

We write  $\mu_\delta$  to denote a Bernoulli distribution, where outcome 1 occurs with probability  $\delta$  and 0 with probability  $1 - \delta$  where  $0 \leq \delta \leq 1$ . Moreover, we use  $\mu_\delta^k$  to denote a probability distribution over  $k$ -tuples, where each bit of a  $k$ -tuple is drawn independently according to  $\mu_\delta$ . Finally, let  $u \leftarrow \mu_\delta^k$  denote that a  $k$ -tuple  $u$  is chosen according to  $\mu_\delta^k$ .

The protocol execution between two probabilistic algorithms  $A$  and  $B$  is denoted by  $\langle A, B \rangle$ . The output of  $A$  in such a protocol execution is denoted by  $\langle A, B \rangle_A$  and of  $B$  by  $\langle A, B \rangle_B$ . Finally, let  $\langle A, B \rangle_{\text{trans}}$  denote the transcript of communication between  $\langle A, B \rangle_{\text{trans}}$ .

We define a *two phase algorithm*  $A := (A_1, A_2)$  as an algorithm where in the first phase an algorithm  $A_1$  is executed and in the second phase an algorithm  $A_2$ .

**Definition 1.1 (Dynamic weakly verifiable puzzle.)** A *dynamic weakly verifiable puzzle (DWVP)* is defined by a probabilistic algorithm  $P$  called a *problem poser*. A *problem solver*  $S := (S_1, S_2)$  for  $P$  is a probabilistic two phase algorithm. We write  $P_n(\pi)$  to denote the execution of  $P$  with the randomness fixed to  $\pi \in \{0, 1\}^n$ , and  $(S_1, S_2)(\rho)$  to denote the execution of both  $S_1$  and  $S_2$  with the randomness fixed to  $\rho \in \{0, 1\}^*$ .

In the first phase, the poser  $P_n(\pi)$  and the solver  $S_1(\rho)$  interact. As the result of the interaction  $P_n(\pi)$  outputs a verification circuit  $\Gamma_V$  and a hint circuit  $\Gamma_H$ . The algorithm  $S_1(\rho)$  produces no output. The circuit  $\Gamma_V$  takes as input  $q \in Q$ , an answer  $y \in \{0, 1\}^*$ , and outputs a bit. We say that an answer  $(q, y)$  is a correct solution if and only if  $\Gamma_V(q, y) = 1$ . The circuit  $\Gamma_H$  on input  $q \in Q$  outputs a hint such that  $\Gamma_V(q, \Gamma_H(q)) = 1$ .

In the second phase,  $S_2$  takes as input  $x := \langle P_n(\pi), S_1(\rho) \rangle_{\text{trans}}$ , and has oracle access to  $\Gamma_V$  and  $\Gamma_H$ . The execution of  $S_2$  with the input  $x$  and the randomness fixed to  $\rho$  is denoted by  $S_2(x, \rho)$ . The queries of  $S_2$  to  $\Gamma_V$  and  $\Gamma_H$  are called *verification queries* and *hint queries* respectively. The algorithm  $S_2$  asks at most  $h$  hint queries,  $v$  verification queries, and succeeds if and only if it makes a verification query  $(q, y)$  such that  $\Gamma_V(q, y) = 1$ , and it has not previously asked for a hint query on  $q$ .

**Definition 1.2 ( $k$ -wise direct-product of DWVPs.)** Let  $g : \{0, 1\}^k \rightarrow \{0, 1\}$  be a monotone function and  $P^{(1)}$  a problem poser as in Definition 1.1. The  $k$ -wise direct product of  $P^{(1)}$  is a DWVP defined by a probabilistic algorithm  $P^{(g)}$ . We write  $P_{kn}^{(g)}(\pi^{(k)})$  to denote the execution of  $P^{(g)}$  with the randomness fixed to  $\pi^{(k)} := (\pi_1, \dots, \pi_k)$  where for each  $1 \leq i \leq n : \pi_i \in \{0, 1\}^n$ . Let  $(S_1, S_2)(\rho)$  be a solver for  $P^{(g)}$  as in Definition 1.1. In the first phase, the algorithm  $S_1(\rho)$  sequentially interacts in  $k$  rounds with  $P_{kn}^{(g)}(\pi^{(k)})$ . In the  $i$ -th round  $S_1(\rho)$  interacts with  $P_n^{(1)}(\pi_i)$ , and as the result  $P_{kn}^{(g)}(\pi^{(k)})$  generates circuits  $\Gamma_V^i, \Gamma_H^i$ . Finally, after  $k$  rounds  $P_{kn}^{(g)}(\pi^{(k)})$  outputs a verification circuit

$$\Gamma_V^{(g)}(q, y_1, \dots, y_k) := g(\Gamma_V^1(q, y_1), \dots, \Gamma_V^k(q, y_k))$$

and a hint circuit

$$\Gamma_H^{(k)}(q) := (\Gamma_H^1(q), \dots, \Gamma_H^k(q)).$$

If it is clear from a context we omit the parameter  $n$  and write  $P(\pi)$  instead of  $P_n(\pi)$  where  $\pi \in \{0, 1\}^n$ .

A verification query  $(q, y)$  of a solver  $S$  for which a hint query on this  $q$  has been asked before can not be a successful verification query. Therefore, without loss of generality, we make the assumption that  $S$  does not ask verification queries on  $q$  for which a hint query has been asked before. Furthermore, we assume that once  $S$  asked a successful verification query, it does not ask any further hint or verification queries.

Let  $C$  be a circuit that corresponds to a solver  $S$  as in Definition 1.1. Similarly as for a two phase algorithm, we write  $C(\rho) := (C_1, C_2)(\rho)$  to denote that  $C$  in the first phase uses a circuit  $C_1$  and in the second phase a circuit  $C_2$ . Additionally, the randomness in both phases is fixed to  $\rho \in \{0, 1\}^*$ .

**Experiment**  $Success^{P,C}(\pi, \rho)$

**Oracle:** A problem poser  $P$ , a solver circuit  $C = (C_1, C_2)$ .

**Input:** Bitstrings  $\pi \in \{0, 1\}^n$ ,  $\rho \in \{0, 1\}^*$ .

**Output:** A bit  $b \in \{0, 1\}$ .

**Run**  $\langle P(\pi), C_1(\rho) \rangle$

$(\Gamma_V, \Gamma_H) := \langle P(\pi), C_1(\rho) \rangle_P$

$x := \langle P(\pi), C_1(\rho) \rangle_{\text{trans}}$

**Run**  $C_2^{\Gamma_V, \Gamma_H}(x, \rho)$

**if**  $C_2^{\Gamma_V, \Gamma_H}(x, \rho)$  asks a verification query  $(q, y)$  such that  $\Gamma_V(q, y) = 1$  **then**  
**return** 1

**return** 0

We define the *success probability* of  $C$  in solving a puzzle defined by  $P$  as

$$\Pr_{\pi, \rho}[Success^{P,C}(\pi, \rho) = 1]. \quad (0.0.1)$$

Furthermore, we say that  $C$  succeeds for  $\pi, \rho$  if  $Success^{P,C}(\pi, \rho) = 1$ .

