in \{0, 1\}^{\ell_{\text{wit}}}</math> (a witness that <math>x \in L</math>)</p>	$\begin{array}{ccc} w & & 1^k, x \\ \downarrow & & \downarrow \\ \boxed{P} & & \boxed{V} \end{array}$
<p><b>Step V1.1 (Verifier’s hash):</b> Verifier chooses a random hash function <math>h \leftarrow_{\text{R}} \text{Hash}_6</math> and sends <math>h</math>.  <b>Steps P,V1.2 (Prover’s “verification key”):</b> Prover chooses <math>VK = 0^{\ell_{\text{VK}}}</math> and sends <math>c_{\text{VK}} = \text{Com}_1(VK [= 0^{\ell_{\text{VK}}}] )</math> to the verifier.</p>	$\begin{array}{c} \leftarrow h \leftarrow_{\text{R}} \text{Hash}_6 \\ \\ \xrightarrow{c_{\text{VK}} = \text{Com}_1(VK [= 0^{\ell_{\text{VK}}}] )} \end{array}$
<p><b>Steps V,P2.x (Verifier’s first challenge):</b> Verifier chooses <math>r_1 = 0^k</math>, computes <math>c_{r_1} = \text{Com}_5(h(r_1))</math> and proves knowledge of <math>r_1</math> using a ZKUA.</p>	<p><i>Slot 1</i>  <math display="block">\leftarrow c_{r_1} = \text{UAKCom}_5^h(r_1 [= 0^k])</math></p>
<p><b>Steps P,V3.x (Breaking opportunities):</b> Prover and verifier engage in a <math>T_2(k)</math>, and <math>T_3(k)</math>-secure brute force breaking opportunities.</p>	<p>“Unsafe” period  <math>B_{\text{easy}} = \text{BFOP}_2; B_{\text{hard}} = \text{BFOP}_3</math></p>
<p><b>Steps V,P4.x (Verifier’s second challenge):</b> Verifier chooses <math>r_2 = 0^k</math>, computes <math>c_{r_2} = \text{Com}_5(h(r_2))</math> and proves knowledge of <math>r_2</math> using a ZKUA.</p>	<p><i>Slot 2</i>  <math display="block">\leftarrow c_{r_2} = \text{UAKCom}_5^h(r_2 [= 0^k])</math></p>
<p><b>Step P,V5.x (Commitment to “Signature”):</b> Prover lets <math>\sigma = 0^{\ell_{\text{sig}}}</math> and sends <math>c_{\text{sig}} = \text{KCom}_5(\sigma)</math> to the verifier.</p>	$\xrightarrow{c_{\text{sig}} = \text{Com}_5(\sigma [= 0^{\ell_{\text{sig}}}] )}$
<p><b>Steps P,V6.x (“committed” universal argument):</b>  Prover and verifier run <math>T_6(k)</math>-sound universal argument UA for [KOLM] where prover sends <math>T_5</math>-strong commitments to its messages . Honest prover uses commitments to “junk” (i.e. <math>0^k</math>) in this stage.  <b>Statement [KOLM]:</b> Let <math>M = 2T_{0.1}(k)</math>. For <math>j \in [\ell_{\text{VK}}]</math> let <math>\ell_j = (VK_j) \cdot \ell_{\text{VK}} + j</math> (i.e., <math>\ell_j \in [2\ell_{\text{VK}}]</math>) and let <math>\ell_j^1 = \ell_j \cdot M</math> and <math>\ell_j^2 = (4\ell_{\text{VK}} + 1 - \ell_j)M</math>. <b>Then</b>, for every <math>j \in [\ell_{\text{VK}}]</math> there exist <math>s \in \{1, 2\}</math>, a TM <math>\Pi_s</math> of description size <math>\leq \ell_j^s - k</math> and a string <math>r_s</math> such that: <b>(a)</b> <math>\Pi_s</math> outputs <math>r_s</math> within <math>\leq T_{1.4}(k)</math> steps <i>and</i> <b>(b)</b> <math>r_s</math> is consistent with <math>c_{r_s}</math>. That is, <math>h(r_s) \in \text{Com}^{-1}(c_{r_s})</math>.</p>	$\xrightarrow{c_{\text{UA}} = \text{Com}_5 \text{UA}_6 \text{ of [KOLM]}}$
<p><b>Step P.7.1 (Commitment to Witness):</b> Prover sends <math>c_{\text{wit}} = \text{Com}_4(w)</math> to the verifier.  <b>Steps P,V7.2.x (WI proof):</b> Prover proves to verifier using a <math>T_5(k)</math>-WI proof that one of the following holds: <b>either</b>  <b>[WIT]</b> <math>\text{Com}^{-1}(c_{\text{wit}})</math> is a witness for <math>x</math> <b>or</b>  <b>[BFOP]</b> Broke <math>B_{\text{hard}}</math> <b>or</b>  <b>[UA]</b> <math>\text{Com}^{-1}(c_{\text{UA}})</math> is accepting transcript. <b>or</b>  <b>[SIG]</b> Broke <math>B_{\text{easy}}</math> and <math>c_{\text{sig}}</math> is commit to sig on <math>x</math>.</p>	$\xrightarrow{c_{\text{wit}} = \text{Com}_4(w)}$ $\boxed{\begin{array}{c} \overline{\overline{\text{WIP}_5 \text{ that } [\text{WIT}] / \\ [\text{BFOP}] / [\text{UA}] / [\text{SIG}]}} \end{array}}$

(The WBC compiler changes a last prover message  $m$  of a sub-proof systems (i.e.,  $B_{\text{easy}}, B_{\text{hard}}$  and the final WIP) to  $\text{Com}_4(m)$  ,  $\text{Com}_4(w' [= 0^{\ell_{\text{wit}}}] )$  and WI-proof that either  $m$  convinces the verifier or  $w'$  is a witness for  $x$ .)

**Protocol 3.1.** Non-Malleable Concurrent Zero Knowledge (before WBC-compiler)

## 4 Construction of a Concurrent and Non-Malleable Zero-Knowledge Protocol

### 4.1 Preliminaries

**Hardness assumptions.** We will make use of a number of “complexity levels” in our protocol and its analysis. As the analysis is quite delicate, and for sake of understandability, we do *not* attempt to optimize the number of complexity levels (described below), but rather we choose a very conservative setting of parameters in order to simplify the presentation to the best extent possible. We assume we have primitives that with security parameter  $k'$  are secure against  $2^{k'/\epsilon}$  sized circuits, (in the sense that no  $2^{k'/\epsilon}$ -size circuit can break them with success better than  $2^{-k'/\epsilon}$ ) but can be completely broken in time  $2^{k'}$ . We assume that our adversary’s running time is  $T_0(k)$  (e.g.,  $T_0(k) = k^{\log k}$  or  $T_0(k) = 2^{k^\delta}$ ). Define  $T_i(k) = 2^{\log(T_0(k))^{(1/\epsilon)^{30i}}}$ . By appropriate scaling, we can obtain for every constant  $i$ , a primitive that is secure against  $T_i(k)$ -sized adversaries but is completely broken in time much less than  $T_{i+0.1}(k)$ . We call such a primitive  $T_i(k)$ -secure and we sometimes use a subscript  $i$  to denote it (e.g.,  $\text{Com}_i$ ). We say that a probabilistic event is  $T_i(k)$ -observable if there is a  $T_i(k)$ -time computable predicate that decides whether or not the event holds. Note that we’ll sometimes drop  $k$  when it can be inferred from the context. We say that  $f(k) \ll g(k)$  if  $2^{\log^{(1/\epsilon)} f(k)} = g(k)^{o(1)}$ .

Throughout this paper *negligible* will mean probability that is less than  $1/T_0(k)^c$  for any fixed  $c > 0$ . We say that two random variables  $X$  and  $Y$  are  $(s, \epsilon)$ -computational indistinguishable if no  $s^{O(1)}$ -sized circuit can distinguish between  $X$  and  $Y$  with  $\epsilon^{\Omega(1)}$  advantage. We say that they are  $s$  indistinguishable if they are  $(s, 1/s)$ -indistinguishable.

For sake of visual simplicity, we will often drop the dependence on the global security parameter  $k$ , and simply write  $T_i$  for  $T_i(k)$ .

### 4.2 The protocol.

Let  $L$  be an NP language, where the statement is of length  $\ell_{\text{stmt}}$  and the witness is of length  $\ell_{\text{wit}}$  (both polynomially related to  $k$ ). We now describe a concurrent non-malleable  $T_{4.1}(k)^{O(1)}$ -time simulatable zero-knowledge protocol for  $L$ . A concurrent execution of the protocol involves  $\text{poly}(k) \leq T_0(k)$  concurrent sessions in which the adversary plays the verifier, and one session (also concurrent with the others) in which the adversary plays the prover. We will present a  $T_{4.1}(k)^{O(1)}$ -time simulator that outputs a string indistinguishable to the transcript of all these executions, along with a witness to the statement proven by the adversary (unless this statement is a copy of a statement proven in one of the other sessions).

#### 4.2.1 Components.

We use the following components in our protocol:

- A  $T_6$ -secure signature scheme. We denote by  $\ell_{\text{VK}}$  the length of the verification key and by  $\ell_{\text{sig}}$  the length of a signature on messages of length  $\ell_{\text{stmt}}$ .
- A  $T_6$ -secure hash function ensemble  $\text{Hash}_6$  of functions mapping  $\{0, 1\}^*$  to  $\{0, 1\}^{\ell_h}$ .

- Non-interactive computationally-hiding, perfect binding commitment schemes at various strengths.  $\text{Com}_i$  indicates a commitment secure against  $T_i(k)$ -time adversaries and breakable in time  $\ll T_{i+0.1}$ .
- A  $T_6$ -sound constant-round public coin *universal argument*, which we denote by UA [BG01]. By combining this with a standard constant-round zero-knowledge argument of knowledge for  $\mathbf{NP}$  (e.g., [FS90] or [BAR01]<sup>14</sup>), we also have a  $T_6(k)$ -sound, zero-knowledge universal argument (ZKUA) where the zero-knowledge property holds with polynomial simulation overhead (for adversaries of size  $\leq T_6$ ) and the output of the simulator is indistinguishable for  $T_5(k)$ -sized adversaries. See [BAR01, BG01, BAR04] for more details.
- We denote by  $\text{KCom}_i$  (short for “knowledge commitment”) the interactive commitment scheme where the sender commits to a value  $x$  using  $\text{Com}_i$  and then proves knowledge of  $x$  using a constant-round zero-knowledge argument of knowledge, which is sound against  $T_6(k)$ -sized adversaries and indistinguishable for  $T_i(k)$ -sized adversaries. (Again, we’ll use the protocol of [BAR01] as the zero-knowledge argument in this scheme.)
- We denote by  $\text{UAKCom}_i^h$  for the protocol where the sender uses the hash function  $h$  to first hash  $x$  and then commits to  $h(x)$  using  $\text{Com}_i$  and proves knowledge of  $x$  using a zero-knowledge universal argument which is sound against  $T_6(k)$ -sized adversaries and indistinguishable for  $T_i(k)$ -sized adversaries.
- $T_i(k)$ -secure one way functions for various levels  $i$ . We use the notation  $\text{OWF}_i : \{0, 1\}^{\ell_{\text{OWF}_i}} \rightarrow \{0, 1\}^{\ell_{\text{OWF}_i}}$ .
- We call the following sub-protocol a *brute force breaking opportunity of level  $i$* : the verifier chooses  $r \leftarrow_{\mathbf{R}} \{0, 1\}^{\ell_{\text{OWF}_i}}$  and sends  $y = \text{OWF}_i(r)$  to the prover. The prover responds with  $\text{Com}_5(r')$  (where the honest prover chooses  $r' = 0^{\ell_{\text{OWF}_i}}$ ) and a proof of knowledge of  $r'$  using a constant-round zero-knowledge argument of knowledge for  $\mathbf{NP}$  (with  $T_6(k)$  soundness and  $T_5(k)$  indistinguishability). We denote this protocol by  $\text{BFOP}_i$  and we say the prover *broke* this instance of the protocol if  $r' \in \text{OWF}^{-1}(y)$ . We assume that  $\text{OWF}$  is a permutation for simplicity (as otherwise the verifier may send an element  $y$  that is not in the range of  $\text{OWF}$ ). This assumption is not necessary, as we can also have the verifier prove in ZK that its challenge  $y$  is in the range, or replace the one-way function with a commitment scheme. However, we avoid this complication in describing the protocol and its simulation.

**Note:** We assume that all the proof systems we use as components (WI,ZK) etc.. have the following properties:

- The verifier is *stateless*. By this we mean that each message of the verifier can be computed using fresh randomness and the previous public transcript. (In particular, this holds for public coins (a.k.a. Arthur-Merlin) protocols.)
- The prover’s messages are composed of a sequence of unopened commitments and then at the end a message  $m$ . The verifier then decides whether to accept by applying a publicly known polynomial-time predicate on the entire transcript.

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<sup>14</sup>We’ll actually use the latter protocol, since it will be convenient for us to assume that the proof systems we use as sub-protocols are public-coin systems.

It is not hard to verify that such components exist under our assumptions.

Note also that for the proofs of knowledge we will use the property that given a prover algorithm  $P_*$  of size  $T$  that causes the verifier to accept the statement  $x$  with probability at least  $\mu$ , the knowledge extractor can using  $\text{poly}(T/\mu)$  steps to output a witness for  $x$  with probability at least  $1 - \mu$ .<sup>15</sup>

#### 4.2.2 Operation of the protocol.

Our non-malleable zero-knowledge protocol is [Protocol 3.1](#) (Page 16).<sup>16</sup> It consists of the following stages:

**Initial phase (Steps V1.1 , P1.2):** Verifier chooses a hash function  $h$  in  $\text{Hash}_6$ . Prover commits using  $\text{Com}_1$  to a string  $VK$ . (Honest prover lets  $VK = 0^{\ell_{VK}}$ .)

