Efficient Privacy-Preserving Biometric Identification

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Motivating Scenario: Private No-Fly Checking
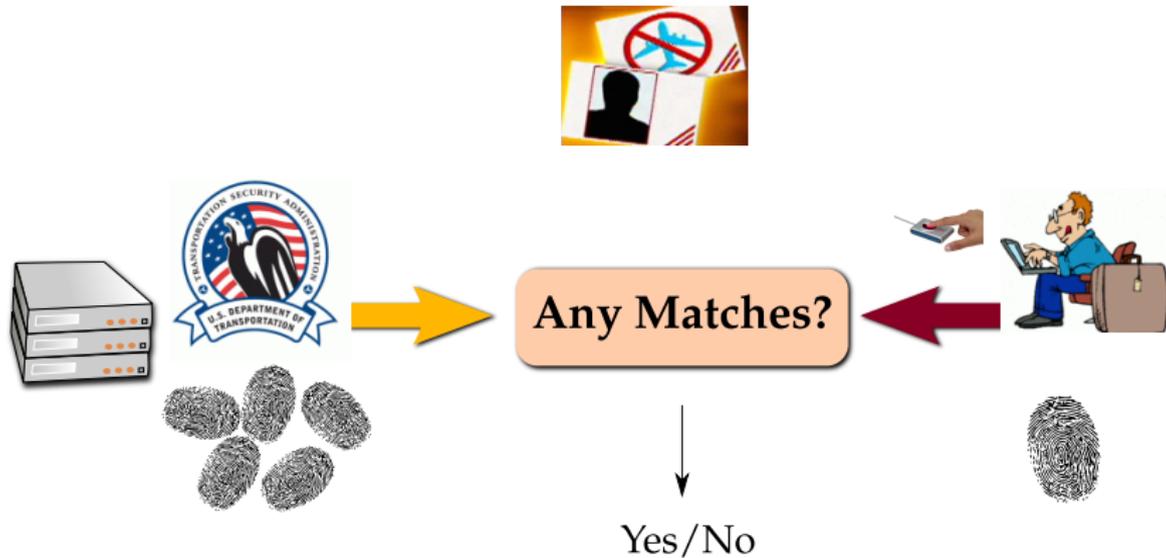
Any Matches?

Yes/No

Threat Models

- *Semi-honest* adversary
  - Must follow the protocol correctly
- *Malicious* adversary
 - Can deviate arbitrarily from the protocol

In both threat models, an adversary attempts to break either the *correctness* or the *privacy* property of the protocol.

Threat Models

- *Semi-honest* **adversary**
  - **Must follow the protocol correctly**
- *Malicious* adversary
  - Can deviate arbitrarily from the protocol

In both threat models, an adversary attempts to break either the *correctness* or the *privacy* property of the protocol.

Filterbank-based Fingerprint Recognition [Jain et al., 2000]

FingerCode $v = [100, 78, \cdots, 213]$ FingerCode $v' = [9, 242, \cdots, 6]$

Match By Euclidean Distance
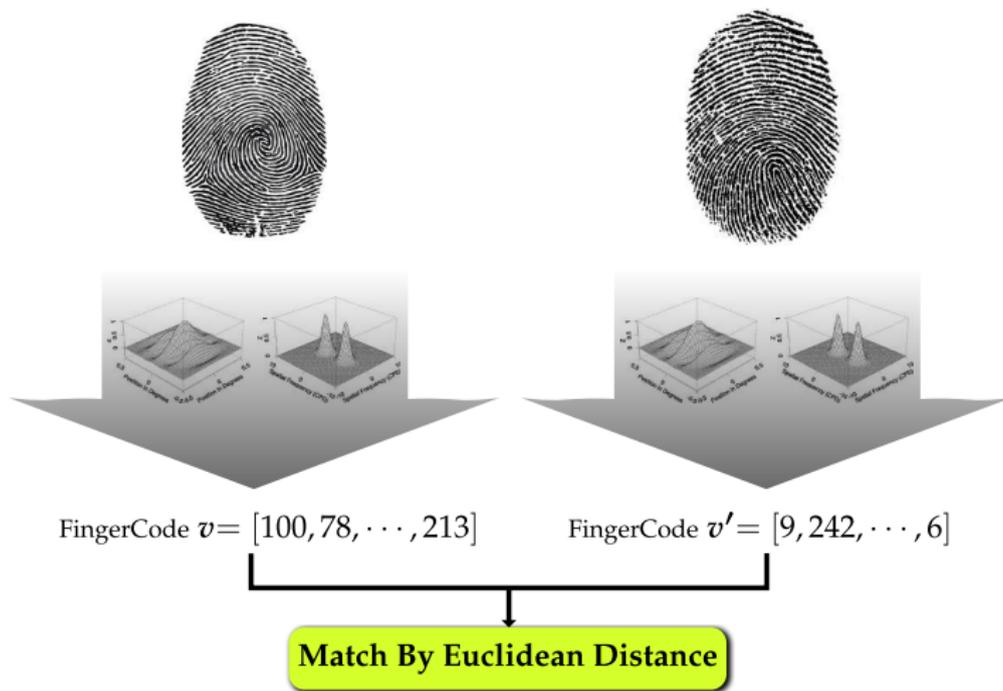
Also used by Barni et al. [2010].