**Theorem 1.3 (Security amplification for a dynamic weakly verifiable puzzle.)** *Let  $P^{(1)}$  be a fixed problem poser as in Definition 1.1, and  $P^{(g)}$  be a poser for the  $k$ -wise direct product of  $P^{(1)}$ . There exists a probabilistic algorithm  $Gen$  with oracle access to: a solver circuit  $C$  for  $P^{(g)}$ , a monotone function  $g : \{0, 1\}^k \rightarrow \{0, 1\}$  and  $P^{(1)}$ . Additionally,  $Gen$  takes as input parameters  $\varepsilon, \delta$ , the value  $n$  being the length of the input bitstring to  $P^{(1)}$ , the number of verification queries  $v$  and hint queries  $h$  asked by  $C$ , and outputs a solver circuit  $D$  for  $P^{(1)}$  as in Definition 1.1 such that the following holds:  
If  $C$  is such that*

$$\Pr_{\pi^{(k)}, \rho} \left[ Success^{P^{(g)}, C}(\pi^{(k)}, \rho) = 1 \right] \geq 8(h + v) \left( \Pr_{u \leftarrow \mu_\delta^k} [g(u) = 1] + \varepsilon \right)$$

*then  $D$  satisfies almost surely*

$$\Pr_{\pi, \rho} \left[ Success^{P^{(1)}, D}(\pi, \rho) = 1 \right] \geq (\delta + \frac{\varepsilon}{6k}).$$

*Additionally,  $D$  requires oracle access to  $g, P^{(1)}, C$ , and asks at most  $\frac{6k}{\varepsilon} \log(\frac{6k}{\varepsilon}) h$  hint queries and one verification query. Finally,  $Size(D) \leq Size(C) \cdot \frac{6k}{\varepsilon}$  and  $Time(Gen) = poly(k, \frac{1}{\varepsilon}, n, v, h)$ .*

Let  $hash : Q \rightarrow \{0, 1, \dots, 2(h + v) - 1\}$ , the idea is to partition  $Q$  such that the set of preimages of 0 for  $hash$  contains  $q \in Q$  on which  $C$  is not allowed to ask hint queries, and the first successful verification query  $(q, y)$  of  $C$  is such that  $hash(q) = 0$ . Therefore, if  $C$  makes a verification query  $(q, y)$  such that  $hash(q) = 0$ , then we know that no hint query is ever asked on this  $q$ .

We denote the  $i$ -th query of  $C$  by  $q_i$  if it is a hint query, and by  $(q_i, y_i)$  if it is a verification query. We define now an experiment *CanonicalSuccess* in which  $Q$  is partitioned using a function  $hash$ . We say that a solver circuit  $C$  succeeds in the experiment *CanonicalSuccess* if it asks a successful verification query  $(q_j, y_j)$  such that  $hash(q_j) = 0$ , and no hint query  $q_i$  is asked before  $(q_j, y_j)$  such that  $hash(q_i) = 0$ .

**Experiment**  $\text{CanonicalSuccess}^{P,C,\text{hash}}(\pi, \rho)$

**Oracle:** A problem poser  $P$ , a solver circuit  $C = (C_1, C_2)$ ,  
a function  $\text{hash} : Q \rightarrow \{0, \dots, 2(h+v) - 1\}$ .

**Input:** Bitstrings  $\pi \in \{0, 1\}^n$ ,  $\rho \in \{0, 1\}^*$ .

**Output:** A bit  $b \in \{0, 1\}$ .

**Run**  $\langle P(\pi), C_1(\rho) \rangle$   
 $(\Gamma_V, \Gamma_H) := \langle P(\pi), C_1(\rho) \rangle_P$   
 $x := \langle P(\pi), C_1(\rho) \rangle_{\text{trans}}$

**Run**  $C_2^{\Gamma_V, \Gamma_H}(x, \rho)$   
 Let  $(q_j, y_j)$  be the first verification query of  $C_2$  such that  $\Gamma_v(q_j, y_j) = 1$ .  
**if**  $C_2$  does not succeed for any verification query **then**  
     **return** 0

**If**  $(\Gamma_V(q_j, y_j) = 1)$  **and**  $(\forall i < j : \text{hash}(q_i) \neq 0)$  **and**  $(\text{hash}(q_j) = 0)$  **then**  
     **return** 1  
**else**  
     **return** 0

We define the *canonical success probability* of a solver  $C$  for  $P$  with respect to a function  $\text{hash}$  as

$$\Pr_{\pi, \rho}[\text{CanonicalSuccess}^{P,C,\text{hash}}(\pi, \rho) = 1]. \quad (0.0.2)$$

For fixed  $\text{hash}$  and a problem poser  $P$  a *canonical success* of  $C$  for  $\pi, \rho$  is a situation where  $\text{CanonicalSuccess}^{P,C,\text{hash}}(\pi, \rho) = 1$ . We show that if a solver circuit  $C$  for  $P^{(g)}$  often succeeds in the experiment  $\text{Success}$ , then it is also often successful in the experiment  $\text{CanonicalSuccess}$ . Let  $\mathcal{H}$  be the family of pairwise independent functions  $Q \rightarrow \{0, 1, \dots, 2(h+v) - 1\}$ . We write  $\text{hash} \leftarrow \mathcal{H}$  to denote that  $\text{hash}$  is chosen from  $\mathcal{H}$  uniformly at random.<sup>1</sup>

**Lemma 1.4 (Success probability in solving a  $k$ -wise direct product of  $P^{(1)}$  with respect to a function  $\text{hash}$ .)** For fixed  $P$  let  $C$  be a solver for  $P$  with the success probability at least  $\gamma$ , asking at most  $h$  hint queries and  $v$  verification queries. There exists a probabilistic algorithm **FindHash** that takes as input: parameters  $\gamma$ ,  $n$ , the number of verification queries  $v$  and hint queries  $h$ , and has oracle access to  $C$  and  $P$ . Furthermore, **FindHash** runs in time  $O((h+v)^4/\gamma^4)$ , and with high probability outputs a function  $\text{hash} \in \mathcal{H}$  such that the canonical success probability of  $C$  with respect to  $\text{hash}$  is at least  $\frac{\gamma}{16(h+v)}$ .

**Proof.** We fix a problem poser  $P$  and a solver  $C$  for  $P$  in the whole proof of Lemma 1.4. For all  $m, n \in \{1, \dots, (h+v)\}$  and  $k, l \in \{0, 1, \dots, 2(h+v) - 1\}$  by the pairwise independence property of  $\mathcal{H}$ , we have

$$\forall q_m, q_n \in Q, q_m \neq q_n : \Pr_{\text{hash} \leftarrow \mathcal{H}}[\text{hash}(q_m) = k \mid \text{hash}(q_n) = l] = \Pr_{\text{hash} \leftarrow \mathcal{H}}[\text{hash}(q_m) = k] = \frac{1}{2(h+v)}. \quad (0.0.3)$$

Let  $\mathcal{P}_{\text{Success}}$  be a set containing all  $(\pi, \rho)$  for which  $\text{Success}^{P,C}(\pi, \rho) = 1$ . We fix  $(\pi^*, \rho^*) \in \mathcal{P}_{\text{Success}}$  and are interested in the probability over a choice of function  $\text{hash}$  of the event

<sup>1</sup>It is possible to implement a random function  $\text{hash}$  efficiently by for example building its function table on the fly.

$\text{CanonicalSuccess}^{P,C,\text{hash}}(\pi^*, \rho^*) = 1$ . Let  $(q_j, y_j)$  denote the first query such that  $\Gamma_V(q_j, y_j) = 1$ . We have

$$\begin{aligned}
& \Pr_{\text{hash} \leftarrow \mathcal{H}} [\text{CanonicalSuccess}^{P,C,\text{hash}}(\pi^*, \rho^*) = 1] \\
&= \Pr_{\text{hash} \leftarrow \mathcal{H}} [\text{hash}(q_j) = 0 \wedge (\forall i < j : \text{hash}(q_i) \neq 0)] \\
&= \Pr_{\text{hash} \leftarrow \mathcal{H}} [\forall i < j : \text{hash}(q_i) \neq 0 \mid \text{hash}(q_j) = 0] \Pr_{\text{hash} \leftarrow \mathcal{H}} [\text{hash}(q_j) = 0] \\
&\stackrel{(0.0.3)}{=} \frac{1}{2(h+v)} \left( 1 - \Pr_{\text{hash} \leftarrow \mathcal{H}} [\exists i < j : \text{hash}(q_i) = 0 \mid \text{hash}(q_j) = 0] \right) \\
&\stackrel{(0.0.3)}{=} \frac{1}{2(h+v)} \left( 1 - \Pr_{\text{hash} \leftarrow \mathcal{H}} [\exists i < j : \text{hash}(q_i) = 0] \right) \\
&\stackrel{(\text{u.b})}{\geq} \frac{1}{2(h+v)} \left( 1 - \sum_{i < j} \Pr_{\text{hash} \leftarrow \mathcal{H}} [\text{hash}(q_i) = 0] \right) \\
&\stackrel{(0.0.3)}{\geq} \frac{1}{4(h+v)}. \tag{0.0.4}
\end{aligned}$$