**First “slot” (Steps V,P2.x):** Verifier chooses a string  $r_1$  and commits to prover to  $r_1$  using  $\text{UAKCom}_5^h$ . (Honest verifier uses  $r_1 = 0^k$ .)

**“Unsafe period” - brute force challenge (Steps P,V3.x):** Prover and verifier engage in two breaking opportunities (in parallel, although this doesn’t matter) one that is  $T_2$ -secure which we call  $B_{\text{easy}}$  and the other that is  $T_3$ -secure which we call  $B_{\text{hard}}$ .

**Second “slot” (Steps V,P4.x):** Verifier chooses a string  $r_2$  and commits to prover to  $r_2$  using  $\text{UAKCom}_5^h$ . (Honest verifier uses  $r_2 = 0^k$ .)

**Commitment to “signature” (Step P5):** Prover sends to verifier  $\text{Com}_5(\sigma)$  where  $\sigma = 0^{\ell_{\text{sig}}}$ .

**“Committed” universal argument (Steps P,V6.x):** Prover and verifier run a  $T_6$ -sound universal argument for the statement **[KOLM]** (see below), but the prover does not send its messages in the clear but rather using  $T_5$ -secure commitments. Note that the universal argument is a public-coins/Arthur-Merlin protocol and hence the verifier does not need to view the prover’s messages to compute its own. However, of course, the verifier cannot verify the correctness of the universal argument.

**Commitment to witness (Step P7.1):** Prover sends a  $T_4$ -secure commitment to the witness  $c_{\text{wit}} = \text{Com}_4(w)$ .

**WI Proof (Steps P,V7.2.x):** Prover proves to verifier using a statistically-sound (with soundness error  $2^{-k}$  which we assume is  $\ll 1/T_6$ )<sup>17</sup>,  $T_5$ -WI proof that one of the following conditions hold **[WIT]** or **[BFOP]** or **[UA]** or **[SIG]** (see below).

<sup>15</sup>This is actually a weak property than standard proof of knowledge, which requires the extractor to run in time  $\frac{1}{\mu}\text{poly}(T)$ . However, in our context of super-polynomial simulation, this weaker property will be sufficient.

<sup>16</sup>Actually, as noted below, [Protocol 3.1](#) is not a complete description of the protocol as it ignores a “compiler” that we apply to it to get the final protocol. However, this compiler can and should be ignored in the first reading.

<sup>17</sup>We can use also a  $T_6$ -computationally sound argument here.

**The statements proven.** The statements used in the above proof systems are the following:

[**KOLM**] Let  $M = 2T_{0.1}$ . For  $j \in [\ell_{\text{VK}}]$  let  $\ell_j = (VK_j) \cdot \ell_{\text{VK}} + j$ . In other words,  $\ell_j$  maps  $\langle j, VK_j \rangle$  to  $[2\ell_{\text{VK}}]$  in a one-to-one manner. Let  $\ell_j^1 = \ell_j \cdot M$  and  $\ell_j^2 = (4\ell_{\text{VK}} + 1 - \ell_j)M$ . **Then**, for every  $j \in [\ell_{\text{VK}}]$ , for either  $s = 1$  or  $s = 2$ , there exists a TM  $\Pi_s$  of description size  $\leq \ell_j^s - k$  and a string  $r_s$  such that: **(a)**  $\Pi_s$  outputs  $r_s$  within  $\leq T_{1.4}(k)$  steps *and* **(b)**  $r_s$  is consistent with  $c_{r_s}$ . That is,  $h(r_s) \in \text{Com}^{-1}(c_{r_s})$ .

[**WIT**] The commitment  $c_{\text{wit}}$  contains a witness to the statement  $x$ .

[**BFOP**]  $B_{\text{hard}}$  is broken: Let  $y$  be the first message sent by the verifier in the  $B_{\text{hard}}$  protocol of Steps P,V3.x. Let  $c$  be the second message sent by the prover in this protocol. Then  $c$  contains a commitment to  $r'$  such that  $y = \text{OWF}(r')$ .

[**UA**] The committed universal argument transcript is an accepting transcript for the statement [**KOLM**].

[**SIG**] The commitment  $c_{\text{sig}}$  is a valid signature on the statement  $x$  with respect to the public key  $VK$  that is committed to in  $c_{\text{VK}}$ , *and*  $B_{\text{easy}}$  is broken: let  $y$  be the first message sent by the verifier in the  $B_{\text{easy}}$  protocol of Steps P,V3.x. Let  $c$  be the second message sent by the prover in this protocol. Then  $c$  contains a commitment to  $r'$  such that  $y = \text{OWF}_2(r')$ .

### 4.2.3 Witness-based continuation (WBC) compiler.

We will need to apply the following transformation to the prover strategy of this protocol. It may be better to ignore this transformation in the first reading. The crucial observation for this transformation is that all messages sent by the prover during the protocol fall into one of the following categories:

**Commitments** - messages that contain only unopened commitments.

**Verification messages for UAKCom** - messages that the prover sends when it is acting as a verifier in Steps V,P2.x and V,P4.x. We assume that these can be computed in a stateless way, without any need for internal state, just by looking at the transcript.

**Final messages of a WI/ZK proof** - the last message in a WI/ZK proof. We note that we can ensure that all of the prover messages in the zero-knowledge or WI proof are commitments except for the last message. We also note that given the proof transcript so far, it can be decided in polynomial-time whether or not this message causes the verifier of the proof to accept. These messages occur in the following places: the last messages of  $B_{\text{easy}}$  and  $B_{\text{hard}}$  of Steps V,P3.x and the last message of the final WIP of Steps P,V7.2.x.

Our compiler does not change the prover's behavior on the first two kinds of messages. However, instead of sending a message  $m$  of the last type, it will send  $\text{Com}_4(m)$ ,  $\text{Com}_4(w)$  and a WI proof of knowledge that either  $m$  causes the verifier to accept this particular sub-proof or that  $w$  is a witness for  $x$ . The WI proof will be statistically sound and witness indistinguishable for  $T_5$ -sized adversaries. We can use a standard 3-round proof for this part (e.g. parallelized [BLU87]). Even the honest prover will use a commitment to  $0^{\ell_{\text{wit}}}$  instead of a commitment to the witness in this compiler. The final protocol that is obtained after the WBC compiler is applied to [Protocol 3.1](#) is called **Protocol  $\mathcal{X}$** .

**Inner and outer prover algorithms.** It is useful to separate the prover algorithm for Protocol  $\mathcal{X}$  into two components: the *inner* prover and the *outer* prover. The inner prover is the prover strategy for the uncompiled protocol (i.e., Protocol 3.1). The outer prover stands between the inner prover and the verifier for Protocol  $\mathcal{X}$ , and adds the WBC layer to the behavior of the inner prover. We consider two strategies for the outer prover. **The relaying strategy:** in this strategy the outer provers simply relays the messages from the inner prover to the verifier, and when given the last message  $m$  of some WI/ZK proof, it uses  $\text{Com}_4(m), \text{Com}_4(0^{\ell_{\text{wit}}})$  as its message and then runs the WI proofs proving that  $m$  causes the verifier to accept. If  $m$  does *not* cause the verifier to accept then the outer provers does not continue in the execution (however, this will never happen if the inner prover is honest). Note that to use this strategy the outer prover does not need to have any private input, such as the witness for the statement being proven. **The witness-based strategy:** We will want to maintain the property that it is possible for the outer prover to switch over from using the relaying strategy to using the witness-based strategy at any point during the proof. In the witness-based strategy, the outer prover, knowing a witness to  $x \in L$ , acts as follows:

- If the prover reaches a point when it must send a commitment, it commits to “junk” (i.e., all zeros) messages of appropriate length.
- If the prover reaches a point when it must send a “stateless” message because it is playing a verifier within a proof, then it acts honestly.
- If the prover reaches a point when it must begin giving a WI proof of knowledge corresponding to the last message of an inner proof, then it replaces  $\text{Com}_4(m)$  with a commitment to “junk” (all zeros), and commits to the witness  $\text{Com}_4(w)$ . It then uses the witness condition to complete the WI proof of knowledge.
- If the prover has already committed according to the relaying strategy  $\text{Com}_4(m), \text{Com}_4(0^{\ell_{\text{wit}}})$ , then the prover finishes the WI proof of knowledge using knowledge of  $m$  and the rest of the inner transcript so far. This is possible because in order to prove that the verifier would accept  $m$  within the inner proof, one only needs to look at the (inner) transcript – this is because the verifier is stateless.

As noted above, the honest prover for the protocol will be using the relaying strategy (although this is not crucial, and will be changed for the adaptive case).

**Properties of the WBC compiler.** We note that the WBC compiler has the following effects on the WI or ZK proofs it is applied to:

1. It does not ruin the WI or ZK property.
2. The compiled proof is still sound as a proof system of the combined statement (i.e., that the original statement holds *or* that the commitment contains a witness).
3. It does not ruin the proof of knowledge property (if the original proof system had such a property) in the following sense: if with probability  $\geq \mu$  it holds that the combined proof successfully ends *and* the commitment of the WBC layer does not contain witness, then we can extract a witness for original statement in time  $\text{poly}(T/\mu)$  (where  $T$  is the prover’s running time).

4. We can continue the proof at any point with a witness without access to the internal coins of the original WI/ZK prover.

### 4.3 The (actual) simulator Sim.

Our simulator for Protocol  $\mathcal{X}$ , which we denote by Sim, is a straight-line black-box simulator<sup>18</sup>. This simulator does *not* get a witness as input, and hence will break  $B_{\text{hard}}$  to facilitate the simulation. That is, when simulating the prover Sim will deviate from the honest prover strategy by:

- Choosing a verification key  $VK$  for the signature scheme, and use a commitment to this key (as opposed to  $0^{\ell_{VK}}$ ) in the commitment  $c_{VK}$  of Step P1.2. (Sim will use the same verification key in all honest-prover sessions).<sup>19</sup>
- Using a commitment to  $0^{\ell_{\text{wit}}}$  instead of the real witness in Step P7.1.
- Breaking  $B_{\text{hard}}$  and use that to facilitate the WIP of Steps P,V7.2.x.

Like the honest prover, the simulator Sim will use the *relaying* outer-prover strategy for the WBC layer.

When simulating the verifier, Sim will follow the honest verifier strategy. However, when the execution of such a session is completed successfully and the statement proven was not proven in some previous honest-prover session, , the simulator Sim will use  $T_{4,1}$ -time to break all  $\text{Com}_4$  commitments used by the adversary that may contain a witness (i.e., the commitment  $c_{\text{wit}}$  and all commitments of the WBC-compiler). If it finds such a witness, Sim will output this witness as an auxiliary output. Otherwise, it will output `ss-failure`. A more detailed description of Sim appears in [Section 6](#), in the language of the UC framework.

We make two claims regarding Sim:

**Lemma 4.1** (Indistinguishable output). *The simulator Sim’s output is  $(T_4(k), 1/T_0(k))$ -computationally indistinguishable from the transcript of a real concurrent execution of  $\text{Adv}$  with the honest provers and verifier.*

**Lemma 4.2** (Witness is output). *The probability that in an honest verifier’s session of the simulated transcript it holds that the verifier accepts a statement  $x$  that was not proved before in an honest prover session, and none of the  $T_4$ -strong commitments contains a witness for  $x$  is less than  $1/T_{0.5}$ .*

Proving both [Lemma 4.2](#) and [Lemma 4.1](#) is done in [Section 6](#) (in the proof of [Theorem 6.2](#)).<sup>20</sup>

**Complexity levels.** Throughout the protocol and analysis, we make an extensive use of various complexity levels. For convenience we list all these levels in [Table 1](#) ([Page 23](#)) up to polynomial factors (e.g., identifying  $T_0$  and  $(T_0)^5$ ). We again stress that we have not tried to minimize the number of complexity levels used.

<sup>18</sup> This simulator Sim will actually be the simulator we use to prove that Protocol  $\mathcal{X}$  UC-realizes the ideal zero-knowledge functionality with quasi-polynomial overhead, in the UC framework. However, for ease of understanding for those not intimately familiar with the UC framework, we describe Sim here informally. This is easily converted to a formal description in the UC framework (which we do in [Section 6](#)).

<sup>19</sup>We note that by some slight complication to the protocol, it is possible to have the simulator follow the honest strategy also in this step.

<sup>20</sup>We need [Lemma 4.2](#) to prove [Lemma 4.1](#).

Size and time of adversary, number of sessions.	$T_0$
Value of $M$ in definition of statement <b>[KOLM]</b> .	$T_{0.1}$
Distinguishing advantage between VSim and Sim, between Sim and real execution.	$\frac{1}{T_{0.5}}$
Probability of simulation soundness failure in VSim, Sim.	$\frac{1}{T_{0.6}}$
Strength of commitment to verification key $VK$ ( $c_{VK}$ ).	$T_1$
Running time of VSim verifier (VHV).	$T_{1.1}$
Running time of VSim prover (VHP) in Case 3: win = 'UA'.	$T_{1.5}$
Security of $B_{\text{easy}}$ .	$T_2$
Running time of VSim prover (VHP) in Case 2: win = 'SIG'.	$T_{2.5}$
Security of $B_{\text{hard}}$ .	$T_3$
Running time of Sim prover algorithm.	$T_{3.5}$
Running time of VSim prover (VHP) in Case 1: win = 'BFOP'.	
Security of commitment to witness $c_{\text{wit}}$ , commitments to witness and response in WBC protocol.	$T_4$
Running time of Sim verifier (time to extract witness).	$T_{4.1}$
Security of all other commitments in protocol.	$T_5$
Indistinguishability of WI and ZK protocol used.	
Soundness and knowledge soundness of all proof system used.	$T_6$
Strength of hash function and signature scheme.	

