

Non-Adaptive Universal One-Way Hash Functions from Arbitrary One-Way Functions

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Abstract. In this work we give the first *non-adaptive* construction of *universal one-way hash functions* (UOWHFs) from arbitrary one-way functions. Our construction uses $O(n^9)$ calls to the one-way function, has a key of length $O(n^{10})$, and can be implemented in NC1 assuming the underlying one-way function is in NC1.

Prior to this work, the best UOWHF construction used $O(n^{13})$ *adaptive* calls and a key of size $O(n^5)$ (Haitner, Holenstein, Reingold, Vadhan and Wee [Eurocrypt '10]). By the result of Applebaum, Ishai and Kushilevitz [FOCS '04], the above implies the existence of UOWHFs in NC0, given the existence of one-way functions in NC1.

We also show that the PRG construction of Haitner, Reingold and Vadhan (HRV, [STOC '10]), with small modifications, yields a relaxed notion of UOWHFs, which is a function family which can be (inefficiently) converted to UOWHF by changing the functions on a negligible fraction of the inputs. In order to analyze this construction, we introduce the notion of *next-bit unreachable entropy*, which replaces the next-bit pseudoentropy notion used by HRV.

Keywords: universal one-way hash function; one-way function; non-adaptive.

1 Introduction

A wide class of cryptographic primitives can be constructed from *one-way functions*, which is the minimal assumption for cryptography. Two important such primitives are *pseudorandom generators* (PRGs) [31, 11] and *universal one-way hash functions* (UOWHFs) also known as, target-collision resistant (TCR) hash functions [27]. PRGs and UOWHFs are useful for constructing even more powerful primitives such as encryption, digital signatures and commitments. Yet, the optimal efficiency of black-box constructions of PRGs and UOWHFs from one-way functions is not fully understood. In this paper, we focus on constructions of UOWHF, a relaxation of *collision-resistant hash function* (CRHF) introduced by Naor and Yung [27]. Informally, a keyed function family $\mathcal{F} =$

$\{f_k: \{0, 1\}^n \rightarrow \{0, 1\}^m\}_k$ is a UOWHF if $m < n$, and, for every poly-time algorithm A , and for every input $x \in \{0, 1\}^n$, the following holds: with high probability over the choice of a uniformly random key k , $A(k, x)$ cannot find a collision $x' \neq x$ with $f_k(x) = f_k(x')$.

There are several important efficiency measures to account for when considering black-box constructions of UOWHFs and PRGs from one-way functions. For PRG constructions, one aims to minimize the seed length and the number of calls to the one-way function f . For UOWHF constructions, there is a need to minimize the key length and the number of calls to f . Besides these two measurements, another important parameter is the *adaptivity* of the calls. That is, whether the invocations of the one-way function are independent of the output of previous calls. A non-adaptive construction naturally gives rise to a, more efficient, parallel algorithm. By contrast, if the calls are adaptive, one must make them sequentially.

The first UOWHF construction from arbitrary one-way functions is due to Rompel [28] (see [23] for a full proof of Rompel's construction). The efficiency was then improved by Haitner, Holenstein, Reingold, Vadhan and Wee (HHRVW [16]), who give a construction of UOWHF using $O(n^{13})$ *adaptive* calls, and with a key of size $O(n^7)$, which can be improved easily to size $O(n^5 \log n)$ (see Observation 1.3). Notably, prior to the work presented here, there was no non-adaptive UOWHF construction.

The above construction of HHRVW [16] uses ideas similar to the ones used in the constructions of PRGs. Still, the best PRG constructions from arbitrary one-way functions are more efficient. Currently, the state-of-the-art construction of PRGs uses $O(n^4 \log n)$ bits of random seed and $O(n^3 \log n)$ *non-adaptive* calls to the one-way function, or alternatively seed of size $O(n^3 \log^2 n)$ with $O(n^3 \log n)$ *adaptive* calls [18, 30]. Constructing a UOWHF using $\tilde{O}(n^3)$ calls to the one-way function is still an interesting open question.

These efficiency gaps between UOWHFs and PRGs constructions are even more surprising in the light of the similarities between the constructions. Specially, for more structured one-way functions such as permutations or regular functions, there is essentially no efficiency gap between PRG and UOWHF constructions.³ Moreover, the constructions are very similar to each other and use similar techniques. For example, the method of *randomized iterate* is used for the constructions of both primitives from unknown-regular one-way functions [15, 32, 2]. Recently, Mazon and Zhang [26] introduced non-adaptive constructions for both UOWHF and PRG from an unknown-regular one-way function. Their constructions for both primitives have in common a similar structure and are composed of the same building-block operations.

Example 1.1 (Similarity between black-box construction of PRGs and UOWHFs, known-regular [20, 32]). For a concrete example, assume $f: \{0, 1\}^n \rightarrow \{0, 1\}^n$ is

³ f is called *regular* if for every n and x, x' with $|x| = |x'| = n$ it holds that $|f^{-1}(f(x))| = |f^{-1}(f(x'))|$. We say that the function is *unknown-regular* if the *regularity parameter*, $|f^{-1}(f(x))|$, may not be a computable function of n .

a regular one-way function with regularity parameter r , such that no poly-time algorithm can invert f with probability more than ϵ (for a negligible ϵ).

Then

$$G(h_1, h_2, x) = (h_1, h_2, h_1(f(x)), h_2(x))$$

is a PRG, where the functions $h_1: \{0, 1\}^n \rightarrow \{0, 1\}^{n-r-\Theta(\log 1/\epsilon)}$ and $h_2: \{0, 1\}^n \rightarrow \{0, 1\}^{r+\Theta(\log 1/\epsilon)+\log n}$ are hash functions from appropriate hash families. Similarly, $\mathcal{C} = \{C_k = G(z \oplus k)\}_k$ is a UOWHF when taking $h_2: \{0, 1\}^n \rightarrow \{0, 1\}^{r+\Theta(\log 1/\epsilon)-\log n}$, and using the same function G .

Example 1.2 (Similarity between black-box construction of PRGs and UOWHFs, unknown regular [26]). Another example is the following. For an unknown-regular one-way function $f: \{0, 1\}^n \rightarrow \{0, 1\}^n$,

$$G(h, x_1, \dots, x_n) = (h(f(x_1), x_2), h(f(x_2), x_3), \dots, h(x_{t-1}, f(x_n)), x_n)$$

is a PRG for a hash function $h: \{0, 1\}^{2n} \rightarrow \{0, 1\}^{n+\log n}$ from a suitable family. The following similar function

$$C(h, x_1, \dots, x_n) = (f(x_1), h(f(x_1), x_2), h(f(x_2), x_3), \dots, h(x_{t-1}, f(x_n)), x_n,$$

can be converted into a UOWHF by taking the family $\mathcal{C} = \{C_k = C(z \oplus k)\}_k$, when taking $h: \{0, 1\}^{2n} \rightarrow \{0, 1\}^{n-\log n}$.

Furthermore, the first constructions from (unstructured) arbitrary one-way functions of PRGs, by Hastad, Impagliazzo, Levin and Luby [20], and the constructions of UOWHFs by Rompel [28] and HHRVW [16], shared a similar framework. This framework includes first constructing a non-uniform version of the desired primitive, and then eliminating the non-uniform (short) advice by enumerating over all possible advices, and combining the constructions together. This enumeration and combining step has a significant efficiency cost for both primitives.

By contrast, in their beautiful work, Haitner, Reingold and Vadhan (HRV [18]) introduced a simpler and more efficient framework to construct PRGs from arbitrary one-way functions. By introducing a notion called *next-bit pseudoentropy*, they give a very efficient and simple non-adaptive construction of PRGs from one-way functions. This work starts by showing that the function $g(h, x) = (h, f(x), h(x))$, where h is a hash function from some appropriate 2-universal family, has non-trivial next-bit pseudoentropy. The work proceeds by describing a procedure that extracts pseudorandomness from next-bit pseudoentropy (see Figure 1 for a sketch of the construction). As stated above, this construction has $O(n^4 \log n)$ random seed size with $O(n^3 \log n)$ calls, which is a significant improvement over [20]. One main reason for this efficiency improvement is that this framework no longer requires the non-uniformity elimination step. Unfortunately, there is no analog to this construction for UOWHFs. Adapting the framework of HRV [18] to improve the efficiency of UOWHF constructions is still an interesting open question.

1.1 Our Contribution

In this paper, we partially answer the last question above. Our first result is (the first) non-adaptive construction of UOWHF from arbitrary one-way functions. We achieve this by introducing a construction that does not have the non-uniformity elimination step. By the result of Applebaum, Ishai and Kushilevitz [4], the above implies the existence of UOWHFs in NC0, assuming the existence of one-way functions in NC1.⁴ In addition, our construction reduces the call complexity over HHRVW [16], and uses $O(n^9)$ calls to the one-way function instead of $O(n^{13})$. On the negative side, the key length of our construction is $O(n^{10})$, instead of $O(n^5)$.

Next, aiming to close the still remaining gap between PRG and UOWHF constructions, we show that small modifications to the PRG construction of HRV [18] yield a relaxed notion of UOWHF, which we call “almost-UOWHF”. Informally, a function family is almost-UOWHF if by changing the functions on a negligible fraction of the inputs, we can convert it into a (perfect) UOWHF. To analyze the almost-UOWHF construction, we introduce the notion of *next-bit unreachable entropy*, an analogue of *next-bit pseudoentropy* used in [18]. Similarly to the PRG construction, our almost-UOWHF construction uses $O(n^3 \log n)$ non-adaptive calls to the one-way function and has a key of size $O(n^4 \log n)$. More details below.

Non-Adaptive UOWHF from One-Way Functions In their construction of UOWHFs from one-way functions, HHRVW [16] define the notion of *accessible entropy*.⁵ Informally, for a function g , the accessible entropy of g^{-1} is a bound on the entropy of the output of every *collision finder for g* (i.e., of every poly-time algorithm that, given an input x , always outputs a pre-image of $g(x)$).

HHRVW [16] show how a one-way function $f: \{0, 1\}^n \rightarrow \{0, 1\}^n$ can be used to construct a function $\rho: \{0, 1\}^{n^5} \rightarrow \{0, 1\}^{n^5}$ such that, for a uniformly chosen input $X \leftarrow \{0, 1\}^{n^5}$, there is a gap between the *entropy* of X given $\rho(X)$, and the *accessible entropy* of ρ^{-1} . Namely, there exists some $\ell \in \mathbb{N}$, such that for every collision finder A for ρ , the following holds with all but a negligible probability: the size of $\rho^{-1}(\rho(X))$ is at least $2^{\ell + \omega(\log n)}$, while for every input X , the support size of the output of $A(X)$ is at most 2^ℓ .⁶ When ℓ is known, it is not hard to convert such a function to UOWHF, but here the parameter ℓ depends on f and may be unknown. To overcome this obstacle, HHRVW construct UOWHF candidates C_1, \dots, C_t from ρ , one for each $1 \leq \ell \leq t = n^2 / \log n$, out of which

⁴ The result of Applebaum, Ishai and Kushilevitz [4] implies that, using a method called randomized encoding, the existence of UOWHF in NC1 implies the existence of UOWHF in NC0.

⁵ We use the term accessible entropy to denote accessible entropy of functions. Somewhat different notions of accessible entropy are used in other contexts, for example to construct statistically-hiding commitments from one-way functions ([19]).

⁶ The actual definition of inaccessible entropy ignores some events that have a negligible probability.

at least one is an UOWHF. Then, for each ℓ , HHRVW feed the output of C_ℓ into itself repeatedly and obtain a new function $C'_\ell(x)$ which is also an UOWHF, but is additionally sufficiently compressing. Finally, the concatenation $C(x) := C'_1(x), \dots, C'_t(x)$ is a UOWHF if at least one of the C_ℓ is. The transformation from C_ℓ to C'_ℓ introduces adaptivity into the constructions by HHRVW and Rompel, and the combination of parallel and sequential composition increases the number of calls to f by a factor of n^9 in HHRVW, and increases the key length by a factor of $\log n$.