Non-private Protocol

$V = \{v_1, v_2, \cdots, v_M\}$ $v' = \{v'_1, v'_2, \cdots, v'_N\}$

Euclidean Distance

$d = \{d_1, d_2, \cdots, d_M\}$

Finding Minimum

$$d^* = \min_{1 \leq i \leq M} (d_i)$$

Retrieve Identity

Record(i^*), if $d^* = d_{i*} < \varepsilon$;
$\bot$, otherwise.

Privacy-preserving Protocol

$V = \{v_1, v_2, \cdots, v_M\}$ $v' = \{v'_1, v'_2, \cdots, v'_N\}$

| Euclidean Distance | Homomorphic Encryption |

$d = \{d_1, d_2, \cdots, d_M\}$

| Finding Minimum | Garbled Circuits |

$d^* = \min_{1 \leq i \leq M} (d_i)$

| Retrieve Identity | Backtracking Protocol |

Record(i^*), if $d^* = d_{i*} < \varepsilon$;
$\perp$, otherwise.

Privacy-preserving Protocol

$$V = \{v_1, v_2, \cdots, v_M\}$$

$$v' = \{v'_1, v'_2, \cdots, v'_N\}$$

Euclidean Distance

Homomorphic Encryption

$$d = \{d_1, d_2, \cdots, d_M\}$$

Finding Minimum

$$d^* = \min_{1 \leq i \leq M} (d_i)$$

Retrieve Identity

Record(i^*), if $d^* = d_{i*} < \varepsilon$; $\perp$, otherwise.

Euclidean Distance

Let d_i be the distance between $\boldsymbol{v}_i = [v_{i,j}]_{1 \leq j \leq N}$ and $\boldsymbol{v}' = [v'_j]_{1 \leq j \leq N}$

$$d_i = \|\boldsymbol{v}_i - \boldsymbol{v}'\|^2 = \sum_{j=1}^{N} (v_{i,j} - v'_j)^2$$

$$= \underbrace{\sum_{j=1}^{N} v_{i,j}^2}_{S_{i,1}} + \underbrace{\sum_{j=1}^{N} (-2v_{i,j} \cdot v'_j)}_{S_{i,2}} + \underbrace{\sum_{j=1}^{N} v_j'^2}_{S_3}$$

For privacy, want to compute $[\![d_i]\!]_{\mathsf{pk}}$.

Additive Homomorphic Encryption

$$\left.\begin{array}{l} [\![a]\!]_{\mathsf{pk}} \\[2ex] [\![b]\!]_{\mathsf{pk}} \end{array}\right\} \implies [\![a + b \mod p]\!]_{\mathsf{pk}} = [\![a]\!]_{\mathsf{pk}} \cdot [\![b]\!]_{\mathsf{pk}}$$

$$\left.\begin{array}{l} [\![a]\!]_{\mathsf{pk}} \\[2ex] c \end{array}\right\} \implies [\![c \cdot a \mod p]\!]_{\mathsf{pk}} = [\![a]\!]_{\mathsf{pk}}^{c}$$

We used Paillier cryptosystem [Catalano et al., 2001, Paillier, 1999] in our prototype.

Additive Homomorphic Encryption

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$$\left.\begin{array}{l} [\![a]\!] \\ \\ c \end{array}\right\} \Longrightarrow [\![c \cdot a \mod p]\!] = [\![a]\!]^c$$

We used Paillier cryptosystem [Catalano et al., 2001, Paillier, 1999] in our prototype.