Table 1: Complexity levels and quantities used in the protocol and proof (up to polynomial factors).



## 5 The Virtual Simulator VSim.

To prove [Lemma 4.2](#) we will construct a “virtual simulator”, denoted by VSim. This will not be a “real” simulator in the sense that, unlike Sim, VSim will get as an additional input all the honest parties’ private inputs (and hence in particular it will have access to all the witnesses used by these parties when proving)<sup>21</sup>. Nevertheless this simulator will be useful to prove [Lemma 4.2](#) since we’ll prove that **(a)** the virtual simulator’s output is computationally indistinguishable from the output of the real simulator even by  $\text{poly}(T_5)$ -sized distinguishers, and **(b)** for the virtual simulator, the probability that the “bad” event of [Lemma 4.2](#) (namely the event that in an honest verifier’s session there is an accepted proof for a new theorem without a commitment to the witness) only happens with roughly  $1/T_{0.6}$  probability. Since this event is observable in time  $T_{4.1} \ll T_5$  this would imply [Lemma 4.2](#).<sup>22</sup>

The following observation will be very useful for us: it is enough to provide such a simulator for the case that there are some  $m (\leq T_0(k))$  honest provers interacting with the adversary and only *one* honest verifier, with no other interaction going on. This is shown in detail in [Section 6](#).

**Organization of this section.** We start by describing the virtual simulator VSim in [Section 5.1](#). After we describe VSim we will prove that it satisfies the following three properties:

**Completeness:** ([Section 5.2](#)) The probability that VSim fails to simulate and aborts the computation is  $\ll 1/T_{0.6}$ .

**Strong indistinguishability:** ([Section 5.3](#)) The output of VSim is  $(T_5, 1/T_0)$ -indistinguishable from the output of the “real” simulator Sim.

**Simulation soundness:** ([Section 5.4](#)) The probability that in the transcript outputted by VSim, in the session where the adversary interacts with the honest verifier the verifier accepts a statement  $x$  but yet  $c_{\text{wit}}$  does *not* contain a commitment to a witness for  $x$  is  $\ll 1/T_{0.6}$ .

### 5.1 Description of the Virtual Simulator VSim

Similarly to Sim, the simulator VSim will be composed of  $m + 1$  separate interactive strategies for simulating the  $m$  honest provers and the honest verifier, where we denote these strategies by  $\text{VHP}_1, \dots, \text{VHP}_m$  and VHV. However, these strategies will not be completely independent, and will use some global variables as means of coordination. We assume that the execution happens in discrete time, where at time  $t$  the adversary adaptively decides in which session it wants to send its next message. The virtual simulator’s strategy is sketched in [Figure 1](#) ([Page 25](#)) although this figure would probably be easier to parse after at least skimming through the following subsections.<sup>23</sup>

<sup>21</sup> In the language of the UC framework, the environment  $\mathcal{Z}$  will provide witnesses for honest prover sessions to VSim.

<sup>22</sup> Note that this means that the virtual simulator can *not* commit to a real witness in the  $c_{\text{wit}}$  commitment in the view it outputs. Nor can it depart from the relaying strategy for its outer prover.

<sup>23</sup> For the benefit of the reader who is not intimately familiar with the UC framework, we present VSim in an intuitive manner here, not referring to the environment  $\mathcal{Z}$  and ideal process. However, we will make use of VSim inside a hybrid experiment within the UC framework in [Section 6](#). This will be done in a way that is obvious given our description of VSim.

Honest Prover Sessions			Honest Verifier Session	Size of $v\mathcal{S}$
Case 1: safe BFOP VHP <sub>1</sub> Adv	Case 2: unsafe BFOP $VK = VK'$ VHP <sub>2</sub> Adv	Case 3: unsafe BFOP $VK \neq VK'$ VHP <sub>3</sub> Adv	Adv	VHV
Break $B_{\text{hard}}$ :			$h \leftarrow_{\text{R}} \text{Hash}_5$	
			$c'_{\text{VK}} = \text{Com}_1(VK')$	
			(VSim learns $VK'$ )	
$\leftarrow \text{OWF}_3(r)$			VHV Slot 1:	
$\xrightarrow{(*)\text{Com}_5(r)}$		Slot 1 $\uparrow$	$r'_1 \leftarrow_{\text{R}} \{0, 1\}^{\ell'_1}$	
...			$\leftarrow c'_{r_1} = \text{UAKCom}_5^h(r'_1)$	
$OR^\dagger$	Break $B_{\text{easy}} \cdot \ddagger$	Don't break BFOP	Unsafe Period:	
	$\leftarrow \text{OWF}_2(r)$		safe = false	
	$\xrightarrow{(*)\text{Com}_5(r)}$		$B_{\text{easy}} = \text{BFOP}_2;$	
	...		$B_{\text{hard}} = \text{BFOP}_3;$	
			safe = true	
$\leftarrow \text{OWF}_3(r)$		Slot 2 $\downarrow$	VHV Slot 2:	
$\xrightarrow{(*)\text{Com}_5(r)}$			$r'_2 \leftarrow_{\text{R}} \{0, 1\}^{\ell'_2}$	
...		$\forall j$ construct $\Pi_1^j$ or $\Pi_2^j$	$\leftarrow c'_{r_2} = \text{UAKCom}_5^h(r'_2)$	
			$\xrightarrow{c'_{\text{sig}} = \text{Com}_5(\sigma')}$	
			$\xrightarrow{\text{Com}_5\text{UA}_6 \text{ of } [\mathbf{KOLM}]}$	
			$\xrightarrow{c'_{\text{wit}} = \text{Com}_4(w)}$	
			WIP	
win = 'BFOP' $\sim T_{3.5}$ steps	win = 'SIG' $\sim T_{2.5}$ steps	win = 'UA' $\sim T_{1.5}$ steps		
			$\sim T_{1.1}$ steps	

$\dagger$ In Case 1, the message (\*) of  $B_{\text{hard}}$  is scheduled either before or after the unsafe period

$\ddagger$ Note that by the time this point is reached, VSim already knows whether or not  $VK = VK'$ .

Figure 1: Operation of the virtual simulator VSim

### 5.1.1 Notations, inputs and global variables.

**Notation.** Since there is only one session in which the adversary interacts with the honest verifier, we will call this session the *honest verifier session*. Also, we will typically use primes to denote the messages sent in this session (e.g., use  $c'_{\text{wit}}$  for the commitment to the witness in this session). Whenever a computation of a particular step by the simulator uses super-polynomial time or memory, we will explicitly note the resources taken in square brackets.

**Inputs.** VSim uses the following inputs (whose total size is bounded by  $(T_0)^2$ ).

- The adversary’s code<sup>24</sup> Adv.
- All private and public inputs used by *all* the honest parties in the protocol<sup>25</sup>.

**Global Variables.** VSim will use the following global variables:

- $t$  - will always store the current time.
- $(VK, SK)$  - initialized to be a verification and signing key pair chosen using the signature key-generating algorithm.
- $VK'$  - represents the verification key that the adversary uses in the honest verifier session. It is initially empty.
- $vS$  - the current internal state of the simulated honest verifier VHV. In addition, VSim maintains the *history* of all updates to this string. Thus, we will use the notation  $vS[t]$  to denote the contents of  $vS$  just after the step of time  $t$ .

**Note:** When the verifier uses fresh randomness to compute its message at time  $t$ , this randomness is only added to the string  $vS$  at time  $t$ , and not before that. Also, we only add to  $vS$  the *internal* state of the verifier. Hence, if the verifier is running a public-coin sub-protocol (in which it is stateless) then we do not add anything to  $vS$  during this sub-protocol.

- **safe** - a Boolean flag, initially set to **true**. Intuitively, this flag tells the simulated honest provers when it is safe to break the  $B_{\text{hard}}$  challenge.
- **in-trans** - the transcript of the *inner prover* messages. That is, all the messages sent by the inner provers during the protocol (essentially containing aside from the public transcript the plain-texts  $m$  of the last messages in the various WI/ZK subproofs). The virtual simulator’s goal is that **in-trans** will be  $(T_5, 1/T_{0.6})$ -indistinguishable from the corresponding “inner transcript” of Sim. Of all the global variables, only **in-trans** will be modified by the simulated prover.

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<sup>24</sup> In the UC framework, this would include the code of the environment  $\mathcal{Z}$  and the code of the adversary  $\mathcal{A}$ , as well as the code of any other aspects of the simulation outside of what VSim does.

<sup>25</sup> In the UC framework, these would be provided by the environment  $\mathcal{Z}$ .

**The witness-assisted continuation procedure Cont.** We denote the *residual strategy* of a simulated honest prover  $VHP_i$  at time  $t$  by  $VHP_{i,t}$ . We will have a  $\text{poly}(k)$ -time procedure called **Cont** which will take a number  $i \in [m]$  which identifies a simulated honest prover  $VHP_i$  and a time  $t$ . It will then return a *different* residual prover strategy  $VHP_{i,t}$ . This residual prover strategy will be a  $\text{poly}(k)$ -time interactive algorithm which we'll later prove to be  $(T_4, 1/T_{0.6})$  indistinguishable from the “real” simulated prover residual strategy  $VHP_{i,t}$ . We describe the procedure **Cont** in [Section 5.1.4](#).

### 5.1.2 Simulation of Honest Verifier VHV.

We denote the “virtual honest verifier” algorithm used by **VSim** by **VHV**. We describe its operation by describing where it departs from the strategy used by the actual honest verifier.

- In all steps the verifier will add its internal state to the global variable  $vS$  as it proceeds. However, we note that in most parts of the proof, the verifier is *stateless* and hence has no internal state. The only place where it will need to maintain internal state is when executing the two instances of **UAKCom**. We will explicitly describe below the data that the verifier is recording and deleting during these steps. **Important Note:** we assume that **VHV** does *not* choose all its random tape in advance, but selects the randomness required to compute a particular message when needed. Thus, the state variable  $vS$  at time  $t$  does *not* contain the randomness that will be used by **VHV** at time  $t' > t$ .
- After adversary commits to  $VK'$  (Step P1.2), the verifier breaks this commitment using  $T_{1.1}$  time and records  $VK'$ . [Time needed for this step:  $T_{1.1}$ , Memory needed:  $\text{poly}(k)$ ]
- If  $VK' \neq VK$ , the verifier lets  $j_0$  be the first index such that  $VK'_{j_0} \neq VK_{j_0}$ . Otherwise it lets  $j_0 = 1$ . It lets  $\ell'(j_0) = VK'_{j_0} \cdot \ell_{VK} + j_0$  and lets  $\ell'_1 = \ell'(j_0) \cdot M$  and  $\ell'_2 = (4\ell_{VK} + 1 - \ell'(j_0)) \cdot M$ . Note that  $\ell'_1$  and  $\ell'_2$  can be computed from the global variables  $VK$  and  $VK'$ , and hence we may assume that they are global variables as well. Recall that  $M = 2T_{0.1}$ .
- When entering into Steps V,P2.x (the **UAKCom** of  $r_1$ ) the verifier will choose  $r'_1$  as a random string in  $\{0,1\}^{\ell'_1}$ . It will record  $r'_1$  in  $vS$  (note that  $|r'_1| = \ell'_1$ ). It will also record the (polynomial-sized) randomness used in computing the proof. At the end of the proof the verifier will *remove* the string  $r'_1$  from  $vS$ . [Time required for this step:  $\text{poly}(T_0)$ , Memory required during the computation of step:  $\ell'_1 + \text{poly}(k)$ ]
- At the start of Steps P,V3.x (breaking opportunity), **VHV** will set the **safe** global variable to **false**. At the end of these steps it will set this variable back to **true**.
- The verifier will also perform the analogous computation in Steps V,P4.x, choosing  $r'_2$  at random from  $\{0,1\}^{\ell'_2}$ . [Time required for this step:  $\text{poly}(T_0)$ , Memory required during the computation of step:  $\ell'_2 + \text{poly}(k)$ ]

**Note:** The only times  $vS$  will contain a super-polynomial sized string will be during the computation of these two steps. See [Figure 1](#) for a graphic depiction of the verifier’s operation and the size of  $vS$ .

### 5.1.3 Simulation of the honest prover VHP

We now describe the operation of the simulated honest prover  $VHP_i$ . Note that, apart from using the global variables,  $VHP_i$  is a straight-line interactive algorithm. As before, we only describe the ways in which  $VHP_i$  deviates from the honest prover strategy. **Important note:** Like  $\text{Sim}$ ,  $VHP_i$  will use the relaying outer prover strategy. Thus, when describing the simulated strategy, we only describe the strategy for the *inner prover*. Because the outer prover strategies of both  $\text{VSim}$  and  $\text{Sim}$  are identical, later it will be sufficient to prove this strategy is  $(T_5, 1/T_{0.6})$  indistinguishable from the simulated inner strategy. Whenever, computing an output message of the inner strategy,  $VHP_i$  will add that message to the in-trans global variable.