Observation 1.3 (The key-length in HHRVW [16]) *The described above step of removing non-uniformity in HHRVW actually increases the size of the key by a n^2 factor: while the transformation from C_ℓ to C'_ℓ only increases the key length by a factor of $\log n$ for each ℓ , HHRVW use a different key for each such candidate, and the key of the final construction is the concatenation of the t keys. Our observation is that it is possible to use the same key for all the candidates. This reduces the key-length from $O(n^7)$ to $O(n^5 \log n)$.*

By viewing ℓ as an unknown regularity parameter of ρ , we replace the parallel and sequential composition in HHRVW by applying the recent construction of [26] of non-adaptive UOWHF from (unknown) regular one-way functions. Namely, for $m = n^5$ hash functions $h_1, \dots, h_m: \{0, 1\}^{2^m} \rightarrow \{0, 1\}^{m - \log n}$ from a universal family \mathcal{H} , and inputs z_1, \dots, z_m , let

$$C(h_1, \dots, h_{m-1}, z_1, \dots, z_m) = \\ h_1, \dots, h_{m-1}, \rho(z_1), h_1(z_1, \rho(z_2)), \dots, h_{m-1}(z_{m-1}, \rho(z_m)), z_m.$$

Following [26], we show that C is (length-decreasing) *collision resistant on random inputs*, and can be easily be converted to UOWHF (see Section 2 for the definition of collision resistant on random inputs and discussion). The above gives rise to the following result.

Theorem 1.4 (Non-Adaptive UOWHF from OWF, informal). *There exists a black-box construction of UOWHF from any one-way function that uses $O(n^9)$ non-adaptive calls to the one-way function. Moreover, the construction has key length and output length of $O(n^{10})$, and is computable in NC1 using oracle calls to f .*

We note that, since ρ is not a regular function (indeed, there is a negligible fraction of inputs for which ρ may have fewer collisions), the use of [26] is not straightforward, and the security proof requires a new analysis. An overview of the proof is given in Section 2.1.

Next, using the result of Applebaum, Ishai and Kushilevitz [4], who construct a UOWHF in NC0 based on a UOWHF in NC1 and randomized encodings, we get the following corollary.

Corollary 1.5 (UOWHF in NC0, informal) *Assuming that one-way functions exist in NC1, there exists a UOWHF in NC0.*

Efficient Almost-UOWHF from One-Way Functions Our second construction is inspired by the work of HRV [18] on PRG constructions from one-way functions. We show that small modifications to the PRG of [18] yield an *almost-UOWHF*. Informally, a shrinking, keyed function family

$$\mathcal{F} = \{f_k : \{0, 1\}^n \rightarrow \{0, 1\}^m\}_k$$

is an almost-UOWHF if, for every key k , there exists a negligible-sized set of inputs \mathcal{B}_k such that the following holds for every poly-time algorithm A , and every input $x \in \{0, 1\}^n$: With all but negligible probability over the choice of a uniformly random key k , $A(k, x)$ cannot find a collision $x' \neq x$ with $f_k(x) = f_k(x')$, unless $x' \in \mathcal{B}_k$ (see Definition 5.1 for the formal definition).

We note that, similarly to the above definition of almost-UOWHF, we can also define an “almost-PRG”. However, unlike UOWHF, it is easy to see that an almost-PRG is a (standard) PRG. Hence, viewing the HRV construction as an “almost-PRG”, we believe that the UOWHF analog of the HRV construction is essentially our almost-UOWHF. While we do not know if an almost-UOWHF can be converted efficiently into a UOWHF, in our non-adaptive construction we are able to remove the negligible-sized set \mathcal{B}_k (due to which the construction is only almost-UOWHF) at the cost of more repetitions and calls to the one-way function (see Section 2.1 for more details). Thus, the almost-UOWHF construction emphasizes that this need of eliminating the negligible-sized set is the *main efficiency gap* between the currently known constructions of PRGs and UOWHFs.

We get the following theorem.

Theorem 1.6. [*Almost-UOWHF from OWF, informal*] *There exists a black-box construction of an almost-UOWHF with key length $O(n^4 \log n)$ from one-way functions with input length n . The construction makes $O(n^3 \log n)$ non-adaptive calls to the underlying one-way function.*

Next-bit unreachable entropy. In their work, HRV [18] define the notion of *next-bit pseudoentropy*. HRV first show how to construct a function with non-trivial (i.e., larger than the input size) next-bit pseudoentropy. Then, using this function, HRV construct an efficient and simple PRG. To replace the notion of next-bit pseudoentropy in our construction, we define the notion of *next-bit unreachable entropy*, a variant of inaccessible entropy, defined by HHRVW [16], that allows us to achieve almost-UOWHF using a similar construction to the above PRG. We discuss the definition and the motivation behind it in detail in Section 2.2.

1.2 Additional Related Work

Next-block pseudoentropy and inaccessible entropy. A different variant of inaccessible entropy, for online generator, was defined and used by Haitner, Reingold, Vadhan and Wee [19] to construct statistically hiding commitments. Chen Horel

and Vadhan [1] pointed out that the HRVW [19] notion of accessible entropy and next-block pseudoentropy are deeply related to each other. Recently, Haitner, Mazor and Silbak [17] showed that incompressibility implies next-bit pseudoentropy.

UOWHFs from regular one-way functions. Constructions of UOWHF from *regular* one-way functions are more efficient. Besides the mentioned above constructions from unknown-regular one-way functions [15, 32, 2, 26], Naor and Yung [27] construct an UOWHF using 1 call to an 1-to-1 one-way functions, and [32] give a construction from known-regular one-way functions, using $\omega(1)$ non-adaptive calls.

Additionally, a few refinements of regularity were considered. Barhum and Maurer [8] show an adaptive construction for UOWHF that uses $O(ns^6(n))$ key-length under the assumption that $|f^{-1}(f(x))|$ is concentrated in an interval of size $2^{s(n)}$. Yu, Gu, Li and Weng [32] give adaptive constructions with key of length $O(n \log n)$, for functions with polynomial fraction of inputs x such that $|f^{-1}(f(x))|$ is maximal.

Lower bounds. The lower bounds for black-box UOWHF and PRG constructions from one-way functions are relatively far from the upper bounds. Gennero, Gertner, Katz and Trevisan [13] prove that any black-box PRG construction $G: \{0, 1\}^m \rightarrow \{0, 1\}^{m+s}$ from f must use $\Omega(s/\log n)$ calls to f . Similarly, any black box UOWHF construction with input size m and output size $m - s$ must use $\Omega(s/\log n)$ calls. Holenstein and Sinha [21] prove that any black-box PRG construction from a one-way function f must use $\Omega(n/\log n)$ calls to f , even for 1-bit stretching. Barhum and Holenstein [7] give an analog lower bound of $\Omega(n/\log n)$ calls 1-bit compressing UOWHF constructions. These lower bounds hold even when the one-way function f is unknown-regular. In this case, these bounds are known to be tight ([15, 32, 2, 26]).

(Multi)-collision resistant hash functions (CRHFs). UOWHF is a relaxation of CRHF. In the latter, we require that for a random function from the family, no adversary can find a collision (x, x') . Constructing a CRHF is a more challenging task, and its complexity is still not clear. Asharov and Segev [6] prove that there is no black-box construction of CRHFs even from indistinguishable obfuscation (iO) additionally to a one-way permutation. Holmgren and Lombardi [22] show how to construct CRHF from exponentially secure OWF, under an assumption on the probability to invert two independent one-way function challenges. Recent works also study a relaxation of CRHF, called Multi-Collision Resistant hash functions (MCRH) [24, 9, 10]. Rothblum and Vasudevan [29] show a non-constructive transformation from MCRH to CRHF for some range of parameters.

Low-complexity cryptography. As described above, Applebaum, Ishai and Kushilevitz [4] develop a general method to construct cryptographic primitives in NC0 based on primitives in higher complexity classes. HRV [18] use this method

in order to prove the existence of PRG in NC0, assuming one-way function in NC1. Applebaum, Haramaty-Krasne, Ishai, Kushilevitz and Vaikuntanathan [3] show the existence of CRHF with low algebraic degree and linear shrinkage based on a specific assumption. Based on the assumption that random local function is a one-way function (Goldreich [14]), Applebaum and Moses [5] construct a UOWHF with constant locality and linear shrinkage.

1.3 Paper Organisation

Section 2 gives a high-level description of our constructions and proof technique. Section 3 gives formal definitions. The non-adaptive UOWHF construction and its security reduction to one-way functions are in Section 4. Finally, Section 5 provides the formal definition of almost-UOWHF and next-bit unreachable entropy, as well as the almost-UOWHF construction. The security reduction from the almost-UOWHF construction to one-way functions is in the full version of this paper [25].

2 Our Technique

In this section, we provide a detailed description of our constructions and proof technique. In both of the proofs, we first construct a function that is *collision resistant on random inputs*, and then use known techniques to convert it into a UOWHF. Informally, a function C is collision resistant on random input if, given a random input x , no adversary can find $x' \neq x$ with $C(x') = C(x)$.

Definition 2.1 (Collision resistance on random inputs) *Let n be a security parameter. A function $f: \{0, 1\}^{m(n)} \rightarrow \{0, 1\}^{\ell(n)}$ is collision resistant on random inputs if for every probabilistic polynomial-time adversary A , the probability that A succeeds in the following game is negligible in n :*

1. Choose $x \leftarrow \{0, 1\}^{m(n)}$.
2. Let $x' \leftarrow A(1^n, x) \in \{0, 1\}^{m(n)}$.
3. A succeeds if $x \neq x'$ and $f(x) = f(x')$.

In contrast, the security requirement in the definition of UOWHF is called *target-collision resistance* (see Definition 3.3), according to which the adversary can choose x , but without knowing the randomly chosen key for the function. It is well known that a collision resistant on random input function C that is length-decreasing (i.e., $\ell < m$) can be converted into a UOWHF defined by

$$\mathcal{C} = \left\{ C_k: \{0, 1\}^m \rightarrow \{0, 1\}^\ell \right\}_{k \in \{0, 1\}^m},$$

for $C_k(x) = C(k \oplus x)$. The key length of the resulting UOWHF is the same as the input length of C , and the complexity of the UOWHF is similar to the complexity of C . It is not hard to see that the other direction also holds. That

is, by adding the key to the input and output of the function, a UOWHF can be converted into a (shrinking) collision resistant on random input function. A similar notion and transformation can be defined also for the case of almost-UOWHFs. Below, we show how to construct collision resistant on random input functions.

2.1 Non-Adaptive UOWHF

We start with a high-level description of the constructions of [16] and [26].

UOWHF from Unknown-Regular One-Way Functions

Mazor and Zhang (MZ [26]) showed how to construct a non-adaptive UOWHF from an unknown-regular one-way function $f : \{0, 1\}^n \rightarrow \{0, 1\}^n$. For hash functions

$h_1, \dots, h_{n-1} : \{0, 1\}^{2n} \rightarrow \{0, 1\}^{n-\log n}$ from a hash family \mathcal{H} , and n inputs $x_1, \dots, x_n \in \{0, 1\}^n$, MZ [26] show that, for the right choice of \mathcal{H} , the function $C : \mathcal{H}^n \times \{0, 1\}^{n^2} \rightarrow \mathcal{H}^n \times \{0, 1\}^{2n+(n-1)(n-\log n)}$, defined by

$$\begin{aligned} C(h_1, \dots, h_n, x_1, \dots, x_n) \\ = h_1, \dots, h_n, f(x_1), h_1(x_1, f(x_2)), \dots, h_{n-1}(x_{n-1}, f(x_n)), x_n \end{aligned}$$

is collision resistant on random inputs. Since this function is also shrinking, it can be converted into an UOWHF easily by a standard construction.⁷

Intuitively, for a regular function f and i.i.d uniform random variables X_1, X_2 over $\{0, 1\}^n$, given any fixing of $f(X_1)$, the entropy of the pair $X_1, f(X_2)$ is exactly n . To see the above, recall that for a regular f with an (unknown) regularity parameter Δ , it holds that there are exactly Δ possible values for X_1 given $f(X_1)$, and exactly $2^n/\Delta$ possible values for $f(X_2)$. Thus, the regularity parameter Δ “cancels out” when considering the number of possible values (given $f(X_1)$) of the pair $X_1, f(X_2)$, as this number is $\Delta \cdot 2^n/\Delta = 2^n$. It follows that the compression of the pair $X_1, f(X_2)$ does not create too many collisions. This fact can be used in order to reduce the problem of inverting f , into finding a collision for C .