We denote the set of those  $(\pi, \rho)$  for which  $\text{CanonicalSuccess}^{P,C,\text{hash}}(\pi, \rho) = 1$  by  $\mathcal{P}_{\text{Canonical}}$ . For  $(\pi, \rho)$  for which  $C$  succeeds canonically, we have  $\text{Success}^{P,C}(\pi, \rho) = 1$ . Hence,  $\mathcal{P}_{\text{Canonical}} \subseteq \mathcal{P}_{\text{Success}}$ , and we conclude

$$\begin{aligned}
& \Pr_{\substack{\text{hash} \leftarrow \mathcal{H} \\ \pi, \rho}} [\text{CanonicalSuccess}^{P,C,\text{hash}}(\pi, \rho) = 1] \\
&= \Pr_{\substack{\text{hash} \leftarrow \mathcal{H} \\ (\pi, \rho) \in \mathcal{P}_{\text{Success}}}} [\text{hash}(q_j) = 0 \wedge (\forall i < j : \text{hash}(q_i) \neq 0)] \\
&= \mathbb{E}_{(\pi, \rho) \in \mathcal{P}_{\text{Success}}} \left[ \Pr_{\text{hash} \leftarrow \mathcal{H}} [\text{hash}(q_j) = 0 \wedge (\forall i < j : \text{hash}(q_i) \neq 0)] \right] \\
&\stackrel{(0.0.4)}{\geq} \frac{\gamma}{4(h+v)}. \tag{0.0.5}
\end{aligned}$$

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**Algorithm: FindHash** $(\gamma, n, h, v)$

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**Oracle:** A problem poser  $P$ , a solver circuit  $C$  for  $P$ .

**Input:** Parameters  $\gamma, n$ . The number of hint  $h$  and verification  $v$  queries.

**Output:** A function  $\text{hash} : Q \rightarrow \{0, 1, \dots, 2(h+v) - 1\}$ .

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for  $i = 1$  to  $32(h+v)^2/\gamma^2$  do:
   $\text{hash} \leftarrow \mathcal{H}$ 
   $\text{count} := 0$ 
  for  $j := 1$  to  $32(h+v)^2/\gamma^2$  do:
     $\pi \xleftarrow{\$} \{0, 1\}^n$ 
     $\rho \xleftarrow{\$} \{0, 1\}^*$ 
    if  $\text{CanonicalSuccess}^{P,C,\text{hash}}(\pi, \rho) = 1$  then
       $\text{count} := \text{count} + 1$ 
  if  $\text{count} \geq \frac{\gamma}{12(h+v)} \frac{32(h+v)^2}{\gamma^2}$  then
    return  $\text{hash}$ 
return  $\perp$ 

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We show that **FindHash** chooses  $hash \in \mathcal{H}$  such that the canonical success probability of  $C$  with respect to  $hash$  is at least  $\frac{\gamma}{16(h+v)}$  almost surely. Let  $\mathcal{H}_{Good}$  denote a family of functions  $hash \in \mathcal{H}$  for which

$$\Pr_{\pi, \rho} [CanonicalSuccess^{P, C, hash}(\pi, \rho) = 1] \geq \frac{\gamma}{8(h+v)}, \quad (0.0.6)$$

and  $\mathcal{H}_{Bad}$  be the family of functions  $hash \in \mathcal{H}$  such that

$$\Pr_{\pi, \rho} [CanonicalSuccess^{P, C, hash}(\pi, \rho) = 1] \leq \frac{\gamma}{16(h+v)}. \quad (0.0.7)$$

Let  $N$  denote the number of iterations of the inner loop of **FindHash**. For a fixed  $hash$ , we define independent, identically distributed binary random variables  $X_1, \dots, X_N$  such that

$$X_i = \begin{cases} 1 & \text{if in the } i\text{-th iteration of the inner loop } count \text{ is increased} \\ 0 & \text{otherwise.} \end{cases}$$

We show now that **FindHash** is unlikely to return  $hash \in \mathcal{H}_{Bad}$ . For  $hash \in \mathcal{H}_{Bad}$  by (0.0.7) we have  $\mathbb{E}_{\pi, \rho}[X_i] \leq \frac{\gamma}{16(h+v)}$ . Therefore, for any fixed  $hash \in \mathcal{H}_{Bad}$  using the Chernoff bound we get <sup>2</sup>

$$\Pr_{\pi, \rho} \left[ \frac{1}{N} \sum_{i=1}^N X_i \geq \frac{\gamma}{12(h+v)} \right] \leq \Pr_{\pi, \rho} \left[ \frac{1}{N} \sum_{i=1}^N X_i \geq (1 + \frac{1}{3}) \mathbb{E}[X_i] \right] \leq e^{-\frac{\gamma}{16(h+v)} N/27} \leq e^{-\frac{2}{27} \frac{(h+v)}{\gamma}}.$$

The probability that  $hash \in \mathcal{H}_{Good}$ , when picked, is not returned amounts

$$\Pr_{\pi, \rho} \left[ \frac{1}{N} \sum_{i=1}^N X_i \leq \frac{\gamma}{12(h+v)} \right] \leq \Pr_{\pi, \rho} \left[ \frac{1}{N} \sum_{i=1}^N X_i \leq (1 - \frac{1}{3}) \mathbb{E}[X_i] \right] \leq e^{-\frac{\gamma}{8(h+v)} N/18} \leq e^{-\frac{2}{9} \frac{(h+v)}{\gamma}},$$

where we once more used the Chernoff bound. We show that the probability of picking a  $hash \in \mathcal{H}_{Good}$  is at least  $\frac{\gamma}{8(h+v)}$ . We prove this statement by contradiction. Let assume us that

$$\Pr_{hash \leftarrow \mathcal{H}} [hash \in \mathcal{H}_{Good}] < \frac{\gamma}{8(h+v)}. \quad (0.0.8)$$

We have

$$\begin{aligned} & \Pr_{\substack{hash \leftarrow \mathcal{H} \\ \pi, \rho}} [CanonicalSuccess^{P, C, hash}(\pi, \rho) = 1] \\ &= \Pr_{\substack{hash \leftarrow \mathcal{H} \\ \pi, \rho}} [CanonicalSuccess^{P, C, hash}(\pi, \rho) = 1 \mid hash \in \mathcal{H}_{Good}] \Pr_{hash \leftarrow \mathcal{H}} [hash \in \mathcal{H}_{Good}] \\ & \quad + \Pr_{\substack{hash \leftarrow \mathcal{H} \\ \pi, \rho}} [CanonicalSuccess^{P, C, hash}(\pi, \rho) = 1 \mid hash \notin \mathcal{H}_{Good}] \Pr_{hash \leftarrow \mathcal{H}} [hash \notin \mathcal{H}_{Good}] \\ &\leq \Pr_{hash \leftarrow \mathcal{H}} [hash \in \mathcal{H}_{Good}] + \Pr_{\substack{hash \leftarrow \mathcal{H} \\ \pi, \rho}} [CanonicalSuccess^{P, C, hash}(\pi, \rho) = 1 \mid hash \notin \mathcal{H}_{Good}] \\ &\stackrel{(0.0.6)}{<} \stackrel{(0.0.8)}{<} \frac{\gamma}{8(h+v)} + \frac{\gamma}{8(h+v)} = \frac{\gamma}{4(h+v)}, \end{aligned}$$

but this contradicts (0.0.5). Therefore, we know that the probability of choosing a  $hash \in \mathcal{H}_{Good}$  amounts at least  $\frac{\gamma}{8(h+v)}$  where the probability is taken over a choice of  $hash$ .

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<sup>2</sup>For  $X = \sum_{i=1}^N X_i$  and  $0 < \delta \leq 1$  we use the Chernoff bounds in the form  $\Pr[X \geq (1 + \delta)\mathbb{E}[X]] \leq e^{-\mathbb{E}[X]\delta^2/3}$  and  $\Pr[X \leq (1 - \delta)\mathbb{E}[X]] \leq e^{-\mathbb{E}[X]\delta^2/2}$ .