- The prover has an internal variable `win` which can take a value in  $\{\text{'none'}, \text{'BFOP'}, \text{'SIG'}, \text{'UA'}\}$ . Initially it is set to `'none'`. Intuitively, this variable tells the simulated prover in which way it can “win” the session and convince the verifier in the final WI proof.
- The prover computes a signature  $\sigma$  on the statement proven in this session using the signing key  $SK$ .
- When the prover obtains the first message of the  $\text{UAKCom}_5^h(r_1)$  of Steps V,P2.x (i.e., the commitment  $c_{r_1} = \text{Com}_5(h(r_1))$ ) it lets  $t_1$  store the current time.
- When the prover obtains the first “challenge” message of the breaking opportunity in Steps V,P3.x, it checks whether the global `safe` flag is set to `true`. If so, then it breaks the  $B_{\text{hard}}$  challenge [using  $T_{3.5}$  steps] and sets `win` = `BFOP`. Note this is depicted as Case 1 in [Figure 1](#). Otherwise, we must already be finished with Slot 1 and in particular with  $\text{KCom}_5(VK')$  in the honest verifier session. Therefore, the variable  $VK'$  is already set. If  $VK' = VK$  then the prover breaks  $B_{\text{easy}}$  and sets `win` = `'SIG'` [using  $T_{2.1}$  steps]. Note that this is Case 2 of [Figure 1](#). In both cases the prover now has information which will allow it to successfully run the WI proof of Steps P,V7.2.x.
- When the prover obtains the first message of the  $\text{UAKCom}_5^h(r_2)$  of Steps V,P4.x (i.e., the commitment  $c_{r_2} = \text{Com}_5(h(r_2))$ ) it lets  $t_2$  store the current time.
- When the simulated prover gets to the start of the “committed” universal argument (Steps P,V6.x), if `win`  $\neq$  `'none'` then it just uses “junk” commitments in this part. It then uses its `win` strategy to continue and finish the WI proof. If `win` = `'none'` then the simulated prover does the following: (note that in this case we are in Case 3 of [Figure 1](#))
  1. For  $s = 1, 2$  do the following:
    - (a) The prover obtains for each  $j \in [m] \setminus \{i\}$ ,  $\tilde{\text{VHP}}_{j,t_s} = \text{Cont}(j, t_s)$ . Note that all of these are polynomial-time and polynomial-size algorithms. Thus, the advice needed for all of them together is less than  $m \cdot \text{poly}(k) \leq (T_0)^2$ . Note that the procedure `Cont` is described below.
    - (b) It then uses  $vS[t_s]$  to obtain the residual VHV algorithm at time  $t_s$ . Note that the residual verifier’s running time is bounded by  $\text{poly}(T_{1.1})$  and its description is bounded by  $\ell'_s + \text{poly}(k)$ .
    - (c) Note that the advice needed to describe these residual algorithms is bounded by  $\ell'_s + o(T_{0.1})$ .

- (d) It combines all the algorithms described in (a) and (b) above with the adversary’s algorithm to obtain a stand-alone prover algorithm  $P_*$  for the universal argument of knowledge of slot  $s$ .<sup>26</sup>
  - (e) It lets  $\tilde{\Pi}_s$  be the probabilistic program that on the empty input does the following:
    - Let  $\mu = 1/(T_{0.6})^3$ .
    - Use the knowledge extractor of the universal argument to obtain from  $P_*$  the string  $r^*$  that is compatible with the hash given at the start of the universal argument, with probability  $1-\mu$ , assuming that the probability that  $P_*$  convinces the universal argument verifier is at least  $\mu$ .
  - (f) Note that  $\tilde{\Pi}_s$  can be described with  $\ell'_s + O(T_{0.1})$  bits and its running time is  $\text{poly}(1/\mu) \cdot (m \cdot \text{poly}(k) + \text{poly}(T_{1.1})) \ll T_{1.2}$ .
  - (g) Let  $\Pi_s$  be the *deterministic* program that is obtained by derandomizing  $\tilde{\Pi}_s$  using a pseudorandom generator for size  $T_{1.2}$ , going over all options for the pseudorandom generator’s seed, outputting  $r_s$  and  $v$  such that  $\text{Com}(h(r_s); v) = c_{r_s}$  if such strings are found. Under our assumption there exists such a generator with seed size  $< \log(T_{1.3}(k))$ . Hence that  $\Pi_s$  has the same description size as  $\tilde{\Pi}$  and its running time is  $\text{poly}(T_{1.3})$  steps.
  - (h) If  $\Pi_s$  does *not* output such a witness on the empty string then abort the simulation and output **ext-failure**.
2. For every  $j \in [\ell_{\text{vk}}]$ , because  $\langle j_0, VK'_{j_0} \rangle \neq \langle j, VK_j \rangle$ , there is an  $s \in \{1, 2\}$  such that  $\ell'_s \leq \ell_j^s - M$ . Thus, we can use  $\Pi_s$  (whose size is  $\ell'_s + o(M)$ ) as a witness to run the universal argument. Note that running the universal argument on a statement verifiable in time  $\text{poly}(T_{1.3})$  will take us time  $\ll T_{1.4}$ .
  3. After the universal argument is finished it sets **win** = ‘UA’ and continues with the simulation.
- By the time we get to the WIP of Steps P,V7.2.x, **win** is already different from ‘none’ and prover has information that allows to finish successfully this step.

#### 5.1.4 Description of Cont.

The procedure **Cont** takes as input a number  $i \in [m]$  which identifies a simulated honest prover  $\text{VHP}_i$  and a time  $t$ . It retrieves from the common inputs and global variables the inner transcript up to the point  $t$ , and the witness  $w$  for the statement proved by  $\text{VHP}_i$ . It then returns a  $\text{poly}(k)$ -time residual prover strategy  $\tilde{\text{VHP}}_{i,t}$ . This residual prover strategy is a true interactive algorithm in the sense that it will not access any of the global variables and only use what is hardwired into it. The procedure **Cont** runs in  $\text{poly}(k)$ -time. We’ll later prove that  $\tilde{\text{VHP}}_{i,t}$  is  $(T_4, 1/T_{0.6})$  indistinguishable from the “real” simulated prover residual strategy  $\text{VHP}_{i,t}$  *even if the distinguisher gets access to the contents of all global variables at time  $t$  as an additional input*.

**Operation of Cont.** To describe the operation of **Cont**, we can simply describe the residual strategy  $\tilde{\text{VHP}}_{i,t}$ . The residual strategy will be basically to use the *witness-based outer prover*

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<sup>26</sup>The crucial point here is that none of these algorithm utilize the internal coins that  $\text{VHP}_i$  uses during the execution of the UA of slot  $s$ , in the session where  $\text{VHP}_i$  plays the role of the *verifier*.

*strategy.* That is, it will get as input the inner transcript of the  $i^{\text{th}}$  session up to point  $t$  and the witness for the statement proven in that session. Given the WBC-compiler we use, it is quite obvious what  $\tilde{\text{VHP}}_{i,t}$  will do: continue from this point using only “junk” commitments for commitment type messages, use the honest strategy for verification messages (which are stateless, and so can be computed from the public transcript.), and use the witness instead of the actual message to facilitate the WI proof.

## 5.2 Completeness of VSim

Recall that as we described VSim, there is a possibility that it will abort the computation and output `ext-failure`.<sup>27</sup> In this section we argue that this event only happens with negligible probability.

**Lemma 5.1** (VSim is complete). *The probability that VSim outputs `ext-failure` is at most  $1/T_{0.6}$ .*

*Proof.* The intuition behind this lemma is as follows: the only way that VSim outputs `ext-failure` is if it fails to extract  $r_1$  or  $r_2$  from a universal argument given to it by the adversary in some honest-prover session. Now, the only reason why the proof of knowledge of the universal argument doesn’t immediately imply that this won’t happen is that for the purposes of extraction VSim uses the witness-based strategy of the WBC compiler. However, because the success of the proof is a polynomial-time (and so in particular a  $T_4$ -time) observable event, the stand-alone prover constructed using witness-based continuation will have essentially the same success probability as the prover obtained from the actual VSim simulation, and hence this witness-based prover can be used just as well to extract  $r_1$  or  $r_2$ . We now proceed with the formal proof.

Suppose, for the sake of contradiction, that VSim outputs `ext-failure` with probability at least  $1/T_{0.6}$ . Now, as mentioned above, the only places where VSim may abort is in the extraction of the verifier’s challenges  $r_1$  and  $r_2$  by one of the  $\text{VHP}_i$ ’s.

Let us order all the UAKCom’s done in the honest prover sessions by the timing of the *last* message in that sub-protocol. Under our assumption, there exists  $i \in [m]$  and  $s \in \{1, 2\}$  such that with probability at least  $1/(T_0 \cdot T_{0.6}) \geq 1/(T_{0.6})^2$  the extraction of  $r_s$  in the  $i^{\text{th}}$  session is the *first* extraction that fails in the simulation (i.e., the universal argument ends successfully when simulating it for the first time, but extraction from it fails). This implies that there exists a prefix  $\pi$  of the simulation up until the time the universal argument of the Slot  $s$  in the  $i^{\text{th}}$  session starts, such that if we continue the simulation from the prefix  $\pi$  then with probability at least  $1/(T_{0.6})^2$  the following will hold simultaneously:

1. The virtual simulator will *not* output `ext-failure` before the last message of this proof is sent.
2. The universal argument will finish successfully.
3. The virtual simulator will output `ext-failure` because of extraction failure in this universal argument.

( $\pi$  contains both the transcript up to that point and the internal state of all parties up to that point.)

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<sup>27</sup>We note that the simulator does not abort in the case that a session ends because of the adversary’s “fault” (i.e., the adversary fails to successfully complete some sub-protocol). In this case, the simulator simply outputs the partial transcript of the session.



Indeed, let  $\mathbf{H}_A$  denote the transcript of the simulation starting from  $\pi$  until the point that universal argument ends. Now let  $\mathbf{H}_B$  denote this transcript where in all the cases the WBC compiler is used by the simulated honest provers, we use a commitment to the witness of the statement proven, instead of to a junk string. Note that both  $\mathbf{H}_A$  and  $\mathbf{H}_B$  are generated using  $\ll T_4$  time and hence  $\mathbf{H}_A$  and  $\mathbf{H}_B$  are  $T_4$ -indistinguishable.

Now, we let  $\mathbf{H}_C$  denote the transcript where whenever some virtual honest prover sends as part of the WBC compiler  $\text{Com}_4(w)\text{Com}_4(m)$ , it uses the first option (proving that  $w$  is a witness) rather than the second option (proving that  $m$  is valid) in the WI system.<sup>28</sup> Clearly  $\mathbf{H}_B$  and  $\mathbf{H}_C$  are  $T_4$ -indistinguishable by the WI property.

We now define  $\mathbf{H}_D$  to be the hybrid where *all* commitments of type  $\text{Com}_4(m)$  sent by the virtual honest provers are commitments to “junk”. Since we no longer use the coins used in generating these commitments,  $\mathbf{H}_D$  is  $T_4$ -indistinguishable from  $\mathbf{H}_C$ .<sup>29</sup>

Now, by  $T_4$  indistinguishability, we claim that with probability at least  $1/(T_{0.6})^2 - 1/T_4 \geq 1/2(T_{0.6})^2$  the following will hold simultaneously in  $\mathbf{H}_D$ :

- The virtual simulator will *not* output `ext-failure` before the last message of this proof is sent.
- The universal argument will finish successfully.

However, the only difference between  $\mathbf{H}_D$  and the transcript of a simulation where all virtual honest provers use a witness-based continuation is that in a witness-based continuation we never output `ext-failure`. Therefore, also in the latter case the universal argument will finish successfully with probability at least  $1/2(T_{0.6})^2$ . Now consider the prover algorithm  $P_*$  for the universal argument of this session that the virtual simulator obtains by combining all the witness based continuations from  $\pi$  and the residual honest verifier continued from  $\pi$ . This means that  $P_*$  will convince the verifier to accept with probability at least  $1/2(T_{0.6})^2 \geq 1/(T_{0.6})^3$  and hence starting from  $\pi$ , the knowledge extractor will obtain a witness from this prover with probability at least  $1 - (T_{0.6})^3$ , and hence will output `ext-failure` with probability less than  $1/2(T_{0.6})^2$ , contradicting Property 3 of the prefix  $\pi$  as stated above. □

### 5.3 $T_5$ -Indistinguishability of VSim

In this section, we will argue that the simulations produced by `Sim` and `VSim` are  $(T_5, 1/T_{0.5})$ -indistinguishable<sup>30</sup>. Note that it will be important to have indistinguishability against adversaries that are much stronger than  $T_4$ , because we will need to argue that even an adversary that can break the commitment  $c_{\text{wit}} = \text{Com}_4(w)$ , where  $w$  is the witness, cannot distinguish between simulations. We will use this fact later to argue that simulation-soundness for `VSim` implies simulation-soundness for `Sim`.

The indistinguishability argument will be through a series of hybrids. These hybrids will employ rewinding strategies; this means we will take care to ensure problems of efficiency in concurrent

<sup>28</sup>Note that  $m$  is always valid in the simulation, since if the simulator can't come up with a valid  $m$  it simply outputs `ext-failure` and does not go through with the WBC compiler.

<sup>29</sup>Actually later commitments may depend on the coins used by the earlier commitments. Thus, to move from  $\mathbf{H}_C$  to  $\mathbf{H}_D$  we change these commitments to junk one by one, starting from the last commitment sent.

