

We write $u \leftarrow \mu_\delta^k$ to denote a tuple u of length k which each element is independently drawn from the Bernoulli distribution with parameter δ .

We denote the protocol execution between probabilistic algorithms A and B by $\langle A, B \rangle$. Additionally, the output of A in such a protocol execution is denoted by $\langle A, B \rangle_A$.

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 $P(\pi)$ to denote the execution of P with the randomness fixed to π , and $S_1(\rho)$ to denote that in the execution of the first phase the randomness of S is fixed to ρ . The poser $P(\pi)$ and the solver $S_1(\rho)$ interacts. As the result of the interaction $P(\pi)$ outputs circuits Γ_V , Γ_H , and $x \in \{0, 1\}^*$. The algorithm $S_1(\rho)$ produces no output. The circuit Γ_V takes as input $q \in Q$, an answer $y \in \{0, 1\}^*$, and outputs a bit. An answer (q, y) is a correct solution if and only if $\Gamma_V(q, y) = 1$. The circuit Γ_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 , and has oracle access to Γ_V and Γ_H . The execution of S_2 with the input x and the randomness fixed to ρ is denoted by $S_2(x, \rho)$. The queries of S_2 to Γ_V are called verification queries, and to Γ_H hint queries. The algorithm S_2 can ask 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 $P^{(g)}(\pi^{(k)})$ to denote the execution of $P^{(g)}$ with the randomness fixed to $\pi^{(k)} := (\pi_1, \dots, \pi_k)$. Let $S := (S_1, S_2)$ be a solver for $P^{(g)}$ as in Definition 1.1. The algorithm $P^{(g)}$ sequentially interacts in k rounds with S_1 such that in the i th round $(x_i, \Gamma_V^i, \Gamma_H^i) := \langle P^{(1)}(\pi_i), S_1(\rho) \rangle_{P^{(g)}}$. Finally, $P^{(g)}$ outputs: a verification circuit

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

a hint circuit

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

and a puzzle $x^{(k)} := (x_1, \dots, x_k)$.

Let C be a random circuit that corresponds to a solver S in Definition 1.1. Similarly as for two phase algorithm, we write $C := (C_1, C_2)$ to denote that C in the first phase uses C_1 , and in the second phase C_2 . Let C be any solver for $P^{(1)}$ defined as in Definition 1.1. A verification query (q, y) of C for which a hint query on this q has been asked before can not be a successfully verification query. Therefore, without loss of generality we make an assumption that C does not ask verification queries on $q \in Q$, for which a hint query has been asked before.

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

Oracle: A problem poser P , a solver circuit $C^{(\cdot, \cdot)}$.

Input: Bitstrings π, ρ .

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

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

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

If $C_2^{\Gamma_V, \Gamma_H}$ asks a verification query (q, y) and $\Gamma_V(q, y) = 1$ **then**

return 1

return 0

The success probability of C in solving a puzzle defined by P in the experiment $Success$ is

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

TODO: Do the circuit bound is well defined?

TODO: What happens when $8(h + v) \left(\Pr_{\mu \leftarrow \mu_\delta^k} [g(\mu) = 1] + \varepsilon \right) \geq 1$ then the formula does not work

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 the poser for the k -wise direct product of $P^{(1)}$. There exists a probabilistic algorithm $Gen(C, g, \varepsilon, \delta, n, v, h)$ which takes as input: a solver circuit C for the puzzle posed by $P^{(g)}$, a monotone function $g : \{0, 1\}^k \rightarrow \{0, 1\}$, parameters ε, δ, n , the number of verification queries v , and hint queries h asked by C , and outputs a random circuit D such that the following holds:
If C is such that*

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

then D satisfies almost surely

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

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

The Theorem 1.3 implies that if there is no good solver for a puzzle defined by $P^{(1)}$, then a good solver for a k -wise direct product of $P^{(1)}$ does not exist.

TODO: Write it more clearly, give more intuition about the function $g()$ and then why we can approach the problem in this way.

The idea of the algorithm Gen is to find $k - 1$ puzzles and a position for an input puzzle x , such that when C runs with these $k - 1$ puzzles and x placed on the right position, then x is often successfully solved. To find such a position for x and $k - 1$ puzzles Gen runs C repeatedly on different $k - 1$ tuples of puzzles. Even if Gen finds a set of puzzles and a position for x , such that x is often solved it may still not constitute a valid solution, as an additional requirement is needed that this happens often for q on which a hint query was not asked before. To satisfy this requirement we split Q .

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

hint query is ever asked on this q . In the experiment *CanonicalSuccess* a circuit C succeeds if and only if it ask a verification query on $q \in P_{hash}$ and no hint query is asked on $q \in P_{hash}$. Finally, Lemma 1.4 states that it is possible to find $hash$ such that success probability of C in the experiment *CanonicalSuccess* is not much worser than in the experiment *Success*. In the experiment *CanonicalSuccess* 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.

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

Oracle: A problem poser P . A solver circuit $C^{(\cdot, \cdot)}$.