Inaccessible Entropy from One-Way Functions In order to construct an UOWHF from an arbitrary one-way function, given a one-way function $f : \{0, 1\}^n \rightarrow \{0, 1\}^n$, HHRVW [16] first construct a function g , that takes as input an index $i \in [n]$, string $x \in \{0, 1\}^n$ and a description of a random hash function h from a 3-wise independent hash family \mathcal{H} , and outputs h , together with the i first bits of $h(f(x))$. That is, $g(i, x, h) = (h, h(f(x))_{\leq i})$. HHRVW [16] showed that for every collision finder algorithm A , there are sets $\{\mathcal{L}_w\}_{w \in ([n] \times \{0, 1\}^n \times \mathcal{H})}$, such that, for a random input $W \leftarrow ([n] \times \{0, 1\}^n \times \mathcal{H})$,

⁷ MZ actually show it is enough to use a single hash function. The number of repetitions n is necessary only to make the function shrinking.

1. $\Pr[A(W) \notin \mathcal{L}_W] = \text{neg}(n)$, and,
2. $H(W \mid g(W)) - \mathbf{E}[\log(|\mathcal{L}_W|)] \geq \log n/n$,

where H is the entropy function. The above $\log n/n$ is a gap between the *entropy* of W given $g(W)$, to its *accessible average max entropy*.

HHRVW [16] then showed, using standard concentration bounds, that for $\rho = g^{n^4}$ (i.e., $\rho(w_1, \dots, w_{n^4}) = g(w_1), \dots, g(w_{n^4})$, the concatenation of the outputs of n^4 independent invocations of g), both the entropy and the accessible entropy are highly concentrated around their means. That is, there exist some $\ell \in \mathbb{N}$ and $s = \omega(\log n)$ such that $|\rho^{-1}(\rho(z))| \geq 2^{\ell+s}$ for all but negligible fraction of z 's, and the following holds. For every collision finder A for ρ , there exist sets $\{\mathcal{L}_z\}_{z \in \text{Domain}(\rho)}$ such that (1) $|\{\mathcal{L}_z\}| \leq 2^\ell$ for all but negligible fraction of z 's, and (2), $\Pr[A(z) \notin \mathcal{L}_z] = \text{neg}(n)$ for every collision finder A for ρ .

We now proceed to describing our construction. In the following we view ρ as a function from $\{0, 1\}^m$ to $\{0, 1\}^k$, for $m, k = O(n^5)$ (using a proper encoding of the input).

Our Construction Thinking of ℓ as the regularity parameter of the function ρ , we use the MZ construction of in order to build a non-adaptive UOWHF. That is, for hash functions $h_1, \dots, h_{m-1}: \{0, 1\}^m \times \{0, 1\}^k \rightarrow \{0, 1\}^{m-\log n}$ from a universal family \mathcal{H} , and inputs z_1, \dots, z_m , let

$$\begin{aligned} C(h_1, \dots, h_{m-1}, z_1, \dots, z_m) \\ = h_1, \dots, h_{m-1}, \rho(z_1), h_1(z_1, \rho(z_2)), \dots, h_{m-1}(z_{m-1}, \rho(z_m)), z_m. \end{aligned}$$

We show that C is collision resistant on random inputs. Indeed, assume that $|\rho^{-1}(\rho(z))| \geq 2^{\ell+\omega(\log n)}$ for every $z \in \{0, 1\}^m$. Then the image size of ρ is at most $2^m \cdot 2^{-\ell-\omega(\log n)}$. Thus, for $Z_1, Z_2 \leftarrow \{0, 1\}^m$ and $H_1 \leftarrow \mathcal{H}$, any poly-time algorithm cannot find a collision for $\rho(Z_1), H_1(Z_1, \rho(Z_2))$, since it only has

$$|\mathcal{L}_{Z_1}| \cdot |\text{Image}(\rho)| \leq 2^\ell \cdot (2^m \cdot 2^{-\ell-\omega(\log n)}) = 2^{m-\omega(\log n)}$$

possible values to choose from, and the probability for each such value to collide with $Z_1, \rho(Z_2)$ on H_1 is $2^{-m+\log n}$. Thus, by the union bound, the probability that there is a collision for Z_1, Z_2 inside the set $\mathcal{L}_{Z_1} \times \text{Image}(\rho)$ is negligible. By a similar argument, the analysis shows that it is impossible to find a collision for the entire function C .

However, there is an issue with the above idea. Note that the condition concerning the pre-image size of an image of ρ holds only with overwhelming probability, which may pose a problem. Indeed, let

$$\mathcal{B} = \left\{ z \in \{0, 1\}^m : |\rho^{-1}(\rho(z))| < 2^{\ell+\omega(\log n)} \right\}$$

be the set of all untypical inputs. The size of $\rho(\mathcal{B})$ can be much larger than $2^m \cdot 2^{-\ell-\omega(\log n)}$, the number of “typical” images. Thus, by choosing X'_2 from this set, the adversary might be able to find a collision (Z'_1, Z'_2) for $\rho(Z_1), H_1(Z_1, \rho(Z_2))$.

Fortunately, it turns out that this issue can be resolved by a more careful analysis, which yields the following key insight: for every collision (z'_1, \dots, z'_m) for C found by an efficient algorithm, it holds that if $z'_i \in \mathcal{B}$ for some i , it must hold that $z'_{i+1} \in \mathcal{B}$ as well. It follows from the above that in this case, z'_m is also in \mathcal{B} . Since C outputs its last input z_m , and with all but a negligible probability $z_m \notin \mathcal{B}$, we have that (z'_1, \dots, z'_m) is not a valid collision.

Remark 2.2 (Using a more shrinking hashing). The actual gap s between the accessible and real entropy of ρ^{-1} is $s \approx n^3$. Thus, the first part of the argument above will work even if the hash functions will output only $m - n^3 + \omega(\log n)$ bits. In this case, however, we will not be able to show that it is infeasible to find a collision inside \mathcal{B} . The above suggests the following construction of an *almost-UOWHF*: let $t \approx n^2$, and for $h_1, \dots, h_{t-1}, z_1, \dots, z_t$, consider

$$\begin{aligned} C(h_1, \dots, h_{t-1}, z_1, \dots, z_t) \\ = h_1, \dots, h_{t-1}, \rho(z_1), h_1(z_1, \rho(z_2)), \dots, h_{t-1}(z_{t-1}, \rho(z_t)), z_t, \end{aligned}$$

for $h_i: \{0, 1\}^{m+k} \rightarrow \{0, 1\}^{m-n^3/2}$.

For large enough t , the above function is shrinking. For a random input $(h_1, \dots, h_{t-1}, z_1, \dots, z_t)$ it is hard to find a collision (z'_1, \dots, z'_t) , such that $z'_i \notin \mathcal{B}$ for every i . The latter implies that all the collisions that can be found by an efficient algorithm come from a negligible-sized set. Such a function can easily be converted into an almost-UOWHF, which yields a construction with $O(n^6)$ non-adaptive calls, and key length of $O(n^7)$ bits. It turns out, see next section, that there are better approaches for constructing almost-UOWHFs.

2.2 Next-bit unreachable entropy.

As mention above, HRV [18] defined the notion of *next-bit pseudoentropy*. Roughly, a function $g: \{0, 1\}^m \rightarrow \{0, 1\}^\ell$ has next-bit pseudoentropy k , if for random $X \leftarrow \{0, 1\}^m$ and $I \leftarrow [\ell]$ the bit $g(X)_I$ has pseudoentropy k/ℓ given $g(X)_{<I}$.⁸ HRV [18] used a one-way function to construct a function $g: \{0, 1\}^m \rightarrow \{0, 1\}^\ell$ with non-trivial (i.e., larger than m) next-bit pseudoentropy. This function g is then used to construct an efficient and simple PRG (see Section 2.3 for a high-level description of the construction).

To replace the notion of next-bit pseudoentropy in our construction, we define the notion of *next-bit unreachable entropy*, a variant of inaccessible entropy, defined by HHRVW [16], that allows us to achieve almost-UOWHF using a similar construction to the above PRG.

Remark 2.3 (Motivating the definition). Before presenting our definition, we start with some intuition. As in the case of next-bit pseudoentropy, we would like to say that a function g has non trivial “next-bit inaccessible entropy” if,

⁸ That is, $g(X)_I$ is indistinguishable from some random variable Z (jointly distributed with X and I), such that $H(Z \mid g(X)_{<I}) \geq k/\ell$. Here, $H(Z \mid g(X)_{<I})$ is the conditional Shannon entropy of Z given $g(X)_{<I}$ (see Section 3.5).

for random X and I , the accessible entropy of $g(X)_I$ given $g(X)_{<I}$ is smaller than its real entropy. That is, for any adversary that, given X and I , outputs X' with $g(X)_{<I} = g(X')_{<I}$, it holds that the entropy of $g(X')_I$ is small (smaller than $H(g(X)_I \mid g(X)_{<I})$).

However, there is an issue with this definition: If for some fixing x, i of X, I , the accessible entropy of $g(X')_I$ is noticeable, the adversary can make it to be almost one. Indeed, assume that given i, x the adversary can find, with noticeable probability, \hat{x} such that $g(\hat{x})_{<i} = g(x)_{<i}$ and $g(\hat{x}) \neq g(x)$. In this case, using simple amplification, the adversary can set its output x' to be equal to each one of x or \hat{x} with probability $1/2$. In this case, the entropy of $g(X')_I$ can be arbitrarily close to 1. In particular, the entropy may be larger than the real entropy

$$H(g(X)_I \mid g(X)_{<I} = g(x)_{<i})$$

(which is at most $|g(X)_I| = 1$). For this reason, we only focus on inputs for which the entropy of $g(X')_I$ is negligible (that is, no PPT adversary can find an input X' such that $g(X)_{<I} = g(X')_{<I}$ and $g(X')_I \neq g(X)_I$).

Unfortunately, while the above gives a definition that is strong enough to work with, we are not able to construct it from a one-way function. Thus, we consider a weaker definition, in which we allow the above property to hold only for a large fraction of the inputs. That is, we define the sets $\mathcal{U} = \{\mathcal{U}_i\}_{i \in [\ell]}$ of inputs which are *unreachable* to the adversary in the following sense. First, we require that it is hard for every adversary to get inside \mathcal{U}_i . That is, for every $x \notin \mathcal{U}_i$, it is hard to find $x \in \mathcal{U}_i$ with $g(x)_{<i} = g(x')_{<i}$. Secondly, we require that the next-bit inaccessible entropy property will hold inside \mathcal{U} . That is, for every $x \in \mathcal{U}_i$ it is hard to find x' **inside** \mathcal{U}_i such that $g(x)_{<i} = g(x')_{<i}$ and $g(x')_i \neq g(x)_i$. While it may be easy to find such an x' outside of \mathcal{U}_i , if the size of \mathcal{U}_i is large enough, the above promises that every such collision will be a member of a (respectively) small set and will look (somewhat) untypical. This property will be useful in the construction. We give more examples below the definition.