<sup>30</sup>Again, the proof in this section can easily be translated to the language of the UC framework.



simulation do not arise.<sup>31</sup> Our overall strategy is to use zero-knowledge simulation only as an intermediary between straight-line simulation hybrids, so that the rewinding deals with only a single protocol execution. In this way, our hybrid simulators will never need to deal with the interaction between rewinding the adversary in one session and the rewinding of the adversary in another session. We call this the *technique of intermediate rewinding hybrids*.

**Lemma 5.2** ( $T_5$ -indistinguishability of VSim and Sim). *The outputs of Sim and VSim are  $(T_5, 1/T_{0.5})$ -indistinguishable.*

*Proof.* Recall that in our setting, the adversary is only involved in a single session in which the adversary plays the role of Prover, and the simulator plays the role of Verifier. All other history and state information is given as nonuniform advice to the adversary.

We will maintain the invariant that all our hybrids will run in time polynomial in  $T_{4.5}$ , which is sufficient time to break  $B_{\text{hard}}$  and extract the witness from the single session in which the adversary plays the role of the prover. Therefore, for sake of arguing indistinguishability, if these hybrids are used as subroutines within a  $\text{poly}(T_5)$  procedure, this would yield another  $\text{poly}(T_5)$  procedure.

We note that because we need indistinguishability against strong adversaries, what we'll prove is the  $(T_5, 1/T_{0.5})$  indistinguishability of the *inner* transcripts, which makes sense, since the outer prover strategy of VSim and Sim is identical (namely, the relaying strategy).

The inputs to all hybrids will be the same as the inputs to VSim. Let  $\mathbf{H}_A = \text{Sim}$ .

Let  $m < T_0$  be the maximum number of sessions in which the adversary plays the role of Verifier and the simulator plays the role of Prover.

### 5.3.1 Moving to simulation of VHV.

**Using long  $r_1$  and  $r_2$ .** The only difference between the simulations of the honest verifier in VSim and Sim is that in VSim, the simulated honest verifier uses the UAKCom protocol to commit to random strings of super-polynomial length.

So we define a hybrid  $\mathbf{H}_{B/1}$  that is identical to  $\mathbf{H}_A$  except that the simulator uses the (rewinding/non-BB) ZK simulator for the ZK Universal Argument of Knowledge for  $r_1$ . The  $(T_5, 1/T_5)$ -indistinguishability of  $\mathbf{H}_A$  from  $\mathbf{H}_B$  follows from the ZK property as follows: We construct a  $T_5$ -time verifier  $V'$  to play the role of a verifier in the stand-alone ZK Universal Argument of Knowledge. This verifier  $V'$  internally runs the  $\mathbf{H}_A$  simulation of all parties except for the prover's role in the ZK Universal Argument of Knowledge (recall that the simulated verifier plays the prover in this argument). It is crucial to note that this simulation does not need to record the internal state of the simulated verifier during this argument to carry out the rest of the simulation. Therefore  $V'$  is independent of the internal state of the prover in the universal argument, and so a valid stand-alone verifier. Hence, if there were a  $T_5^{O(1)}$ -time distinguisher for  $\mathbf{H}_B$  and  $\mathbf{H}_A$ , it would yield a  $T_5^{O(1)}$ -time distinguisher for the ZK property of the universal argument with the same distinguishing probability.

Similarly, we may define a hybrid  $\mathbf{H}_C$  that is identical to  $\mathbf{H}_B$  except that the simulator uses the ZK simulator for the ZK Universal Argument of Knowledge for  $r_2$ . Note that the ZK simulation for  $r_2$  is disjoint from the simulation for  $r_1$ . The  $(T_5, 1/T_5)$ -indistinguishability of  $\mathbf{H}_C$  and  $\mathbf{H}_B$  follows from an identical argument to the above.

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<sup>31</sup>Actually, we will use non-black-box simulation instead of rewinding-based simulation, because we use the protocol of [BAR01]. However, once the code of the adversary is given to the simulator, non-black-simulation is only easier than rewinding, and thus the intuitions we have on when rewinding work still hold.

Then we define hybrid  $\mathbf{H}_D$  that is identical to  $\mathbf{H}_C$  except that the simulator commits using  $\text{Com}_5$  to the hash under  $h$  of random strings  $r_1$  and  $r_2$  of length  $\ell_{j_0}^1$  and  $\ell_{j_0}^2$  respectively, where these lengths are defined according to the rules of  $\text{VSim}$ . Note that the lengths of these strings are still polynomial in  $T_{0,1}$ , and therefore the overall running time of the hybrid simulator is still polynomial in  $T_5$ . Therefore the indistinguishability of  $\text{Com}_5$  implies the  $(T_5, 1/T_5)$ -indistinguishability of  $\mathbf{H}_D$  and  $\mathbf{H}_C$ .

We define hybrid  $\mathbf{H}_E$  that is identical to  $\mathbf{H}_D$  except that the simulator uses the honest prover strategy to prove knowledge of  $r_1$  and  $r_2$  in the  $\text{UAKCom}$  protocol. Again the  $(T_5, 1/T_5)$ -indistinguishability of  $\mathbf{H}_E$  and  $\mathbf{H}_D$  follows from the ZK property of the Universal Argument, by the argument given above for the indistinguishability of  $\mathbf{H}_A$  and  $\mathbf{H}_B$ . We note that hybrid  $\mathbf{H}_E$  is now a straight-line simulation.

This technique of intermediate rewinding hybrids is one that we will use repeatedly. In the sequel, we will not explicitly go through all these hybrids, but go immediately to the end result.

### 5.3.2 Moving to simulation of VHP

**Committing to valid signatures.** We define hybrid  $\mathbf{H}_F$  to be identical to  $\mathbf{H}_E$ , except that all sessions set  $c_{\text{sig}}$  to be a commitment using  $\text{Com}_4$  to  $\sigma_i$ , which is a signature using signing key  $SK$  to the theorem  $x_i$  being proved in the  $i$ 'th session. By the security of the commitment scheme  $\text{Com}_5$ , it follows that hybrid  $\mathbf{H}_F$  is  $(T_5, 1/T_5)$ -indistinguishable from  $\mathbf{H}_E$ . Note also that  $\mathbf{H}_F$  is a straight-line simulation.

**Breaking  $B_{\text{easy}}$  when needed.** Recall that  $\text{VSim}$ , for certain sessions, breaks  $B_{\text{easy}}$ . We define hybrid  $\mathbf{H}_G$  to be identical to  $\mathbf{H}_F$  except that in certain sessions,  $B_{\text{easy}}$  is broken, according to the same criteria used by  $\text{VSim}$ . Again using the technique of intermediate rewinding hybrids above, we obtain that hybrid  $\mathbf{H}_G$  is  $(T_5, 1/T_5)$ -indistinguishable from  $\mathbf{H}_F$ . The crucial observation that is needed to make this work is that no other party has access to the internal state a virtual prover  $\text{VHP}_i$  uses during the execution of the zero-knowledge argument of  $B_{\text{easy}}$ .

**Satisfying ‘UA’ when needed.** We define hybrid  $\mathbf{H}_H$  to be identical to  $\mathbf{H}_G$  except that it follows the strategy given in the description of  $\text{VSim}$  to decide for which sessions to commit to a valid universal argument for the statement ‘UA’. [Lemma 4.2](#) shows that with probability at least  $1 - (1/T_{0,6})$ , and in time  $\text{poly}(T_{1,5})$ , the hybrid simulator can produce a valid universal argument for the ‘UA’ condition (otherwise it outputs `ext-failure` in which case  $\mathbf{H}_H$  halts). This procedure uses rewinding, but it will be very important to us later that the rewinded sessions are simulated using witness-based continuation. Note that since every message of the committed Universal Argument is committed using  $\text{Com}_5$ , we obtain the  $(T_5, 1/T_{0,5})$ -indistinguishability of hybrids  $\mathbf{H}_H$  and  $\mathbf{H}_G$ .

**Using other success conditions in WIP.** We are almost ready to compare our hybrid with  $\text{VSim}$ . Now the only difference between hybrid  $\mathbf{H}_H$  and  $\text{VSim}$  is that  $\mathbf{H}_H$  still always breaks  $B_{\text{hard}}$  and uses the ‘BFOP’ condition to complete the final Witness-Indistinguishable Proof (WIP), whereas  $\text{VSim}$  sometimes does not break  $B_{\text{hard}}$  and it uses multiple conditions in the WIP. Note however that these same conditions are true in hybrid  $\mathbf{H}_H$ , though it just does not use them.

So, we first consider a hybrid  $\mathbf{H}_I$  that is identical to  $\mathbf{H}_H$ , except that in the final WIP, for every session, hybrid  $\mathbf{H}_I$  uses the same conditions for success that  $\text{VSim}$  would. Therefore, by the WI property of the WIP, we have that hybrid  $\mathbf{H}_I$  is  $(T_5, 1/T_5)$ -indistinguishable from  $\mathbf{H}_H$ .

**Eliminating unnecessary breakings of  $B_{\text{hard}}$**  Finally, we construct our final hybrid  $\mathbf{H}_J = \text{VSim}$ , in which  $B_{\text{hard}}$  is not broken in certain sessions, according to the rules of  $\text{VSim}$ . The  $(T_5, 1/T_5)$ -indistinguishability of  $\mathbf{H}_J$  and  $\mathbf{H}_I$  follows using the same arguments (the technique of intermediate rewinding hybrids) used to show the indistinguishability of hybrids  $\mathbf{H}_G$  and  $\mathbf{H}_F$ . Here, when arguing indistinguishability based on ZK, in order to build a stand-alone verifier  $V'$ , we must observe that even though certain  $B_{\text{hard}}$  sessions that need to be modified in this hybrid may overlap with Slot 2, which may need to be “rewound” in order to generate valid Committed Universal Arguments for use in other sessions, this rewinding is done using witness-based continuation, and therefore is independent of the stand-alone prover’s internal state. Note that  $V'$  can incorporate knowledge of  $r_1$  and  $r_2$  and the randomness used to produce Universal Arguments of Knowledge of these strings, because all this information is only  $T_{0.1}^{O(1)}$  in length, and our  $V'$  is a  $T_4$ -size circuit.

Thus, we obtain the result that the outputs of  $\text{Sim}$  and  $\text{VSim}$  are  $(T_5, 1/T_{0.5})$ -indistinguishable.  $\square$

#### 5.4 Simulation-Soundness of $\text{VSim}$

In this section we prove that  $\text{VSim}$  satisfies the simulation-soundness property. Namely, we prove the following lemma:

**Lemma 5.3** (Simulation-soundness of  $\text{VSim}$ ). *The probability that in the transcript output by  $\text{VSim}$  all the following three conditions hold simultaneously:*

1. *The verifier of the honest-verifier session accepts the proof.*
  2. *The statement  $x'$  proven in the honest-verifier session is distinct from all statements proven in the other sessions.*
  3. *None of the  $T_4$ -secure commitment in the interaction contains a witness to the fact that  $x' \in L$ .*
- is less than  $1/T_{0.5}$ .*

We note that [Lemma 5.3](#) also implies that Protocol  $\mathcal{X}$  satisfies the standard (non-simulation) soundness property. This is because standard soundness follows from applying the simulation soundness property to an adversary that ignores everything that happens outside of the honest verifier session.

We prove [Lemma 5.3](#) by proving the following sequence of propositions:

**Proposition 5.4** (**[BFOP]** false in HV session). *The probability that in the transcript output by  $\text{VSim}$  both following conditions hold is at most  $1/T_3$ :*

- *The simulated verifier  $\text{VHV}$  accepts the proof given by the adversary in the honest verifier session.*
- and
- *The condition **[BFOP]** of the honest verifier holds (i.e., if we let  $y$  be the first message and  $\text{Com}(r)$  be the second message of the sub-protocol  $B_{\text{hard}}$  of the honest verifier session, then  $y = \text{OWF}(r)$ )*
- and

- *The witness-based continuation of  $B_{\text{hard}}$  in the honest verifier session does not contain a commitment to a witness.*

*Proof.* Suppose otherwise. Fix a “typical” partial transcript  $\pi$  of the history up to the point the simulated honest verifier VHV sends the first message of  $B_{\text{hard}}$  (i.e.,  $y = \text{OWF}_3(r)$ ) to the prover, such that with at least  $1/T_3$  probability if we continue the simulation from  $\pi$  then all three events mentioned above will occur. We let  $s = s(\pi)$  be all the internal states of all simulated parties until that point. Note that  $|\pi|, |s| \leq \text{poly}(T_0)$ . Now, since during the entire execution of this instance of  $B_{\text{hard}}$ , (i.e., the “unsafe” period) the simulator VSim always uses  $\ll T_{2.6}$  computational steps, we get that there exists a  $T_{2.6}$ -size adversary that with probability  $\geq 1/T_3$  finishes this  $B_{\text{hard}}$  successfully with its second message containing  $\text{Com}(r')$  with  $\text{OWF}(r') = y$  and *without* the commitment in the WBC part containing a witness. This means that conditioning on the event (that happens with at least  $1/T_3$  probability) that the second message contains such a successful commitment, and we still have  $1/T_3$  probability that the proof will finish successfully without containing a witness. This means that with probability at least  $1/T_3$  if we continue the execution up to the point where  $\text{Com}_4(m), \text{Com}_4$  are sent it will be the case that  $m$  is a valid message and there is still  $1/T_3$  probability that the WIPOK of the WBC continuation will finish successfully. In such a case we can extract  $m$  in  $\text{poly}(T_3)$  time, and repeating this entire procedure  $\text{poly}(T_3)$  time we can obtain enough messages  $m$  to extract  $r'$  thus inverting  $\text{OWF}_3$  with  $\text{poly}(T_3)$  time and contradicting its security.  $\square$