Private Euclidean Distance

$$[\![d_i]\!] = \left[\!\left[\sum_{j=1}^{N} v_{i,j}^2 + \underbrace{\sum_{j=1}^{N} (-2v_{i,j}v_j')}_{S_{i,2}} + \underbrace{\sum_{j=1}^{N} v_j'^2}_{S_3} \right]\!\right]$$

$$\underbrace{\phantom{\sum_{j=1}^{N} v_{i,j}^2}}_{S_{i,1}}$$

$$= [\![S_{i,1}]\!] \cdot [\![S_{i,2}]\!] \cdot [\![S_3]\!]$$

$$[\![S_{i,2}]\!] = \left[\!\left[\sum_{j=1}^{N} (-2v_{i,j}v_j') \right]\!\right] = \prod_{j=1}^{N} [\![-2v_{i,j}]\!]^{v_j'}$$

Improving the Efficiency

- **Modular exponentiation is slow.** For every i, computing $[\![S_{i,2}]\!]$ requires N modular exponentiations. Overall, it involves MN modular exponentiations

- **Encode many messages in one homomorphic encryption**
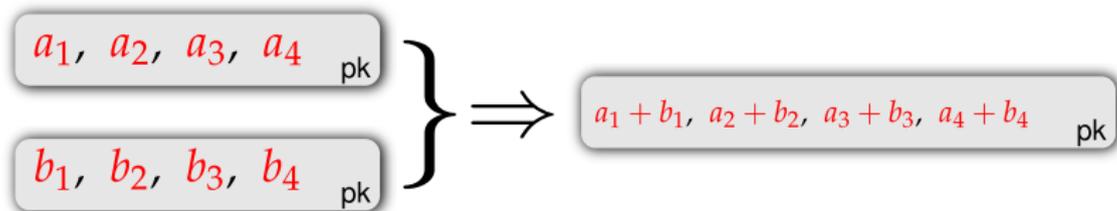
Packing was introduced by Sadeghi et al. [2009] to save bandwidth, but is exploited more aggressively here to save computation also.

Padding 0's to Ensure Correctness

$$51, 28, 72$$

$$+ \quad 39, 92, 22$$

$$\overline{ \quad 91, 20, 94}$$

$$\bullet \quad \boxed{51, 28, 72 \;_{\text{pk}}}$$

$$\boxed{39, 92, 22 \;_{\text{pk}}}$$

$$\boxed{91, 20, 94 \;_{\text{pk}}}$$

$$051, 028, 072$$

$$+ \quad 039, 092, 022$$

$$\overline{ \quad 090, 120, 094}$$

$$\bullet \quad \boxed{051, 028, 072 \;_{\text{pk}}}$$

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$$\boxed{090, 120, 094 \;_{\text{pk}}}$$

Vertical Partitioning to Speedup Computing $[\![S_{i,2}]\!]$

$$[\![S_{i,2}]\!] = \prod_{j=1}^{N} [\![-2v_{i,j}]\!]^{v'_j}$$

$$\begin{bmatrix} -2v_{1,1} & -2v_{1,2} & \cdots & -2v_{1,N} \\ -2v_{2,1} & -2v_{2,2} & \cdots & -2v_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ -2v_{\kappa,1} & -2v_{\kappa,2} & \cdots & -2v_{\kappa,N} \end{bmatrix}$$

Vertical Partitioning to Speedup Computing $[\![S_{i,2}]\!]$

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$$[\![S_{1,2}\|S_{2,2}\| \cdots \|S_{\kappa,2}]\!] = \prod_{1 \leq j \leq N} [\![-2v_{1,j}v_j'\|-2v_{2,j}v_j'\| \cdots \|-2v_{\kappa,j}v_j']\!]$$

$$\begin{bmatrix} -2v_{1,1} & -2v_{1,2} & \cdots & -2v_{1,N} \\ -2v_{2,1} & -2v_{2,2} & \cdots & -2v_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ -2v_{\kappa,1} & -2v_{\kappa,2} & \cdots & -2v_{\kappa,N} \end{bmatrix}$$

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$$[\![-2v_{1,j}v_j'\|-2v_{2,j}v_j'\| \cdots \|-2v_{\kappa,j}v_j']\!] = [\![-2v_{1,j}\|-2v_{2,j}\| \cdots \|-2v_{\kappa,j}]\!]^{v_j'}$$

