

Compositional Synthesis of Leakage Resilient Programs

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Abstract. A promising approach to defend against side channel attacks is to build programs that are *leakage resilient*, in a formal sense. One such formal notion of leakage resilience is the *n-threshold-probing model* proposed in the seminal work by Ishai et al. [15]. In a recent work [8], Eldib and Wang have proposed a method for automatically synthesizing programs that are leakage resilient according to this model, for the case $n = 1$. In this paper, we show that the *n-threshold-probing model* of leakage resilience enjoys a certain compositionality property that can be exploited for synthesis. We use the property to design a synthesis method that efficiently synthesizes leakage-resilient programs in a compositional manner, for the general case of $n > 1$. We have implemented a prototype of the synthesis algorithm, and we demonstrate its effectiveness by synthesizing leakage-resilient versions of benchmarks taken from the literature.

1 Introduction

Side channel attacks are well recognized as serious threat to the security of computer systems. Building a system that is resilient to side channel attacks is a challenge, particularly because there are many kinds of side channels (such as, power, timing, and electromagnetic radiation) and attacks on them. In an effort to establish a principled solution to the problem, researchers have proposed formal definitions of resilience against side channel attacks, called *leakage resilience* [15, 14, 10–12, 2]. The benefit of such formal models of side-channel-attack resilience is that a program proved secure according to a model is guaranteed to be secure against all attacks that are permitted within the model.

The previous research has proposed various notions of leakage resilience. In this paper, we focus on the *n-threshold-probing model* proposed in the seminal work by Ishai et al. [15]. Informally, the model says that, given a program represented as a Boolean circuit, the adversary learns nothing about the secret by

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executing the program and observing the values of at most n nodes in the circuit (cf. Section 2 for the formal definition). The attractive features of the model include its relative simplicity, and the relation to *masking*, a popular countermeasure technique used in security practice. More precisely, the security under the n -threshold-probing model is equivalent to the security under n^{th} -order *masking* [21], and often, the literature uses the terminologies interchangeably [2, 5, 9, 8, 4, 3]. Further, as recently shown by Duc et al. [7], the security under the model also implies the security under the *noisy* leakage model [20] in which the adversary obtains information from every node with a probabilistically distributed noise.

In a recent work, Eldib and Wang [8] have proposed a synthesis method that, given a program represented as a circuit, returns a functionally equivalent circuit that is leakage resilient according to the n -threshold-probing model, for the case $n = 1$ (i.e., the adversary observes only one node). The method is a constraint-based algorithm whereby the constraints expressing the necessary conditions are solved in a CEGAR (counterexample-guided abstraction refinement) style. In this work, we extend the synthesis to the general case where n can be greater than 1. Unfortunately, naively extending (the monolithic version of) their algorithm to the case $n > 1$ results in a method whose complexity is double exponential in n , leading to an immediate roadblock.⁴ As we show empirically in Section 5, the cost is highly substantial, and the naive monolithic approach fails even for the case $n = 2$ on reasonably simple examples.

Our solution to the problem is to exploit a certain *compositionality* property admitted by the leakage resilience model. We state and prove the property formally in Theorems 2 and 3. Roughly, the compositionality theorems say that composing n -leakage-resilient circuits results in an n -leakage-resilient circuit, under the condition that the randoms in the components are disjoint. The composition property is quite general and is particularly convenient for synthesis. It allows a compositional synthesis method which divides the given circuit into smaller sub-circuits, synthesizes n -leakage-resilient versions of them, and combines the results to obtain an n -leakage-resilient version of the whole. The correctness is ensured by using disjoint randoms in the synthesized sub-circuits. Our approach is an interesting contrast to the approach that aims to achieve compositionality without requiring the disjointness of the component’s randoms, but instead at the cost of additional randoms at the site of the composition [5, 3].

We remark that the compositionality is not at all obvious and quite unexpected. Indeed, at first glance, n -leakage resilience for each individual component seems to say nothing about the security of the composed circuit against an adversary who can observe the nodes of multiple different components in the composition. To further substantiate the non-triviality, we remark that the compositionality property is quite sensitive, and for example, it fails to hold if the

⁴ Their paper [8] also shows a compositional algorithm. However, compositionality becomes non-trivial when $n > 1$ because then the adversary can observe nodes from the different components of the composition.

bounds are relaxed even slightly so that the adversary makes at most n observations within each individual component but the total number of observations is allowed to be just one more than n (cf. Example 2).

To synthesize n -leakage-resilient sub-circuits, we extend the monolithic algorithm from [8] to the case where n can be greater than 1. We make several improvements to the baseline algorithm so that it scales better for the case $n > 1$ (cf. Section 4.1). We have implemented a prototype of our compositional synthesis algorithm, and experimented with the implementation on benchmarks taken from the literature. We summarize our contributions below.

- A proof that the n -threshold-probing model of leakage resilience is preserved under certain circuit compositions (Section 3).
- A compositional synthesis algorithm for the leakage-resilience model that utilizes the compositionality property (Section 4).
- Experiments with a prototype implementation of the synthesis algorithm (Section 5).

The rest of the paper is organized as follows. Section 2 introduces preliminary definitions and notations, including the formal definition of the n -threshold-probing model of leakage resilience. Section 3 states and proves the compositionality property. Section 4 describes the compositional synthesis algorithm. We report on the experience with a prototype implementation of the algorithm in Section 5, and discuss related work in Section 6. We conclude the paper in Section 7. Appendix contains the omitted proofs.

2 Preliminaries

We use boldface font for finite sequences. For example, $\mathbf{b} = b_1, b_2, \dots, b_n$. We adopt the standard convention of the literature [9, 8, 4, 3] and assume that a *program* is represented as an acyclic Boolean circuit.⁵ We assume the usual Boolean operators, such as XOR gates \oplus , AND gates \wedge , OR gates \vee , and NOT gates \neg .

A program has three kinds of inputs, *secret inputs* (often called *keys*) ranged over by k , *public inputs* ranged over by p , and *random inputs* ranged over by r . Informally, secret inputs contain the secret bits to be protected from the adversary, public inputs are those that are visible and possibly given by the adversary, and random inputs contain bits that are generated uniformly at random (hence, it may be more intuitive to view randoms as not actual “inputs”).

Consider a program P with secret inputs k_1, \dots, k_x . In the n -threshold-probing model of leakage resilience, we prepare $n+1$ -*split shares* of each k_i (for $i \in \{1, \dots, x\}$):

$$r_{i,1}, \dots, r_{i,n}, k_i \oplus \left(\bigoplus_{j=1}^n r_{i,j} \right)$$

⁵ In the implementation described in Section 5, following the previous works [9, 8], we convert the given C program into such a form.

where each $r_{i,j}$ is fresh. Note that the split shares sum to k_i , and (assuming that $r_{i,j}$'s are uniformly independently distributed) observing up to n many shares reveals no information about k_i . Adopting the standard terminology of the literature [15], we call the circuit that outputs such split shares the *input encoder* of P . The leakage resilience model also requires an *output decoder*, which sums the split shares at the output. More precisely, suppose P has y many $n+1$ -split outputs $\mathbf{o}_1, \dots, \mathbf{o}_y$ (i.e., $|\mathbf{o}_i| = n+1$ for each $i \in \{1, \dots, y\}$). Then, the output decoder for P is, for each $\mathbf{o}_i = o_{i,1}, \dots, o_{i,n+1}$, the circuit $\bigoplus_{j=1}^{n+1} o_{i,j}$. For example, Fig. 1 shows a 2+1-split circuit with the secret inputs k_1, k_2 , public inputs p_1, p_2 , random inputs r_1, r_2, r_3, r_4 , and two outputs. Note that the input encoder (the region **Input Encoder**) introduces the randoms, and the output decoder (the region **Output Decoder**) sums the output split shares.

We associate a unique label (ranged over by α) to every gate of the circuit. We call the *nodes* of P , $nodes(P)$, to be the set of labels in P excluding the gates internal to the input encoder and the output decoder part of P (but including the outputs of the input encoder and the inputs to the output decoder). Intuitively, $nodes(P)$ are the nodes that can be observed by the adversary. For example, in Fig. 1, the observable nodes are the ones in the region **Observable Nodes** labeled $\alpha_1, \dots, \alpha_{15}$.

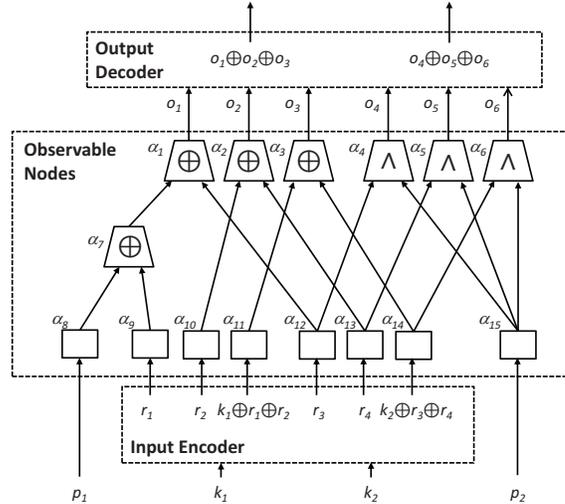


Fig. 1. Example of a 2-leakage-resilient circuit

Let ν be a mapping from the inputs of P to $\{0, 1\}$. Let $\alpha = \alpha_1, \dots, \alpha_n$ be a vector of nodes in $nodes(P)$. We define the *evaluation*, $\nu_P(\alpha)$, to be the vector $b_1, \dots, b_n \in \{0, 1\}^n$, such that each b_i is the valuation of the node α_i when evaluating P under ν . For example, let P' be the circuit from Fig. 1. Let ν map p_1, r_1, k_2 to 0, and the others to 1. Then, $\nu_{P'}(\alpha_{11}, \alpha_1) = 0, 1$.

Let us write $\nu[\mathbf{v} \mapsto \mathbf{b}]$ for the store ν except that each v_i is mapped to b_i (for $i \in \{1, \dots, m\}$) where $\mathbf{v} = v_1, \dots, v_m$ and $\mathbf{b} = b_1, \dots, b_m$. Let P be a circuit with secret inputs \mathbf{k} , public inputs \mathbf{p} , and random inputs \mathbf{r} . For $\mathbf{b}_p \in \{0, 1\}^{|\mathbf{p}|}$, $\mathbf{b}_k \in \{0, 1\}^{|\mathbf{k}|}$, $\alpha \in nodes(P)^*$, and $\mathbf{b}_\alpha \in \{0, 1\}^{|\alpha|}$, let $\#_P(\mathbf{b}_p, \mathbf{b}_k, \alpha, \mathbf{b}_\alpha) = |\{\mathbf{b} \in \{0, 1\}^{|\mathbf{r}|} \mid \nu[\mathbf{r} \mapsto \mathbf{b}]_P(\alpha) = \mathbf{b}_\alpha\}|$ where $\nu = \{\mathbf{p} \mapsto \mathbf{b}_p, \mathbf{k} \mapsto \mathbf{b}_k\}$. We define $\mu_P(\mathbf{b}_p, \mathbf{b}_k, \alpha)$ to be the finite map from each $\mathbf{b}_\alpha \in \{0, 1\}^{|\alpha|}$ to $\#_P(\mathbf{b}_p, \mathbf{b}_k, \alpha, \mathbf{b}_\alpha)$.