**Proposition 5.5** ([SIG] false in HV session: part 1). *The probability that in the transcript output by VSim, it holds that:*

1.  $VK = VK'$
2. *The statement  $x'$  proven in the honest verifier session is distinct from all statements proven in honest provers session.*
3. *The condition [SIG] holds in the honest verifier session (in particular, the commitment  $c'_{\text{sig}}$  contains a valid signature for  $x'$ ).*

*is at most  $1/T_6$ .*

*Proof.* The entire simulation (even considering breaking of BFOP) takes less than  $T_5$  steps, and since breaking  $c'_{\text{wit}}$  takes  $\ll T_6$  steps, if the proposition was false we’d get a  $\ll T_6$ -size forging algorithm for the signature scheme with  $\geq 1/T_6$  success probability.  $\square$

**Proposition 5.6** ([SIG] false in HV session: part 2). *The probability that in the transcript output by VSim, it holds that:*

1.  $VK \neq VK'$
2. *The condition [SIG] holds in the honest verifier session (in particular,  $B_{\text{easy}}$  is broke.).*
3. *The witness-based continuation of  $B_{\text{easy}}$  in the honest verifier session does not contain a commitment to a witness.*

*is at most  $1/T_2$ .*

*Proof.* If  $VK \neq VK'$  then we never break an “unsafe”  $B_{\text{easy}}$  or  $B_{\text{hard}}$ , and never use more than  $T_{0.9}$ -time during the unsafe period. This means that in the same way as in [Proposition 5.4](#),  $B_{\text{easy}}$  cannot be broken in this case.  $\square$

**Proposition 5.7** ([**UA**] false in HV session). *The probability that in the transcript output by VSim the condition [**UA**] holds in the honest verifier session (i.e., the decommitted universal argument transcript is an accepting proof for [**KOLM**]) is at most  $1/T_5$ .*

*Proof.* First note that for the particular  $r'_1$  and  $r'_2$  chosen by the VSim verifier, with very high probability (i.e., at least  $1 - 2^{-k+2}$ ) their Kolmogorov complexity is more than  $\ell'_1 - k$  and  $\ell'_2 - k$  respectively. Now, suppose otherwise that the statement [**UA**] holds with probability at least  $1/T_5$ . Let  $\pi$  be a partial transcript of all simulation up to the point the universal argument starts, and let  $sp = sp(\pi)$  be the internal state of the simulated *honest provers* (and not the verifier) up to this point. We claim that if the probability that [**UA**] holds in a continuation of  $\pi$  is at least  $1/T_5$  then we have a time  $T_{5.5}$  algorithm that with advice  $\pi, sp$  outputs a witness to the statement [**KOLM**]. We do that by simply considering a  $T_{5.5}$ -time standalone prover for the universal argument that with advice  $\pi, sp$  combines all the simulated honest provers and the adversary into one, and breaks the level 5 commitments we use to commit to the universal argument. The reason this adversary does not need to use the honest verifier’s internal state is that the universal argument is a public-coin protocol and hence the honest verifier does not need any internal state to continue it. We then use the knowledge extractor of the universal argument to extract a witness from this standalone prover algorithm.

The witness for [**KOLM**] contains in particular two strings  $\tilde{r}_1$  and  $\tilde{r}_2$  such that for  $s = 1, 2$ ,  $\tilde{r}_s$  is consistent with the commitment  $c'_{r'_s}$  and for every  $j \in [\ell_{\text{VK}}]$ , either the Kolmogorov complexity of  $\tilde{r}_1$  is at most  $\ell_j^1 - k$  or the Kolmogorov complexity of  $\tilde{r}_2 - k$  is at most  $\ell_j^2 - k$ . For  $j = j_0$  (the index chosen by the verifier VSim) we have that because the commitment  $c'_{r'_s}$  is perfectly binding, there is an  $s \in \{1, 2\}$  such that the Kolmogorov complexity of  $\tilde{r}_s$  is at most  $\ell'_s - k$  but  $h(\tilde{r}_s) = h(r'_s)$ , where  $r'_s$  is the string the verifier chose.

However, with probability  $\geq 1 - 2^{-k}$  the Kolmogorov complexity of  $r'_s$ , which was chosen at random in  $\{0, 1\}^{\ell'_s}$  is *larger* than  $\ell'_s - k$ . Hence we get that  $r'_s \neq \tilde{r}_s$  but  $h(r'_s) = h(\tilde{r}_s)$ . Combining this and considering that the simulated honest verifier chooses the hash at random from the collection  $\text{Hash}_6$ , we obtain a  $T_5^{O(1)}$  algorithm for obtaining collisions for  $h$ , contradicting its  $T_6$ -security.  $\square$

**Proposition 5.8** (WIP is sound). *The probability that in the honest verifier’s session the verifier accepts the WIP of Steps P, V7.2.x but the statement proven is false is at most  $2^{-k}$ .*

*Proof.* The WIP is statistically sound against computationally unbounded adversary. The simulator VSim does not rewind the honest verifier at this point, nor does it use the verifier’s internal state at this point. (In fact, because WIP is public-coins, the verifier doesn’t really have an internal state at this point.)  $\square$

It is not hard to verify that [Propositions 5.4, 5.5, 5.6, 5.7](#) and [5.8](#) together imply [Lemma 5.3](#).  $\square$

## 6 Construction of a Concurrently Secure Multi-Party Protocol

In this section, we describe how our protocol and the analysis thereof can be used to build a protocol for secure multi-party computation, with quasi-polynomial simulation. We build upon

the work of [CLOS02]. In [CLOS02], it is shown how to UC-realize any polynomial-time functionality (based on standard hardness assumptions) in the UC framework of [CAN00B], but using a trusted setup assumption. However, this assumption is only used to UC-realize the  $\mathcal{F}_{\text{ZK}}$  functionality. The remainder of the construction does not rely on the trusted setup assumption, and instead builds on the  $\mathcal{F}_{\text{ZK}}$ -hybrid model. The  $\mathcal{F}_{\text{ZK}}$ -hybrid model is a model in which all parties have access to polynomially many ideal zero-knowledge functionalities. Equivalently, one can describe this model as one where all parties have access to a single instance of the ideal functionality  $\hat{\mathcal{F}}_{\text{ZK}}$  for an NP-complete language like SAT;  $\hat{\mathcal{F}}_{\text{ZK}}$  is a multi-session multiple-use version of the ideal zero knowledge functionality. Below, when we refer to the  $\hat{\mathcal{F}}_{\text{ZK}}$ -hybrid model, we refer to the model with common access by all parties to a single instance of the  $\hat{\mathcal{F}}_{\text{ZK}}$  functionality.<sup>32</sup> The session ID we call  $sid$  is sufficient to identify different calls to the functionality.) The  $\hat{\mathcal{F}}_{\text{ZK}}$  functionality is shown in Figure 2 below.

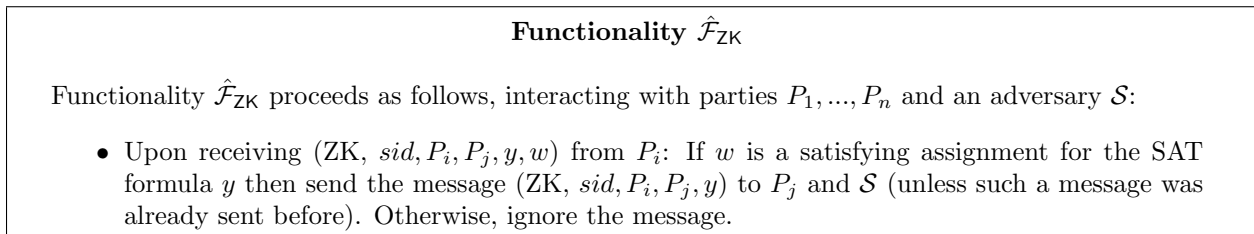


Figure 2: The multiple-use multi-session version of  $\mathcal{F}_{\text{ZK}}$

We first note that the constructions of [CLOS02] can be applied to adversaries and environments that are stronger than polynomial-time simply by growing the security parameter and assuming that the hardness assumptions hold against stronger adversaries. In particular, we will instantiate these protocols to work against  $T_4^{O(1)}$  adversaries. So, we use the following version of the theorem proven by [CLOS02]:

**Theorem 6.1.** [CLOS02] *Assume that (enhanced) trapdoor permutations secure against  $T_5^{O(1)}$ -sized circuits exist. Then, for any well-formed multi-party ideal functionality  $\mathcal{F}$ , there exists a non-trivial protocol that UC-realizes  $\mathcal{F}$  in the  $\hat{\mathcal{F}}_{\text{ZK}}$ -hybrid model in the presence of malicious, static  $T_4^{O(1)}$ -time adversaries and environments (with polynomial simulation overhead).*

Our aim is to show that Protocol  $\mathcal{X}$  UC-realizes the  $\hat{\mathcal{F}}_{\text{ZK}}$  functionality with  $T_{4.5}$  simulation overhead. Combined with Theorem 6.1, this will yield the result we desire. Note that we *do not* need to invoke the UC theorem on the  $\hat{\mathcal{F}}_{\text{ZK}}$  functionality, because only one instance of this functionality is needed.

We note that alternatively, we could show this result in the Angel-based model of [PS04], and thereby obtain a UC theorem for our protocol. But we choose to give a direct analysis that we obtain  $\hat{\mathcal{F}}_{\text{ZK}}$  in order for our analysis to remain as self-contained as possible.

Thus we will show:

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<sup>32</sup>Note that, because we have only a single instance of the  $\hat{\mathcal{F}}_{\text{ZK}}$  functionality, we have done away with the  $ssid$  session ID's that were present in the  $\hat{\mathcal{F}}_{\text{ZK}}$  functionality defined in [CLOS02], which were needed there for technical reasons.

**Theorem 6.2.** *Assume that collision-resistant hash function families secure against subexponential circuits exist. Then Protocol  $\mathcal{X}$  (using as the statement  $x$  to be proven the tuple “ $(ZK, sid, P_i, P_j, y)$ ” taken from the input to the  $\hat{\mathcal{F}}_{ZK}$  functionality) UC-realizes the  $\hat{\mathcal{F}}_{ZK}$  functionality against  $T_0$ -time static adversaries and environments, with  $T_{4.5}$ -time ideal adversaries.*

Combining Theorems 6.1 and 6.2, we obtain:

**Theorem 6.3.** *Assume that there exist collision-resistant hash function families secure against subexponential ( $2^{k^\epsilon}$ -sized for fixed  $\epsilon > 0$ ) circuits exist. And that there exists  $k^{\log^c k}$ -strong (enhanced) trapdoor permutations (where  $c = c(\epsilon)$  is some constant). Let  $T_0(k) = k^{\log k}$  (and hence  $T_i(k) = 2^{\log^{f(i)} k}$  for some function  $f(\cdot)$ ). Then, for any well-formed multi-party ideal functionality  $\mathcal{F}$ , there exists a non-trivial protocol that UC-realizes  $\mathcal{F}$  in the presence of malicious, static  $T_0$ -time adversaries and environments, with  $T_{4.5}^{O(1)}$ -time ideal adversaries.*

We now proceed to the proof of Theorem 6.2.

*Proof.* Let  $\mathcal{A}$  be a malicious static<sup>33</sup> adversary running in time  $T_0$ . We construct an ideal process adversary  $\mathcal{S}$  with access to  $\hat{\mathcal{F}}_{ZK}$ , which simulates a real execution of Protocol  $\mathcal{X}$  with  $\mathcal{A}$  such that no  $T_0$ -time environment  $\mathcal{Z}$  can distinguish the ideal process with  $\mathcal{S}$  and  $\hat{\mathcal{F}}_{ZK}$  from a real execution of Protocol  $\mathcal{X}$  with  $\mathcal{A}$ .

Recall that  $\mathcal{S}$  interacts with the ideal functionality  $\hat{\mathcal{F}}_{ZK}$  and with the environment  $\mathcal{Z}$ . The ideal adversary  $\mathcal{S}$  starts by invoking a copy of  $\mathcal{A}$  and running a simulated interaction of  $\mathcal{A}$  with the environment  $\mathcal{Z}$  and parties running the protocol. (We refer to the interaction of  $\mathcal{S}$  in the ideal process as *external interaction*. The interaction of  $\mathcal{S}$  with the simulated  $\mathcal{A}$  is called *internal interaction*.)

In the next section, we give a description of the simulator  $\mathcal{S}$ .

## 6.1 Description of $\mathcal{S}$

Informally, the simulator  $\mathcal{S}$  proceeds by following the strategy for  $\text{Sim}$  described above – that is, breaking  $B_{\text{hard}}$  when simulating proofs; and breaking the  $\text{Com}_4$  commitments to the witness in order to extract witnesses from adversarially given proofs. We describe this more formally below:

**Initialization** The simulator  $\mathcal{S}$  initially runs the signature scheme key generation algorithm to obtain a pair  $(VK, SK)$ . Note that the simulator  $\mathcal{S}$  will actually never make use of the signing key  $SK$ . This is introduced here only for technical reasons.  $\mathcal{S}$  uses the same set of corrupted parties as  $\mathcal{A}$ .

**Simulating communication with  $\mathcal{Z}$ .** Every input value that  $\mathcal{S}$  receives from  $\mathcal{Z}$  is written on the input tape of  $\mathcal{A}$  (as if coming from  $\mathcal{A}$ 's environment). Likewise, every output value written by  $\mathcal{A}$  on its own output tape is copied to  $\mathcal{S}$ 's output tape (to be read by the environment  $\mathcal{Z}$ ).