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

Input: Bitstrings: π, ρ .

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

$(x, \Gamma_V, \Gamma_H) := P(\pi)$

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

Let (q_j, y_j) be the first verification query such that $C^{\Gamma_V, \Gamma_H}(q_j, y_j) = 1$, or an arbitrary verification query if C does not succeed.

If $(\forall i < j : q_i \notin P_{hash})$ and $q_j \in P_{hash}$ and $\Gamma_V(q_j, y_j) = 1$

return 1

else

return 0

Similarly as for the experiment *Success*, we define the success probability of C with respect to a function $hash$ in the experiment *CanonicalSuccess* in solving a puzzle defined by P as

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

For fixed $hash$ and $P^{(1)}$ a canonical success of C for $\pi^{(k)}, \rho$ is a situation when $CanonicalSuccess^{P^{(g)}, C^{(\cdot, \cdot)}, hash}(\pi^{(k)}, \rho) = 1$. We show that if for a fixed $P^{(1)}$ a solver circuit C often succeeds in the experiment *Success* for $P^{(g)}$, then it also often successful in the experiment *CanonicalSuccess* for $P^{(g)}$.

Lemma 1.4 (Success probability in solving a k -wise direct product of $P^{(1)}$ with respect to a function $hash$.) For fixed $P^{(1)}$ let C succeed in the experiment *Success* for $P^{(g)}$ with probability γ , asking at most h hint queries and v verification queries. There exists a probabilistic algorithm, with oracle access to C and $P^{(g)}$, that runs in time $O((h+v)^4/\gamma^4)$, and with high probability outputs a function $hash : Q \rightarrow \{0, \dots, 2(h+v) - 1\}$ such that success probability of C with respect to P_{hash} in the experiment *CanonicalSuccess* is at least $\frac{\gamma}{8(h+v)}$.

Proof. We fix $P^{(1)}$ and C in the whole proof. Let \mathcal{H} be a family of pairwise independent hash functions $Q \rightarrow \{0, 1, \dots, 2(h+v) - 1\}$. For all $i \neq j \in \{1, \dots, (h+v)\}$ and $k, l \in \{0, 1, \dots, 2(h+v) - 1\}$ by pairwise independence property of \mathcal{H} , we have

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

Let $\pi^{(k)}, \rho$ be fixed. We consider the experiment *CanonicalSuccess* for $P^{(g)}$. in which we define a binary random variable X for the event that $hash(q_j) = 0$, and for every query q_i asked before $q_j : hash(q_i) \neq 0$. Conditioned on the event $hash(q_i) = 0$, we get

$$\begin{aligned} \Pr_{hash \leftarrow \mathcal{H}}[X = 1] &= \Pr_{hash \leftarrow \mathcal{H}}[hash(q_j) = 0 \wedge \forall i < j : hash(q_i) \neq 0] \\ &= \Pr_{hash \leftarrow \mathcal{H}}[\forall i < j : hash(q_i) \neq 0 \mid hash(q_j) = 0] \Pr_{hash \leftarrow \mathcal{H}}[hash(q_j) = 0]. \end{aligned}$$

Now we use (0.0.3) twice and obtain

$$\begin{aligned}\Pr_{hash \leftarrow \mathcal{H}}[X = 1] &= \frac{1}{2(h+v)} \left(1 - \Pr_{hash \leftarrow \mathcal{H}}[\exists i < j : hash(q_i) = 0 \mid hash(q_j) = 0] \right) \\ &= \frac{1}{2(h+v)} \left(1 - \Pr_{hash \leftarrow \mathcal{H}}[\exists i < j : hash(q_i) = 0] \right).\end{aligned}$$

Finally, we use union bound and the fact that $j \leq (h+v)$ to get

$$\Pr_{hash \leftarrow \mathcal{H}}[X = 1] \geq \frac{1}{2(h+v)} \left(1 - \sum_{i < j} \Pr_{hash \leftarrow \mathcal{H}}[hash(q_i) = 0] \right) \geq \frac{1}{4(h+v)}.$$

Let $\mathcal{P}_{Success}$ be the set of all $(\pi^{(k)}, \rho)$ for which C succeeds in the random experiment *Success* for $P^{(g)}$. Furthermore, we denote the set of those $(\pi^{(k)}, \rho)$ for which $CanonicalSuccess^{P^{(g)}, C(\cdot, \cdot), hash}(\pi^{(k)}) = 1$ by $\mathcal{P}_{Canonical}$. For fixed $\pi^{(k)}, \rho$, if C succeeds canonically, then it also succeeds in the experiment *Success* for $P^{(g)}$. Hence, $\mathcal{P}_{Canonical} \subseteq \mathcal{P}_{Success}$, and we have

$$\begin{aligned}\Pr_{\substack{hash \leftarrow \mathcal{H} \\ \pi^{(k)}, \rho}} \left[CanonicalSuccess^{P^{(g)}, C(\cdot, \cdot), hash}(\pi^{(k)}, \rho) = 1 \right] &= \mathbb{E}_{(\pi^{(k)}, \rho) \in \mathcal{P}_{Success}} \left[\Pr_{hash \leftarrow \mathcal{H}}[X = 1] \right] \\ &\geq \frac{\gamma}{4(h+v)}.\end{aligned}\tag{0.0.4}$$

Algorithm: FindHash

Oracle: A solver circuit $C^{(\cdot, \cdot)}$ for a k -wise direct product of DWVP.