We remark that $\mu_P(\mathbf{b}_p, \mathbf{b}_k, \alpha)$, when normalized by the scaling factor $2^{-|\mathbf{r}|}$, is the joint distribution of the values of the nodes α under the public inputs \mathbf{b}_p and the secret inputs \mathbf{b}_k .

Roughly, the n -threshold-probing model of leakage resilience says that, for any selection of n nodes, the joint distribution of the nodes' values is independent of the secret. Formally, the leakage-resilience model is defined as follows.

Definition 1 (Leakage Resilience). Let P be an $n+1$ -split circuit with secret inputs \mathbf{k} , public inputs \mathbf{p} , and random inputs \mathbf{r} . Then, P is said to be *leakage-resilient under the n -threshold-probing model* (or, simply *n -leakage-resilient*) if for any $\mathbf{b}_p \in \{0, 1\}^{|\mathbf{p}|}$, $\mathbf{b}_k \in \{0, 1\}^{|\mathbf{k}|}$, $\mathbf{b}_k' \in \{0, 1\}^{|\mathbf{k}|}$, and $\alpha \in \text{nodes}(P)^n$, $\mu_P(\mathbf{b}_p, \mathbf{b}_k, \alpha) = \mu_P(\mathbf{b}_p, \mathbf{b}_k', \alpha)$.

We remark that, above, \mathbf{r} includes all randoms introduced by the input encoder as well as any additional ones that are not from the input encoder, if any. For instance, in the case of the circuit from Fig. 1, the randoms are r_1, r_2, r_3, r_4 and they are all from the input encoder.

Informally, the n -threshold-probing model of leakage resilience says that the attacker learns nothing about the secret by executing the circuit and observing the values of up to n many internal gates and wires, excluding those that are internal to the input encoder and the output decoder.

We say that a circuit is *random-free* if it has no randoms. Let P be a random-free circuit with public inputs \mathbf{p} and secret inputs \mathbf{k} , and P' be a circuit with public inputs \mathbf{p} , secret inputs \mathbf{k} , and randoms \mathbf{r} . We say that P' is *IO-equivalent* to P if for any $\mathbf{b}_k \in \{0, 1\}^{|\mathbf{k}|}$, $\mathbf{b}_p \in \{0, 1\}^{|\mathbf{p}|}$, and $\mathbf{b}_r \in \{0, 1\}^{|\mathbf{r}|}$, the output of P when evaluated under $\nu = \{\mathbf{p} \mapsto \mathbf{b}_p, \mathbf{k} \mapsto \mathbf{b}_k\}$ is equivalent to that of P' when evaluated under $\nu[\mathbf{r} \mapsto \mathbf{b}_r]$. We formalize the synthesis problem.

Definition 2 (Synthesis Problem). Given $n > 0$ and a random-free circuit P as input, the *synthesis problem* is the problem of building a circuit P' such that 1.) P' is IO-equivalent to P , and 2.) P' is n -leakage-resilient.

An important result by Ishai et al. [15] is that any random-free circuit can be converted to an IO-equivalent leakage-resilient form.

Theorem 1 ([15]). *For any random-free circuit P , there exists an n -leakage-resilient circuit that is IO-equivalent to P .*

While the result is of theoretical importance, the construction is more of a proof-of-concept in which every gate is transformed uniformly, and the obtained circuits can be quite unoptimized (e.g., injecting excess randoms to mask computations that do not depend on secrets). The subsequent research has proposed to construct more optimized leakage-resilient circuits manually [21, 5], or by automatic synthesis [8]. The latter is the direction of the present paper.

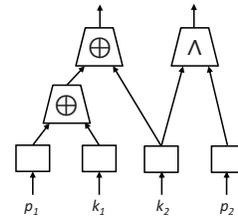


Fig. 2. A circuit computing $(p_1 \oplus k_1 \oplus k_2, k_2 \wedge p_2)$

Example 1. Consider the random-free circuit P shown in Fig. 2 which outputs $(p_1 \oplus k_1 \oplus k_2, k_2 \wedge p_2)$. Let P' be the circuit from Fig. 1. It is easy to see that P' is IO-equivalent to P . Also, it can be shown that P' is 2-leakage resilient. Therefore, P' is a 2-leakage-resilient version of P .

Remark 1. The use of the input encoder and the output decoder is unavoidable. It is easy to see that the input encoder is needed. Indeed, without it, one cannot even defend against an one-node-observing attacker as she may directly observe the secret. To see that the output decoder is also required, consider an one-output circuit without the output decoder and let n be the fan-in of the last gate before the output. Then, assuming that the output depends on the secret, the circuit cannot defend itself against an n -nodes-observing attacker as she may observe the inputs to the last gate.

Remark 2. In contrast to the previous works [5, 3] that implicitly assume that each secret is encoded (i.e., split in $n+1$ shares) by only one input encoder, we allow a secret to be encoded by multiple input encoders. The relaxation is important in our setting because, as remarked before, the compositionality results require disjointness of the randoms in the composed components.

Split and Non-Split Inputs / Outputs. We introduce terminologies that are convenient when describing the compositionality results in Section 3. We use the term *split inputs* to refer to the $n+1$ tuples of wires to which the $n+1$ -split (secret) inputs produced by the input encoder (i.e., the pair of triples $r_1, r_2, k_1 \oplus r_1 \oplus r_2$ and $r_3, r_4, k_2 \oplus r_3 \oplus r_4$ in the example of Fig. 1) are passed, and use the term *non-split inputs* to refer to the wires to which the original inputs before the split (i.e., k_1 and k_2 in Fig. 1) are passed. We define *split outputs* and *non-split outputs* analogously. Roughly, the split inputs and outputs are the inputs and outputs of the attacker-observable part of the circuit (i.e., the region **Observable Nodes** in Fig. 1), whereas the non-split inputs and outputs are those of the whole circuit with the input encoder and the output decoder.

3 Compositionality of Leakage Resilience

This section shows the compositionality property of the n -threshold-probing model of leakage resilience. We state and prove two main results (for space the proofs are deferred to Appendix).

The first result concerns *parallel compositions*. It shows that given two n -leakage-resilient circuits P_1 and P_2 that possibly share inputs, the composed circuit that runs P_1 and P_2 in parallel is also n -leakage resilient, assuming that the randoms in the two components are disjoint. Fig. 3 shows

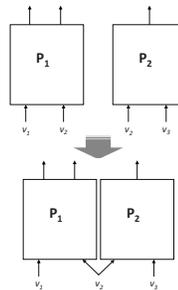


Fig. 3. Parallel composition of P_1 and P_2 .

the diagram depicting the composition. The second result concerns *sequential compositions*, and it is significantly harder to prove than the first one. The sequential composition takes an n -leakage-resilient circuit P_2 having y many (non-split) inputs, and n -leakage-resilient circuits P_{11}, \dots, P_{1y} each having one (non-split) output. The composition is done by connecting each split output of the output-decoder-free part of P_{1i} to the i th split input of the input-encoder-free part of P_2 . Clearly, the composed circuit is IO-equivalent to the one formed by connecting each non-split output of P_{1i} to the i th non-split input of P_2 . The sequential compositionality result states that the composed circuit is also n -leakage resilient, under the assumption that the randoms in the composed components are disjoint. Fig. 4 shows the diagram of the composition. We state and prove the parallel compositionality result formally in Section 3.1, and the sequential compositionality result in Section 3.2.

We remark that, in the sequential composition, if a (non-split) secret input, say k , is shared by some P_{1i} and P_{1j} for $i \neq j$, then the disjoint randomness condition requires k to be encoded by two independent input encoders. This is in contrast to the previous works [5, 3] that only use one input encoder per a secret input. On the other hand, such works require additional randoms at the site of the composition, whereas no additional randoms are needed at the composition site in our case as it directly connects the split outputs of P_{1i} 's to the split inputs of P_2 .

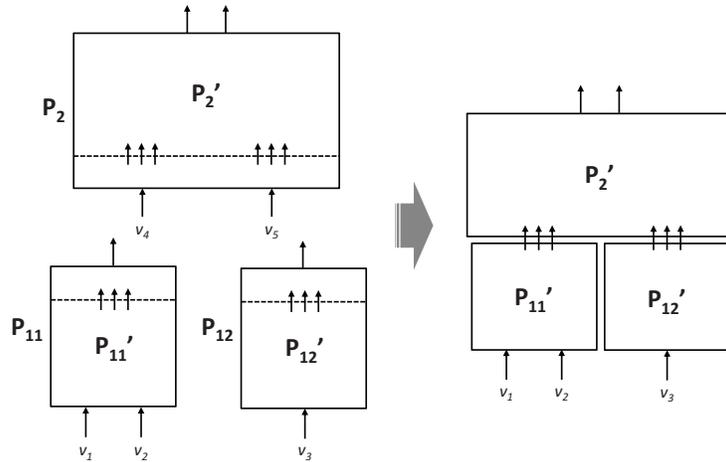


Fig. 4. Sequential composition of P_{11} , P_{12} , and P_2 . Here, P_{11}' (resp. P_{12}') is the output-decoder-free part of P_{11} (resp. P_{12}), and P_2' is the input-encoder-free part of P_2 . The composition connects the split outputs of P_{11}' and P_{12}' to the split inputs of P_2' .

3.1 Parallel Composition

This subsection proves the parallel compositionality result. Let us write $P_1 \parallel P_2$ for the parallel composition of P_1 and P_2 . We state and prove the result.

Theorem 2. *Let P_1 and P_2 be n -leakage-resilient circuits having disjoint randoms. Then, $P_1 \parallel P_2$ is also n -leakage-resilient.*

Remark 3. While Theorem 2 only states that $P_1 \parallel P_2$ can withstand an attack that observes up to n nodes total from the composed circuit, a stronger property can actually be derived from the proof of the theorem. That is, the proof shows that $P_1 \parallel P_2$ can withstand an attack that observes up to n nodes from the P_1 part and up to n nodes from the P_2 part. (However, it is not secure against an attack that picks more than n nodes in an arbitrary way: for example, picking $n + 1$ nodes from one side.)

3.2 Sequential Composition

This subsection proves the sequential compositionality result. As remarked above, the result is significantly harder to prove than the parallel compositionality result. Let us write $(P_{11}, \dots, P_{1y}) \triangleright P_2$ for the sequential composition of P_{11}, \dots, P_{1y} with a y -input circuit P_2 . We state and prove the sequential compositionality result.