We show that **FindHash** picks in one of its iteration  $hash \in \mathcal{H}_{Good}$  almost surely. Let  $K$  be the number of iterations of the outer loop of **FindHash** and  $Y_i$  be a random variable for the event that in the  $i$ -th iteration of the outer loop  $hash \notin \mathcal{H}_{Good}$  is picked. We conclude using  $\Pr_{hash \leftarrow \mathcal{H}}[hash \in \mathcal{H}_{Good}] \geq \frac{\gamma}{8(g+v)}$  and  $K \leq \frac{32(h+v)^2}{\gamma^2}$  that

$$\Pr_{hash \leftarrow \mathcal{H}} \left[ \bigcap_{1 \leq i \leq K} Y_i \right] \leq \left( 1 - \frac{\gamma}{8(h+v)} \right)^K \leq e^{-\frac{\gamma}{8(h+v)}K} \leq e^{-\frac{4(h+v)}{\gamma}}. \quad \square$$

**Circuit**  $\tilde{C}_2^{\Gamma_H, C_2, hash}(x, \rho)$

**Oracle:** A hint circuit  $\Gamma_H$ , a circuit  $C_2$ ,  
a function  $hash : Q \rightarrow \{0, 1, \dots, 2(h+v) - 1\}$ .

**Input:** Bitstrings  $x \in \{0, 1\}^*$ ,  $\rho \in \{0, 1\}^*$ .

**Output:** A tuple  $(q, y)$ .

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Run  $C_2^{(\cdot, \cdot)}(x, \rho)$ 
  if  $C_2^{(\cdot, \cdot)}(x, \rho)$  asks a hint query on  $q$  then
    if  $hash(q) = 0$  then
      return  $\perp$ 
    else
      answer the query of  $C_2^{(\cdot, \cdot)}(x, \rho)$  using  $\Gamma_H(q)$ 

  if  $C_2^{(\cdot, \cdot)}(x, \rho)$  asks a verification query  $(q, y)$  then
    if  $hash(q) = 0$  then
      return  $(q, y)$ 
    else
      answer the verification query of  $C_2^{(\cdot, \cdot)}(x, \rho)$  with 0

return  $\perp$ 

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Given  $C = (C_1, C_2)$  we define a circuit  $\tilde{C} = (C_1, \tilde{C}_2)$ . Every hint query  $q$  asked by  $\tilde{C}$  is such that  $hash(q) \neq 0$ . Furthermore,  $\tilde{C}$  asks no verification queries, instead it returns  $\perp$  or  $(q, y)$  such that  $hash(q) = 0$ .

We say that for a fixed  $\pi, \rho$  the circuit  $\tilde{C}$  succeeds if for  $x := \langle P(\pi), C_1(\rho) \rangle_{trans}$ ,  $(\Gamma_V, \Gamma_H) := \langle P(\pi), C_1(\rho) \rangle_P$  we have

$$\Gamma_V(\tilde{C}_2^{\Gamma_H, C_2, hash}(x, \rho)) = 1.$$

**Lemma 1.5** *For fixed  $P, C$  and  $hash$  the following statement is true*

$$\Pr_{\pi, \rho}[CanonicalSuccess^{P, C, hash}(\pi, \rho) = 1] \leq \Pr_{\substack{\pi, \rho \\ x := \langle P(\pi), C_1(\rho) \rangle_{trans} \\ (\Gamma_V, \Gamma_H) := \langle P(\pi), C_1(\rho) \rangle_P}} [\Gamma_V(\tilde{C}_2^{\Gamma_H, C_2, hash}(x, \rho)) = 1]$$

**Proof.** If for some fixed  $\pi$ ,  $\rho$  and  $hash$  the circuit  $C$  succeeds canonically, then for the same  $\pi$ ,  $\rho$  and  $hash$  also  $\tilde{C}$  succeeds. Using this observation, we conclude that

$$\begin{aligned}
& \Pr_{\pi, \rho} \left[ CanonicalSuccess^{P, C, hash}(\pi, \rho) = 1 \right] \\
&= \mathbb{E}_{\pi, \rho} \left[ CanonicalSuccess^{P, C, hash}(\pi, \rho) = 1 \right] \\
&\leq \mathbb{E}_{\pi, \rho} \left[ \Gamma_V(\tilde{C}_2^{\Gamma_H, C_2, hash}(x, \rho)) = 1 \right] \\
&\quad x := \langle P(\pi), C_1(\rho) \rangle_{trans} \\
&\quad (\Gamma_V, \Gamma_H) := \langle P(\pi), C_1(\rho) \rangle_P \\
&\leq \Pr_{\pi, \rho} \left[ \Gamma_V(\tilde{C}_2^{\Gamma_H, C_2, hash}(x, \rho)) = 1 \right] \\
&\quad x := \langle P(\pi), C_1(\rho) \rangle_{trans} \\
&\quad (\Gamma_V, \Gamma_H) := \langle P(\pi), C_1(\rho) \rangle_P
\end{aligned}$$

□

**Lemma 1.6 (Security amplification of a dynamic weakly verifiable puzzle with respect to hash.)** For fixed  $P^{(1)}$  there exists an algorithm  $Gen$  that takes as input parameters  $\varepsilon, \delta, n, k$ , and outputs a circuit  $D := (D_1, D_2)$  such that the following holds:  
If  $\tilde{C} := (C_1, \tilde{C}_2)$  with oracle access to a solver circuit  $C := (C_1, C_2)$  for  $P^{(g)}$  is such that

$$\Pr_{\substack{\pi^{(k)}, \rho \\ x := \langle P^{(g)}(\pi^{(k)}), C_1(\rho) \rangle_{trans} \\ (\Gamma_H^{(k)}, \Gamma_V^{(g)}) := \langle P^{(g)}(\pi^{(k)}), C_1(\rho) \rangle_{P^{(g)}}}} \left[ \Gamma_V^{(g)}(\tilde{C}_2^{\Gamma_H^{(k)}, C_2, hash}(x, \rho)) = 1 \right] \geq \Pr_{u \leftarrow \mu_\delta^k} [g(u) = 1] + \varepsilon,$$

then  $D$  satisfies almost surely

$$\Pr_{\pi, \rho} \left[ \Gamma_V(D_2^{P^{(1)}, \tilde{C}, hash, g, \Gamma_V, \Gamma_H}(x, \rho)) = 1 \right] \geq (\delta + \frac{\varepsilon}{6k}).$$

$x := \langle P^{(1)}(\pi), D_1^{P^{(1)}, \tilde{C}}(\rho) \rangle_{trans}$   
 $(\Gamma_H, \Gamma_V) := \langle P^{(1)}(\pi), D_1^{P^{(1)}, \tilde{C}}(\rho) \rangle_{P^{(1)}}$

Additionally,  $Gen$  requires oracle access to  $g$ ,  $P^{(1)}$ ,  $\tilde{C}$ . Furthermore,  $D$  asks at most  $\frac{6k}{\varepsilon} \log(\frac{6k}{\varepsilon}) h$  hint queries and no verification queries. Finally,  $Size(D) \leq Size(C) \frac{6k}{\varepsilon}$  and  $Time(Gen) = poly(k, \frac{1}{\varepsilon}, n, v, h)$ .

Before proving Lemma 1.6 we define additional algorithms that are later used by  $Gen$ . First, we are interested in the probability that for  $u \leftarrow \mu_\delta^k$  and a bit  $b \in \{0, 1\}$  the function  $g$  with the first input bit set to  $b$  takes value 1. The estimate of this probability is calculated by the algorithm *EstimateFunctionProbability*.