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<sup>33</sup>Note that this proof is given for static adversaries, but we later sketch how to extend this analysis to adaptive adversaries.



**Simulating “ZK” activations where the prover is not corrupted.** In the ideal process, when an honest prover  $P_i$  receives an input  $(\text{ZK}, \text{sid}, P_i, P_j, y, w)$  from the environment  $\mathcal{Z}$ , then  $P_i$  writes this message on its outgoing communication tape for  $\hat{\mathcal{F}}_{\text{ZK}}$ . Recall that by convention, the  $(\text{ZK}, \text{sid}, P_i, P_j, y)$  part of this message (i.e. everything but the witness) is public and can be read by  $\mathcal{S}$ . Now, upon seeing that  $P_i$  writes a “ZK” message for  $\hat{\mathcal{F}}_{\text{ZK}}$ , the simulator  $\mathcal{S}$  initiates a simulation (described below) of a real party  $P_i$  interacting with another real (possibly corrupt) party  $P_j$  executing Protocol  $\mathcal{X}$ , with the statement  $x = “(\text{ZK}, \text{sid}, P_i, P_j, y)”$ . We note that if  $P_j$  is not corrupted,  $\mathcal{S}$  simulates the messages of  $P_j$  acting exactly as an honest verifier following Protocol  $\mathcal{X}$ . If  $P_j$  is corrupted, then its messages come from  $\mathcal{A}$ . Note that  $\mathcal{S}$  will only allow delivery of  $P_i$ ’s message in the ideal process to  $\hat{\mathcal{F}}_{\text{ZK}}$ , and the delivery of  $\hat{\mathcal{F}}_{\text{ZK}}$ ’s message to  $P_j$ , if the simulation ends with  $P_j$  accepting the simulated proof.

The simulator follows the honest prover protocol when simulating  $P_i$ , except in the inner protocol, it deviates from the honest prover as follows: **(1)** It computes and sends  $c_{\text{VK}} = \text{Com}_4(\text{VK})$  instead of using  $0^{\ell_{\text{VK}}}$ . **(2)** It acts as the honest prover until it reaches the  $B_{\text{hard}}$  subprotocol. When  $P_i$  receives the challenge  $y = \text{OWF}_3(r)$ , the simulator (running in  $T_{3,5}$ -time) inverts OWF (which we assume to be a permutation) to recover  $r$ . Then  $P_i$  sends  $\text{Com}_5(r)$  to  $P_j$ , and provides a proof of knowledge of  $r$  according to the honest prover strategy in the ZK argument of knowledge for  $B_{\text{hard}}$ . **(3)** The simulator then reverts to an honest simulation of  $P_i$ , until it reaches the commitment to the witness. At this point,  $P_i$  sends  $\text{Com}_4(0^{\ell_{\text{wit}}})$  instead of the commitment to the witness (which  $\mathcal{S}$  does not have). **(4)** Finally, in the final WI Proof, the simulated  $P_i$  uses the ‘BFOP’ condition to complete the proof.

**Simulating “ZK” activations when the prover is corrupted.** When  $\mathcal{A}$ , controlling corrupted party  $P_i$ , delivers a ZK message  $x = “(\text{ZK}, \text{sid}, P_i, P_j, y)”$  to an uncorrupted party  $P_j$  in the internal (simulated) interaction, then  $\mathcal{S}$  works as follows.  $\mathcal{S}$  simulates the verifier by exactly following the honest verifier strategy. If the protocol ends successfully, then  $\mathcal{S}$  examines all places in the protocol transcript where the prover used  $\text{Com}_4$  to commit to a string. Because  $\mathcal{S}$  runs in time  $T_{4,1}$ , it can break each of these commitments. It checks to see if any of these strings is a valid witness for the statement  $y$  (i.e. a satisfying assignment to  $y$ ). If any one (chosen arbitrarily) of these strings  $w$  is a valid witness, then  $\mathcal{S}$  forces party  $P_i$  to send  $“(\text{ZK}, \text{sid}, P_i, P_j, y, w)”$  to  $\hat{\mathcal{F}}_{\text{ZK}}$ , and delivers  $\hat{\mathcal{F}}_{\text{ZK}}$ ’s response to  $P_j$ . If none of these strings is a valid witness, and yet the adversary succeeds in convincing the honest verifier, then  $\mathcal{S}$  halts and outputs **ss-failure**.

We note that the above simulation is a straight-line simulation that does not require rewinding any party’s state. Therefore, if multiple sessions are interleaved, the simulation proceeds exactly as described above, independently for each session.

We next proceed to the indistinguishability proof.

## 6.2 Indistinguishability

We now prove that  $\mathcal{Z}$  cannot distinguish an interaction of (multiple concurrent calls to) Protocol  $\mathcal{X}$  with  $\mathcal{A}$ , from an interaction in the ideal process with  $\hat{\mathcal{F}}_{\text{ZK}}$  and  $\mathcal{S}$ . In order to show this, we examine several hybrid experiments. Note that we assume without loss of generality that both  $\mathcal{A}$  and  $\mathcal{Z}$  are deterministic.

Let hybrid  $\mathbf{H}_{\mathcal{A}}$  be the simulated interaction described above. We define the output of this hybrid to be the transcript of the “internal” simulated interaction with  $\mathcal{A}$ . Note that this is enough



to compute the output of the environment  $\mathcal{Z}$ . Note that the running time of  $\mathbf{H}_A$  is less than  $T_{4.1}$ , where the most time-consuming step is the extraction of the witness.

**Simulation Soundness: Correctness of extraction.** We first make use of the *simulation soundness* condition to show that the simulated “witness extraction” succeeds with overwhelming probability:

Let  $\mathbf{H}_B$  be the “simulated interaction” above, but with the following differences: In this hybrid, we replace the ideal functionality  $\hat{\mathcal{F}}_{\text{ZK}}$  with one that *does not require* witnesses to be provided by corrupted parties in the ideal execution. That is, if the ideal functionality receives the message  $(\text{ZK}, \text{sid}, P_i, P_j, y)$  from party  $P_i$  – and  $P_i$  is corrupted – then it simply forwards the message to  $P_j$  without verifying anything. Furthermore, in this hybrid, when the party  $P_i$  is corrupted and attempts to prove  $x = (\text{ZK}, \text{sid}, P_i, P_j, y)$  to  $P_j$ , then the simulator simply checks if the protocol succeeds, and if so, it forwards the message to the modified ideal functionality. Note that the running time of  $\mathbf{H}_B$  is less than  $T_{3.5}$ , where the most time-consuming step is the breaking of  $B_{\text{hard}}$ . (That is, because  $\mathbf{H}_B$  does not invoke the witness extracting procedure, its running time is significantly smaller than the running time of  $\mathbf{H}_A$ ).

We now argue that  $\mathbf{H}_A$  and  $\mathbf{H}_B$  are *statistically indistinguishable*. Without loss of generality, we may assume that the adversary  $\mathcal{A}$  and the environment  $\mathcal{Z}$  are deterministic. Thus, the only use of randomness arises in the simulation. We also note, for use later, that simulated verifiers use independent randomness (because they behave according to the honest verifier protocol.). Thus, we may define  $\mathbf{H}_A(r)$  and  $\mathbf{H}_B(r)$  to be the outputs of the hybrids when randomness  $r$  is used in the simulation. We note that for any  $r$ , we have that  $\mathbf{H}_A(r)$  is always a prefix of  $\mathbf{H}_B(r)$ , and they are not equal *only* if the simulator halts and outputs `ss-failure` in  $\mathbf{H}_A(r)$ . We want to show that this happens with probability less than  $1/T_{0.5}$ .

We will show that if the probability  $p$  that the simulator halts and outputs `ss-failure` is larger than  $1/T_{0.5}$ , then this will contradict [Lemma 5.3](#).

Let  $m \leq T_0$  be the maximum number of sessions in which the adversary plays the role of the prover.

We consider the following experiment  $E(r)$ : Using randomness  $r$ , both  $\mathbf{H}_A(r)$  and  $\mathbf{H}_B(r)$  are computed. If the outputs are equal,  $E$  outputs “none”. Otherwise  $E$  outputs the number  $i$  corresponding to this first session in which  $\mathbf{H}_A(r)$  fails and outputs `ss-failure` (because it fails to extract a witness).

We define  $p_i$  to be the probability over  $r$  that  $E(r)$  outputs  $i$ . Note that  $\sum_i p_i = p$ . Therefore there exists some number  $j$  such that  $p_j \geq p/T_0$ .

We define a new hybrid  $\mathbf{H}_{A'}$  (which comes “in between” hybrids  $\mathbf{H}_A$  and  $\mathbf{H}_B$ ) as follows: It is the same as  $\mathbf{H}_B$ , except that in the  $j$ 'th session where the adversary plays the role of prover, the simulator acts as  $\mathcal{S}$  does in  $\mathbf{H}_A$ , namely it breaks the  $\text{Com}_4$  commitments made during the  $j$ 'th session in order to recover a witness for the statement being proven. If such a witness is not recovered, then the simulation halts with output `ss-failure`. Note that for all sessions  $i \neq j$  where the adversary plays the role of prover,  $\mathbf{H}_{A'}$  does *not* use the witness extraction procedure, but just uses the honest verifier strategy. The important property of  $\mathbf{H}_{A'}$  is that if we let  $p'$  to be the probability that  $\mathbf{H}_{A'}$  halts and outputs `ss-failure`, then we have  $p' \geq p_j \geq p/T_0$ . We note that the running time of  $\mathbf{H}_{A'}$  is at most  $T_{3.5}$  for sessions  $i \neq j$  and at most  $T_{4.5}$  for simulating the  $j^{\text{th}}$  session.

We next define a hybrid  $\mathbf{H}_{A''}$  (used only for this proof) which is identical to  $\mathbf{H}_{A'}$ , except that is

uses the VSim simulation strategies as follows: All sessions in which the adversary acts as verifier are simulated using VHP, but only the  $j^{\text{th}}$  session where the adversary acts as the prover is simulated using VHV. In this session, the simulation also halts and outputs **ss-failure** if none of the  $\text{Com}_4$  commitments are to a valid witness. All other sessions where the adversary acts as the prover are simulated by using the honest verifier strategy. We observe that all activity in  $\mathbf{H}_{\mathbf{A}'}$  outside of the VSim simulations can be computed in time polynomial in  $T_0$ . Like  $\mathbf{H}_{\mathbf{A}'}$ , that the running time of  $\mathbf{H}_{\mathbf{A}'}$  is at most  $T_{3.5}$  for sessions  $i \neq j$  and at most  $T_{4.5}$  for simulating the  $j^{\text{th}}$  session. Let  $p''$  be the probability that  $\mathbf{H}_{\mathbf{A}'}$  halts with an output of **ss-failure**.

Then, by [Lemma 5.2](#) (strong indistinguishability of Sim and VSim), we have that  $p' \leq p'' + 1/T_{0.5}^2$ . But by [Lemma 5.3](#) (simulation soundness of VSim) and the naming conventions we use for statements, we know that  $p'' \leq 1/T_{0.5}$ .

Therefore,  $p \leq 2T_0/T_{0.5}^2 \leq 1/T_{0.5}$ , and we have that hybrids  $\mathbf{H}_{\mathbf{A}}$  and  $\mathbf{H}_{\mathbf{B}}$  are  $1/T_{0.5}$ -statistically indistinguishable.

**Indistinguishability of prover simulation.** We next move to a sequence of hybrids showing that the simulation of uncorrupted provers is good. We will first move from  $\mathbf{H}_{\mathbf{B}}$  to a situation where the witnesses are used in all uncorrupted prover sessions.

We first define hybrid  $\mathbf{H}_{\mathbf{C}}$  as identical to  $\mathbf{H}_{\mathbf{B}}$ , except that the honest provers in simulation replace the commitment  $c_{\text{wit}} = \text{Com}_4(0^{\ell_{\text{wit}}})$  with a commitment  $c_{\text{wit}} = \text{Com}_4(w)$ , where  $w$  is the witness to the statement being proven in that session. Because both hybrids run in time  $T_{3.5}$ , a standard hybrid argument shows that  $\mathbf{H}_{\mathbf{B}}$  and  $\mathbf{H}_{\mathbf{C}}$  are  $(T_4, 1/T_4)$ -indistinguishable.

Let hybrid  $\mathbf{H}_{\mathbf{D}}$  be identical to  $\mathbf{H}_{\mathbf{C}}$ , except that in all sessions with honest provers, the proving party switches to using the ‘WIT’ condition to complete the final WI proof. A standard hybrid argument based on the WI property of the WI proof shows that  $\mathbf{H}_{\mathbf{C}}$  and  $\mathbf{H}_{\mathbf{D}}$  are  $(T_5, 1/T_5)$ -indistinguishable, since both hybrids run in time  $T_{3.5}$ .

We next define a series of hybrids that we will analyze using the technique of intermediate rewinding hybrids, introduced in [Section 5.3](#). The goal of these hybrids is to switch the behavior of the honest provers in  $\mathbf{H}_{\mathbf{D}}$  to stop breaking  $B_{\text{hard}}$ . The problem with this switch is that we first need to switch to using the (rewinding) ZK simulator for the proof of knowledge within the  $B_{\text{hard}}$  protocol. If we did this for all sessions, we could end up interleaved rewindings that could cause an unacceptable increase in the running time of the hybrid experiment. Therefore, we only switch to one ZK simulator at a time, thus maintaining a good enough running time.