We now define the notion of next-bit unreachable entropy. The formal definition is given in Definition 5.3.

Definition 2.4 (Unreachable entropy, informal) *A function $g: \{0, 1\}^m \rightarrow \{0, 1\}^\ell$ has next-bit unreachable entropy v , if for every $i \in [\ell]$ there exists a set $\mathcal{U}_i \subseteq \{0, 1\}^m$, such that*

1. \mathcal{U}_i are large:

$$\Pr_{x \leftarrow \{0, 1\}^m, i \leftarrow [\ell]} [x \notin \mathcal{U}_i] \leq (m - v)/\ell.$$

2. Hard to get inside \mathcal{U}_i : For every PPT A ,

$$\Pr_{\substack{x \leftarrow \{0, 1\}^m, \\ i \leftarrow [\ell], x' \leftarrow A(x, i)}} [(x' \in \mathcal{U}_i) \wedge (g(x)_{<i} = g(x')_{<i}) \wedge (x \notin \mathcal{U}_i)] = \text{neg}(n).$$

That is, for $x \notin \mathcal{U}_i$, it is hard to find a collision for $g(x)_{<i}$ inside \mathcal{U}_i .

3. The entropy inside \mathcal{U}_i is unreachable: For every PPT \mathbf{A} ,

$$\Pr_{\substack{x \leftarrow \{0,1\}^m, \\ i \leftarrow [\ell], x' \leftarrow \mathbf{A}(x,i)}} [((x' \in \mathcal{U}_i)) \wedge (g(x)_{<i} = g(x')_{<i}) \wedge (g(x)_i \neq g(x')_i)] = \text{neg}(n).$$

That is, even if $x \in \mathcal{U}_i$, it is hard to flip the i -th bit of g while staying inside \mathcal{U}_i .

For example, for every permutation $p: \{0,1\}^m \rightarrow \{0,1\}^m$, the function $g: \{0,1\}^m \rightarrow \{0,1\}^\ell$ defined by $g(x) = p(x)0^{\ell-m}$ has (trivial) next-bit unreachable entropy 0, as can be seen by setting $\mathcal{U}_i = \{0,1\}^m$ for every $i > m$, or the empty set for $i \leq m$. Note also that, without assuming computational hardness, the above sets \mathcal{U}_i are the maximal that respect the definition of unreachable entropy.

More generally, for every *injective* function $g: \{0,1\}^m \rightarrow \{0,1\}^\ell$, we can define \mathcal{U}_i to be the set of all inputs $x \in \{0,1\}^m$, such that there is no $x' \in \{0,1\}^m$ with $g(x)_{<i} = g(x')_{<i}$ while $g(x)_i \neq g(x')_i$.⁹ In this case, it is not hard to see that the probability that a random x is outside of \mathcal{U}_i (for any fixed i) is at least the entropy of $g(X)_i$ given $g(X)_{<i}$ (i.e., $H(g(X)_i | g(X)_{<i})$).¹⁰ Using the chain rule of entropy, we get that for a random index I , the probability that X is outside of \mathcal{U}_I is at least

$$1/\ell \cdot \sum_{i \in \ell} H(g(X)_i | g(X)_{<i}) = 1/\ell \cdot H(g(X)) = m/\ell.$$

By the above observations, it follows that a function g has $v > 0$ next-bit unreachable entropy if the “reachable entropy” of $g(X)_I$ given $g(X)_{<I}$ is smaller than its real entropy.¹¹ In this sense, our definition is a dual version of the next-bit pseudoentropy definition. We show that a very similar function to the function g used by HRV [18] has non-trivial next-bit unreachable entropy. More details on the constructions and the security proof are given below.

2.3 Almost-UOWHF

In this part, we show that small modifications to the PRG of HRV [18] yield an *almost-collision resistant on random inputs* function.

Definition 2.5 (Almost collision resistance on random inputs) Let n be a security parameter. A function $f: \{0,1\}^{m(n)} \rightarrow \{0,1\}^{\ell(n)}$ is *almost collision resistant on random inputs* if there exists a set $\mathcal{B}_n \subseteq \{0,1\}^{m(n)}$, such that

⁹ If the function g is not injective, it is natural to consider $g'(x) = (g(x), x)$. We use a similar construction in Section 5.

¹⁰ Indeed, observe that $H(g(X)_i | g(X)_{<i} = g(x)_{<i}) = 0$ iff $x \in \mathcal{U}_i$. Additionally, $H(g(X)_i | g(X)_{<i} = g(x)_{<i}) \leq 1$ for every x . It follows that $H(g(X)_i | g(X)_{<i}) = \mathbf{E}_{x \leftarrow \{0,1\}^m} [H(g(X)_i | g(X)_{<i} = g(x)_{<i})] \leq \mathbf{E}_{x \leftarrow \{0,1\}^m} [1_{x \notin \mathcal{U}_i}] = \Pr[X \notin \mathcal{U}_i]$.

¹¹ We use the term “reachable entropy” to denote the difference between the real entropy and the next-bit unreachable entropy of $g(X)$.

$|\mathcal{B}_n|/2^{m(n)} = \text{neg}(n)$, and for every probabilistic polynomial-time adversary A , the probability that A succeeds in the following game is negligible in n :

1. Choose $x \leftarrow \{0, 1\}^{m(n)}$.
2. Let $x' \leftarrow A(1^n, x) \in \{0, 1\}^{m(n)}$.
3. A succeeds if $x' \notin \mathcal{B}_n$, $x \neq x'$ and $f(x) = f(x')$.

For a more formal definition, see Definition 2.5. As in the case of (perfect) UOWHF, such a shrinking function can be converted into almost-UOWHF. We start with a high-level description of the one-way function based pseudorandom generator of HRV [18]. The main building block of the construction is a function $g: \{0, 1\}^m \rightarrow \{0, 1\}^\ell$, with $k > m$ next-bit pseudoentropy. On a given input, their PRG starts by using g to construct the following matrix-like structure (see Figure 1): the structure is composed of $q \approx m^2$ rows, where each row contains $t \approx m$ independent copies of $g(X)$, for $X \leftarrow \{0, 1\}^m$, shifted by a random offset between 0 to ℓ . Every fully populated column is then hashed by a hash function $h: \{0, 1\}^q \rightarrow \{0, 1\}^a$, for $a \approx q \cdot k/\ell > q \cdot m/\ell$. Finally, the output of the PRG is the concatenation of the outputs of the hash function applied to every fully populated column (the non-fully populated columns are not part of the output).

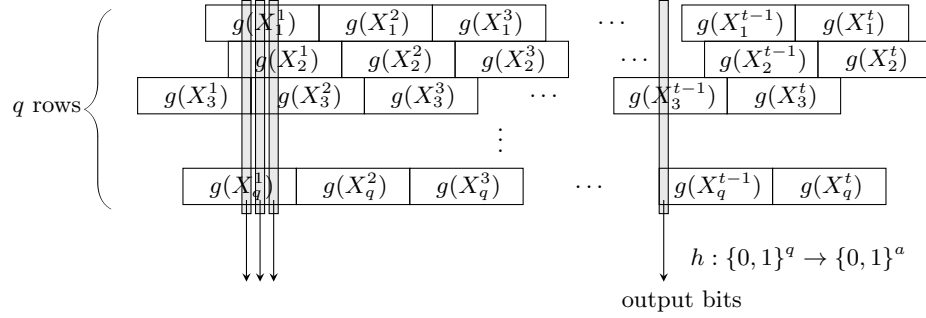


Fig. 1. The PRG construction of HRV [18], $G: \mathcal{H} \times (\{0, 1\}^m)^{t \cdot q} \rightarrow \mathcal{H} \times (\{0, 1\}^a)^{(t-1)\ell}$. There are $q \approx m^2$ rows, each row has $t \approx m$ i.i.d copies of $g(X)$, shifted by a random offset. Every fully populated column, marked in grey, is hashed by $h \in \mathcal{H}$. The almost-UOWHF construction also outputs the columns that are not fully populated.

We prove that slightly tweaking the above construction, and using a different function g , yields a function that is almost collision-resistant on random inputs. Specifically, the output of our construction contains not only the hashed fully populated columns, but also all the columns that are not fully populated (without hashing). Additionally, we choose the parameter a to be smaller than $q \cdot n/m$, in order to make the function length-decreasing. The function g we are using in our construction, is defined by

$$g(h_1, h_2, x) = (h_1, h_2, h_1(f(x)), h_2(x)),$$

for hash functions $h_1, h_2: \{0, 1\}^n \rightarrow \{0, 1\}^n$ from a 3-wise independent family. We prove in Section 5.2 that if f is a one-way function, the above function g has next-bit unreachable entropy $\log n$.¹²

Remark 2.6 (Similarities between our constructions). We note that the function ρ , defined in Section 2.1, is composed of n^4 independent repetitions of a simpler function with random shifts. Thus, our first construction of non-adaptive UOWHF can be modified to be an instantiation of the second (almost-UOWHF) construction, described above, where we apply the hash function on blocks of m columns, instead of hashing every single column (and by taking the number of rows to be larger). This equivalent construction is illustrated in Figure 2, and its security can be proven using a similar proof to the one given in Section 4.

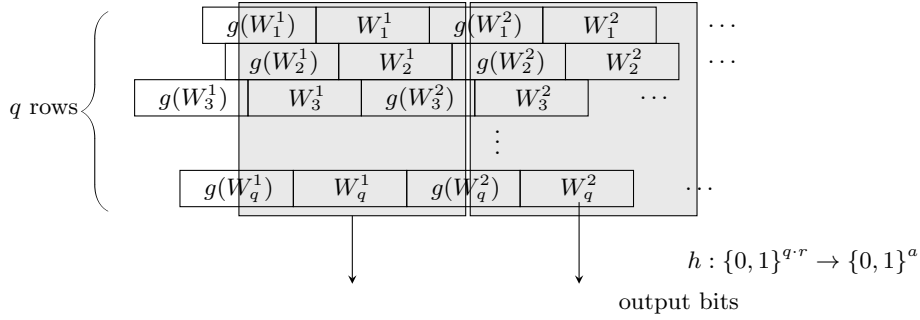


Fig. 2. An equivalent construction to our non-adaptive UOWHF, where $g(h, x) = (h, h(f(x)))$. There are $q \approx n^4$ rows, each row has $t \approx n^5$ i.i.d copies of $(g(W), W)$, shifted by a random offset. Every fully populated block of $r = |(g(W), W)|$ columns, marked in grey, is hashed by $h \in \mathcal{H}$. The UOWHF construction also outputs the columns that are not fully populated.

In the rest of this section we give some details on the security proof. Consider the function σ induced by taking the first hashed column in our almost-UOWHF construction (Figure 1) together with the columns to the left of it. That is,

$$\sigma(h, i_1, \dots, i_q, x_1, \dots, x_q) = h, (g(x_1)_{<i_1}, \dots, g(x_q)_{<i_q}), h(g(x_1)_{i_1}, \dots, g(x_q)_{i_q}),$$

for a hash function $h: \{0, 1\}^q \rightarrow \{0, 1\}^a$ from a universal family \mathcal{H} .

Additionally, consider the function $\hat{\sigma}$, defined similarly to σ , but without applying the hash h on the column. That is,

$$\hat{\sigma}(h, i_1, \dots, i_q, x_1, \dots, x_q) = h, (g(x_1)_{<i_1}, \dots, g(x_q)_{<i_q}), (g(x_1)_{i_1}, \dots, g(x_q)_{i_q}).$$

¹² For the PRG construction, HRV [18] used $g(h, x) = (h, f(x), h(x))$ and Vadhan and Zheng [30] used $g(x) = (f(x), x)$. Observe that, since $h_1(f(x))$ is also a one-way function, our g can be used in the PRG construction.