Input: A set \mathcal{H} .

Output: A function $hash \in \mathcal{H}$.

For $i = 1$ to $32(h+v)^2/\gamma^2$

$hash \xleftarrow{\$} \mathcal{H}$

$count := 0$

For $j := 1$ to $32(h+v)^2/\gamma^2$

$\pi^{(k)} \xleftarrow{\$} \{0, 1\}^{kl}$

If $CanonicalSuccess^{P^{(g)}, C(\cdot, \cdot), hash}(\pi^{(k)}) = 1$ **then**

$count := count + 1$

If $\frac{\gamma^2}{32(h+v)^2} count \geq \frac{\gamma}{6(h+v)}$

return $hash$

return \perp

We show that **FindHash** chooses $hash$ such that the canonical success probability of C with respect to P_{hash} is at least $\frac{\gamma}{4(h+v)}$ almost surely. Let \mathcal{H}_{Good} denote a family of functions $hash \in \mathcal{H}$ for which

$$\Pr_{\pi^{(k)}, \rho} \left[CanonicalSuccess^{P^{(g)}, C(\cdot, \cdot), hash}(\pi^{(k)}, \rho) = 1 \right] \geq \frac{\gamma}{4(h+v)},$$

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

$$\Pr_{\pi^{(k)}, \rho} \left[CanonicalSuccess^{P^{(g)}, C(\cdot, \cdot), hash}(\pi^{(k)}, \rho) = 1 \right] \leq \frac{\gamma}{8(h+v)}.$$

Additionally, for a fixed $hash$, we define binary random variables X_1, \dots, X_N such that

$$X_i = \begin{cases} 1 & \text{if in } i\text{th iteration variable } count \text{ is increased} \\ 0 & \text{otherwise .} \end{cases}$$

We first show that it is unlikely that **FindHash** returns $hash \in \mathcal{H}_{Bad}$. For $hash \in \mathcal{H}_{Bad}$ we have $\mathbb{E}_{\pi^{(k)}, \rho}[X_i] < \frac{\gamma}{8(h+v)}$. Therefore, for any fixed $hash \in \mathcal{H}_{Bad}$ using the Chernoff bound we get

$$\Pr_{\pi^{(k)}, \rho} \left[\frac{1}{N} \sum_{i=1}^N X_i \geq \frac{\gamma}{6(h+v)} \right] \leq \Pr_{\pi^{(k)}, \rho} \left[\frac{1}{N} \sum_{i=1}^N X_i \geq (1 + \frac{1}{3}) \mathbb{E}[X_i] \right] \leq e^{-\frac{\gamma}{4(h+v)} N/27}.$$

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

$$\Pr_{\pi^{(k)}, \rho} \left[\frac{1}{N} \sum_{i=1}^N X_i \leq \frac{\gamma}{6(h+v)} \right] \leq \Pr_{\pi^{(k)}, \rho} \left[\frac{1}{N} \sum_{i=1}^N X_i \leq (1 - \frac{1}{3}) \mathbb{E}[X_i] \right] \leq e^{-\frac{\gamma}{4(h+v)} N/27}.$$

Finally, we show that **FindHash** picks in one of its iteration $hash \in \mathcal{H}_{Good}$ almost surely. Let Y_i be a binary random variable such that

$$Y_i = \begin{cases} 1 & \text{if in } i\text{th iteration } hash \in \mathcal{H}_{Good} \text{ is picked} \\ 0 & \text{otherwise .} \end{cases}$$

From equation (0.0.4) we know that $\Pr_{hash \leftarrow \mathcal{H}}[Y_i = 1] = \mathbb{E}[Y_i] \geq \frac{\gamma}{4(h+v)}$, almost surely. Thus, we get

$$\Pr_{hash \leftarrow \mathcal{H}} \left[\sum_{i=1}^K Y_i = 0 \right] \leq \left(1 - \frac{\gamma}{4(h+v)} \right)^K \leq e^{-\frac{\gamma}{4(h+v)} K}.$$

The bound stated in the Lemma 1.4 is achieved for $K = N = 32(h+v)^2/\gamma^2$. □

We define the following solver circuit \tilde{C} for a k -wise direct product of $P^{(1)}$.

Circuit $\tilde{C}^{\Gamma_V^{(g)}, \Gamma_H^{(g)}, hash, C}(x^{(k)}, \rho)$

Oracle: $\Gamma_V^{(g)}, \Gamma_H^{(k)}, hash, C$

Input: puzzles $x^{(k)}$, bitstring ρ

Output: A tuple (q, y_1, \dots, y_k) or \perp .