#### EstimateFunctionProbability<sup>g</sup>( $b, k, \varepsilon, \delta$ )

**Oracle:** A function  $g : \{0, 1\}^k \rightarrow \{0, 1\}$ .

**Input:** A bit  $b \in \{0, 1\}$ , parameters  $k, \varepsilon, \delta$ .

**Output:** An estimate  $\tilde{g}$  of  $\Pr_{u \leftarrow \mu_\delta^k} [g(b, u_2, \dots, u_k) = 1]$ .

**for**  $i := 1$  **to**  $\frac{64^2}{\varepsilon^2} n$  **do:**

$u \leftarrow \mu_\delta^{(k)}$

$g_i := g(b, u_2, \dots, u_k)$

**return**  $\frac{\varepsilon^2}{64^2 n} \sum_{i=1}^{\frac{64^2}{\varepsilon^2} n} g_i$

**Lemma 1.7** *The procedure **EstimateFunctionProbability**<sup>g</sup>(b, k, ε, δ) outputs an estimate  $\tilde{g}$  of  $\Pr_{u \leftarrow \mu_\delta^k}[g(b, u_2, \dots, u_k) = 1]$  where  $b \in \{0, 1\}$  such that  $|\tilde{g} - \Pr_{u \leftarrow \mu_\delta^k}[g(b, u_2, \dots, u_k) = 1]| \leq \frac{\varepsilon}{8k}$  almost surely.*

**Proof.** We define independent, identically distributed binary random variables  $K_1, K_2, \dots, K_{\frac{64k^2}{\varepsilon^2}n}$  such that for each  $1 \leq i \leq \frac{64k^2}{\varepsilon^2}n$  the random variable  $K_i$  equals  $g_i$ . We use the Chernoff bound to obtain <sup>3</sup>

$$\Pr \left[ \left| \left( \frac{\varepsilon^2}{64k^2n} \sum_{i=1}^{\frac{64k^2}{\varepsilon^2}n} K_i \right) - \mathbb{E}[K_i] \right| \geq \frac{\varepsilon}{8k} \right] \leq 2 \cdot e^{-n/3}. \quad \square$$

The next algorithm **EvaluatePuzzles**<sup>P<sup>(1)</sup>, P<sup>(g)</sup>,  $\tilde{C}$ , hash</sup>( $\pi^{(k)}$ ,  $\rho$ ) evaluates which of  $k$  puzzles of the  $k$ -wise direct product defined by  $P^{(g)}(\rho)$  are solved successfully by  $\tilde{C}(\rho)$ . To decide whether the  $i$ -th puzzle of the  $k$ -wise direct product is solved successfully we need to gain access to verification oracle for the puzzle generated in the  $i$ -th round. Therefore, in the algorithm **EvaluatePuzzles** we use  $P^{(1)}$ , and invoke it  $k$  times to simulate the interaction with  $C_1(\rho)$ . We introduce additional notation. Let us denote by  $\langle P^{(1)}(\pi_i), C_1(\rho) \rangle^i$  the execution of the  $i$ -th round of the simulation, and by  $\langle P^{(1)}(\pi_i), C_1(\rho) \rangle_{P^{(1)}}^i$  the output of  $P^{(1)}(\pi_i)$  in the  $i$ -th round.

**EvaluatePuzzles**<sup>P<sup>(1)</sup>, P<sup>(g)</sup>,  $\tilde{C}$ , hash</sup>( $\pi^{(k)}$ ,  $\rho$ )

**Oracle:** Problem posers  $P^{(1)}$ ,  $P^{(g)}$ , a circuit  $\tilde{C} = (C_1, \tilde{C}_2)$ ,  
a function  $hash : Q \rightarrow \{0, 1, \dots, 2(h + v) - 1\}$ .

**Input:** Bitstrings  $\pi^{(k)} \in \{0, 1\}^{kn}$ ,  $\rho \in \{0, 1\}^*$ .

**Output:** A tuple  $(c_1, \dots, c_k) \in \{0, 1\}^k$ .

**Run**  $\langle P^{(g)}(\pi^{(k)}), C_1(\rho) \rangle$

$(\Gamma_V^{(g)}, \Gamma_H^{(k)}) := \langle P^{(g)}(\pi^{(k)}), C_1(\rho) \rangle_{P^{(g)}}$

$x := \langle P^{(g)}(\pi^{(k)}), C_1(\rho) \rangle_{\text{trans}}$

$(q, y_1, \dots, y_k) := \tilde{C}_2^{\Gamma_H^{(k)}, C_2, hash}(x, \rho)$

**for**  $i := 1$  **to**  $k$  **do:** //simulate  $k$  rounds of interaction

$(\Gamma_V^i, \Gamma_H^i) := \langle P^{(1)}(\pi_i), C_1(\rho) \rangle_{P^{(1)}}^i$

$(c_1, \dots, c_k) := (\Gamma_V^1(q, y_1), \dots, \Gamma_V^k(q, y_k))$

**return**  $(c_1, \dots, c_k)$

All puzzles used by the procedure **EvaluatePuzzles** are generated internally and the algorithm can answer itself all queries to hint and verification oracle.

For fixed  $\pi^{(k)}, \rho$  let  $(\Gamma_V^{(g)}, \Gamma_H^{(k)}) := \langle P^{(g)}(\pi^{(k)}), C_1(\rho) \rangle_{P^{(g)}}$  and  $x := \langle P^{(g)}(\pi^{(k)}), C_1(\rho) \rangle_{\text{trans}}$ . Additionally, we denote by  $(\Gamma_V^i, \Gamma_H^i)$  the verification and hint circuits generated by  $P^{(1)}(\pi_i)$  in the  $i$ -th round of the simulated interaction with  $C_1(\rho)$ . Finally, for  $(q, y_1, \dots, y_k) := \tilde{C}_2(x, \rho)$  we denote the output of  $\Gamma_V^i(q, y_i)$  by  $c_i$ .

We are interested in the success probability of  $\tilde{C}$  when the bitstring  $\pi_1$  is fixed to  $\pi^*$ , and the fact whether  $\tilde{C}$  succeeds in solving the first puzzle defined by  $P^{(1)}(\pi_1)$  is neglected, and

<sup>3</sup>For independent Bernoulli distributed random variables  $X_1, \dots, X_n$  with  $X := \sum_{i=1}^n X_i$  and  $0 \leq \delta \leq 1$  we use the Chernoff bound in the form  $\Pr[|X - \mathbb{E}[X]| \geq \delta \mathbb{E}[X]] \leq 2e^{-\mathbb{E}[X]\delta^2/3}$ .



instead the bit  $b \in \{0, 1\}$  is used as the input on the first position to  $g$ . More formally, we define the surplus as

$$S_{\pi^*, b} = \Pr_{\pi^{(k)}, \rho} [g(b, c_2, \dots, c_k) = 1 \mid \pi_1 = \pi^*] - \Pr_{u \leftarrow \mu^{(k)}} [g(b, u_2, \dots, u_k) = 1]. \quad (0.0.9)$$

The algorithm **EstimateSurplus** returns an estimate  $\tilde{S}_{\pi^*, b}$  for  $S_{\pi^*, b}$ .

**EstimateSurplus** <sup>$P^{(1)}, P^{(g)}, \tilde{C}, g, hash$</sup> ( $\pi^*, b, k, \varepsilon, \delta$ )

**Oracle:** Problem posers  $P^{(1)}, P^{(g)}$ , a circuit  $\tilde{C}$ , a function  $g : \{0, 1\}^k \rightarrow \{0, 1\}$   
a function  $hash : Q \rightarrow \{0, 1, \dots, 2(h + v) - 1\}$ .

**Input:** A bistring  $\pi^* \in \{0, 1\}^n$ , a bit  $b \in \{0, 1\}$ , parameters  $k, \varepsilon, \delta$ .

**Output:** An estimate  $\tilde{S}_{\pi^*, b}$  for  $S_{\pi^*, b}$ .

$\tilde{g}_b := \mathbf{EstimateFunctionProbability}^g(b, k, \varepsilon, \delta)$

**for**  $i := 1$  **to**  $\frac{64k^2}{\varepsilon^2}n$  **do:**

$(\pi_2, \dots, \pi_k) \xleftarrow{\$} \{0, 1\}^{(k-1)n}$

$\rho \xleftarrow{\$} \{0, 1\}^*$

$(c_1, \dots, c_k) := \mathbf{EvaluatePuzzles}^{P^{(1)}, P^{(g)}, \tilde{C}, hash}(\pi^*, \pi_2, \dots, \pi_k, \rho)$

$\tilde{s}_{\pi^*, b}^i := g(b, c_2, \dots, c_k)$

**return**  $\left( \frac{\varepsilon^2 n}{64k^2} \sum_{i=1}^{\frac{64k^2}{\varepsilon^2}n} \tilde{s}_{\pi^*, b}^i \right) - \tilde{g}_b$

**Lemma 1.8** *The estimate  $\tilde{S}_{\pi^*, b}$  returned by **EstimateSurplus** differs from  $S_{\pi^*, b}$  by at most  $\frac{\varepsilon}{4k}$  almost surely.*

**Proof.** We use the union bound and similar argument as in Lemma 1.7 which yields that

$\frac{\varepsilon^2}{16k^2n} \sum_{i=1}^{\frac{16k^2}{\varepsilon^2}n} \tilde{s}_{\pi^*, b}^i$  differs from  $\mathbb{E}[g(b, c_2, \dots, c_k)]$  by at most  $\frac{\varepsilon}{8k}$  almost surely. Together, with Lemma 1.7 we conclude that the surplus estimate returned by **EstimateSurplus** differs from  $S_{\pi^*, b}$  by at most  $\frac{\varepsilon}{4k}$  almost surely.  $\square$

We are ready to define the circuit  $D$  and the algorithm  $Gen$ .