Theorem 3. *Let P_{11}, \dots, P_{1y} be n -leakage-resilient circuits, and P_2 be an y -input n -leakage-resilient circuit, having disjoint randoms. Then, $(P_{11}, \dots, P_{1y}) \triangleright P_2$ is n -leakage-resilient.*

Example 2. As remarked in Section 3, the parallel compositionality result enjoys an additional property that the circuit is secure even under an attack that observes more than n nodes in the composition as long as the observation in each component is at most n . We show that the property does not hold in the case of sequential composition. Indeed, it can be shown that just allowing $n + 1$ observations breaks the security even if the number of observations made within each component is at most n .

To see this, consider the $n+1$ -split circuit shown in Fig. 6. The circuit implements the identity function, and it is easy to see that the circuit is n -leakage resilient. Let P_1 and P_2 be copies of the circuit, and consider the composition $(P_1) \triangleright P_2$. Then, the composed circuit is not secure against an attack that observes m nodes of P_1 for some $1 \leq m \leq n$, and observes $n + 1 - m$ nodes of P_2 such that the nodes picked on the P_2 side are the nodes connected to the nodes that are not picked on the P_1 side.

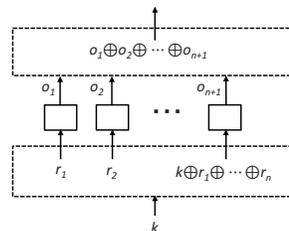


Fig. 6. An n -leakage resilient identity circuit.

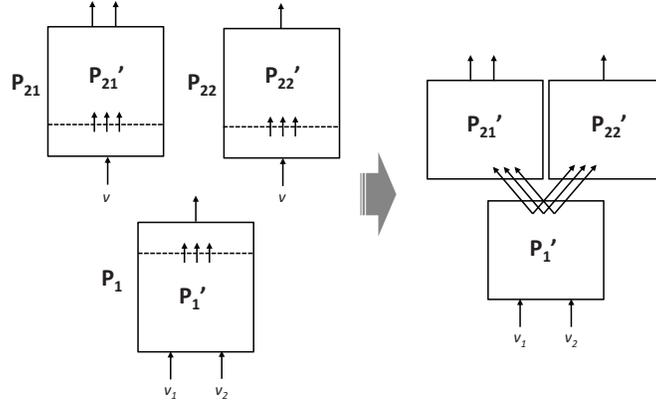


Fig. 5. Output-sharing sequential composition of P_1 , P_{21} , and P_{22} . Here, P_1' is the output-decoder-free part of P_1 , and P_{21}' (resp. P_{22}') is the input-encoder-free part of P_{21} (resp. P_{22}). The composition connects the split output of P_1' to the split inputs of P_{21}' and P_{22}' .

Remark 4. By a reasoning similar to the one used in the proof of Theorem 3, we can show the correctness of a more parsimonious version of parallel composition theorem (Theorem 2) where given P_1 and P_2 that shares a secret, instead of $P_1||P_2$ duplicating split shares of the secret as in Fig. 3, we make one split share tuple to be used in the both sides of the composition. Combining this improved parallel composition with the sequential compositionality result, we obtain compositionality for the case where an output of a circuit is shared by more than one circuit in a sequential composition.

Fig. 5 depicts such an *output-sharing sequential composition*. Here, P_1 , P_{21} , and P_{22} are n -leakage-resilient circuits, and we wish to compose them by connecting the output of P_1 to the input of P_{21} and the input of P_{22} . By the parallel compositionality result, the parallel composition of P_{21} and P_{22} that shares the same input (v) is n -leakage-resilient. Then, it follows that, sequentially composing that parallelly composed circuit with P_1 , as depicted in the figure, is also n -leakage-resilient thanks to the sequential compositionality result.

4 Compositional Synthesis Algorithm

The compositionality property gives a way for a compositional approach to synthesizing leakage-resilient circuits. Algorithm 1 shows the overview of the synthesis algorithm. Given a random-free circuit as an input, the algorithm synthesizes an IO-equivalent n -leakage-resilient circuit. It first invokes the DECOMP operation to choose a suitable decomposition of the given circuit into some number of sub-circuits. Then, it invokes MONOSYNTH on each sub-circuit P_i to synthesize an n -leakage resilient circuit P_i' that is IO-equivalent to P_i . Finally, it returns

the composition of the obtained circuits as the synthesized n -leakage resilient version of the original.

Algorithm 1 The Compositional Synthesis Algorithm

Input: Random-free Circuit P
Output: IO-equivalent n -leakage-resilient circuit

- 1: $P_1, \dots, P_m := \text{DECOMP}(P)$
- 2: **for each** $P_i \in \{P_1, \dots, P_m\}$ **do**
- 3: $P_i' := \text{MONOSYNTH}(P_i)$
- 4: **end for**
- 5: **return** $\text{COMP}(P_1', \dots, P_m')$

COMP is the composition operation, and it composes the given n -leakage-resilient circuits in the manner described in Section 3. MONOSYNTH is a constraint-based “monolithic” synthesis algorithm that synthesizes an n -leakage-resilient circuit that is IO-equivalent to the given circuit without further decomposition. We describe MONOSYNTH in Section 4.1, and describe the decomposition operation DECOMP in Section 4.2.

The algorithm optimizes the synthesized circuits in the following ways. First, as described in Section 4.1, the monolithic synthesis looks for tree-shaped circuits of the shortest tree height. Secondly, as described in Section 4.2, the decomposition and composition is done in a way to avoid unnecessarily making the non-secret-dependent parts leakage resilient, and also to re-use the synthesis results for shared sub-circuits whenever allowed by the compositionality properties.

Remark 5. The compositional algorithm composes the n -leakage-resilient versions of the sub-circuits. Note that the compositionality property states that the result will be n -leakage-resilient after the composition, regardless of how the sub-circuits are synthesized as long as they are also n -leakage-resilient and have disjoint randoms. Thus, in principle, any method to synthesize the n -leakage-resilient versions of the sub-circuits may be used in place of MONOSYNTH. For instance, a possible alternative is to use a database of n -leakage-resilient versions of commonly-used circuits (e.g., obtained via the construction of [15, 5]).

4.1 Constraint-Based Monolithic Synthesis

The monolithic synthesis algorithm is based on and extends the constraint-based approach proposed by Eldib and Wang [8]. The algorithm synthesizes an n -leakage-resilient circuit that is IO-equivalent to the given circuit. The algorithm requires the given circuit to have only one output. Therefore, the overall algorithm to decomposes the whole circuit into such sub-circuits before passing them to MONOSYNTH.

We formalize the algorithm as quantified first-order logic constraint solving. Let P be the random-free circuit given as the input. We prepare a quantifier-free

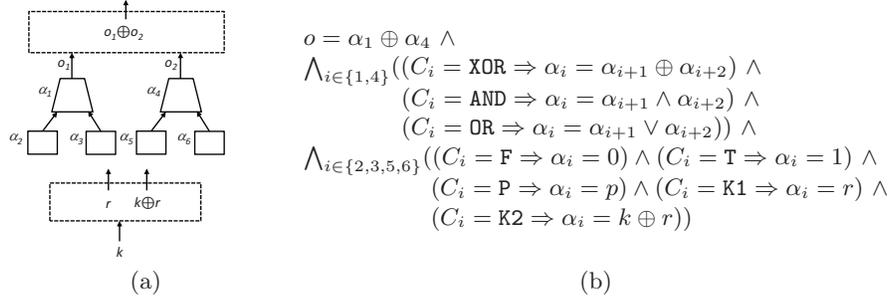


Fig. 7. (a) Skeleton circuit. (b) Φ_{Sk_2} for the skeleton circuit.

formula $\Phi_P(\alpha, \mathbf{p}, \mathbf{k}, o)$ on the free variables $\alpha, \mathbf{p}, \mathbf{k}, o$ that encodes the input-output behavior of P . Formally, $\exists \alpha. \Phi_P(\alpha, \mathbf{p}, \mathbf{k}, o)$ is true iff P outputs o given public inputs \mathbf{p} and secret inputs \mathbf{k} . The variables α are used for encoding the shared sub-circuits within P (i.e., gates of fan-out > 1). For example, for P that outputs $k \wedge p$, $\Phi_P(p, k, o) \equiv o = k \wedge p$.

Adopting the approach of [8], our monolithic algorithm works by preparing *skeleton circuits* of increasing size, and searching for an instance of the skeleton that is n -leakage-resilient and IO-equivalent to P . By starting from a small skeleton, the algorithm biases toward finding an optimized leakage resilient circuit. Formally, a skeleton circuit Sk_ℓ is a tree-shaped circuit (i.e., circuit with all non-input gates having fan-out of 1) of height ℓ whose gates have undetermined functionality except for the parts that implement the input encoder and the output decoder. For example, Fig. 7 (a) shows the 1+1-split skeleton circuit of height 2 with one secret input.

We prepare a quantifier-free *skeleton formula* Φ_{Sk_ℓ} that expresses the skeleton circuit. Formally, $\Phi_{Sk_\ell}(\mathbf{C}, \alpha, \mathbf{p}, \mathbf{k}, \mathbf{r}, o)$ is true iff P' outputs o with the valuations of $nodes(P')$ having the values α given public inputs \mathbf{p} , secret inputs \mathbf{k} , and random inputs \mathbf{r} where P' is Sk_ℓ with its nodes' functionality determined by \mathbf{C} .⁶ We call \mathbf{C} the *control variables*, and write $Sk_\ell(\mathbf{C})$ for the instance of Sk_ℓ determined by \mathbf{C} . For example, Fig. 7 (b) shows Φ_{Sk_ℓ} for the skeleton circuit from Fig. 7 (a), when there is one public input and no randoms besides the one from the input encoder.

The synthesis is now reduced to the problem of finding an assignment to \mathbf{C} that satisfies the constraint $\Phi_{IO}(\mathbf{C}) \wedge \Phi_{LR}(\mathbf{C})$ where $\Phi_{IO}(\mathbf{C})$ expresses that $Sk_\ell(\mathbf{C})$ is IO-equivalent to P , and $\Phi_{LR}(\mathbf{C})$ expresses that $Sk_\ell(\mathbf{C})$ is n -leakage-resilient. As we shall show next, the constraints faithfully encode IO-equivalence and leakage-resilience according to the definitions from Section 2.

⁶ Technically, the number of randoms (i.e., \mathbf{r}) can also be left undetermined in the skeleton. Here, for simplicity, we assume that the number of randoms is determined by the factors such as n , the skeleton height, and the number of secret inputs.