Run $C^{\Gamma_V^{(g)}, \Gamma_H^{(k)}}(x^{(k)}, \rho)$

If C asks a hint query on q **then**

If $q \in P_{hash}$ **then**

return \perp

else

answer the query using $\Gamma_H^{(k)}(q)$

If C asks a verification query (q, y_1, \dots, y_k) **then**

If $q \in P_{hash}$ **then**

return (q, y_1, \dots, y_k)

else

answer the verification query with 0

return \perp

Lemma 1.5 For fixed $P^{(1)}$ and hash the following statement is true

$$\Pr_{\pi^{(k)}, \rho} [\text{CanonicalSuccess}^{P^{(g)}, C, \text{hash}}(\pi^{(k)}, \rho) = 1] \leq \Pr_{\substack{\pi^{(k)}, \rho \\ (x^{(k)}, \Gamma_V^{(g)}, \Gamma_H^{(k)}) := P^{(g)}(\pi^{(k)})}} [\Gamma_V^{(g)}(\tilde{C}^{\Gamma_V^{(g)}, \Gamma_H^{(k)}, \text{hash}}(x^{(k)}, \rho)) = 1].$$

Proof. We observe that for fixed $\pi^{(k)}, \rho$ if C succeeds canonically, then for $(x^{(k)}, \Gamma_V^{(g)}, \Gamma_H^{(g)} := P^{(g)}(\pi^{(k)}))$ we have

$$\Gamma_V^{(g)}(\tilde{C}^{\Gamma_V^{(g)}, \Gamma_H^{(g)}, \text{hash}}(\pi_1, \dots, \pi_k)) = 1.$$

Using this observation, we conclude that

$$\begin{aligned} \Pr_{\pi^{(k)}, \rho} [\text{CanonicalSuccess}^{P^{(g)}, C, \text{hash}}(\pi^{(k)}, \rho) = 1] &= \mathbb{E}_{\pi^{(k)}, \rho} [\Pr [\text{CanonicalSuccess}^{P^{(g)}, C, \text{hash}}(\pi^{(k)}, \rho) = 1]] \\ &\leq \mathbb{E}_{\pi^{(k)}, \rho} [\Pr [\text{CanonicalSuccess}^{P^{(g)}, \tilde{C}, \text{hash}}(\pi^{(k)}, \rho) = 1]] \\ &= \Pr_{\substack{\pi^{(k)}, \rho \\ (x^{(k)}, \Gamma_V^{(g)}, \Gamma_H^{(k)}) := P^{(g)}(\pi^{(k)})}} [\Gamma_V^{(g)}(\tilde{C}^{\Gamma_V^{(g)}, \Gamma_H^{(k)}, \text{hash}}(x^{(k)}, \rho)) = 1]. \end{aligned}$$

□

Therefore, from a circuit C we can build a circuit \tilde{C} that outputs \perp or (q, y_1, \dots, y_k) such that $q \in P_{\text{hash}}$. Furthermore, the circuit \tilde{C} asks no verification queries, and every hint query on q is such that $q \notin P_{\text{hash}}$.

TODO: Hash function is taken from Lemma 1.5

Lemma 1.6 (Security amplification of a dynamic weakly verifiable puzzle with respect to P_{hash} .) For fixed $P^{(1)}$ there exists an algorithm $\text{Gen}(C, g, \varepsilon, \delta, n, v, h, \text{hash})$, which takes as input a solver circuit C for $P^{(g)}$, a monotone function $g : \{0, 1\}^{(k)} \rightarrow \{0, 1\}$, a function $\text{hash} : Q \rightarrow \{0, \dots, 2(h + v) - 1\}$, parameters ε, δ, n , number of verification queries v and hint queries h asked by C , and outputs a circuit D such that the following holds:
If C is such that

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

then D satisfies almost surely

$$\Pr_{\pi, \sigma} [\Gamma_V(D^{P^{(1)}, C, \Gamma_V, \Gamma_H, \text{hash}}(x, \sigma)) = 1] \geq (\delta + \frac{\varepsilon}{6k}).$$

Additionally, Gen requires only oracle access to g , $P^{(1)}$ and C . Furthermore, $\text{Size}(D) \leq \text{Size}(C) \frac{6k}{\varepsilon}$ and $\text{Time}(\text{Gen}) = \text{poly}(k, \frac{1}{\varepsilon}, n, v, h)$.

Proof. First we define helper procedures **EvaluatePuzzles** and **EvaluateSurplus**.

EvaluatePuzzles ^{$P^{(1)}, C, hash$} ($\pi^{(k)}, k$)

Oracle: A circuit C , an algorithm $P^{(1)}$, a function $hash$.

Input: Bitstrings $\pi^{(k)}$, ρ , an integer k .

Output: A tuple (c_1, \dots, c_k) .