**Circuit**  $D = (D_1, D_2)(\rho)$

**Phase I**  $D_1^{P^{(1)}, \tilde{C}}(\rho)$

**Oracle:** A circuit  $\tilde{C} = (C_1, \tilde{C}_2)$ , a poser  $P^{(1)}$ .

**Input:** A bitstring  $\rho \in \{0, 1\}^*$ .

Interact with the problem poser  $\langle P^{(1)}, C_1(\rho) \rangle^1$ .

Let  $(\Gamma_V^*, \Gamma_H^*) := \langle P^{(1)}, C_1(\rho) \rangle_{P^{(1)}}^1$ .

Let  $x^* := \langle P^{(1)}, C_1(\rho) \rangle$ .

**return**  $x^*$

**Phase II**  $D_2^{P^{(1)}, \tilde{C}, hash, g, \Gamma_V^*, \Gamma_H^*}(x^*, \rho)$

**Oracle:** A poser  $P^{(1)}$ , a solver circuit  $\tilde{C} = (C_1, \tilde{C}_2)$ ,  
functions  $hash : Q \rightarrow \{0, 1, \dots, 2(h + v) - 1\}$ ,  $g : \{0, 1\}^k \rightarrow \{0, 1\}$ ,

verification and hint circuits  $\Gamma_V^*, \Gamma_H^*$  produced by  $P^{(1)}$  in the Phase I.  
**Input:** Bitstrings  $x^* \in \{0, 1\}^*$ ,  $\rho \in \{0, 1\}^*$ .  
**Output:** A verification query  $(q, y^*)$ .

---

**for** at most  $\frac{6k}{\varepsilon} \log(\frac{6k}{\varepsilon})$  iterations **do**:  
 $\pi^{(k-1)} \leftarrow$  read  $(k-1) \cdot n$  bits from  $\rho$   
**for**  $i := 2$  **to**  $k$  **do**: // Finish remaining  $k-1$  interactions.  
    Simulate  $\langle P^{(1)}(\pi_i), C_1(\rho) \rangle$   
     $x_i := \langle P^{(1)}(\pi_i), C_1(\rho) \rangle_{\text{trans}}$   
     $(\Gamma_V^i, \Gamma_H^i) := \langle P^{(1)}(\pi_i), C_1(\rho) \rangle_{P^{(1)}}$   
 $\Gamma_V^{(g)} := g(\Gamma_V^*, \Gamma_V^2, \dots, \Gamma_V^k)$   
 $\Gamma_H^{(k)} := (\Gamma_H^*, \Gamma_H^2, \dots, \Gamma_H^k)$   
 $(q, y^*, y_2, \dots, y_k) := \tilde{C}^{\Gamma_V^{(g)}, \Gamma_H^{(k)}, C, \text{hash}}((x^*, x_2, \dots, x_k), \rho)$   
 $(c^*, c_2, \dots, c_k) := (\Gamma_V^*(q, y^*), \Gamma_V^2(q, y_2), \dots, \Gamma_V^k(q, y_k))$   
**if**  $g(1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0$  **then**  
    Make a verification query  $(q, y^*)$   
    **return**  $(q, y^*)$   
**return**  $\perp$

---

**Algorithm**  $\text{Gen}^{P^{(1)}, P^{(g)}, \tilde{C}, g, \text{hash}}(\varepsilon, \delta, n, v, h, k)$

**Oracle:** Posers  $P^{(1)}, P^{(g)}$ , circuit  $\tilde{C}$ , functions  $g : \{0, 1\}^k \rightarrow \{0, 1\}$ ,  
 $\text{hash} : Q \rightarrow \{0, 1, \dots, 2(h+v) - 1\}$ .  
**Input:** Parameters  $\varepsilon, \delta, n, k$ , the number of verification  $v$  and hint  $h$  queries.  
**Output:** A circuit  $D$ .

---

**for**  $i := 1$  **to**  $\frac{6k}{\varepsilon}n$  **do**:  
 $\pi^* \xleftarrow{\$} \{0, 1\}^n$   
 $\tilde{S}_{\pi^*, 0} := \text{EstimateSurplus}^{P^{(1)}, P^{(g)}, \tilde{C}, g, \text{hash}}(\pi^*, 0)$   
 $\tilde{S}_{\pi^*, 1} := \text{EstimateSurplus}^{P^{(1)}, P^{(g)}, \tilde{C}, g, \text{hash}}(\pi^*, 1)$   
**if**  $\exists b \in \{0, 1\} : \tilde{S}_{\pi^*, b} \geq (1 - \frac{3}{4k})\varepsilon$  **then**  
    Let  $C'_1$  be as  $C_1$  except the first round of interaction between  $C_1$  and  $P^{(g)}$  which is simulated internally by using  $P^{(1)}(\pi^*)$   
    Let  $C'_2$  be as  $C_2$  except the solution for the first puzzle which is discarded.  
     $C' := (C'_1, C'_2)$   
     $g'(b_2, \dots, b_k) := g(b, b_2, \dots, b_k)$   
    **return**  $\text{Gen}^{C', P^{(1)}, g', \text{hash}}(\varepsilon, \delta, n, v, h, k-1)$   
// all estimates are lower than  $(1 - \frac{3}{4k})\varepsilon$   
**return**  $D^{P^{(1)}, \tilde{C}, g, \text{hash}}$

**Proof (Lemma 1.6).** First let us consider the case where  $k = 1$ . The function  $g : \{0, 1\} \rightarrow \{0, 1\}$  is either the identity or a constant function. If  $g$  is the identity function, then the circuit  $D^{P^{(1)}, \tilde{C}, g, \text{hash}}$  returned by  $\text{Gen}$  directly uses  $\tilde{C}$  to find a solution. From the assumptions of Lemma 1.6 we know that  $\tilde{C}$  succeeds with probability at least  $\delta + \varepsilon$ . Hence,  $D^{P^{(1)}, \tilde{C}, g, \text{hash}}$  trivially satisfies the statement. When  $g$  is a constant function the statement is vacuously true.

The general case is more involved. We distinguish two possibilities. If  $\text{Gen}$  manages to find in one of the iterations  $\pi^*$  such that an estimate  $\tilde{S}_{\pi^*, b} \geq (1 - \frac{3}{4k})\varepsilon$ , then we define a new monotone function  $g'(b_2, \dots, b_k) := g(b, b_2, \dots, b_k)$ , and a circuit  $\tilde{C}' = (C'_1, \tilde{C}'_2)$ , where

$C'_1$  first internally simulates the interaction between  $C_1$  and  $P^{(1)}(\pi^*)$ , and then interacts with  $P(g')$ . The circuit  $\tilde{C}'_2$  is defined as  $\tilde{C}_2$  with the solution for the first puzzle discarded. In this case the surplus estimate is greater or equal  $1 - \frac{3}{4k}\varepsilon$ , and using Lemma 1.8 we conclude that  $S_{\pi^*,b} \geq \tilde{S}_{\pi^*,b} - \frac{\varepsilon}{4k} \geq 1 - \frac{\varepsilon}{k}$  almost surely. The circuit  $\tilde{C}$  succeeds in solving the  $(k-1)$ -wise direct product of puzzles with probability at least  $\Pr_{u \leftarrow \mu_\delta^{k-1}}[g'(u_1, \dots, u_{k-1})] + \varepsilon$ . We see that in this case  $\tilde{C}'$  satisfies the conditions of Lemma 1.6 for the  $(k-1)$ -wise direct product of puzzles, and we recurse using  $g'$  and  $\tilde{C}'$ .

