The Name of the Title Is Hope

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ABSTRACT

tbd.

CCS CONCEPTS

• **Theory of computation** → **Cryptographic primitives**.

KEYWORDS

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1 INTRODUCTION

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2 PRELIMINARY

2.1 Basic Notations

Point and multi-point functions. Given a domain size N and Abelian group $\mathbb{G}$, a *point function* $f_{\alpha,\beta} : [N] \to \mathbb{G}$ for $\alpha \in [N]$ and $\beta \in \mathbb{G}$ evaluates to β on input α and to $0 \in \mathbb{G}$ on all other inputs. We denote by $\hat{f}_{\alpha,\beta} = (N, \hat{\mathbb{G}}, \alpha, \beta)$ the representation of such a point function. A *multi-point function* $f_{A,B} : [N] \to \mathbb{G}$ for $A = (\alpha_1, \cdots \alpha_t) \in [N]^t$ and $B = (\beta_1, \cdots, \beta_t) \in \mathbb{G}^t$ evaluates to β_i on input α_i for $1 \le i \le t$ and to 0 on all other inputs. Denote $\hat{f}_{A,B}(N, \hat{\mathbb{G}}, A, B)$ the representation of such a point function.

Enote: MPF. Also representation of groups.

2.2 Distributed Multi-Point Functions

Enote: should directly adapt to multi-point function case

We begin by defining a slightly generalized notion of distributed point functions (DPFs), which accounts for the extra parameter $\mathbb{G}'$.

Definition 1 (DPF [1, 3]). *A (2-party)* distributed point function (DPF) *is a triple of algorithms* $\Pi = (\mathsf{Gen}, \mathsf{Eval}_0, \mathsf{Eval}_1)$ *with the following syntax:*

- $\mathsf{Gen}(1^\lambda, \hat{f}_{\alpha,\beta}) \to (k_0, k_1)$*: On input security parameter* $\lambda \in \mathbb{N}$ *and point function description* $\hat{f}_{\alpha,\beta} = (N, \hat{\mathbb{G}}, \alpha, \beta)$*, the (randomized) key generation algorithm* Gen *returns a pair of keys* $k_0, k_1 \in \{0,1\}^*$*. We assume that* N *and* $\mathbb{G}$ *are determined by each key.*
- $\mathsf{Eval}_i(k_i, x) \to y_i$*: On input key* $k_i \in \{0,1\}^*$ *and input* $x \in [N]$ *the (deterministic) evaluation algorithm of server* i*,* Eval_i *returns* $y_i \in \mathbb{G}$.

We require Π *to satisfy the following requirements:*

- ***Correctness:*** *For every* λ*,* $\hat{f} = \hat{f}_{\alpha,\beta} = (N, \hat{\mathbb{G}}, \alpha, \beta)$ *such that* $\beta \in \mathbb{G}$*, and* $x \in [N]$*, if* $(k_0, k_1) \leftarrow \mathsf{Gen}(1^\lambda, \hat{f})$*, then*
$$\Pr\left[\sum_{i=0}^{1} \mathsf{Eval}_i(k_i, x) = f_{\alpha,\beta}(x)\right] = 1$$
- ***Security:*** *Consider the following semantic security challenge experiment for corrupted server* $i \in \{0,1\}$*:*
  1. *The adversary produces two point function descriptions* $(\hat{f}^0 = (N, \hat{\mathbb{G}}, \alpha_0, \beta_0), \hat{f}^1 = (N, \hat{\mathbb{G}}, \alpha_1, \beta_1)) \leftarrow \mathcal{A}(1^\lambda)$*, where* $\alpha_i \in [N]$ *and* $\beta_i \in \mathbb{G}$*.*
  2. *The challenger samples* $b \leftarrow \{0,1\}$ *and* $(k_0, k_1) \leftarrow \mathsf{Gen}(1^\lambda, \hat{f}^b)$*.*
  3. *The adversary outputs a guess* $b' \leftarrow \mathcal{A}(k_i)$*.*

  Denote by $\mathsf{Adv}(1^\lambda, \mathcal{A}, i) = \Pr[b = b'] - 1/2$ *the advantage of* $\mathcal{A}$ *in guessing* b *in the above experiment. For every non-uniform polynomial time adversary* $\mathcal{A}$ *there exists a negligible function* ν *such that* $\mathsf{Adv}(1^\lambda, \mathcal{A}, i) \le \nu(\lambda)$ *for all* $\lambda \in \mathbb{N}$*.*

We will also be interested in applying the evaluation algorithm on *all* inputs. Given a DPF $(\mathsf{Gen}, \mathsf{Eval}_0, \mathsf{Eval}_1)$, we denote by $\mathsf{FullEval}_i$ an algorithm which computes Eval_i on every input x. Hence, $\mathsf{FullEval}_i$ receives only a key k_i as input.