$\Phi_{\text{IO}}(\mathbf{C})$ is the formula below.

$$\forall \alpha, \alpha', \mathbf{p}, \mathbf{k}, \mathbf{r}, o, o'. \Phi_P(\alpha, \mathbf{p}, \mathbf{k}, o) \wedge \Phi_{Sk_\ell}(\mathbf{C}, \alpha', \mathbf{p}, \mathbf{k}, \mathbf{r}, o') \Rightarrow o = o'$$

It is easy to see that Φ_{IO} correctly expresses IO equivalence.

The definition of Φ_{LR} is more involved, and we begin by introducing a useful shorthand notation. Let m be the number of (observable) nodes in Sk_ℓ . Without loss of generality, we assume that $m \geq n$. Let $\sigma \in \{1, \dots, m\}^*$ be a sequence such that $|\sigma| \leq n$, and $\alpha = \alpha_1, \dots, \alpha_m$ be a length m sequence of variables. We write $\alpha\langle\sigma\rangle$ for the sequence of variables $\beta_1, \dots, \beta_{|\sigma|}$ such that $\beta_i = \alpha_{\sigma_i}$ for each $i \in \{1, \dots, |\sigma|\}$. Intuitively, σ represents a selection of nodes observed by the adversary. For example, let $\alpha = \alpha_1, \alpha_2, \alpha_3$ and $\sigma = 1, 3$, then $\alpha\langle\sigma\rangle = \alpha_1, \alpha_3$.

Let $\mathcal{R} = \{0, 1\}^{|\mathbf{r}|}$. Then, $\Phi_{\text{LR}}(\mathbf{C})$ is the formula below.

$$\begin{aligned} & \forall \sigma. \forall \beta, \alpha', \mathbf{p}, \mathbf{k}, \mathbf{k}', o. \\ & \bigwedge_{\mathbf{b} \in \mathcal{R}} \phi[\alpha_{\mathbf{b}}/\alpha][o_{\mathbf{b}}/o] \wedge \phi[\alpha'_{\mathbf{b}}/\alpha][o'_{\mathbf{b}}/o][\mathbf{k}'/\mathbf{k}] \\ & \Rightarrow \sum_{\mathbf{b} \in \mathcal{R}} (\alpha_{\mathbf{b}}\langle\sigma\rangle = \beta) = \sum_{\mathbf{b} \in \mathcal{R}} (\alpha'_{\mathbf{b}}\langle\sigma\rangle = \beta) \end{aligned}$$

where α' is a sequence comprising distinct variables $\alpha_{\mathbf{b}}$ and $\alpha'_{\mathbf{b}}$ such that $|\alpha_{\mathbf{b}}| = |\alpha'_{\mathbf{b}}| = m$ for each $\mathbf{b} \in \mathcal{R}$, o is a sequence comprising distinct variables $o_{\mathbf{b}}$ and $o'_{\mathbf{b}}$ for each $\mathbf{b} \in \mathcal{R}$, and ϕ is the formula $\Phi_{Sk_\ell}(\mathbf{C}, \alpha, \mathbf{p}, \mathbf{k}, \mathbf{b}, o)$. While $\Phi_{\text{LR}}(\mathbf{C})$ is not strictly a first-order logic formula, it can be converted to the form by expanding the finitely many possible choices of σ .

Algorithm 2 MONOSYNTH

Input: Random-free Circuit P

Output: IO-equivalent n -leakage resilient circuit

```

1:  $\ell := \text{INIT\_HEIGHT}$ 
2: loop
3:    $tset := \emptyset; \gamma := n$ 
4:   loop
5:     match FINDCAND( $tset, \gamma$ ) with
6:       nosol  $\rightarrow \ell++$ ; break
7:       | sol( $\mathbf{b}_C$ )  $\rightarrow$  match CHECKCAND( $\mathbf{b}_C$ ) with
8:         success  $\rightarrow$  return  $Sk_\ell(\mathbf{b}_C)$ 
9:         | cex( $tset', \gamma'$ )  $\rightarrow tset := tset \cup tset'; \gamma := \max(\gamma, \gamma')$ 
10:    end loop
11: end loop

```

Because the domains of the quantified variables in Φ_{IO} and Φ_{LR} are finite, one approach to solving the constraint may be first eliminating the quantifiers eagerly and then solving for \mathbf{C} that satisfies the resulting constraint. However, the approach is clearly impractical due to the extreme size of the resulting constraint. Instead, adopting the idea from [8], we solve the constraint by lazily instantiating the quantifiers. The main idea is to divide the constraint solving

process in two phases: the *candidate finding* phase that infers a candidate solution for \mathbf{C} , and the *candidate checking* phase that checks whether the candidate is actually a solution. We run the phases iteratively in a CEGAR style until convergence. Algorithm 2 shows the overview of the process. We describe the details of the algorithm below.

Candidate Checking. The candidate checking phase is straightforward. Note that, after expanding the choices of σ in Φ_{LR} , $\Phi_{\text{IO}}(\mathbf{C}) \wedge \Phi_{\text{LR}}(\mathbf{C})$ only has outermost \forall quantifiers. Therefore, given a concrete assignment to \mathbf{C} , $\mathbf{b}_{\mathbf{C}}$, CHECKCAND directly solves the constraint by using an SMT solver.⁷ (However, naively expanding σ can be costly when $n > 1$, and we show a modification that alleviates the cost in the later part of the subsection.)

Candidate Finding. We describe the candidate finding process FINDCAND. To find a likely candidate, we adopt the idea from [8] and prepare a *test set* that is updated via the CEGAR iterations. In [8], a test set, *tset*, is a pair of sets $tset_p$ and $tset_k$ where $tset_p$ (resp. $tset_k$) contains finitely many concrete valuations of \mathbf{p} (resp. \mathbf{k}). Having such a test set, we can rewrite the constraint so that the public inputs and secret inputs are restricted to those from the test set. That is, $\Phi_{\text{IO}}(\mathbf{C})$ is rewritten to be the formula below.

$$\bigwedge_{(\mathbf{b}_p, \mathbf{b}_k) \in tset_p \times tset_k} \Phi_P(\alpha_{\mathbf{b}_p \mathbf{b}_k}, \mathbf{b}_p, \mathbf{b}_k, o_{\mathbf{b}_p \mathbf{b}_k}) \wedge \Phi_{Sk_\ell}(\mathbf{C}, \alpha'_{\mathbf{b}_p \mathbf{b}_k}, \mathbf{b}_p, \mathbf{b}_k, r_{\mathbf{b}_p \mathbf{b}_k}, o'_{\mathbf{b}_p \mathbf{b}_k}) \wedge o_{\mathbf{b}_p \mathbf{b}_k} = o'_{\mathbf{b}_p \mathbf{b}_k}$$

And, $\Phi_{\text{LR}}(\mathbf{C})$ becomes the formula below.

$$\begin{aligned} & \forall \sigma. \forall \beta. \bigwedge_{(\mathbf{b}_p, \mathbf{b}_k, \mathbf{b}_k') \in tset_p \times tset_k \times tset_k} \bigwedge_{\mathbf{b} \in \mathcal{R}} \\ & \phi[\alpha_{\mathbf{b}_p \mathbf{b}_k \mathbf{b}} / \alpha][o_{\mathbf{b}_p \mathbf{b}_k \mathbf{b}} / o][\mathbf{b}_k / \mathbf{k}] \wedge \phi[\alpha'_{\mathbf{b}_p \mathbf{b}'_k \mathbf{b}} / \alpha][o'_{\mathbf{b}_p \mathbf{b}'_k \mathbf{b}} / o][\mathbf{b}'_k / \mathbf{k}] \\ & \wedge \sum_{\mathbf{b} \in \mathcal{R}} (\alpha_{\mathbf{b}_p \mathbf{b}_k \mathbf{b}}(\sigma) = \beta) = \sum_{\mathbf{b} \in \mathcal{R}} (\alpha'_{\mathbf{b}_p \mathbf{b}'_k \mathbf{b}}(\sigma) = \beta) \end{aligned}$$

where ϕ is the formula $\Phi_{Sk_\ell}(\mathbf{C}, \alpha, \mathbf{b}_p, \mathbf{k}, \mathbf{b}, o)$. We remark that, because fixing the inputs to concrete values also fixes the valuations of some other variables (e.g., fixing \mathbf{p} and \mathbf{k} also fixes α and o in $\Phi_P(\alpha, \mathbf{p}, \mathbf{k}, o)$), the constraint structure is modified to remove the quantifications on such variables.

At this point, the approach of [8] can be formalized as the following process: it eagerly instantiates the possible choices of σ and β to reduce the constraint to a quantifier-free form, and looks for a satisfying assignment to the resulting constraint. This is a sensible approach when n is 1 because, in that case, the number of possible choices of σ is linear in the size of the skeleton (i.e., is m) and the possible valuations of β are simply $\{0, 1\}$. Unfortunately, the number of possible choices of σ grows exponentially in n , and so does that of the possible valuations of β .⁸ We remark that this is expected because σ represents the

⁷ Also, because \mathbf{C} are the only shared variables in Φ_{IO} and Φ_{LR} , the two may be checked independently after instantiating \mathbf{C} .

⁸ Therefore, the complexity of the method is at least double exponential in n assuming that the complexity of the constraint solving process is at least exponential in the size of the given formula.

adversary’s node selection choice, and β represents the valuation of the selected nodes. Indeed, in our experience with a prototype implementation, this method fails even on quite small sub-circuits and with n just 2.

Therefore, we make the following improvements to the base algorithm.

- (1) We restrict the node selection to root-most γ nodes where γ starts at n and is incremented via the CEGAR loop.
- (2) We include node valuations in the test set.
- (3) We use dependency analysis to reduce irrelevant node selections from the constraint in the candidate checking phase.

The rationale for prioritizing the root-most nodes in (1) is that, in a tree-shaped circuit, nodes closer to the root are more likely to be dependent on the secret and therefore are expected to be better targets for the adversary. The number of root-most nodes to select, γ , is incremented as needed by a counterexample analysis (cf. lines 7-9 of Algorithm 2). The test set generation for node valuations described in item (2) is done in much the same way as that for public inputs and secret inputs. We describe the test set generation process in more detail in **Test Set Generation**. With the modifications (1) and (2), the leakage-resilience constraint to be solved in the candidate finding phase is now the following formula.

$$\begin{aligned} \forall \sigma : \gamma. \bigwedge_{(\mathbf{b}_p, \mathbf{b}_k, \mathbf{b}_{k'}, \mathbf{b}_\beta) \in tset_p \times tset_k \times tset_k \times tset_\beta} \bigwedge_{\mathbf{b} \in \mathcal{R}} \\ \phi[\alpha_{\mathbf{b}_p \mathbf{b}_k \mathbf{b}} / \alpha][o_{\mathbf{b}_p \mathbf{b}_k \mathbf{b}} / o][\mathbf{b}_k / \mathbf{k}] \wedge \phi[\alpha'_{\mathbf{b}_p \mathbf{b}'_k \mathbf{b}} / \alpha][o'_{\mathbf{b}_p \mathbf{b}'_k \mathbf{b}} / o][\mathbf{b}'_k / \mathbf{k}] \\ \wedge \sum_{\mathbf{b} \in \mathcal{R}} (\alpha_{\mathbf{b}_p \mathbf{b}_k \mathbf{b}} \langle \sigma \rangle = \mathbf{b}_\beta) = \sum_{\mathbf{b} \in \mathcal{R}} (\alpha'_{\mathbf{b}_p \mathbf{b}'_k \mathbf{b}} \langle \sigma \rangle = \mathbf{b}_\beta) \end{aligned}$$

where $\sigma : \gamma$ restricts σ to the root most γ indexes, $tset_\beta$ is the set of test set elements for node valuations, and ϕ is the formula $\Phi_{Sk_\ell}(\mathbf{C}, \alpha, \mathbf{b}_p, \mathbf{k}, \mathbf{b}, o)$.