$(x^{(k)}, \Gamma_V^{(g)}, \Gamma_H^{(k)}) := P^{(g)}(\pi^{(k)})$

$(q, y^{(k)}) := \tilde{C}^{\Gamma_V^{(g)}, \Gamma_H^{(k)}, hash, C}(x^{(k)}, \rho)$

For $i := 1$ to k **do:**

$(x_i, \Gamma_V^i, \Gamma_H^i) := P^{(1)}(\pi_i)$

For $i := 1$ to k **do:**

$c_i := \Gamma_v^i(q, y_i)$

return (c_1, \dots, c_k)

TODO: Figure out N_K

TODO: Get a sample for $\Pr[g(b, \dots, b) = 1]$

EvaluateSurplus ^{$P^{(1)}, C, hash$} (π^*, b, k)

Oracle: An algorithm $P^{(1)}$, a circuit C , a function $hash$.

Input: A bistring π^* , a bit b , an integer k .

Output: A circuit D .

For $i := 1$ to N_k

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

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

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

$\tilde{S}_{\pi^*, b}^i := g(b, c_2, \dots, c_k) - \Pr_{(u_2, \dots, u_k)}[g(b, u_2, \dots, u_k) = 1]$

return $\frac{1}{N_k} \sum_{i=1}^{N_k} \tilde{S}_{\pi^*, b}^i$

Circuit $D^{C, P^{(1)}}(x^*, \sigma)$

Oracle: A circuit C , a poser $P^{(1)}$, a function $hash$.

Input: A puzzle x^* , a bitstring $\sigma \in \{0, 1\}^*$.

Output: A circuit D .

Let k be the number of input puzzles taken by C .

For $i := 1$ to $\frac{6k}{\epsilon} \log(\frac{6k}{\epsilon})$ **do:**

$\pi^{(k)} \leftarrow$ read $k \cdot n$ bits from σ

$(c_1, \dots, c_k) := \mathbf{EvaluatePuzzles}^{P^{(1)}, C, hash}(\pi^{(k)}, k)$

If $g(1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0$ **then**

For $i := 1$ to k **do:**

$(x_i, \Gamma_V^i, \Gamma_H^i) := P^{(1)}(\pi_i)$

$(q, y_1, \dots, y_k) := \tilde{C}(x^*, x_2, \dots, x_k)$

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    return (q, y1)
return ⊥

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Algorithm $Gen(C, g, \varepsilon, \delta, n, v, h, hash)$

Oracle: $C, g, hash$

Input: $\varepsilon, \delta, n, v, h$

Output: A circuit D

Let k be the number of input puzzles taken by C .

If $k = 1$ **then**

return C

For $i := 1$ **to** $\frac{6k}{\varepsilon} \log(n)$

$\pi^* \leftarrow \{0, 1\}^n$

$\tilde{S}_{\pi^*, 0} := \text{EvaluateSurplus}^{P^{(1)}, C, hash}(\pi^*, 0, k)$

$\tilde{S}_{\pi^*, 1} := \text{EvaluateSurplus}^{P^{(1)}, C, hash}(\pi^*, 1, k)$

If $\tilde{S}_{\pi^*, 0} \geq (1 - \frac{3}{4k})\varepsilon$ **or** $\tilde{S}_{\pi^*, 1} \geq (1 - \frac{3}{4k})\varepsilon$

$C' := C$ with the first input fixed on x^*

$g'(b_2, \dots, b_k) := g(c_1, b_2, \dots, b_k)$

return $Gen(\tilde{C}', g', \varepsilon, \delta, n, v, h, hash)$

// all estimates are lower than $(1 - \frac{3}{4k})\varepsilon$

return $D^{\tilde{C}}$

For $k = 1$ the function $g : \{0, 1\} \rightarrow \{0, 1\}$ is either the identity or a constant function. If g is the identity function then the success probability of C in the random experiment *CanonicalSuccess* is at least $\delta + \varepsilon$, and C can be directly used to solve a puzzle. In case g is a constant function the statement is vacuously true.

For fixed $\pi^{(k)}, \rho$ let $(x^{(k)}, \Gamma_V^{(g)}, \Gamma_H^{(k)}) := P^{(g)}(\pi^{(k)})$. Additionally, for any i such that $1 \leq i \leq k$ let us denote $(x_i, \Gamma_V^i, \Gamma_H^i) := P^{(1)}(\pi_i)$. For $(q, y_1, \dots, y_k) := \tilde{C}(x^{(k)}, \rho)$ we denote $c_i := \Gamma_V^i(q, y_i)$. We define the surplus:

$$S_{\pi^*, b} = \Pr_{\pi^{(k)}} [g(b, c_2, \dots, c_k) = 1] - \Pr_{\mu^{(k)}} [g(b, u_2, \dots, u_k) = 1] \quad (0.0.5)$$

The surplus $S_{\pi^*, b}$ tells us how good \tilde{C} performs when the first puzzle is fixed, and the fact whether \tilde{C} succeeds in solving the puzzle posed by $P^{(1)}(\pi_1)$ is disregarded. Instead, the bit b is used as the first input to g .