2.3 Batch Codes

combinatorial/probabilistic batch codes, with cuckoo hashing a concrete instantiation

2.4 Oblivious Key-Value Stores

Definition 2 (OKVS[2, 4]). *An Oblivious Key-Value Stores (OKVS) scheme is a pair of randomized algorithms* $(\mathsf{Encode}_r, \mathsf{Decode}_r)$ *with respect to a statistical security parameter* λ_{stat} *and a computational security parameter* λ*, a randomness space* $\{0,1\}^\kappa$*, a key space* $\mathcal{K}$*, a value space* $\mathcal{V}$*, input length* n *and output length* $m(n)$*. The algorithms are of the following syntax:*

- $\mathsf{Encode}_r(\{(k_1, v_1), (k_2, v_2), \cdots, (k_n, v_n)\}) \to P$*: On input* n *key-value pairs with distinct keys, the encode algorithm with randomness* r *in the randomness space outputs an encoding* $P \in \mathcal{V}^m \cup \perp$*.*
- $\mathsf{Decode}_r(P, k) \to v$*: On input an encoding from* $\mathcal{V}^m$ *and a key* $k \in \mathcal{K}$*, output a value* v*.*

We require the scheme to satisfy

- ***Correctness:*** *For every* $S \in (\mathcal{K} \times \mathcal{V})^n$*,* $\Pr_{r \leftarrow \{0,1\}^\kappa}[\mathsf{Encode}_r(S) = \perp] \le 2^{-\lambda_{\text{stat}}}$*.*
- ***Obliviousness:*** *Given any distinct key sets* $\{k_1^0, k_2^0, \cdots, k_n^0\}$ *and* $\{k_1^1, k_2^1, \cdots, k_n^1\}$ *that are different, if they are paired with*

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random values then their encodings are computationally indistinguishable, i.e.,

$$\{r, \mathsf{Encode}_r(\{(k_1^0, v_1), \cdots, (k_n^0, v_n)\})\}_{v_1,\cdots,v_n \leftarrow \mathcal{V}, r \leftarrow \{0,1\}^\kappa}$$
$$\approx_c \{r, \mathsf{Encode}_r(\{(k_1^1, v_1), \cdots, (k_n^1, v_n)\})\}_{v_1,\cdots,v_n \leftarrow \mathcal{V}, r \leftarrow \{0,1\}^\kappa}$$

One can obtain a linear OKVS *if in addition require:*

- ***Linearity:*** *There exists a function family* $\{\mathsf{row}_r : \mathcal{K} \to \mathcal{V}^m\}_{r\in\{0,1\}^\kappa}$ *such that* $\mathsf{Decode}_r(P, k) = \langle \mathsf{row}_r(k), P\rangle$.

The Encode process for a linear OKVS is the process of sampling a random P from the set of solutions of the linear system $\{\langle \mathsf{row}_r(k_i), P\rangle = v_i\}_{1\le i\le n}$.

We evaluate an OKVS scheme by its encoding size (output length m), encoding time and decoding time. We stress the following two (linear) OKVS constructions:

Construction 1 (Polynomial). *Suppose* $\mathcal{K} = \mathcal{V} = \mathbb{F}$ *is a field. Set*

- $\mathsf{Encode}(\{(k_i, v_i)\}_{1\le i\le n}) \to P$ *where* P *is the coeffients of a* $(n-1)$*-degree* $\mathbb{F}$*-polynomial* g_P *that* $g_P(k_i) = v_i$ *for* $1 \le i \le n$.
- $\mathsf{Decode}(P, k) \to g_P(k)$.