Unlike (1) and (2), the modification (3) applies to the candidate checking phase. To see the benefit of this modification, note that, even in the candidate checking phase, checking the leakage-resilience condition $\Phi_{LR}(\mathbf{b}_C)$ can be quite expensive because it involves expanding exponentially many possible choices of node selections. To mitigate the cost, we take advantage of the fact that the candidate circuit is fixed in the candidate checking phase, and do a simple dependency analysis on the candidate circuit to reduce irrelevant node-selection choices. We describe the modification in more detail. Let P' be the candidate circuit. For each node of P' , we collect the reachable leafs from the node to obtain the over-approximate set of inputs on which the node may depend. For a node α of P' , let $deps(\alpha)$ be the obtained set of dependent inputs for α . Then, any selection of nodes α such that $\bigcup_{\alpha \in \{\alpha\}} deps(\alpha)$ does not contain all $n+1$ -split shares of some secret is an irrelevant selection and can be removed from the constraint. (Here, we use the symbols α for node labels as in Section 2, and not as node-valuation variables in a constraint.)

Test Set Generation. Recall that our algorithm maintains three kinds of test sets, $tset_p$ for public inputs, $tset_k$ for secret inputs, and $tset_\beta$ for node valuations. As shown in lines 7-9 of Algorithm 2, we obtain new test set elements from candidate check failures (here, by abuse of notation, we write $tset \cup tset'$ for the

component-wise union). We describe the process in more detail. In CHECKCAND, we convert the constraint $\Phi_{\text{IO}}(\mathbf{b}_C) \wedge \Phi_{\text{LR}}(\mathbf{b}_C)$ to a quantifier free formula Φ by expanding the selection choices and removing the universal quantifiers. Then, we use an SMT solver to check the satisfiability of $\neg\Phi$ and return **success** if it is unsatisfiable. Otherwise, the SMT solver returns a satisfying assignment of $\neg\Phi$, and we return the values assigned to variables corresponding to public inputs, secret inputs and node valuations as the new elements for the respective test sets. The number of root-most nodes to select is also raised here by taking the maximum of the root-most nodes observed in the satisfying assignment, γ' , with the current γ .

4.2 Choosing Decomposition

This subsection describes the decomposition procedure DECOMP. Thanks to the generality of the compositionality results, in principle, we can decompose the given circuit into arbitrarily small sub-circuits (i.e., down to individual gates). However, choosing a too fine-grained decomposition may lead to a sub-optimal result.⁹

To this end, we have implemented the following decomposition strategy. First, we run a dependency analysis, similar to the one used in the constraint-based monolithic synthesis (cf. Section 4.1). The analysis result is used to identify the parts of the given circuit that do not depend on any of the secrets. We factor out such *public-only* sub-circuits from the rest so that they will not be subject to the leakage-resilience transformation.

Next, we look for sub-circuits that are used at multiple locations (i.e., whose roots have fan-out > 1), and prioritize them to be synthesized separately and composed at their use sites. Besides the saving in the synthesis effort, the approach can lead a smaller synthesis result when the shared sub-circuit is used in contexts that lead to different outputs (cf Remark 4). Finally, as a general strategy, we apply parallel composition at the root so that we synthesize separately for each output given a multi-output circuit. And, we set a bound on the maximum size of the circuits that will be synthesized monolithically, and decompose systematically based on the bound. As discussed in Section 5, in the prototype implementation, we use an “adaptive” version of the latter decomposition process by adjusting the bound on-the-fly and also opting for a pre-made circuit under certain conditions.

Example 3. Let us apply the compositional synthesis algorithm to the circuit from Fig. 2, for the case $n = 2$. Note that the circuit has no non-trivial public-only sub-circuits or have non-inputs gates with fan-out greater than 1.

First, we apply the parallel compositionality result so that the circuit is decomposed to two parts: the left tree that computes $p_1 \oplus k_1 \oplus k_2$ and the right tree that computes $k_2 \oplus p_2$. The right tree cannot be decomposed further, and we apply MONOSYNTH to transform it to a leakage-resilient form. A possible

⁹ One may make the analogy to compiler optimization. Such a decomposition strategy is analogous to optimizing each instruction individually.

name	$n = 2$			$n = 3$			$n = 4$			name	$n = 2$			$n = 3$			$n = 4$		
	time	size	rds	time	size	rds	time	size	rds		time	size	rds	time	size	rds	time	size	rds
P1	16.2s	123	32	49.4s	138	48	52.7s	160	64	P10	T/O			M/O			M/O		
P2	10.3s	64	16	1m13s	76	24	4m3s	88	32	P11	T/O			T/O			M/O		
P3	M/O			M/O			M/O			P12	T/O			T/O			T/O		
P4	M/O			M/O			M/O			P13	T/O			T/O			T/O		
P5	M/O			M/O			M/O			P14	T/O			T/O			M/O		
P6	M/O			M/O			M/O			P15	T/O			T/O			M/O		
P7	M/O			M/O			M/O			P16	T/O			T/O			T/O		
P8	M/O			M/O			M/O			P17	T/O			T/O			T/O		
P9	T/O			T/O			T/O			P18	T/O			T/O			T/O		

Table 1. Experiment Results: Monolithic Only.

name	$n = 2$				$n = 3$				$n = 4$			
	time	mtc	size	rds	time	mtc	size	rds	time	mtc	size	rds
P1	18.7s	2.7s	125	32	30.2s	4.5s	143	48	1m1s	33.3s	160	64
P2	11.8s	3.6s	65	16	1m7s	17.3s	74	24	2m56s	1m21s	88	32
P3	2.7s	0.8s	50	11	12.3s	6.9s	83	18	3m57s	1m4s	120	26
P4	3.9s	3.1s	42	9	4.5s	2.1s	69	15	1m48s	1m4s	100	22
P5	5.9s	2.1s	63	13	20.2s	6.9s	108	21	5m12s	1m4s	140	30
P6	5.3s	1.4s	65	13	17.4s	6.9s	108	21	4m57s	1m7s	141	30
P7	2m52s	1m28s	80	15	6m13s	4m6s	163	30	9m7s	2m42s	231	44
P8	3m10s	1m48s	77	15	5m8s	3m19s	161	30	8m47s	1m44s	234	44
P9	1.2s	1.1s	33	9	2m58s	2m55s	58	15	1m7s	1m5s	87	22
P10	2m2s	1m1s	583	146	18m37s	4m46s	1027	249	26m51s	5m2s	1598	372
P11	4m9s	1m5s	464	112	24m41s	5m25s	814	192	46m12s	18m28s	1269	288
P12	10m33s	1m5s	1507	370	1h4m19s	5m56s	2643	633	2h14m24s	27m1s	4116	948
P13	17m7s	3.4s	14369	1088	50m5s	16.1s	21163	1824	10h27m40s	1m58s	22123	2688
P14	17m12s	3.4s	14369	1088	50m0s	16.0s	21163	1824	10h27m47s	2m21s	22153	2688
P15	17m15s	3.4s	14625	1088	52m32s	16.4s	21763	1824	10h30m26s	1m35s	22927	2688
P16	16m39s	3.4s	14553	1088	52m10s	14.9s	21773	1824	10h24m23s	1m27s	22922	2688
P17	5h28m27s	4m3s	16066	1594	19h11m33s	7m46s	23568	2592	17h37m27s	2m36s	25236	3712
P18	34m42s	3.7s	60111	3968	1h37m9s	15.5s	78418	6144	17h43m2s	1m54s	74847	8448

Table 2. Experiment Results: Compositional.

synthesis result of this is the right sub-circuit shown in Fig. 1 (i.e., the sub-circuit whose observable part outputs the split output o_4, o_5, o_6).

For the left tree, if the monolithic-synthesis size bound is set to synthesize circuits of height 2, we apply MONOSYNTH directly to the tree. Alternatively, with a lower bound set, we further decompose the left tree to a lower part that computes $p_1 \oplus k_1$ and p_2 (identity function) and an upper part that computes $k \oplus p_2$ where the output of the lower part is to be connected to the “place-holder” input k . Following the either strategy, we may obtain the left sub-circuit of Fig. 1 as a possible result. And, the final synthesis result after composing the left and right synthesis results is the whole circuit of Fig. 1.

5 Implementation and Experiments

We have implemented a prototype of the compositional synthesis algorithm. The implementation takes as input a finite-data loop-free C program and converts the program into a Boolean circuit in the standard way. We remark that, in

principle, a program with non-input-dependent loops and recursive functions may be converted to such a form by loop unrolling and function inlining.

The implementation is written in the OCaml programming language. We use CIL [19] for the front-end parsing and Z3 [6] for the SMT solver used in the constraint-based monolithic synthesis. The experiments are conducted on a machine with a 2.60GHz Intel Xeon E5-2690v3 CPU with 8GB of RAM running a 64-bit Linux OS, with the time limit of 20 hours.

We have run the implementation on the 18 benchmark programs taken from the paper by Eldib and Wang [8]. The benchmarks are (parts of) various cryptographic algorithm implementations, such as a round of AES, and we refer to their paper for the details of the respective benchmarks (we use the same program names).¹⁰ Whereas their experiments synthesized leakage-resilient versions of the benchmarks only for the case n is 1, in our experiments, we do the synthesis for the cases $n = 2$, $n = 3$, and $n = 4$.

We describe the decomposition strategy that is implemented in the prototype. Specifically, we give details of the online decomposition process mentioned in Section 4.2. The implementation employs the following *adaptive* strategy when decomposing systematically based on a circuit size bound. First, we set the bound to be circuits of some fixed height (the experiments use height 3), and decompose based on the bound. However, in some cases, the bound can be too large for the monolithic constraint-based synthesis algorithm to complete in a reasonable amount of time. Therefore, we set a limit on the time that the constraint-based synthesis can spend on constraint solving, and when the time limit is exceeded, we further decompose that sub-circuit by using a smaller bound. Further, when the time limit is exceeded even with the smallest bound, or the number of secrets in the sub-circuit exceeds a certain bound (this is done to prevent out of memory exceptions in the SMT solver), we use a pre-made leakage resilient circuit. Recall from Remark 5 that the compositionality property ensures the correctness of such a strategy.