The procedure **EvaluateSurplus** returns the estimate $\tilde{S}_{\pi^*, b}$ for $S_{\pi^*, b}$. All puzzles used during obtaining the estimate are generated internally. Therefore, it is possible to answer all hint and verification queries, without calls to the verification oracles.

Lemma 1.7 *The estimate $\tilde{S}_{\pi^*, b}$ returned by EvaluateEstimate differs from $S_{\pi^*, b}$ by at most $\frac{\varepsilon}{4k}$ almost surely.*

TODO: Chernoff for the estimate

From Lemma 1.7 we conclude that if $\tilde{S}_{\pi^*,b} \geq (1 - \frac{3}{4k})\varepsilon$, then $S_{\pi^*,b} \geq (1 - \frac{1}{k})\varepsilon$ almost surely.

Let us assume that Gen manages to find an estimate that satisfies $\tilde{S}_{\pi^*,b} \geq (1 - \frac{3}{4k})\varepsilon$. In this case we define a new monotone function $g'(b_2, \dots, b_k) := g(b, b_2, \dots, b_k)$, and a circuit C' which is by fixing the first input of C to x^* , where $(x^*, \Gamma_V^*, \Gamma_H^*) := P^{(1)}(\pi^*)$. The circuit \tilde{C}' satisfies the conditions of Lemma 1.6 and we recurse using C' and g' .

If all estimates are less than $(1 - \frac{3}{4k})\varepsilon$, then intuitively C does not perform much better on the remaining $k-1$ puzzles than an algorithm that solves each puzzle independent with probability δ . However, from the assumption we know that on all k puzzles \tilde{C} has higher success probability. Therefore, it is likely that the first puzzle is correctly solved with probability higher than δ . We now show that this intuition is indeed correct. For a fixed π^* using (0.0.5), we get

$$\begin{aligned} & \Pr_{u \leftarrow \mu_\delta^k} [g(1, u_2, \dots, u_k) = 1] - \Pr_{u \leftarrow \mu_\delta^k} [g(0, u_2, \dots, u_k) = 1] = \\ & \Pr_{\pi^{(k)}} [g(1, c_2, \dots, c_k) = 1 \mid \pi_1 = \pi^*] - \Pr_{\pi^{(k)}} [g(0, c_2, \dots, c_k) = 1 \mid \pi_1 = \pi^*] - (S_{\pi^*,1} - S_{\pi^*,0}). \end{aligned} \quad (0.0.6)$$

From the monotonicity of g we know that for any set of tuples (b_1, \dots, b_k) and sets $\mathcal{B}_0 = \{(b_1, b_2, \dots, b_k) : g(0, b_2, \dots, b_k) = 1\}$, $\mathcal{B}_1 = \{(b_1, b_2, \dots, b_k) : g(1, b_2, \dots, b_k) = 1\}$ we have $G_0 \subseteq G_1$. Hence, we can write (0.0.6):

$$\begin{aligned} & \Pr_{u \leftarrow \mu_\delta^k} [g(1, u_2, \dots, u_k) = 1 \wedge g(0, u_2, \dots, u_k) = 0] = \\ & \Pr_{\pi^{(k)}} [g(1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0 \mid \pi_1 = \pi^*] - (S_{\pi^*,1} - S_{\pi^*,0}). \end{aligned} \quad (0.0.7)$$

Let $G_{u^{(k)}}$ denote the event $g(1, u_2, \dots, u_k) = 1 \wedge g(0, u_2, \dots, u_k) = 0$, and correspondingly $G_{\pi^{(k)}} := g(1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0$. From (0.0.7) we obtain

$$\begin{aligned} \Pr_r [\Gamma_V(D(x^*, r)) = 1 \mid \pi_1 = \pi^*] &= \frac{\Pr_r [\Gamma_V(D(x^*, r)) = 1 \mid \pi_1 = \pi^*] \Pr_{\pi^{(k)}} [G_\pi \mid \pi_1 = \pi^*]}{\Pr_{u \leftarrow \mu_\delta^k} [G_\mu]} \\ &\quad - \frac{\Pr_r [\Gamma_V(D(x^*, r)) = 1 \mid \pi_1 = \pi^*] (S_{\pi^*,1} - S_{\pi^*,0})}{\Pr_{u \leftarrow \mu_\delta^k} [G_\mu]} \end{aligned} \quad (0.0.8)$$