The polynomial OKVS possesses an optimal encoding size $m = n$, but the Encode process is a polynomial interpolation which is only known to be achieved in time $O(n \log^2 n)$. The time for a single decoding is $O(n)$ and that for batched decodings is (amortized) $O(\log^2 n)$.

An alternative construction that has near optimal encoding size but much better running time is as follows.

Construction 2 (3-Hash Garbled Cuckoo Table (3H-GCT)[2, 4]). *Suppose* $\mathcal{V} = \mathbb{F}$ *is a field. Set* $\mathsf{row}_r(k) := \mathsf{row}_r^{\mathsf{sparse}}(k)||\mathsf{row}_r^{\mathsf{dense}}(k)$ *where* $\mathsf{row}_r^{\mathsf{sparse}}$ *outputs a uniformly random weight-*w *vector in* $\{0,1\}^{m_1}$*, and* $\mathsf{row}_r^{\mathsf{dense}}(k)$ *outputs a short dense vector in* $\mathbb{F}^{m_2}$.

- $\mathsf{Encode}(\{(k_i, v_i)\}_{1\le i\le n}) \to P$ *where* P *is solved from the system* $\{\langle \mathsf{row}_r(k_i), P\rangle = v_i\}_{1\le i\le n}$ *using the triangulation algorithm in [4].*
- $\mathsf{Decode}(P, k) \to \langle \mathsf{row}_r(k), P\rangle$.

This OKVS construction features a linear encoding time, constant decoding time while having a linear encoding size.

TBD: Carefully(!) recompute the comparison table for OKVS and insert

We take $w = 3$, the most common option that outruns other choices of w in terms of running time. Restating the conclusion in [4]: given n and λ_{stat}, the choices of e and $\hat{g}$ are $e = 1.223 + \frac{\lambda_{\mathsf{stat}}+9.2}{4.144n^{0.55}}$ and $\hat{g} = \frac{\lambda_{\mathsf{stat}}}{\log_2(en)}$.

TBD: mention some connections to cuckoo hashing

3 NEW DMPF CONSTRUCTIONS

TBD: explain

3.1 Big-State DMPF

TBD: explain

Set $l \leftarrow t$, the upperbound of $|A|$.

procedure Initialize($\{\mathsf{seed}_b^{(0)}, \mathsf{sign}_b^{(0)}\}_{b=0,1}$)
  For $b = 0, 1$, let $\mathsf{seed}_b^{(0)} = [r_b]$ where $r_b \xleftarrow{\$} \{0,1\}^\lambda$.
  For $b = 0, 1$, set $\mathsf{sign}_b^{(0)} = [b||0^{t-1}]$.
end procedure

procedure GenCW($i, A, \{\mathsf{seed}_b^{(i-1)}, \mathsf{sign}_b^{(i-1)}\}_{b=0,1}$)
  Let $\{A^{(i)}\}_{0\le i\le n}$ be defined as in fig. 1.
  Sample a list CW of t random strings from $\{0,1\}^{\lambda+2t}$.
  for $k = 1$ to $|A^{(i-1)}|$ **do**
    Parse $G(\mathsf{seed}_b^{(i-1)}[k]) = \mathsf{seed}_b^0||\mathsf{sign}_b^0||\mathsf{seed}_b^1||\mathsf{sign}_b^1$, for $b = 0, 1$, $\mathsf{seed}_b^0, \mathsf{seed}_b^1 \in \{0,1\}^\lambda$ and $\mathsf{sign}_b^0, \mathsf{sign}_b^1 \in \{0,1\}^t$.
    Compute $\Delta\mathsf{seed}^c = \mathsf{seed}_0^c \oplus \mathsf{seed}_1^c$ and $\Delta\mathsf{sign}^c = \mathsf{sign}_0^c \oplus \mathsf{sign}_1^c$ for $c = 0, 1$.
    Denote path $\leftarrow A^{(i-1)}[k]$.
    if both path$||z$ for $z = 0, 1$ are in $A^{(i)}$ **then**
      $d \leftarrow$ the index of path$||0$ in $A^{(i)}$.
      $CW[d] \leftarrow r||\Delta\mathsf{sign}^0 \oplus e_d||\Delta\mathsf{sign}^1 \oplus e_{d+1}$ where $r \xleftarrow{\$} \{0,1\}^\lambda$, $e_d = 0^{d-1}10^{t-d}$.
    else
      Let z be such that path$||z \in A^{(i)}$.
      $d \leftarrow$ the index of path$||z$ in $A^{(i)}$.
      $$CW[d] \leftarrow \begin{cases} \Delta\mathsf{seed}^1||\Delta\mathsf{sign}^0 \oplus e_d||\Delta\mathsf{sign}^1 & z = 0 \\ \Delta\mathsf{seed}^0||\Delta\mathsf{sign}^0||\Delta\mathsf{sign}^1 \oplus e_d & z = 1 \end{cases}.$$
    end if
  end for
  return CW.
end procedure