Tables 1 and 2 summarize the experiment results. Table 2 shows the results of the compositional algorithm. Table 1 shows the results obtained by the “monolithic-only” version of the algorithm. Specifically, the monolithic-only results are obtained by, first applying the parallel compositionality property (cf. Section 3.1) to divide the given circuit into separate sub-circuit for each output, and then applying the constraint-based monolithic synthesis to each sub-circuit and combining the results. (The per-output parallel decomposition is needed because the constraint-based monolithic synthesis only takes one-output circuits as input – cf. Section 4.1.) The monolithic-only algorithm is essentially the monolithic algorithm of Eldib and Wang [8] with the improvements described in Section 4.1.

¹⁰ Strangely, some of the benchmarks contain inputs labeled as “random” and have random IO behavior (when those inputs are actually treated as randoms), despite the method of [8] only supporting programs with non-random (i.e., deterministic) IO behavior. We treat such “random” inputs as public inputs in our experiments.

We describe the table legends. The column labeled “name” shows the benchmark program names. The columns labeled “time” show the time taken to synthesize the circuit. Here, “T/O” means that the algorithm was not able to finish within the time limit, and “M/O” means that the algorithm aborted due to an out of memory error. The columns labeled “size” show the number of gates in the synthesized circuit, and the columns labeled “rds” show the number of randoms in the synthesized circuit.

The columns labeled “mtc” in Table 2 is the maximum time spent by the algorithm to synthesize a sub-circuit in the compositional algorithm. Our prototype implementation currently implements a sequential version of the compositional algorithm where each sub-circuit is synthesized one at a time in sequence. However, in principle, the sub-circuits may be synthesized simultaneously in parallel, and the columns mtc give a good estimate of the efficiency of such a parallel version of the compositional algorithm. We also remark that the current prototype implementation is unoptimized and does not “cache” the synthesis results, and therefore, it naively applies the synthesis repeatedly on the same sub-circuits that have been synthesized previously.

As we can see from the tables, the monolithic-only approach is not able to finish on many of the benchmarks, even for the case $n = 2$. In particular, it does not finish on any of the large benchmarks (as one can see from the sizes of the synthesized circuits, P13 to P18 are of considerable sizes). By contrast, the compositional approach was able to successfully complete the synthesis for all instances. We observe that the compositional approach was faster for the larger n in some cases (e.g., P9 with $n = 3$ vs. $n = 4$). While this is partly due to the unpredictable nature of the back-end SMT solver, it is also an artifact of the decomposition strategy described above. More specifically, in some cases, the algorithm more quickly detects (e.g., in earlier iterations of the constraint-based synthesis’s CEGAR loop) that the decomposition bound should be reduced for the current sub-circuit, which can lead to a faster overall running time.

We also observe that the sizes of the circuits synthesized by the compositional approach are quite comparable to those of the ones synthesized by the monolithic-only approach, and the same observation can be made to the numbers of randoms in the synthesized circuits. In fact, in one case (P2 with $n = 3$), the compositional approach synthesized a circuit that is smaller than the one synthesized by the monolithic-only approach. While this is due in part to the fact that the monolithic synthesis algorithm optimizes circuit height rather than size, in general, it is not inconceivable for the compositional approach to do better than the monolithic-only approach in terms of the quality of the synthesized circuit. This is because the compositional method could make a better use of the circuit structure by sharing synthesized sub-circuits, and also because of parsimonious use of randoms allowed by the compositionality property. We remark that the circuits synthesized by our method are orders of magnitude smaller than those obtained by naively applying the original construction of Ishai et al. [15] (cf. Theorem 1). For instance, for P18 with $n = 4$, the construction would produce a circuit with more than 3600k gates and 500k randoms.

6 Related Work

Verification and Synthesis for n -Threshold-Probing Model of Leakage Resilience. The n -threshold-probing model of leakage resilience was proposed in the seminal work by Ishai et al. [15]. The subsequent research has proposed methods to build circuits that are leakage resilient according to the model [21, 5, 7, 9, 8, 4, 3]. Along this direction, the two branches of work that are most relevant to ours are *verification* which aims at verifying whether the given (hand-crafted) circuit is leakage resilient [9, 4, 3], and *synthesis* which aims at generating leakage resilient circuits automatically [8]. In particular, our constraint-based monolithic synthesis algorithm is directly inspired and extends the algorithm given by Eldib and Wang [8]. As remarked before, their method only handles the case $n = 1$. By contrast, we propose the first compositional synthesis approach that also works for arbitrary values of n .

On the verification side, the constraint-based verification method proposed in [9] is a precursor to their synthesis work discussed above, and it is similar to the candidate checking phase of the synthesis. Recent papers by Barthe et al. [4, 3] investigate verification methods that aim to also support the case $n > 1$. Compositional verification is considered in [3]. As remarked before, in contrast to the compositionality property described in our paper, their composition does not require disjointness of the randoms in the composed components but instead require additional randoms at the site of the composition. We believe that the compositionality property investigated in their work is complementary to ours, and we leave for future work to combine these facets of compositionality.

We remark that synthesis is substantially harder than verification. Indeed, in our experience with the prototype implementation, most of the running time is consumed by the candidate finding part of the monolithic synthesis process with relatively little time spent by the candidate checking part.

Quantitative Information Flow. *Quantitative information flow* (QIF) [18, 22, 23, 1] is a formal measure of information leak, which is based on an information theoretic notion such as Shannon entropy, Rènyi entropy, and channel capacity. Recently, researchers have proposed QIF-based methods for side channel attack resilience [16, 17] whereby static analysis techniques for checking and inferring QIF are applied to side channels.

It is difficult to directly compare the QIF approach with the n -threshold-probing model of leakage resilience. Whereas the notion of security ensured by the latter is the absence of information leakage against an adversary of a certain restricted observation capability, the security ensured by the QIF approach is typically not of the form in which the adversary’s capability is restricted in some way, but instead some (small amount of) leak is permitted. We remark that, as also observed by [4], in the terminology of information flow theory, the n -threshold-probing model of leakage resilience corresponds to enforcing *probabilistic non-interference* [13] on every n -tuple of the circuit’s internal nodes.

7 Conclusion

We have presented a new approach to synthesizing circuits that are leakage resilient according to the n -threshold-probing model. We have shown that the leakage-resilience model admits a certain compositionality property, which roughly says that composing n -leakage-resilient circuits results in an n -leakage-resilient circuit, assuming the disjointness of the randoms in the composed circuit components. Then, by utilizing the property, we have designed a compositional synthesis algorithm that divides the given circuit into smaller sub-circuits, synthesizes n -leakage-resilient versions of them containing disjoint randoms, and combines the results to obtain an n -leakage-resilient version of the whole.

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A Proofs

A.1 Proof of Theorem 2

Theorem 2. *Let P_1 and P_2 be n -leakage-resilient circuits having disjoint randoms. Then, $P_1||P_2$ is also n -leakage-resilient.*

Proof. Without loss of generality, we assume that P_1 and P_2 have the same public and secret inputs (otherwise, they can be made so by adding dummy connections). Let \mathbf{r}_1 (resp. \mathbf{r}_2) be the randoms in P_1 (resp. P_2). Let \mathbf{p} (resp. \mathbf{k}) be the public (resp. secret) inputs of $P_1||P_2$. Then, the result follows because for any $\mathbf{b}_p \in \{0, 1\}^{|\mathbf{p}|}$, $\mathbf{b}_k, \mathbf{b}_k' \in \{0, 1\}^{|\mathbf{k}|}$, $\alpha \in \text{nodes}(P_1||P_2)^n$, and $\mathbf{b}_\alpha \in \{0, 1\}^n$, we have

$$\begin{aligned} \#_{P_1||P_2}(\mathbf{b}_p, \mathbf{b}_k, \alpha, \mathbf{b}_\alpha) &= \\ 2^{|\mathbf{r}_2|} \cdot \#_{P_1}(\mathbf{b}_p, \mathbf{b}_k, \alpha_1, \mathbf{b}_{\alpha_1}) + 2^{|\mathbf{r}_1|} \cdot \#_{P_2}(\mathbf{b}_p, \mathbf{b}_k, \alpha_2, \mathbf{b}_{\alpha_2}) &= \\ 2^{|\mathbf{r}_2|} \cdot \#_{P_1}(\mathbf{b}_p, \mathbf{b}_k', \alpha_1, \mathbf{b}_{\alpha_1}) + 2^{|\mathbf{r}_1|} \cdot \#_{P_2}(\mathbf{b}_p, \mathbf{b}_k', \alpha_2, \mathbf{b}_{\alpha_2}) &= \\ \#_{P_1||P_2}(\mathbf{b}_p, \mathbf{b}_k', \alpha, \mathbf{b}_\alpha) \end{aligned}$$

where α_1 and α_2 partition α to the nodes inside P_1 and those inside P_2 , and \mathbf{b}_{α_1} (resp. \mathbf{b}_{α_2}) is the part of \mathbf{b}_α corresponding to the valuations of α_1 (resp. α_2). \square

A.2 Proof of Theorem 3

For simplicity, we assume that the circuits have no public inputs, and P_2 only has one (non-split) output. But, the result can be easily extended to the case with public inputs and the case where P_2 has multiple outputs.

We first focus on the case where P_2 has only one (non-split) input. That is, we consider the case where we are given P_1 that takes x many inputs and P_2 that takes one input. Therefore, the goal is to show the following.

Theorem 4. *Let P_1 be an x -input n -leakage-resilient circuit and P_2 be an 1-input n -leakage-resilient circuit, having disjoint randoms. Then, $(P_1) \triangleright P_2$ is n -leakage-resilient.*

The general case where P_2 takes multiple inputs follows directly from the proof of this case and is deferred to Section A.2.

We begin by introducing preliminary definitions and notations that are used in the proof. We represent circuits by their *truth tables* (or, simply *tables*) whose columns are the (observable) nodes of the circuit and rows are the possible valuation of the nodes. Formally, for an x -input circuit P that is $n+1$ -share split, the table of P , $tbl(P)$, has its first $(n+1) \cdot x$ columns correspond to the input nodes,¹¹ followed by some number of intermediate nodes (which may include additional randoms), and followed by $n+1$ columns corresponding to the output nodes. We write $\#rows(t)$ (resp. $\#cols(t)$) for the number of rows (resp. columns) of the table t . We write $t[i]$ for the i th row of the table, and $t(i, j)$ for the value of the (i, j) th entry of t .