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$$[\![S_{1,2}\|S_{2,2}\|\cdots\|S_{\kappa,2}]\!] = \prod_{1 \leq j \leq N} [\![-2v_{1,j}v'_j\|-2v_{2,j}v'_j\|\cdots\|-2v_{\kappa,j}v'_j]\!]$$

$$[\![-2v_{1,j}v'_j\|-2v_{2,j}v'_j\|\cdots\|-2v_{\kappa,j}v'_j]\!] = [\![-2v_{1,j}\|-2v_{2,j}\|\cdots\|-2v_{\kappa,j}]\!]^{v'_j}$$

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Effects of Packing
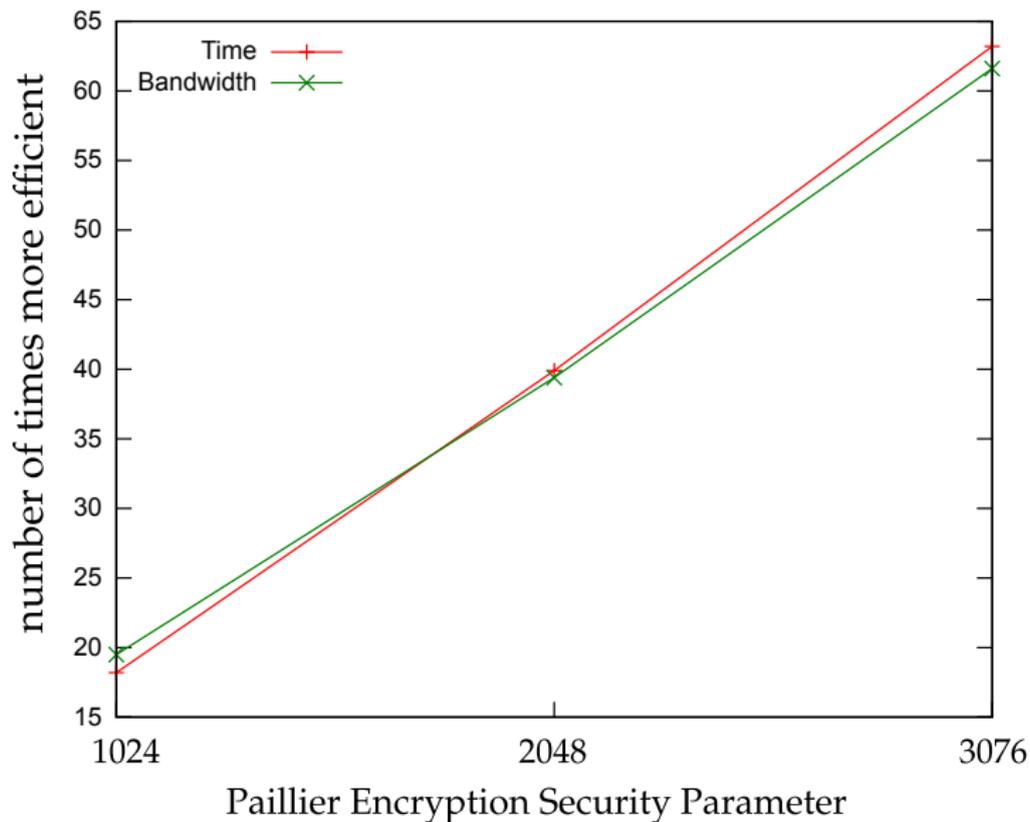
Sharing the Secrets

The server generates nonce masks $r = [r_1, r_2, \cdots, r_M]$ and sends

$$[\![d'_1\| \cdots \|d'_M]\!]_{\mathsf{pk}} = [\![(d_1 + r_1)\|(d_2 + r_2)\| \cdots \|(d_M + r_M)]\!]_{\mathsf{pk}}$$

where pk is the client's public key.

Server	Client
d'_1	r_1
d'_2	r_2
$\vdots$	$\vdots$
d'_M	r_M

Make the sampling range of r_i large enough so that d'_i and d_i is statistically indistinguishable.

Privacy-preserving Protocol

$V = \{v_1, v_2, \cdots, v_M\}$ $v' = \{v'_1, v'_2, \cdots, v'_N\}$

Euclidean Distance

$d' = \{d'_1, d'_2, \cdots, d'_M\}$ $r = \{r_1, r_2, \cdots, r_M\}$

Finding Minimum   **Garbled Circuits**

$d^* = \min_{1 \leq i \leq M}(d_i)$

Retrieve Identity

Record(i^*), if $d^* = d_{i*} < \varepsilon$;
$\perp$, otherwise.