procedure GenConvCW($A, B, \{\mathsf{seed}_b^{(n)}, \mathsf{sign}_b^{(n)}\}$)
  Sample a list CW of t random $\mathbb{G}$-elements.
  for $k = 1$ to $|A|$ **do**
    $\Delta g \leftarrow G_{\mathsf{convert}}(\mathsf{seed}_0^{(n)}[k]) - G_{\mathsf{convert}}(\mathsf{seed}_1^{(n)}[k])$.
    $CW[k] \leftarrow (-1)^{\mathsf{sign}_0^{(n)}[k][k]}(\Delta g - B[k])$.
  end for
  return CW.
end procedure

procedure Correct($\bar{x}, \mathsf{seed}, \mathsf{sign}, CW$)
  Let z be the last bit of $\bar{x}$.
  $C_{\mathsf{seed}}||C_{\mathsf{sign}^0}||C_{\mathsf{sign}^1} \leftarrow \sum_{i=1}^t \mathsf{sign}[i] \cdot CW[i]$, where C_{sign^0} and C_{sign^1} are t-bit.
  return $G_z(\mathsf{seed}) \oplus (C_{\mathsf{seed}}||C_{\mathsf{sign}^z})$.
end procedure

procedure ConvCorrect($x, \mathsf{seed}, \mathsf{sign}, CW$)
  return $G_{\mathsf{convert}}(\mathsf{seed}) \oplus \sum_{i=1}^t \mathsf{sign}[i] \cdot CW[i]$.
end procedure

Figure 2: The parameter l and methods' setting that turns the paradigm of DMPF in fig. 1 into the big-state DMPF.

Public parameters:
The multi-point function family $\{f_{A,B}\}$, an upperbound t of the number of nonzero points ($|A| \leq t$), input domain $[N] = \{0,1\}^n$ and the output group $\mathbb{G}$.
Suppose there is a public PRG $G : \{0,1\}^\lambda \to \{0,1\}^{2\lambda+2l}$. Parse $G = G_0||G_1$ to the left half and right half.
Suppose there is a public PRG $G_{\mathsf{convert}} : \{0,1\}^\lambda \to \mathbb{G}$.

procedure $\textsc{Gen}(1^\lambda, \hat{f}_{A,B})$
  Denote $A = (\alpha_1, \cdots, \alpha_t)$ in lexicographical order, $B = (\beta_1, \cdots, \beta_t)$.
  For $0 \leq i \leq n-1$, let $A^{(i)}$ denote the sorted and deduplicated list of i-bit prefixes of strings in A. Specifically, $A^{(0)} = [\epsilon]$.
  For $0 \leq i \leq n-1$ and $b = 0, 1$, initialize empty lists $\mathsf{seed}_b^{(i)}$ and $\mathsf{sign}_b^{(i)}$.
  $\mathsf{Initialize}(\{\mathsf{seed}_b^{(0)}, \mathsf{sign}_b^{(0)}\}_{b=0,1})$.
  for $i = 1$ to n **do**
    $CW^{(i)} \leftarrow \mathsf{GenCW}(i, A, \{\mathsf{seed}_b^{(i-1)}, \mathsf{sign}_b^{(i-1)}\}_{b=0,1})$.
    for $k = 1$ to $|A^{(i-1)}|$ and $z = 0, 1$ **do**
      if $A^{(i-1)}[k]||z \in A^{(i)}$ **then**
        For $b = 0, 1$, compute $\mathsf{temp}_b \leftarrow \mathsf{Correct}(A^{(i-1)}[k]||z, \mathsf{seed}_b^{(i-1)}[k], \mathsf{sign}_b^{(i-1)}[k], CW^{(i)})$.
        Append the first λ bit of temp_b to $\mathsf{seed}_b^{(i)}$ and the rest to $\mathsf{sign}_b^{(i)}$.
      end if
    end for
  end for
  $CW^{(n+1)} \leftarrow \mathsf{GenConvCW}(A, B, \{\mathsf{seed}_b^{(n)}, \mathsf{sign}_b^{(n)}\}_{b=0,1})$.
  Set $k_b \leftarrow (\mathsf{seed}_b^{(0)}, \mathsf{sign}_b^{(0)}, CW^{(1)}, CW^{(2)}, \cdots, CW^{(n+1)})$.
  return (k_0, k_1).
end procedure