Example 4. Below is a table for the 1+1-share split 1-input circuit. The circuit has 6 nodes $\alpha_1, \dots, \alpha_6$ where the (split) input nodes are α_1, α_2 , the intermediate nodes are α_3, α_4 such that α_3 is an additional random node, and the (split) output nodes are α_5, α_6 . The circuit is wired so that $\alpha_4 = \alpha_1 \oplus 1$, $\alpha_5 = \alpha_4 \oplus \alpha_3$, and $\alpha_6 = \alpha_2 \oplus \alpha_3$. That is, the circuit outputs the XOR of the input with 1 (i.e., it is a negation circuit).

α_1	α_2	α_3	α_4	α_5	α_6
0	0	0	1	1	0
0	0	1	1	0	1
1	1	0	0	0	1
1	1	1	0	1	0
1	0	0	0	0	0
1	0	1	0	1	1
0	1	0	1	1	1
0	1	1	1	0	0

Leakage Resilience as Table Safety The notion of n -leakage-resilience can be formalized as a certain property of tables, which we call *safety*. Informally, a table being n safe means that, the number of rows of the table corresponding to each (non-split) input remains the same even after reducing the table n times by choosing a column and a bit and removing the rows that do not have that bit at that column. We formalize the notion below.

Let $\mathbf{b} \in \{0, 1\}^x$ and $m > 0$. For $\mathbf{a} \in \{0, 1\}^*$ of length at least $x \cdot m$, we write $\mathbf{a} \succeq_{x,m} \mathbf{b}$ if for each $i \in \{1, \dots, x\}$, $b_i = \bigoplus_{(i-1) \cdot m < j \leq i \cdot m} a_j$. Let t be a table such that $\#cols(t) \geq x \cdot m$. The \mathbf{b} restriction of t wrt m , written $\mathbf{b}_m(t)$, is defined to

¹¹ For simplicity, we assume that each secret (non-split) input in P_1 and P_2 is split into shares by a single input encoder. The proof can be adopted to the case where a secret is encoded by multiple input encoders.

be a table comprising the rows i of t such that $t[i] \succeq_{x,m} \mathbf{b}$. Intuitively, $\mathbf{b}_{n+1}(t)$ is the sub-table of t comprising the rows with the non-split input \mathbf{b} (for the $n+1$ split case). For example, let t be the table from Example 4, then $0_2(t)$ is the table comprising the first four rows of t , and $1_2(t)$ is the table comprising the remaining (i.e., the last four) rows of t .

For $(j, b) \in \{1, \dots, \#cols(t)\} \times \{0, 1\}$, we write $t' \xleftarrow{(j,b)} t$ if t' is t but with the rows having the value $\neg b$ at the j th column removed. Intuitively, $t \xleftarrow{(j,b)} tbl(P)$ means that t is the state of the circuit P after the adversary observed the value b at the j th node. For $m \geq 0$, we write $t' \xleftarrow{m} t$ if t' is obtained by m adversary observations from t , that is, if there exist $(j_1, b_1), \dots, (j_m, b_m)$ such that $t = t_1$, $t' = t_m$, and $t_{i+1} \xleftarrow{(j_i, b_i)} t_i$ for each $i \in \{1, \dots, m-1\}$.

Let $m \geq 0$ and $\ell > 0$. We define the notion $x \sim_{m, \ell}$ safe inductively as follows. We say that a table t is $x \sim_{0, \ell}$ safe if for any $\mathbf{b}, \mathbf{b}' \in \{0, 1\}^x$, $\#rows(\mathbf{b}_\ell(t)) = \#rows(\mathbf{b}'_\ell(t))$. For $m > 0$, t is $x \sim_{m, \ell}$ safe if for any t' such that $t' \xleftarrow{1} t$, t' is $x \sim_{m-1, \ell}$ safe. Note that an empty table is $x \sim_{m, \ell}$ safe for any x, m and ℓ . Also, it is immediate from the definition that safety is *monotonic*, that is, if t is $x \sim_{m_1, \ell}$ safe and $m_1 \geq m_2$ then t is also $x \sim_{m_2, \ell}$ safe. Also, the following is immediate from the definition.

Lemma 1. *Suppose $m_1 \leq m_2$. Then, t is $x \sim_{m_2, \ell}$ safe iff for any t' such that $t' \xleftarrow{m_1} t$, t' is $x \sim_{m_2 - m_1, \ell}$ safe.*

It is easy to see that the notion of safety captures leakage resilience. That is, we have the following.

Lemma 2. *The following are equivalent.*

- (1) x -input $n+1$ -split P is n -leakage-resilient.
- (2) $tbl(P)$ is $x \sim_{n, n+1}$ safe.
- (3) For any t such that $t \xleftarrow{n} tbl(P)$, t is $x \sim_{0, n+1}$ safe.

Proof. It is not hard to see that (2) is equivalent to n -leakage-resilience. (2) \Leftrightarrow (3) follows from Lemma 1.

Circuit Composition as Table Composition We capture circuit composition by composition of tables. More precisely, we shall define the table composition operation \triangleright_m so that the composition of the tables $tbl(P_1) \triangleright_{n+1} tbl(P_2)$ is the table of the composed circuit $tbl((P_1) \triangleright P_2)$.

For $m > 0$, let us write $hd(\mathbf{b}, m)$ (resp. $tl(\mathbf{b}, m)$) for the first (resp. last) m elements of \mathbf{b} . For t_1 and t_2 , and $m > 0$ such that $m \leq \#cols(t_1)$ and $m \leq \#cols(t_2)$, we define $t_1 \triangleright_m t_2$ to be the $\#cols(t_1) + \#cols(t_2) - m$ column table such that each $\mathbf{b} \in \{0, 1\}^{\#cols(t_1) + \#cols(t_2) - m}$ appears $i_1 \cdot i_2$ times in the table where i_1 (resp. i_2) is the number of times $hd(\mathbf{b}, \#cols(t_1))$ appears in t_1 (resp. $tl(\mathbf{b}, \#cols(t_2))$ appears in t_2). (Therefore, \mathbf{b} occurs as a row of $t_1 \triangleright_m t_2$ iff $hd(\mathbf{b}, \#cols(t_1))$ occurs as a row of t_1 and $tl(\mathbf{b}, \#cols(t_2))$ occurs as a row of t_2 .) For t_1 and t_2 such that $\#cols(t_1) = \#cols(t_2) = m$, we simply write $t_1 \triangleright t_2$ for $t_1 \triangleright_m t_2$. Note that $t_1 \triangleright t_2 = t_2 \triangleright t_1$.

It can be seen that the table composition correctly captures circuit composition. That is, for $n+1$ -split circuits, we have $tbl((P_1) \triangleright P_2) = tbl(P_1) \triangleright_{n+1} tbl(P_2)$. Also, it is immediate from the definitions that any attack on the composed table can be simulated by an attack on the components. More formally, we have the following.

Lemma 3. *Let $m, \ell > 0$. Then, $t \leftarrow^m t_1 \triangleright_\ell t_2$ iff there exist m_1, m_2, t'_1 , and t'_2 such that $m_1 + m_2 = m$, $t'_1 \leftarrow^{m_1} t_1$, $t'_2 \leftarrow^{m_2} t_2$, and $t = t'_1 \triangleright_\ell t'_2$.*

We define the notion of *deterministic* tables. Roughly a table being deterministic means that split input valuations for the same non-split input leads to the same non-split output. More formally, for $m > 0$ and $\mathbf{b} \in \{0, 1\}^x$ let $outs_{m, \mathbf{b}}(t)$ be the m column subtable of t comprising the last m columns of rows i such that $t[i] \succeq_{x, m} \mathbf{b}$. We call $outs_{m, \mathbf{b}}(t)$ the *output table* for the non-split input \mathbf{b} . We write $nsv(t)$ for the 1-column $\#rows(t)$ -row table t' such that for each row i , $t[i] \succeq_{1, \#cols(t)} t'[i]$. We say that t is $x \sim m$ *deterministic* if for each $\mathbf{b} \in \{0, 1\}^x$, the elements of $nsv(outs_{m, \mathbf{b}}(t))$ are either all 0 or all 1. Because any n -leakage-resilient circuit with which we are concerned is IO-equivalent to a random-free circuit, without loss of generality, we may assume that the table $tbl(P_1)$ (resp. $tbl(P_2)$) is $x \sim n+1$ (resp. $1 \sim n+1$) deterministic.

Our goal is to show Theorem 4. That is, given n -leakage-resilient circuits P_1 and P_2 , the composed circuit $(P_1) \triangleright P_2$ is also n -leakage-resilient. By Lemmas 2, 1, and 3, it follows that it suffices to show that following.

Theorem 5. *Let $m_1 > 0$ and $m_2 > 0$ such that $m_1 + m_2 = n$. Let t_1 and t_2 be tables such that t_1 is $x \sim n+1$ deterministic and $x \sim m_1, n+1$ safe, and t_2 is $1 \sim n+1$ deterministic and $1 \sim m_2, n+1$ safe. Then, $t_1 \triangleright_{n+1} t_2$ is $x \sim 0, n+1$ safe.*

We prove the theorem in the following subsection.

Proof of Theorem 5 First, we prove a few technical lemmas. We write $t_1 \simeq t_2$ if t_1 and t_2 are equivalent up to permutation of the rows. The next lemma shows that, for a table whose rows all sum up to a given value, the numbers of 1's and 0's in each column uniquely determine the table up to row permutation.

Lemma 4. *Let \mathbf{v} be a vector of non-negative integers of length m . Let $b \in \{0, 1\}$. Let t_1 and t_2 be m column tables with $\#rows(t_1) = \#rows(t_2)$ such that for each t_ℓ ($\ell \in \{1, 2\}$), 1.) for every row $\mathbf{b} \in t_\ell$, $b = \bigoplus_{1 \leq i \leq \#cols(t)} b_i$ (i.e., every row sums up to the same value), and 2.) for each column $j \in \{1, \dots, m\}$, there are exactly v_j number of 1's in the j th column of t_ℓ (and hence $\#rows(t_\ell) - v_j$ number of 0's). Then, $t_1 \simeq t_2$.*

Proof. We show that b and \mathbf{v} uniquely determines the table content (up to row permutation) for tables whose row size and column size are fixed. We prove by induction on the column size, m . The case $m = 1$ is immediate, since in this case either the table is all 0's or all 1's.