If $D(x^*, r) \neq \perp$ then we denote $c_i := \Gamma_V^i(q, y_i)$. We can write the first summand of (0.0.8) as

$$\begin{aligned} & \Pr_r [\Gamma_V^{(g)}(D(x^*, r)) = 1 \mid \pi_1 = \pi^*] \Pr_{\pi^{(k)}} [G_\pi \mid \pi_1 = \pi^*] = \\ & \Pr_r [D(x^*, r) \neq \perp \mid \pi_1 = \pi^*] \Pr_{\pi^{(k)}} [c_1 = 1 \mid G_\pi, \pi_1 = \pi^*] \Pr_{\pi^{(k)}} [G_\pi \mid \pi_1 = \pi^*] \end{aligned} \quad (0.0.9)$$

where we make use of the fact that the event G_π implies $D(x^*, r) \neq \perp$. We consider two cases. For $\Pr_{\pi^{(k)}} [g(1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0 \mid \pi_1 = \pi^*] \leq \frac{\varepsilon}{6k}$ then

$$\Pr_{\pi^{(k)}} [c_1 = 1 \mid G_\pi, \pi_1 = \pi^*] \Pr_{\pi^{(k)}} [G_\pi \mid \pi_1 = \pi^*] \leq \frac{\varepsilon}{6k}, \quad (0.0.10)$$

and when $\Pr_{\pi^{(k)}} [g(1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0] > \frac{\varepsilon}{6k}$ then circuit D outputs \perp only if it fails in all $\frac{6k}{\varepsilon} \log(\frac{6k}{\varepsilon})$ iterations to find $\pi^{(k)}$ such that $g(1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0$ which happens with probability

$$\Pr_r [D(x^*, r) = \perp \mid \pi_1 = \pi^*] \leq (1 - \frac{\varepsilon}{6k})^{\frac{6k}{\varepsilon} \log(\frac{6k}{\varepsilon})} \leq \frac{\varepsilon}{6k}. \quad (0.0.11)$$

We conclude that in both cases:

$$\begin{aligned} & \Pr_r[D(x^*, r) \neq \perp \mid \pi_1 = \pi^*] \Pr_{\pi^{(k)}}[c_1 = 1 \mid G_\pi, \pi_1 = \pi^*] \Pr_{\pi^{(k)}}[G_\pi \mid \pi_1 = \pi^*] \\ & \geq \Pr_{\pi^{(k)}}[c_1 = 1 \mid G_\pi, \pi_1 = \pi^*] \Pr_{\pi^{(k)}}[G_\pi \mid \pi_1 = \pi^*] - \frac{\varepsilon}{6k}. \end{aligned} \quad (0.0.12)$$

Therefore, we have

$$\begin{aligned} & \Pr_r[D(x^*, r) \neq \perp \mid \pi_1 = \pi^*] \Pr_{\pi^{(k)}}[c_1 = 1 \mid G_\pi, \pi_1 = \pi^*] \Pr_{\pi^{(k)}}[G_\pi \mid \pi_1 = \pi^*] \\ & = \Pr_{\pi^{(k)}}[c_1 = 1 \wedge g(1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0 \mid \pi_1 = \pi^*] - \frac{\varepsilon}{6k} \\ & = \Pr_{\pi^{(k)}}[g(c_1, c_2, \dots, c_k) = 1 \wedge g(0, c_2, \dots, c_k) = 0 \mid \pi_1 = \pi^*] - \frac{\varepsilon}{6k} \\ & = \Pr_{\pi^{(k)}}[g(c_1, c_2, \dots, c_k) = 1 \mid \pi_1 = \pi^*] - \Pr_{\pi^{(k)}}[g(0, c_2, \dots, c_k) = 0 \mid \pi_1 = \pi^*] - \frac{\varepsilon}{6k}, \end{aligned}$$

and finally by (0.0.5)

$$\begin{aligned} & \Pr_r[D(x^*, r) \neq \perp \mid \pi_1 = \pi^*] \Pr_{\pi^{(k)}}[c_1 = 1 \mid G_\pi, \pi_1 = \pi^*] \Pr_{\pi^{(k)}}[G_\pi \mid \pi_1 = \pi^*] \\ & = \Pr_{\pi^{(k)}}[g(c_1, c_2, \dots, c_k) = 1 \mid \pi_1 = \pi^*] - \Pr_{\mu_\delta^{(k)}}[g(0, \mu_2, \dots, \mu_k) = 0 \mid \pi_1 = \pi^*] - S_{\pi^*, 0} - \frac{\varepsilon}{6k}. \end{aligned} \quad (0.0.13)$$

Inserting this result into the equation (0.0.8) yields

$$\begin{aligned} & \Pr_{r, \pi}[\Gamma_V(D(x, r)) = 1] = \mathbb{E}_\pi \left[\Pr_r[D(x, r) = 1 \mid \pi_1 = \pi^*] \right] \\ & = \mathbb{E}_\pi \left[\frac{\Pr_{\pi^{(k)}}[g(c) = 1 \mid \pi_1 = \pi^*] - \Pr_{\mu_\delta^{(k)}}[g(0, \mu_2, \dots, \mu_k) = 0 \mid \pi_1 = \pi^*] - \frac{\varepsilon}{6k}}{\Pr_{\mu_\delta^k}[G_\mu]} \right] \\ & \quad - \mathbb{E}_\pi \left[\frac{S_{\pi^*, 0} + \Pr_r[\Gamma_V^{(g)}(D(x^*, r)) = 1 \mid \pi_1 = \pi^*](S_{\pi^*, 1} - S_{\pi^*, 0})}{\Pr_{\mu_\delta^k}[G_\mu]} \right] \end{aligned} \quad (0.0.14)$$