procedure $\textsc{Eval}_b(1^\lambda, k_b, x)$
  Parse $k_b = ([\mathsf{seed}], [\mathsf{sign}], CW^{(1)}, CW^{(2)}, \cdots, CW^{(n+1)})$.
  Denote $x = x_1 x_2 \cdots x_n$.
  for $i = 1$ to n **do**
    $\mathsf{seed}||\mathsf{sign} \leftarrow \mathsf{Correct}(x_1 \cdots x_i, \mathsf{seed}, \mathsf{sign}, CW^{(i)})$.
  end for
  return $(-1)^b \cdot \mathsf{ConvCorrect}(x, \mathsf{seed}, \mathsf{sign}, CW^{(n+1)})$.
end procedure

procedure $\textsc{FullEval}_b(1^\lambda, k_b)$
  Parse $k_b = (\mathsf{seed}^{(0)}, \mathsf{sign}^{(0)}, CW^{(1)}, CW^{(2)}, \cdots, CW^{(n+1)})$.
  For $1 \leq i \leq n$, $\mathsf{Path}^{(i)} \leftarrow$ the lexicographical ordered list of $\{0,1\}^i$. $\mathsf{Path}^{(0)} \leftarrow [\epsilon]$.
  for $i = 1$ to n **do**
    for $k = 1$ to 2^{i-1} and $z = 0, 1$ **do**
      $\mathsf{seed}^{(i)}[2k+z]||\mathsf{sign}^{(i)}[2k+z] \leftarrow \mathsf{Correct}(\mathsf{Path}[k]||z, \mathsf{seed}^{(i-1)}[k], \mathsf{sign}^{(i-1)}[k], CW^{(i)})$.
    end for
  end for
  for $k = 1$ to 2^n **do**
    $\mathsf{Output}[k] \leftarrow \mathsf{ConvCorrect}(\mathsf{Path}[k], \mathsf{seed}^{(n)}[k], \mathsf{sign}^{(n)}[k], CW^{(n+1)})$.
  end for
  return Output.
end procedure

Figure 1: The paradigm of our DMPF schemes. We leave the PRG expand length l, methods Initialize, GenCW, GenConvCW, Correct, ConvCorrect **to be determined by specific constructions.**

Set $l \leftarrow 1$.
For $1 \le i \le n$, let OKVS_i be an OKVS scheme (definition 2) with key space $\mathcal{K} = \{0,1\}^{i-1}$, value space $\mathcal{V} = \{0,1\}^{\lambda+2}$ and input length t.
let $\mathsf{OKVS}_{\mathsf{convert}}$ be an OKVS scheme with key space $\mathcal{K} = \{0,1\}^n$, value space $\mathcal{V} = \mathbb{G}$ and input length t.

procedure INITIALIZE($\{\mathsf{seed}_b^{(0)}, \mathsf{sign}_b^{(0)}\}_{b=0,1}$)
For $b = 0, 1$, let $\mathsf{seed}_b^{(0)} = [r_b \xleftarrow{\$} \{0,1\}^\lambda]$ and $\mathsf{sign}_b^{(0)} = [b]$.
end procedure