If all estimates are less than  $(1 - \frac{3}{4k})\varepsilon$ , then intuitively  $C$  does not succeeds on the remaining  $k-1$  puzzles with the higher probability than an algorithm that solves each puzzle independently with probability  $\delta$ . However, from the assumption we know that on all  $k$  puzzles the success probability of  $\tilde{C}$  is higher. Therefore, it is likely that the first puzzle is correctly solved unusual often. It remains to prove that this intuition is indeed correct. Let  $\mathcal{G}_b := \{b_1, b_2, \dots, b_k : g(b, b_2, \dots, b_k) = 1\}$ . We observe that

$$\begin{aligned} \Pr_{u \leftarrow \mu_\delta^k} [u \in G_b] &= \Pr_{u \leftarrow \mu_\delta^k} [g(b, u_2, \dots, u_k) = 1] \\ \Pr_{\pi^{(k)}, \rho} [c \in G_b] &= \Pr_{\pi^{(k)}, \rho} [g(b, c_2, \dots, c_k) = 1]. \end{aligned} \quad (0.0.10)$$

We fix  $\pi^*$  and use (0.0.9), (0.0.10) to obtain

$$\Pr_{u \leftarrow \mu_\delta^k} [u \in G_1] - \Pr_{u \leftarrow \mu_\delta^k} [u \in G_0] = \Pr_{\pi^{(k)}, \rho} [c \in G_1 \mid \pi_1 = \pi^*] - \Pr_{\pi^{(k)}, \rho} [c \in G_0 \mid \pi_1 = \pi^*] - (S_{\pi^*,1} - S_{\pi^*,0}) \quad (0.0.11)$$

Since  $g$  is monotone, we have that  $\mathcal{G}_0 \subseteq \mathcal{G}_1$ , and can write (0.0.11) as

$$\Pr_{u \leftarrow \mu_\delta^k} [u \in \mathcal{G}_1 \setminus \mathcal{G}_0] = \Pr_{\pi^{(k)}, \rho} [c \in \mathcal{G}_1 \setminus \mathcal{G}_0 \mid \pi_1 = \pi^*] - (S_{\pi^*,1} - S_{\pi^*,0}). \quad (0.0.12)$$

Still fixing  $\pi_1 = \pi^*$  we multiply both sides of (0.0.12) by

$$\frac{\Pr_{\rho} [\Gamma_V(D_2(x, \rho)) = 1]}{\Pr_{u \leftarrow \mu_\delta^k} [u \in \mathcal{G}_1 \setminus \mathcal{G}_0]} \cdot \frac{x := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}}}{(\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}}$$

which yields

$$\begin{aligned} & \Pr_{\rho} [\Gamma_V(D_2(x, \rho)) = 1] \\ & \frac{x := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}}}{(\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}} \\ &= \Pr_{\rho} [\Gamma_V(D_2(x, \rho)) = 1] \Pr_{\pi^{(k)}, \rho} [c \in \mathcal{G}_1 \setminus \mathcal{G}_0 \mid \pi = \pi^*] \frac{1}{\Pr_{u \leftarrow \mu_\delta^k} [u \in \mathcal{G}_1 \setminus \mathcal{G}_0]} \\ & \quad - \Pr_{\rho} [\Gamma_V(D_2(x, \rho)) = 1] (S_{\pi^*,1} - S_{\pi^*,0}) \frac{1}{\Pr_{u \leftarrow \mu_\delta^k} [u \in \mathcal{G}_1 \setminus \mathcal{G}_0]} \quad (0.0.13) \\ & \frac{x := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}}}{(\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}} \end{aligned}$$

We make use of the fact that the event  $c \in \mathcal{G}_1 \setminus \mathcal{G}_0$  implies  $D_2(x^*, \rho) \neq \perp$ , and write the first summand of (0.0.13) as

$$\begin{aligned} & \Pr_{\rho} [\Gamma_V(D_2(x, \rho)) = 1] \Pr_{\pi^{(k)}, \rho} [c \in \mathcal{G}_1 \setminus \mathcal{G}_0 \mid \pi_1 = \pi^*] \\ & \frac{x := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}}}{(\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}} \\ &= \Pr_{\rho} [D_2(x, \rho) \neq \perp] \Pr_{\pi^{(k)}, \rho} [c_1 = 1 \mid c \in \mathcal{G}_1 \setminus \mathcal{G}_0, \pi_1 = \pi^*] \Pr_{\pi^{(k)}, \rho} [c \in \mathcal{G}_1 \setminus \mathcal{G}_0 \mid \pi_1 = \pi^*] \\ & \frac{x := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}}}{(\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}} \quad (0.0.14) \end{aligned}$$

Now we consider two cases: if  $\Pr_{\pi^{(k)}, \rho} [c \in \mathcal{G}_1 \setminus \mathcal{G}_0 \mid \pi_1 = \pi^*] \leq \frac{\varepsilon}{6k}$  then

$$\Pr_{\pi^{(k)}} [c_1 = 1 \mid c \in \mathcal{G}_1 \setminus \mathcal{G}_0, \pi_1 = \pi^*] \Pr_{\pi^{(k)}} [c \in \mathcal{G}_1 \setminus \mathcal{G}_0 \mid \pi_1 = \pi^*] \leq \frac{\varepsilon}{6k}, \quad (0.0.15)$$

for  $\Pr_{\pi^{(k)}, \rho} [c \in \mathcal{G}_1 \setminus \mathcal{G}_0] > \frac{\varepsilon}{6k}$  the circuit  $D_2$  outputs  $\perp$  if and only if it fails in all  $\frac{6k}{\varepsilon} \log(\frac{6k}{\varepsilon})$  iterations to find  $\pi^{(k)}$  such that  $g(1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0$  (i.e. in none of the iterations  $c \in \mathcal{G}_1 \setminus \mathcal{G}_0$ ) which happens with probability

$$\Pr_{\rho} [D_2(x, \rho) = \perp] \leq (1 - \frac{\varepsilon}{6k})^{\frac{6k}{\varepsilon} \log(\frac{6k}{\varepsilon})} \leq \frac{\varepsilon}{6k}. \quad (0.0.16)$$

$x := \langle P^{(1)}(\pi), D_1(\rho) \rangle_{\text{trans}}$

We conclude that in both cases:

$$\begin{aligned} & \Pr_{\rho} [D_2(x, \rho) \neq \perp] \Pr_{\pi^{(k)}, \rho} [c_1 = 1 \mid c \in \mathcal{G}_1 \setminus \mathcal{G}_0, \pi_1 = \pi^*] \Pr_{\pi^{(k)}, \rho} [c \in \mathcal{G}_1 \setminus \mathcal{G}_0 \mid \pi_1 = \pi^*] \\ & \geq \Pr_{\pi^{(k)}, \rho} [c_1 = 1 \mid c \in \mathcal{G}_1 \setminus \mathcal{G}_0, \pi_1 = \pi^*] \Pr_{\pi^{(k)}, \rho} [c \in \mathcal{G}_1 \setminus \mathcal{G}_0 \mid \pi_1 = \pi^*] - \frac{\varepsilon}{6k} \\ & \geq \Pr_{\pi^{(k)}, \rho} [c_1 = 1 \wedge c \in \mathcal{G}_0 \setminus \mathcal{G}_1 \mid \pi_1 = \pi^*] - \frac{\varepsilon}{6k} \\ & = \Pr_{\pi^{(k)}, \rho} [g(c_1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0 \mid \pi_1 = \pi^*] - \frac{\varepsilon}{6k} \\ & = \Pr_{\pi^{(k)}, \rho} [g(c) = 1 \mid \pi_1 = \pi^*] - \Pr_{\pi^{(k)}, \rho} [c \in \mathcal{G}_0 \mid \pi_1 = \pi^*] - \frac{\varepsilon}{6k} \\ & \stackrel{(0.0.9)}{=} \Pr_{\pi^{(k)}, \rho} [g(c_1, c_2, \dots, c_k) = 1 \mid \pi_1 = \pi^*] - \Pr_{u \leftarrow \mu_{\delta}^{(k)}} [u \in \mathcal{G}_0] - S_{\pi^*, 0} - \frac{\varepsilon}{6k}. \end{aligned} \quad (0.0.17)$$