It turns out, see detail below, that the following holds for a right choice of the parameter a and for some negligible-sized set of inputs \mathcal{B} : for a random input, every collision found by a collision finder to the function σ is either a collision for $\hat{\sigma}$, or it is inside the set \mathcal{B} . That is, the function h does not make the task of finding a collision (outside of \mathcal{B}) easier.

To see that the above is enough to prove the security of the construction, let C be the almost-UOWHF construction described above, and let \hat{C} be the function defined by the raw matrix-like structure (without applying the hash function on every fully-populated column). Observe that since the function g is (close to be) injective, the function \hat{C} is (not shrinking) collision-resistant on random inputs. A simple hybrid argument yields that every collision finder that, given an input w for C , is able to find a collision $w' \neq w$ for C that is not a collision for \hat{C} (namely, $C(w) = C(w')$ but $\hat{C}(w) \neq \hat{C}(w')$), can be used to find a collision for σ which is not a collision for $\hat{\sigma}$.¹³ Since the latter is hard to find, and since \hat{C} is collision-resistant, the above concludes the proof.

σ is (almost) as hard as $\hat{\sigma}$. It thus left to prove that it is hard to find a collision for σ which is not a collision for $\hat{\sigma}$, outside of the negligible sized set \mathcal{B} . Let A be a collision finder for σ , and let $w' = (h, i_1, \dots, i_q, x'_1, \dots, x'_q)$ be a collision found by $A(w)$, for some $w = (h, i_1, \dots, i_q, x_1, \dots, x_q)$. We show that either $\hat{\sigma}(w) = \hat{\sigma}(w')$, or w' is a member of a small set \mathcal{B} . To do so, we use the next-bit unreachable entropy property of g .

Let $\{\mathcal{U}_i\}_{i \in [\ell]}$ be the sets guaranteed by the next-bit unreachable entropy of g (these sets are independent from the choice of A). By the definition of next-bit unreachable entropy it holds that:

1. for every j such that $x_j \notin \mathcal{U}_{i_j}$, no collision finder can find $x'_j \in \mathcal{U}_{i_j}$ such that $g(x_j)_{<i_j} = g(x'_j)_{<i_j}$, and thus it must hold that $x'_j \notin \mathcal{U}_{i_j}$.
2. Similarly, for every j with $x_j \in \mathcal{U}_{i_j}$, it holds that $g(x_j)_{i_j} = g(x'_j)_{i_j}$, unless $x'_j \notin \mathcal{U}_{i_j}$.

Let \mathcal{J}_w be the set of indices for which x_j is inside the set \mathcal{U}_{i_j} . Formally,

$$\mathcal{J}_w = \{j \in [q] : x_j \in \mathcal{U}_{i_j}\}.$$

By Item 1 above, it holds that $\mathcal{J}_{w'} \subseteq \mathcal{J}_w$. Moreover, Item 2 implies that $g(x_j)_{i_j} = g(x'_j)_{i_j}$ for every $j \in \mathcal{J}_{w'} \cap \mathcal{J}_w$. The above yields the key observation of the proof:

Claim 2.7 *For any collision $w' = (h, i_1, \dots, i_q, x'_1, \dots, x'_q)$ found by a collision finder A , unless $|\mathcal{J}_{w'}|$ is smaller than $|\mathcal{J}_w|$, there are $|\mathcal{J}_w|$ bits in $g(x'_1)_{i_1}, \dots, g(x'_q)_{i_q}$ that get the exact same value as in $g(x_1)_{i_1}, \dots, g(x_q)_{i_q}$ (namely, $g(x_j)_{i_j} = g(x'_j)_{i_j}$ for every $j \in \mathcal{J}_w$).*

Observe that for large enough q , the size of \mathcal{J}_w (for a random w) is concentrated around its mean. Since g has $\log n$ next-bit unreachable entropy, its mean is at

¹³ Furthermore, the hybrid argument yields that w' must be from a small set if the collision for $\hat{\sigma}$ is.

least $q \cdot (1 - \frac{m - \log n}{\ell})$. In the following, assume for simplicity that the size of \mathcal{J}_w is equal to its mean, and that this mean is exactly $q \cdot (1 - \frac{m - \log n}{\ell})$. To conclude the proof, let \mathcal{B} be the negligible-sized set of all inputs $w' = (h, i_1, \dots, i_q, x'_1, \dots, x'_q)$ for which $|\mathcal{J}_{w'}|$ is (much) smaller than $q \cdot (1 - \frac{m - \log n}{\ell})$, and set the length of the output of the hash function h to be $a \approx q \cdot \frac{m - \log n}{\ell} < q \cdot m/\ell$. It follows that the output of every collision finder for σ is either in \mathcal{B} , or agrees with $g(x_1)_{i_1}, \dots, g(x_q)_{i_q}$ on (almost) all the indices in \mathcal{J}_w . However, with all but a negligible probability, there is no string y' that agrees with $y = (g(x_1)_{i_1}, \dots, g(x_q)_{i_q})$ on $q \cdot (1 - \frac{m - \log n}{\ell})$ bits, for which $h(y) = h(y')$, unless $y = y'$. In other words, any such collision for σ is also a collision for $\hat{\sigma}$.

3 Preliminaries

3.1 Notations

We use calligraphic letters to denote sets, uppercase for random variables, and lowercase for values and functions. For $n \in \mathbb{N}$, let $[n] := \{1, \dots, n\}$. Given a vector $s \in \{0, 1\}^n$, let s_i denote its i -th entry, and $s_{\leq i}$ denote its first i entries. Define $s_{< i}$, $s_{> i}$ and $s_{\geq i}$ similarly.

The support of a distribution P over a finite set \mathcal{S} is defined by $\text{Supp}(P) := \{x \in \mathcal{S} : P(x) > 0\}$. For a (discrete) distribution D let $d \leftarrow D$ denote that d was sampled according to D . Similarly, for a set \mathcal{S} , let $s \leftarrow \mathcal{S}$ denote that s is drawn uniformly from \mathcal{S} . For an event W , we use \bar{W} to denote the complement event. For a function $f: \{0, 1\}^n \rightarrow \{0, 1\}^n$, let $\text{Im}(f) := \{f(x) : x \in \{0, 1\}^n\}$ be the image of f .

Let poly denote the set of all polynomials, and let PPT stand for probabilistic polynomial time. A function $\mu: \mathbb{N} \rightarrow [0, 1]$ is negligible, denoted $\mu(n) = \text{neg}(n)$, if $\mu(n) < 1/p(n)$ for every $p \in \text{poly}$ and large enough n . For a security parameter n , a function $f: \{0, 1\}^{m(n)} \rightarrow \{0, 1\}^{\ell(n)}$ is efficiently computable if it is computable in polynomial time in n .

3.2 One-Way Functions

We now formally define basic cryptographic primitives. We start with the definition of one-way function.

Definition 3.1 (One-way function) *A polynomial-time computable function $f: \{0, 1\}^* \rightarrow \{0, 1\}^*$ is called a one-way function if for every probabilistic polynomial time algorithm A , there is a negligible function $\mu: \mathbb{N} \rightarrow [0, 1]$ such that for every $n \in \mathbb{N}$*

$$\Pr_{x \leftarrow \{0, 1\}^n} [A(f(x)) \in f^{-1}(f(x))] \leq \mu(n)$$

For simplicity we assume that the one-way function f is length-preserving. That is, $|f(x)| = |x|$ for every $x \in \{0, 1\}^*$. This can be assumed without loss of generality, and is not crucial for our constructions.

Immediately from the definition of a one-way function, we get the following simple observation.

Claim 3.2 *For every one-way function $f: \{0,1\}^n \rightarrow \{0,1\}^n$ there exists a negligible function $\mu(n)$ such that for every input $x \in \{0,1\}^n$ it holds that $|f^{-1}(f(x))| \leq 2^n \cdot \mu(n)$.*

3.3 Universal One Way Hash Functions

We now formally define UOWHF.

Definition 3.3 (Universal one-way hash function) *Let n be a security parameter. A family of functions $\mathcal{F} = \left\{ f_z: \{0,1\}^{m(n)} \rightarrow \{0,1\}^{\ell(n)} \right\}_{z \in \{0,1\}^{k(n)}}$ is a family of universal one-way hash functions (UOWHFs) if it satisfies:*

1. *Efficiency: Given $z \in \{0,1\}^{k(n)}$ and $x \in \{0,1\}^{m(n)}$, $f_z(x)$ can be evaluated in time $\text{poly}(n)$.*
2. *Shrinking: $\ell(n) < m(n)$.*
3. *Target Collision Resistance: For every probabilistic polynomial-time adversary \mathbf{A} , the probability that \mathbf{A} succeeds in the following game is negligible in n :*
 - (a) *Let $(x, \text{state}) \leftarrow \mathbf{A}(1^n) \in \{0,1\}^{m(n)} \times \{0,1\}^*$.*
 - (b) *Choose $z \leftarrow \{0,1\}^{k(n)}$.*
 - (c) *Let $x' \leftarrow \mathbf{A}(\text{state}, z) \in \{0,1\}^{m(n)}$.*
 - (d) *\mathbf{A} succeeds if $x \neq x'$ and $f_z(x) = f_z(x')$.*

A relaxation of the target collision resistance property can be done by requiring the function to be collision resistant only on random inputs (see Definition 2.1). The following lemma states that it is enough to construct a function that is collision resistant on random inputs, in order to get UOWHF.

Lemma 3.4 (From random inputs to targets, folklore) *Let n be a security parameter. Let $F: \{0,1\}^{m(n)} \rightarrow \{0,1\}^{\ell(n)}$ be an efficiently computable length-decreasing function. Suppose F is collision-resistant on random inputs. Then $\left\{ F_y: \{0,1\}^{m(n)} \rightarrow \{0,1\}^{\ell(n)} \right\}_{y \in \{0,1\}^{m(n)}}$, for $F_y(x) := F(y \oplus x)$, is an UOWHF.*

3.4 Hash Families

2-universal and t -wise independent hash families are an important ingredient in our constructions. In this section, we formally define this notion, together with some useful properties of such families.

Definition 3.5 (2-universal and t -wise independent families)

A family of functions $\mathcal{F} = \left\{ f: \{0,1\}^n \rightarrow \{0,1\}^\ell \right\}$ is 2-universal if for every $x \neq x' \in \{0,1\}^n$ it holds that $\Pr_{f \leftarrow \mathcal{F}}[f(x) = f(x')] \leq 2^{-\ell}$. \mathcal{F} is t -wise independent

if for all $x_1 \neq \dots \neq x_t \in \{0,1\}^n$, the random variables $F(x_1), \dots, F(x_t)$ for $F \leftarrow \mathcal{F}$ are independent and uniformly distributed over $\{0,1\}^\ell$.

A family is **explicit** if given a description of a function $f \in \mathcal{F}$ and $x \in \{0,1\}^n$, $f(x)$ can be computed in polynomial time (in n, ℓ). Such family is **constructible** if it is explicit and there is a PPT algorithm that given $x \in \{0,1\}^n$ and $y \in \{0,1\}^\ell$ outputs a uniform $f \in \mathcal{F}$, such that $f(x) = y$.

It is well-known that for every constant t , there are constructible families of t -wise independent functions with description size $O(t \cdot (n + \ell))$ in NC1. The next lemma, proven in the full version of this paper ([25]), will be useful in the proof.