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

$$\Pr_\pi \left[\left(S_{\pi, 0} \leq (1 - \frac{1}{2k})\varepsilon \right) \wedge \left(S_{\pi, 1} \leq (1 - \frac{1}{2k})\varepsilon \right) \right] < 1 - \frac{\varepsilon}{6k}, \quad (0.0.15)$$

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

$$\Pr_\pi \left[\left(S_{\pi, 0} \leq (1 - \frac{1}{2k})\varepsilon \right) \wedge \left(S_{\pi, 1} \leq (1 - \frac{1}{2k})\varepsilon \right) \right] \geq 1 - \frac{\varepsilon}{6k}. \quad (0.0.16)$$

Let us define a set

$$\mathcal{W} = \left\{ \pi : \left(S_{\pi, 0} \leq (1 - \frac{1}{2k})\varepsilon \right) \wedge \left(S_{\pi, 1} \leq (1 - \frac{1}{2k})\varepsilon \right) \right\} \quad (0.0.17)$$

and use \mathcal{W}^c to denote the complement of \mathcal{W} . We bound the second summand in (0.0.14)

$$\begin{aligned} \mathbb{E}_\pi \left[S_{\pi^*,0} + \Pr_r[\Gamma_V^{(g)}(D(x^*, r)) = 1 \mid \pi_1 = \pi^*](S_{\pi^*,1} - S_{\pi^*,0}) \right] \\ = \mathbb{E}_{\pi \in \mathcal{W}^c} \left[S_{\pi^*,0} + \Pr_r[\Gamma_V^{(g)}(D(x^*, r)) = 1 \mid \pi = \pi^*](S_{\pi^*,1} - S_{\pi^*,0}) \right] \\ + \mathbb{E}_{\pi \in \mathcal{W}} \left[S_{\pi^*,0} + \Pr_r[\Gamma_V^{(g)}(D(x^*, r)) = 1 \mid \pi = \pi^*](S_{\pi^*,1} - S_{\pi^*,0}) \right] \end{aligned} \quad (0.0.18)$$

$$\leq \frac{\varepsilon}{6k} + \mathbb{E}_{\pi \in \mathcal{W}^c} \left[S_{\pi^*,0} + \Pr_r[\Gamma_V^{(g)}(D(x^*, r)) = 1 \mid \pi = \pi^*]\left((1 - \frac{1}{2k})\varepsilon - S_{\pi^*,0}\right) \right] \quad (0.0.19)$$

$$\leq \frac{\varepsilon}{6k} + 1 - \frac{\varepsilon}{2k} = 1 - \frac{\varepsilon}{3k} \quad (0.0.20)$$

Finally, we insert this result into equation (0.0.14) and make use of the fact

$$\begin{aligned} \Pr[g(u) = 1] &= \Pr[(g(0, \mu_2, \dots, \mu_k) = 1) \vee (g(1, \mu_2, \dots, \mu_k) = 1 \wedge g(0, \mu_2, \dots, \mu_k) = 0 \wedge \mu_1 = 1)] \\ &= \Pr[g(0, \mu_2, \dots, \mu_k) = 1] + \Pr[g(1, \mu_2, \dots, \mu_k) = 1 \wedge g(0, \mu_2, \dots, \mu_k) = 0] \Pr[\mu_1 = 1] \end{aligned}$$

which yields

$$\Pr_{r,\pi}[D(x, r) = 1] \geq \mathbb{E}_\pi \left[\frac{\Pr_{\pi^{(k)}}[g(c) = 1 \mid \pi_1 = \pi^*] - \Pr_{\mu_\delta^{(k)}}[g(0, \mu_2, \dots, \mu_k) = 0] - (1 - \frac{1}{6k})\varepsilon}{\Pr_{\mu_\delta^k}[G_\mu]} \right]$$

Using the assumptions of Lemma 1.6, we get

$$\begin{aligned} \Pr_{r,\pi}[\Gamma_V(D(x, r)) = 1] &\geq \frac{\Pr_{\mu_\delta^{(k)}}[g(\mu) = 1] + \varepsilon + \Pr_{\mu_\delta^{(k)}}[g(0, \mu_2, \dots, \mu_k) = 0] - (1 - \frac{1}{6k})\varepsilon}{\Pr_{\mu_\delta^k}[G_\mu]} \\ &\geq \frac{\varepsilon + \delta \Pr_{\mu_\delta^{(k)}}[G_\mu] - (1 - \frac{1}{6k})\varepsilon}{\Pr_{\mu_\delta^k}[G_\mu]} \geq \delta + \frac{\varepsilon}{6k} \quad \square \end{aligned}$$

TO ASK: Is notation $\rho \overset{\$}{\leftarrow} \{0, 1\}^*$ correct.