We show the inductive case. Let $m > 1$ and t be a table satisfying the requirements 1.) and 2.) for b and \mathbf{v} . Let t_0 (resp. t_1) be $m - 1$ column subtable of t comprising the columns $2, \dots, m$ of t , but only taking the rows i such that $t(i, 1) = 0$ (resp. $t(i, 1) = 1$). For each $i \in \{2, \dots, m\}$, let v_{0i} be the number of times 1 occurs in the $i - 1$ st column of t_0 and let $v_{1i} = v_i - v_{0i}$. Let $\mathbf{v}_0 = v_{02}, \dots, v_{0m}$ and $\mathbf{v}_1 = v_{12}, \dots, v_{1m}$. Then, t_0 (resp. t_1) satisfies the requirement with b (resp. $\neg b$) and \mathbf{v}_0 (resp. \mathbf{v}_1). By induction hypothesis, t_0 and t_1 are uniquely determined, and therefore, so is t .

We use the above lemma to show the following, which says that, if a table is at least 1 safe, then non-split inputs that map to the same non-split output value have the same split output valuations.

Lemma 5. *Let t be $x \sim m$ deterministic and $x \sim 1, m$ safe. Let $\mathbf{b}, \mathbf{b}' \in \{0, 1\}^x$. Let $t_1 = \text{outs}_{m, \mathbf{b}}(t)$ and $t_2 = \text{outs}_{m, \mathbf{b}'}(t)$. Then, either $t_1 \simeq t_2$, or $\text{nsv}(t_1)$ and $\text{nsv}(t_2)$ have no common elements.*

Proof. Note that, because of 1 safety, for each $j \in \{1, \dots, m\}$, the number of 1's and 0's in the j th column of t_1 must be the same as those of t_2 . Suppose $\text{nsv}(t_1)$ and $\text{nsv}(t_2)$ have a common element. Then, by determinism, every row of t_1 and t_2 sums up to a same value. Therefore, by Lemma 4, we have $t_1 \simeq t_2$.

Next, we prove a couple of lemmas that focus on the case where the tables considered are $n + 1$ column tables that are $1 \sim _, n + 1$ safe. The first lemma, Lemma 6, is used to prove Lemma 7. Lemma 7 is used in a part of the proof of Theorem 5 that focuses on the output columns of tables obtained from P_1 and the input columns of the tables obtained from P_2 , which will be $n + 1$ column tables that are $1 \sim _, n + 1$ safe.

Lemma 6. *Let t be a table with $\#cols(t) = n + 1$. Then, t is $1 \sim n, n + 1$ safe iff 1.) t contains every element of $\{0, 1\}^{n+1}$ as a row, and 2.) each element of $\{0, 1\}^{n+1}$ appears the same number of times in t .*

Proof. The if direction is trivial. We show the only if direction. Suppose that t is $1 \sim n, n + 1$ safe. We show that 1.) and 2.) must be satisfied.

First, we show that 1.) is satisfied. Let \mathbf{b}_0 be a row of t . Then, any \mathbf{b}' that differs from \mathbf{b}_0 at one entry must also appear as a row of t since otherwise the adversary can distinguish the 0-restriction and 1-restriction after observing all n columns except for that entry. Because any $\mathbf{b} \in \{0, 1\}^{n+1}$ can be reached from \mathbf{b}_0 via a series of one-entry changes, any such \mathbf{b} must appear as a row of t .

Finally, note that by the same reasoning as above, for any row \mathbf{b} of t , any \mathbf{b}' different from \mathbf{b} in one entry must appear the same number of times as \mathbf{b} . Hence, 2.) is also satisfied.

For a table t and $j \in \{1, \dots, \#cols(t)\}$, we say that the column j is *fixed* in t if there exists $b \in \{0, 1\}$ such that for any $i \in \{1, \dots, \#rows(t)\}$, $t(i, j) = b$ (i.e., the column is all b). Note that a table is $1 \sim m, _$ safe only if there are at least m unfixed columns. For a table t and $S \subseteq \{1, \dots, \#cols(t)\}$, we write $t|_S$ for the table comprising the columns S of t .

Lemma 7. *Let $m_1 \geq 0$, $m_2 \geq 0$ and $n = m_1 + m_2$. Let t_1 and t_2 be $n + 1$ column tables such that t_1 (resp. t_2) is $1 \sim m_1, n + 1$ safe (resp. $1 \sim m_2, n + 1$ safe). Then, $t_1 \triangleright t_2$ is $1 \sim 0, n + 1$ safe.*

Proof. We prove by simultaneous induction on n , m_1 and m_2 . The base case where $n = 0$, $m_1 = 0$, or $m_2 = 0$ follows from Lemma 6 because $m_2 = n$ or $m_1 = n$ in this case.

We show the inductive case. Firstly, consider the case the fixed columns of t_1 and t_2 are the same. Without loss of generality, we assume that the fixed columns have the same values in t_1 and in t_2 since otherwise $t_1 \triangleright t_2$ is empty and the result is immediate. Let t'_1 (resp. t'_2) be the sub-table of t_1 (resp. t_2) comprising the unfixed columns. Let k be the number of fixed columns. Then, t'_1 (resp. t'_2) is $1 \sim m_1 - k, n - k + 1$ (resp. $1 \sim m_2 - k, n - k + 1$) safe (in fact, they are m_1 and m_2 safe). Therefore, by induction hypothesis, $t'_1 \triangleright t'_2$ is $1 \sim 0, n - k + 1$ safe. Because $t_1 \triangleright t_2$ is $t'_1 \triangleright t'_2$ but with the k fixed columns of t_1 (or t_2) added, $t_1 \triangleright t_2$ is $1 \sim 0, n + 1$ safe.

Continuing with the inductive case, we now consider the case the fixed columns of t_1 and t_2 are not the same. Suppose that there exists a column that is fixed in t_2 but not in t_1 (the argument is similar for the case when there is a column that is fixed in t_1 but not in t_2). Let $j \in \{1, \dots, n + 1\}$ be fixed in t_2 but not in t_1 . Let b be the entry of the j th column of t_2 , and let $t'_1 \stackrel{(j,b)}{\leftarrow} t_1$. Let $S = \{1, \dots, n + 1\} \setminus \{j\}$. Then, $t'_1|_S$ is $1 \sim m_1 - 1, n$ safe, and $t_2|_S$ is $1 \sim m_2, n$ safe. Therefore, by induction hypothesis, $t'_1|_S \triangleright t_2|_S$ is $1 \sim 0, n$ safe. Because $t'_1 \triangleright t_2$ is $t'_1|_S \triangleright t_2|_S$ but with an additional all b column, $t'_1 \triangleright t_2$ is $1 \sim 0, n + 1$ safe. Finally, because $t_1 \triangleright t_2 = t'_1 \triangleright t_2$, the result follows.

We are now ready to prove Theorem 5, restated here.

Theorem 5. *Let $m_1 > 0$ and $m_2 > 0$ such that $m_1 + m_2 = n$. Let t_1 and t_2 be tables such that t_1 is $x \sim n + 1$ deterministic and $x \sim m_1, n + 1$ safe, and t_2 is $1 \sim n + 1$ deterministic and $1 \sim m_2, n + 1$ safe. Then, $t_1 \triangleright_{n+1} t_2$ is $x \sim 0, n + 1$ safe.*

Proof. Let t_1^{out} be the last $n + 1$ columns of t_1 . If all rows of t_1^{out} sum up to the same value, then by Lemma 5, the result follows.

Otherwise, it means that not every row of t_1 maps to the same non-split output. Then, by Lemma 5 again, for each non-split output valuation (i.e., 0 or 1), the output tables are equivalent for all inputs that maps to the same output.

Let $\mathbf{b}, \mathbf{b}' \in \{0, 1\}^x$ be non-split inputs of t_1 that map to different outputs. That is, there exist rows i and j of t_1 with $t_1[i] \succeq_{x, n+1} \mathbf{b}$, $t_1[j] \succeq_{x, n+1} \mathbf{b}'$, and $(\bigoplus_{1 \leq \ell \leq n+1} a_\ell) \neq (\bigoplus_{1 \leq \ell \leq n+1} a'_\ell)$ where $\mathbf{a} = tl(t_1[i], n + 1)$ and $\mathbf{a}' = tl(t_1[j], n + 1)$. Let t'_1 be the table comprising the rows of $outs_{n+1, \mathbf{b}}(t_1)$ and $outs_{n+1, \mathbf{b}'}(t_1)$. Let t_2^{in} be the table comprising the first $n + 1$ columns of t_2 . Then, for any $m \geq 0$, to show $t_1 \triangleright_{n+1} t_2$ is $x \sim m, n + 1$, it suffices to show that $t'_1 \triangleright t_2^{in}$ is $1 \sim m, n + 1$ safe (for arbitrary such t'_1 constructed from some $\mathbf{b}, \mathbf{b}' \in \{0, 1\}^x$ mapping to different outputs). Because t_1 is $x \sim m_1, n + 1$ safe, t'_1

is $1 \sim m_1, n + 1$ safe. Also, because t_2 is $1 \sim m_2, n + 1$ safe, $t_2^{i^n}$ is $1 \sim m_2, n + 1$ safe. Therefore, by Lemma 7, $t_1' \triangleright t_2^{i^n}$ is $1 \sim 0, n + 1$ safe, and the result follows.

Remark 6. In the definition of sequential composition, we have left unspecified which wire of the P_1 's split output is connected to which wire of the P_2 's split input. Because the table joining operation $\text{tbl}(P_1) \triangleright_{n+1} \text{tbl}(P_2)$ is insensitive to how the rows of $\text{tbl}(P_1)$ and $\text{tbl}(P_2)$ are permuted, the proof shows that the compositionality result holds regardless of the connection choice.

Case P_2 Has Multiple Inputs We now extend the sequential compositionality result to the case P_2 has multiple inputs. In this case, we have y many circuits $P_{11}, P_{12}, \dots, P_{1y}$ whose outputs will be connected to P_2 , and we denote the composed circuit as $(P_{11}, P_{12}, \dots, P_{1y}) \triangleright P_2$. The goal is to show the following.

Theorem 3. *Let P_{11}, \dots, P_{1y} be n -leakage-resilient circuits, and P_2 be an y -input n -leakage-resilient circuit, having disjoint randoms. Then, $(P_{11}, \dots, P_{1y}) \triangleright P_2$ is n -leakage-resilient.*

The case follows immediately from the proof shown above for the case where P_2 only has one input. This is because, for $n = m_1 + m_2$ and each P_{1i} , Theorem 5 implies that attacking P_{1i} m_2 times and P_2 m_1 times and composing them cannot distinguish the secret inputs given to P_{1i} . Also, because of the disjointness of the randoms in the components, attacks on P_{1j} for $j \neq i$ has no effect on the table of P_{1i} . Then, because m_2 safety of P_2 implies m_2 safety of the portion of $\text{tbl}(P_2)$ corresponding to the i th input, the result follows. We remark that the proof actually shows that the composition $(P_{11}, \dots, P_{1y}) \triangleright P_2$ can withstand an attack where the adversary observes m_2 nodes of P_2 and m_{1i} nodes of each P_{1i} such that $n \geq m_2 + \max_i(m_{1i})$.