procedure GENCW($i, A, \{\mathsf{seed}_b^{(i-1)}, \mathsf{sign}_b^{(i-1)}\}_{b=0,1}$)
Let $\{A^{(i)}\}_{0 \le i \le n}$ be defined as in fig. 1.
Sample a list V of t random strings from $\{0,1\}^{\lambda+2}$.
for $k = 1$ to $|A^{(i-1)}|$ **do**
Parse $G(\mathsf{seed}_b^{(i-1)}[k]) = \mathsf{seed}_b^0 || \mathsf{sign}_b^0 || \mathsf{seed}_b^1 || \mathsf{sign}_b^1$, for $b = 0, 1$, $\mathsf{seed}_b^0, \mathsf{seed}_b^1 \in \{0,1\}^\lambda$ and $\mathsf{sign}_b^0, \mathsf{sign}_b^1 \in \{0,1\}$.
Compute $\Delta\mathsf{seed}^c = \mathsf{seed}_0^c \oplus \mathsf{seed}_1^c$ and $\Delta\mathsf{sign}^c = \mathsf{sign}_0^c \oplus \mathsf{sign}_1^c$ for $c = 0, 1$.
Denote path $\leftarrow A^{(i-1)}[k]$.
if both path$||z$ for $z = 0, 1$ are in $A^{(i)}$ **then**
$V[k] \leftarrow r || \Delta\mathsf{sign}^0 \oplus 1 || \Delta\mathsf{sign}^1 \oplus 1$, where $r \xleftarrow{\$} \{0,1\}^\lambda$.
else
Let z be such that path$||z \in A^{(i)}$.
$V[k] \leftarrow \Delta\mathsf{seed}^1 || \Delta\mathsf{sign}^0 \oplus (1-z) || \Delta\mathsf{sign}^1 \oplus z$.
end if
end for
return $\mathsf{OKVS}_i.\mathsf{Encode}(\{A^{(i-1)}[k], V[k]\}_{1 \le k \le |A^{(i-1)}|})$.
end procedure

procedure GENCONVCW($A, B, \{\mathsf{seed}_b^{(n)}, \mathsf{sign}_b^{(n)}\}$)
Sample a list V of t random $\mathbb{G}$-elements.
for $k = 1$ to $|A|$ **do**
$\Delta g \leftarrow G_{\mathsf{convert}}(\mathsf{seed}_0^{(n)}[k]) - G_{\mathsf{convert}}(\mathsf{seed}_1^{(n)}[k])$.
$V[k] \leftarrow (-1)^{\mathsf{sign}_0^{(n)}[k][k]}(\Delta g - B[k])$.
end for
return $\mathsf{OKVS}_{\mathsf{convert}}(\{A[k], V[k]\}_{1 \le k \le t})$.
end procedure

procedure CORRECT($\bar{x}, \mathsf{seed}, \mathsf{sign}, CW$)
Suppose $\bar{x} = x_1 x_2 \cdots x_i$ and let $\bar{x}^- = x_1 \cdots x_{i-1}$.
$C_{\mathsf{seed}} || C_{\mathsf{sign}^0} || C_{\mathsf{sign}^1} \leftarrow \mathsf{OKVS}_i.\mathsf{Decode}(CW, \bar{x}^-)$, where C_{sign^0} and C_{sign^1} are bits.
return $G_z(\mathsf{seed}) \oplus (C_{\mathsf{seed}} || C_{\mathsf{sign}^z})$.
end procedure

procedure CONVCORRECT($x, \mathsf{seed}, \mathsf{sign}, CW$)
return $G_{\mathsf{convert}}(\mathsf{seed}) \oplus \mathsf{OKVS}_{\mathsf{convert}}.\mathsf{Decode}(CW, x)$.
end procedure

Figure 3: The parameter l and methods' setting that turns the paradigm of DMPF in fig. 1 into the OKVS-based DMPF.

3.2 Batch-Code DMPF

display the batch-code DMPF

3.3 OKVS-based DMPF

TBD: explain

3.4 Comparison

Comparison table dependent to PRG & F-MUL(list the formulas?)
analyze tradeoff
distributed gen advantage

3.5 Distributed Key Generation

4 APPLICATIONS

4.1 PCG for OLE from Ring-LPN

Characterize parameters
show nonregular optimization
plug in new DMPF and show overall optimization

4.2 PSI-WCA

plug in new DMPF and analyze advantage interval
plug in distributed gen

4.3 Heavy-hitters

private heavy-hitter
or parallel ORAM?

5 ACKNOWLEDGMENTS

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A BATCH-CODE DMPF SCHEME

B SECURITY PROOFS