Let  $m < T_0$  be the maximum number of sessions in which the adversary plays the role of Verifier and an honest party plays the role of Prover.

We consider a sequence of hybrids, for each  $i \in [1, m]$ , called  $\mathbf{H}_{\mathbf{E}/i}$ ,  $\mathbf{H}_{\mathbf{F}/i}$ , and  $\mathbf{H}_{\mathbf{G}/i}$ . The “order” of these hybrids will be  $\mathbf{H}_{\mathbf{E}/1}, \mathbf{H}_{\mathbf{F}/1}, \mathbf{H}_{\mathbf{G}/1}, \mathbf{H}_{\mathbf{E}/2}, \mathbf{H}_{\mathbf{F}/2}, \mathbf{H}_{\mathbf{G}/2}, \mathbf{H}_{\mathbf{E}/3}, \dots, \mathbf{H}_{\mathbf{G}/m}$ . We will maintain the invariant that  $\mathbf{H}_{\mathbf{G}/i}$  will be a straight-line execution for all  $i \in [1, m]$ .

Hybrid  $\mathbf{H}_{\mathbf{E}/i}$  is identical to the previous hybrid (that is  $\mathbf{H}_{\mathbf{D}}$  in the case of  $\mathbf{H}_{\mathbf{E}/1}$ ), except that in the  $i^{\text{th}}$  session where an honest party  $P$  plays the prover when interacting in Protocol  $\mathcal{X}$ , the party  $P$  will switch from giving a proper ZK proof of knowledge for  $\text{Com}_4(r' = r)$  inside the  $B_{\text{hard}}$  subprotocol, to giving a (rewinding-based) ZK simulated proof instead. We argue that hybrid  $\mathbf{H}_{\mathbf{E}/i}$  is  $(T_5, 1/T_5)$ -indistinguishable from the previous hybrid as follows: We construct a  $T_{3.5}$ -time verifier  $V'$  to play the role of a verifier in the stand-alone ZK proof of knowledge. This verifier  $V'$  internally runs the previous hybrid execution for all parties except for the prover role of  $P$  in the ZK proof of knowledge. We observe that as such,  $V'$  is a valid stand-alone verifier. Hence, if there were a

$T_4^{O(1)}$ -time distinguisher for  $\mathbf{H}_{\mathbf{E}/i}$  and the previous hybrid, it would yield a  $T_4^{O(1)}$ -time distinguisher for the ZK property of the ZK proof with the same distinguishing probability.

Hybrid  $\mathbf{H}_{\mathbf{F}/i}$  is identical to  $\mathbf{H}_{\mathbf{E}/i}$ , except that in the  $i$ 'th session, in the  $B_{\text{hard}}$  subprotocol, the experiment stops breaking the verifier's challenge  $y = \text{OWF}_3(r)$ , and the response commitment  $\text{Com}_5(r)$  will be replaced by  $\text{Com}_5(0^{\ell_{\text{OWF}_3}})$ . (Recall that we assume OWF is a permutation.) By the indistinguishability property of  $\text{Com}_4$ , and the fact that all hybrids run in time less than  $T_{3.5}$  we have that  $\mathbf{H}_{\mathbf{F}/i}$  is  $(T_5, 1/T_5)$ -indistinguishable from  $\mathbf{H}_{\mathbf{E}/i}$ .

Finally,  $\mathbf{H}_{\mathbf{G}/i}$  is identical to  $\mathbf{H}_{\mathbf{F}/i}$ , except that in the  $i$ 'th session, the simulation of ZK proof of knowledge for  $\text{Com}_5(0^{\ell_{\text{OWF}_3}})$  is replaced with an honest ZK proof of knowledge. Again, we have that  $\mathbf{H}_{\mathbf{G}/i}$  is  $(T_5, 1/T_5)$ -indistinguishable from  $\mathbf{H}_{\mathbf{F}/i}$ , by the ZK property, using the same argument as above. Note also that hybrid  $\mathbf{H}_{\mathbf{G}/i}$  is a straight-line execution (i.e. it has no rewinding), as promised.

We note that hybrid  $\mathbf{H}_{\mathbf{G}/m}$  can be implemented in time only polynomial in  $T_0$ . The only difference remaining between the environment's view of  $\mathbf{H}_{\mathbf{G}/m}$  and the real world interaction is that in the real world,  $c_{\text{VK}}$  is  $\text{Com}_4(0^{\ell_{\text{VK}}})$ . Thus, the  $(T_4, 1/T_4)$ -indistinguishability of  $\mathbf{H}_{\mathbf{G}/m}$  and the real world interaction follows from a standard hybrid argument based on the indistinguishability of the commitment scheme, and the fact that both hybrid  $\mathbf{H}_{\mathbf{G}/m}$  and the real world interaction are implementable in time polynomial in  $T_0$ .

With this, the theorem is established.  $\square$

## 7 Security against Adaptive Adversaries

In this section, we sketch how to obtain security against adaptive adversaries for our zero knowledge protocol, which immediately implies such security for secure multi-party computation using the results of [CLOS02]. For adaptive security, we will assume the existence of one-way permutations secure against subexponential adversaries.

The high-level idea is that the Witness-Based Continuation (WBC) property almost gives us adaptive security automatically: When a proving party is corrupted, we could explain all previous messages using the witness in the witness-based continuation. (Note that simulated verifiers act honestly, so there is no need to "explain" their behavior.) The only problem with this approach is that the WI proof involved in WBC compiler is not secure against adaptive adversaries: If one gives a WI proof that either  $X$  is true or  $Y$  is true, using a witness for  $X$ , then there is no generic way to explain that proof using a witness for  $Y$ .

We alleviate this technical problem using ideas introduced in [CLOS02]. Instead of giving a standard WI proof inside the WBC compiler, we construct a specialized proof system. We first recall some concepts from [CLOS02]:

**Underlying standard commitment.** The basic underlying commitment scheme  $\text{Com}_5$  is the standard non-interactive commitment scheme based on a one-way permutation  $f$  (that is  $T_5$ -secure) and a hard-core predicate  $b$  of  $f$ . That is, in order to commit to a bit  $\sigma$ , one computes  $\text{Com}_5(\sigma) = \langle f(U_k), b(U_k) \oplus \sigma \rangle$ , where  $U_k$  is the uniform distribution over  $\{0, 1\}^k$ . Note that  $\text{Com}_5$  is computationally secret, and produces pseudorandom commitments: that is, the distributions  $\text{Com}_5(0)$ ,  $\text{Com}_5(1)$ , and  $U_{k+1}$  are computationally indistinguishable.

**The Feige-Shamir Commitment Scheme.** We briefly describe the Feige-Shamir trapdoor commitment scheme [FSS89], which is based on the zero-knowledge proof for Hamiltonicity of Blum [BLU87].

First, we fix a graph  $G$  (with  $q$  nodes) with a Hamiltonian cycle. (We will specify the graph to be used later.) Then, in order to commit to 0, the committer commits to a random permutation of  $G$  using the underlying commitment scheme  $\text{Com}_5$  (and decommits by revealing the entire graph and the permutation). In order to commit to 1, the committer commits to a graph containing a randomly labeled  $q$ -cycle only (and decommits by opening this cycle only). Note that the ability to decommit to both 0 and 1 implies that the committer knows a Hamiltonian cycle in  $G$ . On the other hand, given a Hamiltonian cycle in  $G$ , it is possible to generate commitments that are indistinguishable from legal ones, and yet have the property that one can decommit to both a 0 and a 1. Note that if the graph  $G$  is not hamiltonian, then this commitment scheme is a perfectly-binding computationally-hiding scheme.

**The modified graph-based commitment  $\text{Com}^G$ .** Our graph-based scheme, introduced in [CLOS02], which we denote  $\text{Com}^G$ , differs from the [FS89] scheme above in the following way:

To commit to a 0, the sender picks a random permutation  $\pi$  of the nodes of  $G$ , and commits to the entries of the adjacency matrix of the permuted graph one by one, using  $\text{Com}_5$ . The sender also commits (using  $\text{Com}_5$ ) to the permutation  $\pi$ . These values are sent to the receiver as  $c = \text{Com}^G(0)$ . To decommit, the sender decommits to  $\pi$  and decommits to every entry of the adjacency matrix. The receiver verifies that the graph it received is  $\pi(G)$ .

To commit to a 1, the sender chooses a randomly labeled  $q$ -cycle, and for all the entries in the adjacency matrix corresponding to edges on the  $q$ -cycle, it uses  $\text{Com}_5$  to commit to 1 values. For all the other entries, including the commitment to the permutation  $\pi$ , it simply produces random values from  $U_{k+1}$  (for which it does not know the decommitment!) These values are sent to the receiver as  $c = \text{Com}^G(1)$ . To decommit, the sender opens only the entries corresponding to the randomly chosen  $q$ -cycle in the adjacency matrix.

This commitment scheme has the property of being computationally secret, *i.e.* the distributions  $\text{Com}^G(0)$  and  $\text{Com}^G(1)$  are computationally indistinguishable for any graph  $G$ . Also, given the opening of any commitment to both a 0 and 1, one can extract a Hamiltonian cycle in  $G$ . Finally, as with the scheme of [FS89], given a Hamiltonian cycle in  $G$ , one can generate commitments to 0 and then open those commitments to both 0 and 1.

Furthermore, here if the simulator has knowledge of a Hamiltonian cycle in  $G$ , it can also produce a random tape for the sender explaining  $c = \text{Com}^G(0)$  as a commitment to both 0 and 1. If, upon corruption of the sender, the simulator has to demonstrate that  $c$  is a commitment to 0 then all randomness is revealed. To demonstrate that  $c$  was generated as a commitment to 1, the simulator opens the commitments to the edges in the  $q$ -cycle and claims that all the unopened commitments are merely uniformly chosen strings (rather than commitments to the rest of  $G$ ). This can be done since commitments produced by the underlying commitment scheme  $\text{Com}_5$  are pseudorandom.

**Modified Witness-Based Continuation Compiler.** Recall that in the WBC Compiler, the prover uses a weak commitment  $\text{Com}_4$  to commit to its “inner” response  $c_m = \text{Com}_4(m)$ . We will change how the prover commits to the witness  $c_w$  (see below). It then proves a WI proof that either the message  $m$  from  $c_m$  is a valid response in the inner protocol, or that the witness  $w$  from  $c_w$  is a good witness for  $x$ .

We will change the protocol as follows: We will still use  $c_m = \text{Com}_4(m)$ . We then consider the statement, that the message  $m$  from  $c_m$  is a valid response in the inner protocol, as an NP statement, and use a canonical reduction to construct a graph  $G_m$ , such that any witness to the truth of this statement can be mapped to some Hamiltonian cycle in  $G_m$ . We then use  $c_w = \text{Com}_4^{G_m}(w)$ .

We also canonically construct a graph  $G_w$  corresponding to the statement that there is a valid opening message  $w$  for  $c_w$  that is a valid witness for  $x$ . We now use our graph based commitment scheme  $\text{Com}^{G_m}$  to provide a parallelized Blum proof of the Hamiltonicity of  $G_w$ . Namely, the following is done  $k$  times in parallel:

1. The prover uses  $\text{Com}^{G_m}$  to commit to a randomly permuted adjacency matrix for  $G_w$ .
2. The verifier responds with a single challenge bit  $b$ .
3. If  $b = 0$ , the prover provides the permutation and opens all commitments. If  $b = 1$ , the prover opens only the entries corresponding to a Hamiltonian cycle in  $G_w$ .

Note that this is still a statistically sound and  $(T_5, 1/T_5)$ -indistinguishable WI-system proving that either  $\text{Com}_4(w)$  contains a witness or  $\text{Com}_4(m)$  contains a valid message.

We note that we have changed the honest prover’s strategy to always use the witness-based outer prover strategy (although instead of sending commitments to “junk” messages it will just send a random string of the appropriate length). The key observation is that a simulator can use knowledge of a Hamiltonian cycle in  $G_m$  (if  $m$  is a well-formed response in the inner protocol) to provide responses to all queries in this protocol without knowing the witness (and therefore without knowing a Hamiltonian cycle in  $G_w$ ) – this would be by always using  $\text{Com}^{G_m}(0)$ , and then opening it to whatever is necessary. But by the explainability property of  $\text{Com}^{G_m}$ , such a simulator could also explain its actions by providing honest-looking randomness in the protocol above.

We omit the details here, but this suffices to establish security against adaptive adversaries, without relying on erasures by honest parties.

## 8 Conclusions and future directions.

We presented a general feasibility result for secure multi-party computation in the general-concurrent setting, under well-studied assumptions. In some sense, this work brings provable security closer to practice, since the security properties, which are proven under standard assumptions, are strong enough to model what happens in realistic networks. However, in terms of efficiency our constructions leaves much room for improvement. Even though polynomial simulation is impossible, there is also room for improvement on our protocol in terms of the simulation overhead. We hope that the ideas presented here will prove useful in obtaining more practical protocols, which still can be proven secure in the general concurrent setting under well-understood assumptions. An example for such a problem is obtaining a practical fully concurrent and non-malleable commitment scheme under such well-known number-theoretic assumptions such as the hardness of factoring or the discrete logarithm problem.

On a technical level, we introduced a new technique for “condensing” protocols to achieve stronger security. We believe this technique may have many other applications. In particular, we believe there is hope for using such techniques to obtain a concurrent zero-knowledge protocol using a constant number of communication rounds, with polynomial simulation overhead. Such a protocol is known if we allow super-polynomial simulation, but it would be nice to obtain it using polynomial simulation, since, unlike the case of general computation, super-polynomial simulation does not seem necessary in this case.

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