Lemma 3.6 *Let $f: \{0,1\}^n \rightarrow \{0,1\}^n$ be a function, and $\mathcal{H} = \{h: \{0,1\}^n \rightarrow \{0,1\}^n\}$ a two-wise independent family. For every $x \in \{0,1\}^n$ and $c \in \mathbb{N}$ the following holds.*

$$\Pr_{h \leftarrow \mathcal{H}}[|\{x': h(f(x')) = h(f(x))\}| \geq |f^{-1}(f(x))| + n^{2c}] \leq 2/n^c.$$

3.5 Entropy and Accessible Entropy

The *Shannon entropy* of a random variable X is defined by

$$H(X) = - \sum_{x \in \text{Supp}(X)} \Pr[X = x] \cdot \log(\Pr[X = x]).$$

The conditional entropy of a random variable X given Y , is defined as $H(X | Y) = \mathbf{E}_{y \leftarrow Y}[H(X | Y=y)]$. For a number $p \in [0,1]$, we will use $H(p)$ to denote the entropy of a random variable distributed according to *Bernoulli*(p). That is $H(p) = -p \log p - (1-p) \log(1-p)$.

The *min entropy* of a random variable X is defined by

$$H_\infty(X) = \min_{x \in \text{Supp}(X)} \log \frac{1}{\Pr[X = x]},$$

and the *max entropy* of X is defined by $H_0(X) = \log|\text{Supp}(X)|$.

Lastly, for random variables X and Y , the sample entropy of $x \in \text{Supp}(X)$ (with respect to X) is defined by $H_X(x) = -\log \Pr[X = x]$, and the sample entropy of x given $y \in \text{Supp}(Y)$ is defined by $H_{X|Y}(x|y) = -\log \Pr[X = x | Y = y]$. The following equality is immediate from the definitions above.

$$H(X | Y) = \mathbf{E}_{x \leftarrow X, y \leftarrow Y}[H_{X|Y}(x | y)] \quad (1)$$

For a function g , we also use the following notation, defined in [16], for the entropy of g^{-1} .

Definition 3.7 (Real entropy) *Let n be a security parameter and $g: \{0,1\}^n \rightarrow \{0,1\}^m$ be a function.*

We say that g^{-1} has real Shannon entropy k if $H(X|g(X)) = k$, where X is uniformly distributed on $\{0, 1\}^n$.

We say that g^{-1} has real min-entropy at least k if there is a negligible function $\varepsilon = \varepsilon(n)$ such that $\Pr_{x \leftarrow X}[H_{X|g(X)}(x|g(x)) \geq k] \geq 1 - \varepsilon(n)$.

We say that g^{-1} has real max-entropy at most k if there is a negligible function $\varepsilon = \varepsilon(n)$ such that $\Pr_{x \leftarrow X}[H_{X|g(X)}(x|g(x)) \leq k] \geq 1 - \varepsilon(n)$.

[16] also introduced the notion of accessible max-entropy. A collision finder for a function g is an algorithm that, given input x , always outputs x' such that $g(x) = g(x')$. g^{-1} has small accessible entropy, if the output of every collision finder for g comes from a small set.

Definition 3.8 (Collision finder) For a function $g: \{0, 1\}^{m(n)} \rightarrow \{0, 1\}^{\ell(n)}$, an algorithm A is a g -collision finder if for every $x \in \{0, 1\}^{m(n)}$ it holds that $\Pr[g(A(1^n, x)) = g(x)] = 1$.

Definition 3.9 (accessible max-entropy) Let n be a security parameter and $g: \{0, 1\}^{m(n)} \rightarrow \{0, 1\}^{\ell(n)}$ be a function. We say that g^{-1} has accessible max-entropy at most k if for every PPT g -collision finder A and for every $n \in \mathbb{N}$, there exists a family of sets $\{\mathcal{L}(x)\}_{x \in \{0, 1\}^{m(n)}}$ each of size at most $2^{k(n)}$ such that $x \in \mathcal{L}(x)$ for all x , and $\Pr_{x \leftarrow \{0, 1\}^{m(n)}}[A(1^n, x) \in \mathcal{L}(x)] \geq 1 - \text{neg}(n)$.

The next theorems are implicit in [16] and will be useful in our constructions.

Theorem 3.10 (Entropy gap, implicit in [16]). Let $f: \{0, 1\}^n \rightarrow \{0, 1\}^n$ be a one-way function. Then there exists $\ell = \ell(n)$, $s = \omega(\log n)$ and an efficiently computable function $g: \{0, 1\}^{n^5} \rightarrow \{0, 1\}^{n^5}$ such that:

1. g^{-1} has real min-entropy at least $\ell + s$.
2. g^{-1} has accessible max-entropy at most ℓ .
3. g is computable in NC1 using $O(n^4)$ non-adaptive oracle calls to the one-way function.

Theorem 3.11 (Implied by Claim 4.9, [16]). Let $f: \{0, 1\}^n \rightarrow \{0, 1\}^n$ be a one-way function and let $\mathcal{H} = \{h: \{0, 1\}^n \rightarrow \{0, 1\}^n\}$ be a family of constructible, three-wise independent hash functions.¹⁴ Then, for every PPT A , every constant $c > 0$ and every $i \in [n]$, it holds that:

$$\Pr_{\substack{h \leftarrow \mathcal{H}, \\ x \leftarrow \{0, 1\}^n, \\ x' \leftarrow A(1^n, h, x, i)}} \left[\begin{aligned} & (f(x') \neq f(x)) \wedge (h(f(x))_{<i} = h(f(x'))_{<i}) \\ & \wedge i > n - (\log |f^{-1}(f(x'))| - c \log n) \end{aligned} \right] = \text{neg}(n).$$

¹⁴ Actually, the proof in [16] only requires two-wise independence.

3.6 Useful Facts

We will use the well known Chernoff bound in our proof.

Fact 3.12 (Chernoff bound) *Let A_1, \dots, A_n be independent random variables s.t. $A_i \in \{0, 1\}$ and let $\hat{A} = \sum_{i=1}^n A_i$. For every $\epsilon \in [0, 1]$ It holds that:*

$$\Pr \left[\left| \hat{A} - \mathbf{E}[\hat{A}] \right| \geq \epsilon \cdot \mathbf{E}[\hat{A}] \right] \leq 2 \cdot e^{-\epsilon^2 \cdot \mathbf{E}[\hat{A}]/3}.$$

4 Non-adaptive UOWHF From One-Way Functions

In this part we construct and prove the security of our non-adaptive UOWHF. This is done by combining the construction of [16] with the non-adaptive construction of UOWHF for unknown-regular one-way functions of [26].

We start with the construction. Let $g: \{0, 1\}^{m(n)} \rightarrow \{0, 1\}^{k(n)}$ be a function with a sufficient gap between the real min-entropy and the max accessible entropy of g^{-1} . Let $\mathcal{H}_n = \left\{ h: \{0, 1\}^{m(n)+k(n)} \rightarrow \{0, 1\}^{m(n)-\log n} \right\}$ be a 2-universal hash family. For every $t \in \mathbb{N}$, define the function $C_t: \mathcal{H}_n^{t-1} \times (\{0, 1\}^{m(n)})^t \rightarrow \mathcal{H}_n^{t-1} \times \{0, 1\}^{k(n)} \times (\{0, 1\}^{m(n)-\log n})^{t-1} \times \{0, 1\}^{m(n)}$, by

$$C_t(h_1, \dots, h_{t-1}, x_1, \dots, x_t) := \\ h_1, \dots, h_{t-1}, g(x_1), h_1(x_1, g(x_2)), \dots, h_{t-1}(x_{t-1}, g(x_t)), x_t.$$

Note that the above function is length decreasing when $(t-1)\log n > k(n)$. The next theorem states that, for the right choice of parameters, C_t is also collision resistant.

Theorem 4.1. *Let $\ell = \ell(n)$, $s = \omega(\log n)$ and let $g: \{0, 1\}^{m(n)} \rightarrow \{0, 1\}^{k(n)}$ be a function. Assume that g^{-1} has real min-entropy at least $\ell + s$ and accessible max entropy at most ℓ . Then the function C_t is collision resistant on random inputs, for every $t \in \text{poly}$.*

Corollary 4.2 *There exists a black-box construction of UOWHF from any one-way function that uses $O(n^9)$ non-adaptive calls to the one-way function. Moreover, the construction has key length and output length of $O(n^{10})$, and is computable in NC1 using oracle calls to f .*

Proof. Let $k = m = n^5$ and $t = k/\log n + 2$. By Theorem 3.10, there is a efficiently computable (using $O(n^4)$ non-adaptive calls to the one-way function f) function $g: \{0, 1\}^m \rightarrow \{0, 1\}^k$ such that g^{-1} has real min-entropy at least $\ell + s$ and accessible max-entropy at most ℓ . The proof is now immediate from Theorem 4.1 and lemma 3.4, together with the fact that there is an explicit 2-universal family $\mathcal{H} = \left\{ h: \{0, 1\}^{m+k} \rightarrow \{0, 1\}^{m-\log n} \right\}$ with description size $O(m+k)$ in NC1.

Using the general method of randomized encoding, Applebaum, Ishai and Kushilevitz [4] showed how to compile CRHF in NC1 to a CRHF in NC0. By observing their proof applies also for UOWHFs, we get the following corollary.

Corollary 4.3 *Assuming that one-way functions exist in NC1, there exists a UOWHF in NC0.*

We now prove Theorem 4.1. Let m, k, ℓ, g and t be as in Theorem 4.1. We will need the following two claims. The first, which is straight-forward from the definition of accessible entropy, states that every collision for C_t comes from a small set. The proof, which is a simple reduction, is given in the full version of this paper ([25]).

Claim 4.4 *For every collision-finder algorithm for C_t it holds that there exists a family of sets $\{\mathcal{L}(x)\}_{x \in \{0,1\}^m}$ each of size at most 2^ℓ such that*

$$\begin{array}{l} \mathbf{Pr} \quad [\exists i \in [t] \text{ s.t. } g(x'_i) = g(x_i) \wedge x'_i \notin \mathcal{L}(x_i)] = \text{neg}(n). \\ h := (h_1, \dots, h_{t-1}) \leftarrow \mathcal{H}_n^{t-1}, \\ x := (x_1, \dots, x_t) \leftarrow (\{0,1\}^{m(n)})^{t(n)} \\ (h, (x_1, \dots, x'_t)) \leftarrow A(1^n, h, x) \end{array}$$

For the second claim we will need the following definition. Let

$$\begin{aligned} \mathcal{T}_n &:= \left\{ x \in \{0,1\}^{m(n)} : H_{X|g(X)}(x|g(x)) \geq \ell + s \right\} \\ &= \left\{ x \in \{0,1\}^m : |g^{-1}(g(x))| \geq 2^{\ell+s} \right\}. \end{aligned}$$

That is, \mathcal{T}_n is the set of all “typical” inputs x for g , for which $H_{X|g(X)}(x|g(x))$ is large.

The second claim considers the function C_d for every $d \in \text{poly}$. It states that for typical inputs, i.e., $x_1, \dots, x_d \in \mathcal{T}$, there is no collision x'_1, \dots, x'_d for C_d such that x'_1 is from a small set \mathcal{G} .

Claim 4.5 *For every $d, n \in \mathbb{N}$, set $\mathcal{G} \subseteq \{0,1\}^{m(n)}$ of size at most $2^{\ell(n)}$ and $x = (x_1, \dots, x_d) \in \mathcal{T}_n^d$ it holds that*

$$\begin{array}{l} \mathbf{Pr} \quad \left[\begin{array}{l} \exists x' = (x'_1, \dots, x'_d) \text{ s.t.} \\ x'_1 \in \mathcal{G} \wedge (x'_1, g(x'_2)) \neq (x_1, g(x_2)) \wedge C_d(h, x) = C_d(h, x') \end{array} \right] \\ \leq d \cdot \mu(n), \end{array}$$

for some negligible function μ .

We prove Claim 4.5 below, but first we use them in order to prove Theorem 4.1.

Proof (Proof of Theorem 4.1). Let A be a PPT collision-finder algorithm of C_t such that

$$\begin{array}{l} \mathbf{Pr} \quad [x \neq x' \wedge C_t(h, x) = C_t(h, x')] = \alpha(n). \\ h := (h_1, \dots, h_{t-1}) \leftarrow \mathcal{H}_n^{t-1}, \\ x := (x_1, \dots, x_t) \leftarrow (\{0,1\}^{m(n)})^{t(n)} \\ (h, x') \leftarrow A(1^n, h, x) \end{array} \quad (2)$$

We will show that α must be negligible.