For the second summand of (0.0.13) we show that if we do not recurse, then the majority of the estimates is low almost surely. Let us assume that

$$\Pr_{\pi, \rho} \left[ \left( S_{\pi, 0} \leq (1 - \frac{1}{2k})\varepsilon \right) \wedge \left( S_{\pi, 1} \leq (1 - \frac{1}{2k})\varepsilon \right) \right] < 1 - \frac{\varepsilon}{6k}, \quad (0.0.18)$$

then the algorithm recurses almost surely. Therefore, under the assumption that  $Gen$  does not recurse, we have almost surely

$$\Pr_{\pi, \rho} \left[ \left( S_{\pi, 0} \leq (1 - \frac{1}{2k})\varepsilon \right) \wedge \left( S_{\pi, 1} \leq (1 - \frac{1}{2k})\varepsilon \right) \right] \geq 1 - \frac{\varepsilon}{6k}. \quad (0.0.19)$$

Let us define a set

$$\mathcal{W} = \left\{ \pi : \left( S_{\pi, 0} \leq (1 - \frac{1}{2k})\varepsilon \right) \wedge \left( S_{\pi, 1} \leq (1 - \frac{1}{2k})\varepsilon \right) \right\} \quad (0.0.20)$$

and use  $\mathcal{W}^c$  to denote the complement of  $\mathcal{W}$ . We bound the second summand in (0.0.13)

$$\begin{aligned}
& \mathbb{E}_{\pi^*} [S_{\pi^*,0} + \Pr_{\substack{x:=\langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}} \\ (\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}}} [\Gamma_V(D_2^{\tilde{C}}(x, \rho)) = 1] (S_{\pi^*,1} - S_{\pi^*,0})] \\
&= \mathbb{E}_{\pi^* \in \mathcal{W}^c} [S_{\pi^*,0} + \Pr_{\substack{x:=\langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}} \\ (\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}}} [\Gamma_V(D_2^{\tilde{C}}(x, \rho)) = 1] (S_{\pi^*,1} - S_{\pi^*,0})] \\
&\quad + \mathbb{E}_{\pi^* \in \mathcal{W}} [S_{\pi^*,0} + \Pr_{\substack{x:=\langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}} \\ (\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}}} [\Gamma_V(D_2^{\tilde{C}}(x, \rho)) = 1] (S_{\pi^*,1} - S_{\pi^*,0})] \\
&\leq \frac{\varepsilon}{6k} + \mathbb{E}_{\pi^* \in \mathcal{W}^c} [S_{\pi^*,0} + \Pr_{\substack{x:=\langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}} \\ (\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}}} [\Gamma_V(D_2^{\tilde{C}}(x, \rho)) = 1] ((1 - \frac{1}{2k})\varepsilon - S_{\pi^*,0})] \\
&\leq \frac{\varepsilon}{6k} + 1 - \frac{\varepsilon}{2k} = 1 - \frac{\varepsilon}{3k} \tag{0.0.21}
\end{aligned}$$

We observe that

$$\begin{aligned}
\Pr_{u \leftarrow \mu_\delta^k} [g(u) = 1] &= \Pr[u \in \mathcal{G}_0 \vee (u \in \mathcal{G}_1 \setminus \mathcal{G}_0 \wedge u_1 = 1)] \\
&= \Pr[u \in \mathcal{G}_0] + \Pr[u \in \mathcal{G}_1 \setminus \mathcal{G}_0] \Pr[u_1 = 1]. \tag{0.0.22}
\end{aligned}$$

Finally, we insert (0.0.17) and (0.0.21) into equation (0.0.13) and use (0.0.22) to obtain

$$\Pr_{\substack{x:=\langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}} \\ (\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}}} [\Gamma_V(D_2^{\tilde{C}}(x, \rho)) = 1] \geq \mathbb{E}_{\pi^*} \left[ \frac{\Pr_{\pi^{(k)}} [g(c) = 1 \mid \pi_1 = \pi^*] - \Pr_{u \leftarrow \mu_\delta^k} [u \in \mathcal{G}_0] - (1 - \frac{1}{6k})\varepsilon}{\Pr_{u \leftarrow \mu_\delta^k} [u \in \mathcal{G}_1 \setminus \mathcal{G}_0]} \right].$$

Using the assumptions of Lemma 1.6, we get

$$\begin{aligned}
\Pr_{\substack{x:=\langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{\text{trans}} \\ (\Gamma_V, \Gamma_H) := \langle P^{(1)}(\pi^*), D_1(\rho) \rangle_{P^{(1)}}}} [\Gamma_V(D_2^{\tilde{C}}(x, \rho)) = 1] &\geq \frac{\Pr_{u \leftarrow \mu_\delta^k} [g(u) = 1] + \varepsilon + \Pr_{u \leftarrow \mu_\delta^k} [u \in \mathcal{G}_0] - (1 - \frac{1}{6k})\varepsilon}{\Pr_{u \leftarrow \mu_\delta^k} [u \in \mathcal{G}_1 \setminus \mathcal{G}_0]} \\
&\geq \frac{\varepsilon + \delta \Pr_{u \leftarrow \mu_\delta^k} [u \in \mathcal{G}_1 \setminus \mathcal{G}_0] - (1 - \frac{1}{6k})\varepsilon}{\Pr_{u \leftarrow \mu_\delta^k} [u \in \mathcal{G}_1 \setminus \mathcal{G}_0]} \geq \delta + \frac{\varepsilon}{6k} \tag{0.0.23}
\end{aligned}$$

**Proof (Theorem 1.3).** We show that Theorem 1.3 follows from Lemmas 1.4 and 1.6. First given a solver circuit  $C = (C_1, C_2)$  such that

$$\Pr_{\pi^{(k)}, \rho} [Success^{P^{(g)}, C}(\pi^{(k)}, \rho) = 1] \geq 8(h + v) \left( \Pr_{u \leftarrow \mu_\delta^k} [g(u) = 1] + \varepsilon \right)$$

we apply Lemma 1.4 to find a function *hash* such that

$$\Pr_{\pi^{(k)}, \rho} [CanonicalSuccess^{P^{(g)}, C, hash}(\pi^{(k)}, \rho) = 1] \geq \Pr_{u \leftarrow \mu_\delta^k} [g(u) = 1] + \varepsilon.$$

By Lemma 1.5 we know that it is possible to create a circuit  $\tilde{C} = (C_1, \tilde{C}_2)$  with oracle access to *hash* and  $C$  such that

$$\Pr_{\substack{x:=\langle P(\pi), C_1(\rho) \rangle_{\text{trans}} \\ (\Gamma_V^{(g)}, \Gamma_H^{(k)}) := \langle P(\pi), C_1(\rho) \rangle_P}} [\Gamma_V^{(g)}(\tilde{C}_2^{\Gamma_H^{(k)}, C_2, hash}(x, \rho)) = 1] \geq \Pr_{u \leftarrow \mu_\delta^k} [g(u) = 1] + \varepsilon$$

Now, we apply Lemma 1.6 for the function *hash* and the circuit  $\tilde{C}$  and obtain a circuit  $D$  such that

$$\Pr_{\substack{\pi, \rho \\ x := \langle P^{(1)}(\pi), D_1(\rho) \rangle_{\text{trans}} \\ (\Gamma_H, \Gamma_V) := \langle P^{(1)}(\pi), D_1(\rho) \rangle_{P^{(1)}}}} [\Gamma_V(D_2(x, \rho)) = 1] \geq (\delta + \frac{\varepsilon}{6k}). \quad (0.0.24)$$

Finally, we create a circuit  $\tilde{D}$  that first runs the circuit  $D$ , and then make a verification query using  $(q, y)$  returned by  $D$ . We know that probability that the verification query  $(q, y)$  succeeds amounts at least  $(\delta + \frac{\varepsilon}{6k})$ . Therefore, we have

$$\Pr_{\pi, \rho} \left[ \text{Success}^{P^{(1)}, \tilde{D}}(\pi, \rho) = 1 \right] \geq (\delta + \frac{\varepsilon}{6k}). \quad \square$$