For $n \in \mathbb{N}$, let $\{\mathcal{L}(x)\}_{x \in \{0,1\}^{m(n)}}$ be the family promised by Claim 4.4. Let $H = (H_1, \dots, H_{t-1}) \leftarrow \mathcal{H}_n^{t-1}$ and $X = (X_1, \dots, X_t) \leftarrow (\{0,1\}^{m(n)})^{t(n)}$ be random variables, and let $(\cdot, X') \leftarrow A(1^n, H, X)$ be the output of A . Let W_1^n be the event that A found a valid collision. By construction, this event can be written as follows: There exists $i \in [t(n)]$, such that,

1. $(X'_i, g(X'_{i+1})) \neq (X_i, g(X_{i+1}))$, and

- 2.

$$\begin{aligned} & (g(X_i), H_i(X_i, g(X_{i+1})), \dots, H_{t-1}(X_{t-1}, g(X_t)), X_t) \\ &= (g(X'_i), H_i(X'_i, g(X'_{i+1})), \dots, H_{t-1}(X'_{t-1}, g(X'_t)), X'_t). \end{aligned}$$

Observe that, by definition of the function C , the last condition is equivalent to $C_{t-i+1}(H_{i,\dots,t-1}, X_{i,\dots,t}) = C_{t-i+1}(H_{i,\dots,t-1}, X'_{i,\dots,t})$.

Additionally, we define the following two events. Let W_2^n be the event that exists $i \in [t(n)]$ such that $X_i \notin \mathcal{T}_n$, and let W_3^n be the event that there exists $i \in [t(n)]$ such that $g(X_i) = g(X'_i)$ and $X'_i \notin \mathcal{L}(X_i)$.

It holds that,

$$\alpha \leq \Pr[W_2^n] + \Pr[W_3^n] + \Pr[W_1^n \wedge \overline{W_2^n} \wedge \overline{W_3^n}].$$

Finally, observe that $\Pr[W_2^n] = \text{neg}(n)$ by the assumption that g^{-1} has min-entropy at least $\ell + s$ and the union bound, and $\Pr[W_3^n] = \text{neg}(n)$ by Claim 4.4. Additionally, $\Pr[W_1^n \wedge \overline{W_2^n} \wedge \overline{W_3^n}] = \text{neg}(n)$ by Claim 4.5 and the union bound (choosing $\mathcal{G} = \mathcal{L}(X_i)$).

4.1 Proving Claim 4.5

Fix n , and omit it from the notation. Let $\mathcal{T} = \mathcal{T}_n$ and $\mathcal{B} := \{0,1\}^m \setminus \mathcal{T}$. Recall that, by Theorem 3.10 and the definition of real min-entropy, it holds that $|\mathcal{B}| = \varepsilon(n) \cdot 2^m$ for some $\varepsilon \in \text{neg}(n)$. Let $g(\mathcal{T}) := \{g(x) : x \in \mathcal{T}\}$. The next claim is the main part of the proof of Claim 4.5. It states that for every small set \mathcal{G} and strings x_1, x_2 , the following holds with overwhelming probability over $h \in \mathcal{H}$. For every x'_1, x'_2 such that $x'_1 \in \mathcal{G}$ and $h(x_1, g(x_2)) = h(x'_1, g(x'_2))$ it holds that x'_2 is non-typical (that is, $x'_2 \in \mathcal{B}$). Moreover, the number of such collision is small.

Claim 4.6 *Let $\mathcal{B} := \{0,1\}^m \setminus \mathcal{T}$. Let $x_1, x_2 \in \{0,1\}^m$, and let $\mathcal{G} \subseteq \{0,1\}^m$ be a set of size at most 2^ℓ . For $h \in \mathcal{H}$, let*

$$\mathcal{G}_h = \{x'_2 : \exists x'_1 \in \mathcal{G} \text{ s.t. } (x'_1, g(x'_2)) \neq (x_1, g(x_2)) \wedge h(x_1, g(x_2)) = h(x'_1, g(x'_2))\}.$$

Then, $\Pr_{h \leftarrow \mathcal{H}}[\mathcal{G}_h \subseteq \mathcal{B} \wedge |\mathcal{G}_h| \leq 2^\ell] \geq 1 - n(\varepsilon(n) + 2^{-s(n)})$.

Proof (Proof of Claim 4.6). We start with showing that $\Pr_{h \leftarrow \mathcal{H}}[\mathcal{G}_h \subseteq \mathcal{B}] \geq 1 - n \cdot 2^{-s(n)}$. Indeed,

$$\begin{aligned}
& \Pr_{h \leftarrow \mathcal{H}}[\mathcal{G}_h \not\subseteq \mathcal{B}] \\
&= \Pr_{h \leftarrow \mathcal{H}} \left[\begin{array}{c} \exists (x'_1, x'_2) \in \mathcal{G} \times \mathcal{T} \text{ s.t.} \\ (x'_1, g(x'_2)) \neq (x_1, g(x_2)) \wedge h(x_1, g(x_2)) = h(x'_1, g(x'_2)) \end{array} \right] \\
&= \Pr_{h \leftarrow \mathcal{H}} [\exists (x'_1, y') \in \mathcal{G} \times g(\mathcal{T}) \text{ s.t. } (x'_1, y') \neq (x_1, g(x_2)) \wedge h(x_1, g(x_2)) = h(x'_1, y')] \\
&\leq n \cdot 2^{-m} \cdot |\mathcal{G}| \cdot |g(\mathcal{T})| \\
&\leq n \cdot 2^{-m} \cdot 2^\ell \cdot 2^m / 2^{\ell+s} \\
&= n \cdot 2^{-s(n)}
\end{aligned}$$

where the first inequality holds since $\Pr_{h \leftarrow \mathcal{H}}[h(x_1, g(x_2)) = h(x'_1, y')] \leq n \cdot 2^{-m}$ for every $(x'_1, y') \neq (x_1, g(x_2))$ together with the union bound. The second inequality holds since by definition of \mathcal{T} it must hold that $|g(\mathcal{T})| \leq 2^m / 2^{\ell+s}$.

We next show that $\Pr_{h \leftarrow \mathcal{H}}[|\mathcal{G}_h \cap \mathcal{B}| \geq 2^\ell] \leq n \cdot \varepsilon(n)$, which concludes the proof. We start with computing the expectation of $|\mathcal{G}_h \cap \mathcal{B}|$:

$$\begin{aligned}
\mathbf{E}_{h \leftarrow \mathcal{H}}[|\mathcal{G}_h \cap \mathcal{B}|] &\leq n \cdot 2^{-m} \cdot |\mathcal{G}| \cdot |\mathcal{B}| \\
&\leq n \cdot 2^{-m} \cdot 2^\ell \cdot \varepsilon(n) \cdot 2^m \\
&\leq n \cdot \varepsilon(n) \cdot 2^\ell.
\end{aligned}$$

The claim now follows by Markov and the Union bound.

We are now ready to prove Claim 4.5 using Claim 4.6. Intuitively, Claim 4.6 shows that if x'_1 is from a small set, x'_2 is from a small set too. Thus, we can continue by induction, to prove that also x'_d is from the set \mathcal{B} . It follows that, $x'_d \neq x_d$ with overwhelming probability (as $x_d \in \mathcal{T}$), which is enough since the output of C_d includes x_d .

Proof (Proof of Claim 4.5). Fix $n \in \mathbb{N}$, $x = (x_1, \dots, x_d) \in \mathcal{T}_n^d$ and a set $\mathcal{G} \subseteq \{0, 1\}^m$. For $h = (h_1, \dots, h_{d-1}) \in H^{d-1}$, let

$$\mathcal{COL}(h, x) = \left\{ x' = (x'_1, \dots, x'_d) \in \mathcal{G} \times (\{0, 1\}^m)^{d-1} : \begin{array}{c} (x_1, g(x_2)) \neq (x'_1, g(x'_2)) \\ \wedge C_d(h, x) = C_d(h, x') \end{array} \right\}$$

be the set containing all the possible collision of h, x with $x'_1 \in \mathcal{G}$ and $(x_1, g(x_2)) \neq (x'_1, g(x'_2))$. Similarly, for every $i \in \{0, \dots, d-1\}$, let

$$\mathcal{COL}_i(h_1, \dots, h_i, x) = \left\{ x' \in \mathcal{G} \times (\{0, 1\}^m)^{d-1} : \begin{array}{c} (x_1, g(x_2)) \neq (x'_1, g(x'_2)) \\ \wedge \forall j \in [i] \ h_j(x_j, g(x_{j+1})) = h_j(x'_j, g(x'_{j+1})) \end{array} \right\}$$

That is, all inputs with $x'_1 \in \mathcal{G}$ and $(x_1, g(x_2)) \neq (x'_1, g(x'_2))$ that collide with i blocks of C_d . It is clear that for every x and h ,

$$\mathcal{COL}(h, x) \subseteq \mathcal{COL}_{d-1}(h, x) \subseteq \dots \subseteq \mathcal{COL}_0(x) \quad (3)$$

We want to show that with high probability over the choice of h , it holds that $\mathcal{COL}(h, x)$ is empty.

For every $i \in [d-1]$, let W_i be the event (over the choice of $h_1, \dots, h_{i-1} \leftarrow \mathcal{H}^{i-1}$) that there exists a set \mathcal{G}_i of size at most 2^ℓ , such that for every $x' \in \mathcal{COL}_{i-1}(h_1, \dots, h_{i-1}, x)$, it holds that $(x'_i, g(x'_{i+1})) \neq (x_i, g(x_{i+1}))$ and $x'_i \in \mathcal{G}_i$.

For $i \in [d]$, let \widehat{W}_i be the event that there exists a set \mathcal{G}_i of size at most 2^ℓ such that for every $x' \in \mathcal{COL}_{i-1}(h_1, \dots, h_{i-1}, x)$, it holds that $x'_i \neq x_i$ and $x'_i \in \mathcal{G}_i$.

Observe that $\Pr[W_i \mid \widehat{W}_i] = 1$. We will show that, for every $1 \leq i < d$, it holds that

$$\Pr[\widehat{W}_{i+1} \mid W_{\leq i}] \geq 1 - n(\varepsilon(n) + 2^{-s(n)}) \quad (4)$$

Furthermore, $\Pr[W_1] = 1$. Indeed, let $\mathcal{G}_1 = \mathcal{G}$. By assumption $x_1 \in \mathcal{G}$ and $(x'_1, g(x'_2)) \neq (x_1, g(x_2))$ for every $x'_1, x'_2 \in \mathcal{COL}_0(x)$.

To see that Equation (4) holds, fix $1 \leq i < d$. Let $H' \leftarrow \mathcal{H}^{d-1}|_{W_{\leq i}}$, and observe that H'_i is uniformly distributed over \mathcal{H} . By the definition of W_i , it holds that for every $x' \in \mathcal{COL}_{i-1}(H'_{\leq i}, x)$ it holds that $(x'_i, g(x'_{i+1})) \neq (x_i, g(x_{i+1}))$ and $x'_i \in \mathcal{G}_i$ for some set \mathcal{G}_i of size at most 2^ℓ . Define

$$\mathcal{G}_{i+1} := \left\{ x'_{i+1} : \begin{array}{l} \exists x'_i \in \mathcal{G}_i \text{ s.t.} \\ (x'_i, g(x'_{i+1})) \neq (x_i, g(x_{i+1})) \wedge H'_i(x_i, g(x_{i+1})) = H'_i(x'_i, g(x'_{i+1})) \end{array} \right\}.$$

By definition $x'_{i+1} \in \mathcal{G}_{i+1}$ for every $x' \in \mathcal{COL}_i(H'_{\leq i}, x)$. Applying Claim 4.6 we get that with all but $n(\varepsilon(n) + 2^{-s(n)})$ probability over the choice of H'_i , it holds that $|\mathcal{G}_{i+1}| \leq 2^\ell$. Moreover, with the same probability $\mathcal{G}_{i+1} \subseteq \mathcal{B}$, which implies that $x'_{i+1} \neq x_{i+1}$ (since by assumption, $x_{i+1} \in \mathcal{T}_n$).

To conclude, we get that for every $x' \in \mathcal{COL}(h, x) \subseteq \mathcal{COL}_{d-1}(h, x)$ it holds that $x'_d \neq x_d$ with probability at least

$$\begin{aligned} \Pr[\widehat{W}_d] &\geq \Pr[\widehat{W}_d \mid W_{< d}] \cdot \prod_{1 \leq i \leq d-1} \Pr[W_i \mid W_{< i}] \\ &\geq \Pr[\widehat{W}_d \mid W_{< d}] \cdot \prod_{1 \leq i \leq d-1} \Pr[W_i, \widehat{W}_i \mid W_{< i}] \\ &= \Pr[\widehat{W}_d \mid W_{< d}] \cdot \prod_{1 \leq i \leq d-1} \left(\Pr[W_i \mid \widehat{W}_i, W_{< i}] \cdot \Pr[\widehat{W}_i \mid W_{< i}] \right) \\ &\geq (1 - n(\varepsilon(n) + 2^{-s(n)}))^d \\ &\geq 1 - d \cdot n(\varepsilon(n) + 2^{-s(n)}) \\ &= 1 - d \cdot \text{neg}(n). \end{aligned}$$

Where the penultimate inequality holds by Equation (4) and the fact that $\Pr[W_i \mid \widehat{W}_i, W_{< i}] = 1$. Recall that C_d outputs x_d . Thus, the above implies that $C_d(h, x) \neq C_d(h, x')$, which implies that $\mathcal{COL}(h, x) = \emptyset$ with the same probability.

5 Almost-UOWHF From One-Way Functions

In this section we formally define almost-UOWHF and next-bit unreachable entropy, and show how to construct them from one-way functions.

5.1 Almost-UOWHF

In this part we formally define almost-UOWHF. The definition of almost-UOWHF is similar to the definition of almost collision resistance on random input (Definition 2.5).

Definition 5.1 (Almost universal one-way hash function) *Let n be a security parameter. A family of functions*

$$\mathcal{F} = \left\{ f_z: \{0, 1\}^{m(n)} \rightarrow \{0, 1\}^{\ell(n)} \right\}_{z \in \{0, 1\}^{k(n)}}$$

is a family of almost universal one-way hash functions (almost-UOWHF) if it satisfies:

1. *Efficiency: Given $z \in \{0, 1\}^{k(n)}$ and $x \in \{0, 1\}^{m(n)}$, $f_z(x)$ can be evaluated in time $\text{poly}(n)$.*
2. *Shrinking: $\ell(k) < m(k)$.*
3. *Almost Target Collision Resistance: There exist sets $\{\mathcal{B}_z\}_{z \in \{0, 1\}^{k(n)}}$ such that $|\mathcal{B}_z|/2^{m(n)} = \text{neg}(n)$, and for every probabilistic polynomial-time adversary A , the probability that A succeeds in the following game is negligible in n :*
 - (a) *Let $(x, \text{state}) \leftarrow A(1^n) \in \{0, 1\}^{m(n)} \times \{0, 1\}^*$.*
 - (b) *Choose $z \leftarrow \{0, 1\}^{k(n)}$.*
 - (c) *Let $x' \leftarrow A(\text{state}, z) \in \{0, 1\}^{m(k)}$.*
 - (d) *A succeeds if $x' \notin \mathcal{B}_z$, $x \neq x'$ and $f_z(x) = f_z(x')$.*

The proof of the next lemma is similar to the proof of Lemma 3.4.

Lemma 5.2 (From random inputs to targets, almost version) *Let n be a security parameter. Let $F: \{0, 1\}^{m(n)} \rightarrow \{0, 1\}^{\ell(n)}$ be an efficiently computable length-decreasing function. Suppose F is almost collision-resistant on random inputs. Then $\left\{ F_y: \{0, 1\}^{m(n)} \rightarrow \{0, 1\}^{\ell(n)} \right\}_{y \in \{0, 1\}^{m(n)}}$, for $F_y(x) := F(y \oplus x)$, is an almost-UOWHF.*

5.2 Next-Bit Unreachable Entropy

In this section we present the notion of next-bit unreachable entropy, and construct a function with next-bit unreachable entropy from one-way functions. Intuitively, we say that a function $g: \{0, 1\}^m \rightarrow \{0, 1\}^\ell$ has next-bit unreachable entropy v if for every $i \in [\ell]$, there is a set $\mathcal{U}_i \subseteq \{0, 1\}^m$, such that, on the average over x , each x is a member of $(\ell - m + v)$ such sets, and, given $x \in \{0, 1\}^m$, a poly-time algorithm cannot find $x' \in \mathcal{U}_i$ with $g(x)_{<i} = g(x')_{<i}$, but $g(x)_i \neq g(x')_i$.

Definition 5.3 A function $g: \{0, 1\}^{m(n)} \rightarrow \{0, 1\}^{\ell(n)}$ has next-bit unreachable entropy v , if the following holds. For every $n \in \mathbb{N}$ and $i \in [\ell(n)]$ there exists a set $\mathcal{U}_{i,n} \subseteq \{0, 1\}^{m(n)}$, such that

1. $\mathcal{U}_{i,n}$ are large: For every $n \in \mathbb{N}$,

$$\Pr_{x \leftarrow \{0,1\}^{m(n)}, i \leftarrow [\ell(n)]} [x \notin \mathcal{U}_{i,n}] \leq (m(n) - v(n))/\ell(n).$$

2. Hard to get inside $\mathcal{U}_{i,n}$: For every PPT A ,

$$\Pr_{\substack{x \leftarrow \{0,1\}^{m(n)}, \\ i \leftarrow [\ell(n)], x' \leftarrow A(1^n, x, i)}} [(x' \in \mathcal{U}_{i,n}) \wedge (g(x)_{<i} = g(x')_{<i}) \wedge (x \notin \mathcal{U}_{i,n})] = \text{neg}(n).$$

3. The entropy inside $\mathcal{U}_{i,n}$ is unreachable: For every PPT A ,

$$\Pr_{\substack{x \leftarrow \{0,1\}^{m(n)}, \\ i \leftarrow [\ell(n)], \\ x' \leftarrow A(1^n, x, i)}} [(x' \in \mathcal{U}_{i,n}) \wedge (g(x)_{<i} = g(x')_{<i}) \wedge (g(x)_i \neq g(x')_i)] = \text{neg}(n).$$

We stress that for $x \notin \mathcal{U}_i$, Item 2 is stronger compared to Item 3. While Item 2 implies that it is hard to flip the i -th bit of g with inputs from \mathcal{U}_i , Item 2 requires that it is hard to find (any) input from \mathcal{U}_i that agrees with x on the $i - 1$ first bits.

The definition above is especially useful when the function g is close to be injective. Formally,

Definition 5.4 A function g is almost-injective if

$$\Pr_{x \leftarrow \{0,1\}^m} [|g^{-1}(g(x))| > 1] = \text{neg}(n).$$

We use the above definition for the construction of almost-UOWHF in Section 5.3. The following claim, proved in the full version of this paper ([25]), shows how to construct a function with non-trivial next-bit unreachable entropy from a one-way function.

Theorem 5.5. Let $f: \{0, 1\}^n \rightarrow \{0, 1\}^n$ be a one-way function and let $\mathcal{H} = \{h: \{0, 1\}^n \rightarrow \{0, 1\}^n\}$ be a family of constructible, three-wise independent hash functions. Let $g: \mathcal{H}^2 \times \{0, 1\}^n \rightarrow \mathcal{H}^2 \times \{0, 1\}^{2n}$ be defined by $g(h_1, h_2, x) = (h_1, h_2, h_1(f(x)), h_2(x))$. Then g is an almost-injective function with next-bit unreachable entropy $c \log(n)$, for every constant $c > 0$.

Moreover, the input and output size of g are of length $O(n)$.

5.3 Next-Bit Unreachable Entropy to Almost-UOWHF

The Construction We now describe our main construction. We start with some notations.

A *position vector* $p \in [\ell]^q$ is just a vector of indexes from $[\ell]$. For a function $g: \{0,1\}^m \rightarrow \{0,1\}^\ell$, input vector $w = (x_1, \dots, x_q) \in (\{0,1\}^m)^q$ and a position vector $p = (i_1, \dots, i_q) \in [\ell]^q$, let $g_p(w) := g(x_1)_{i_1}, \dots, g(x_q)_{i_q}$. Similarly, define $g_{<p}(w) := g(x_1)_{<i_1}, \dots, g(x_q)_{<i_q}$, and $g_{\geq p}(w)$ analogously. For a number $k \in \mathbb{N}$, let $p+k := (i_1+k, \dots, i_q+k)$. For a number t , let $g^t: \{0,1\}^{tm} \rightarrow \{0,1\}^{t\ell}$ be the t -fold repetition of g , i.e., $g^t(x_1, \dots, x_t) = g(x_1), \dots, g(x_t)$.

We are now ready to present the construction (see Figure 1).

Construction 5.6 (Almost-UOWHF) *Let n be a security parameter, and let $q = q(n), t = t(n)$ and $k = k(n)$ be parameters. Let $g: \{0,1\}^{m(n)} \rightarrow \{0,1\}^{\ell(n)}$ be a function, and let $\mathcal{H}_n = \{h: \{0,1\}^{q(n)} \rightarrow \{0,1\}^{k(n)}\}$ be a 2-universal hash family. Define the function $C: \mathcal{H}_n \times [\ell(n)]^{q(n)} \times (\{0,1\}^{m(n) \cdot t(n)})^{q(n)} \rightarrow \mathcal{H}_n \times [\ell(n)]^{q(n)} \times \{0,1\}^{\ell(n) \cdot q(n) + (t(n)-1) \cdot \ell \cdot k(n)}$ by*

$$C(h, p, z) := \\ h, p, g'_{<p}(z), h(g'_p(z)), h(g'_{p+1}(z)), \dots, h(g'_{p+(t-1)\ell-1}(z)), g'_{\geq p+(t-1)\ell}(z),$$

for $g' = g^t$.

The main theorem of this part is stated below and proven in the full version of this paper ([25]). Informally, it states that when g is an almost-injective function with non-trivial next-bit unreachable entropy, and for the right choice of parameters, the above construction is almost-collision resistant on random inputs.

Theorem 5.7. *Let $g: \{0,1\}^{m(n)} \rightarrow \{0,1\}^{\ell(n)}$ be an efficient, almost-injective function with next-bit unreachable entropy $v(n) \in \mathbb{N}$. For every $q \in \text{poly}$ and $\varepsilon \in 1/\text{poly}$ such that $H(4\varepsilon(n)) \leq 0.1v(n)/\ell(n)$, $q = \omega\left(\log n \cdot \max\left\{\ell, \frac{\ell}{\varepsilon^2(\ell-m-v)}\right\}\right)$ and for $k = q(m-v/3)/\ell$, $t = 3(\ell-m)/v + 2$ the function C as in Construction 5.6 is efficient, shrinking and almost collision resistant on random inputs.*

This gives the following corollary.

Corollary 5.8 *Let $s = \omega(1)$. Assuming that one-way functions exist, there exists an almost-UOWHF with key length $O(n^4 \cdot s)$. Moreover, the almost-UOWHF construction makes $O(n^3 \cdot s)$ non-adaptive calls to the underlying one-way function.*

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