Garbled Circuits Protocol
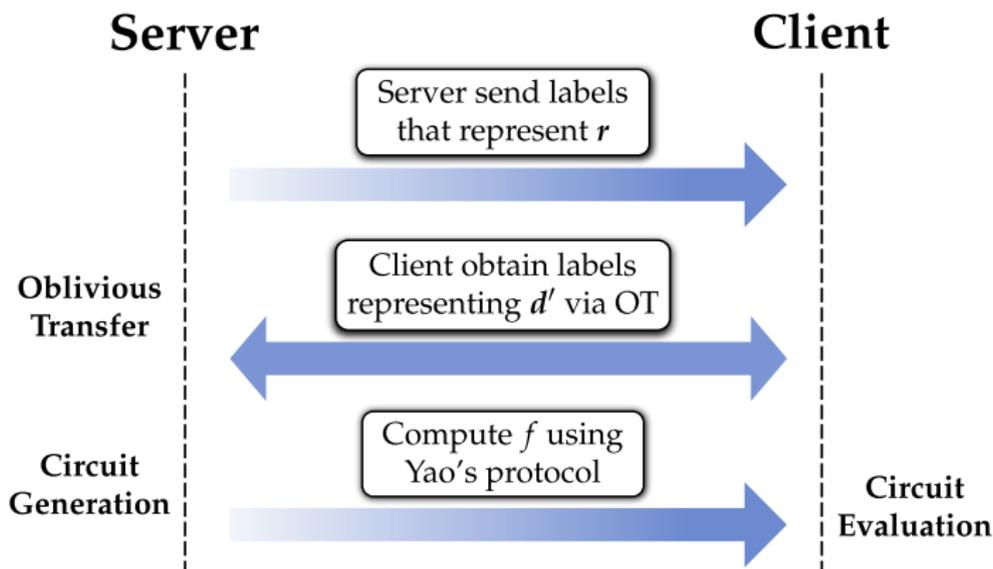
- Efficient oblivious transfer protocol combining schemes from both [Naor and Pinkas, 2001] and [Ishai et al., 2003]
- Standard garbled circuits [Yao, 1986] combined with free-XOR technique [Kolesnikov and Schneider, 2008]

Finding the Minimum Differnce
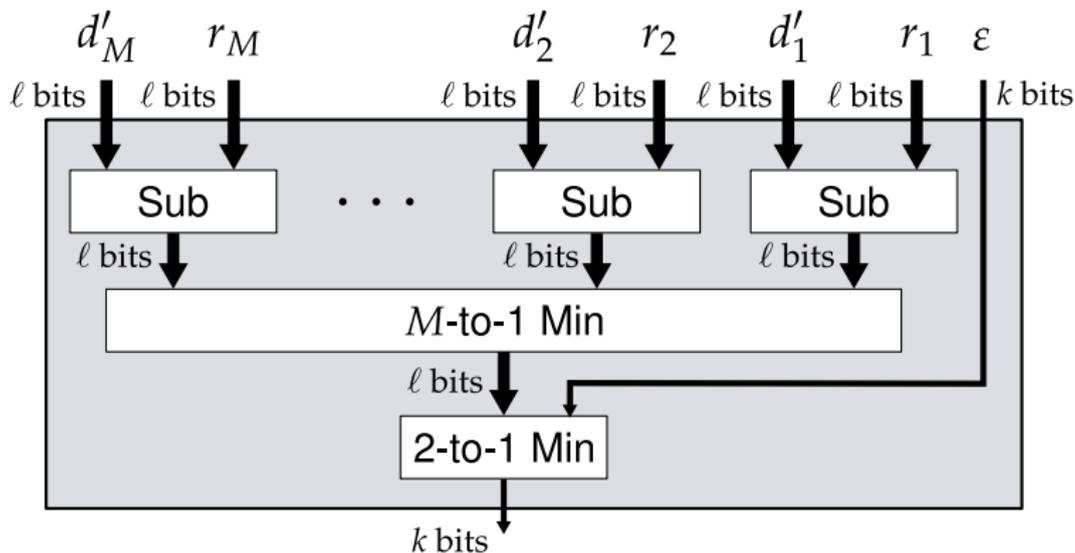
Reducing the Bit-width
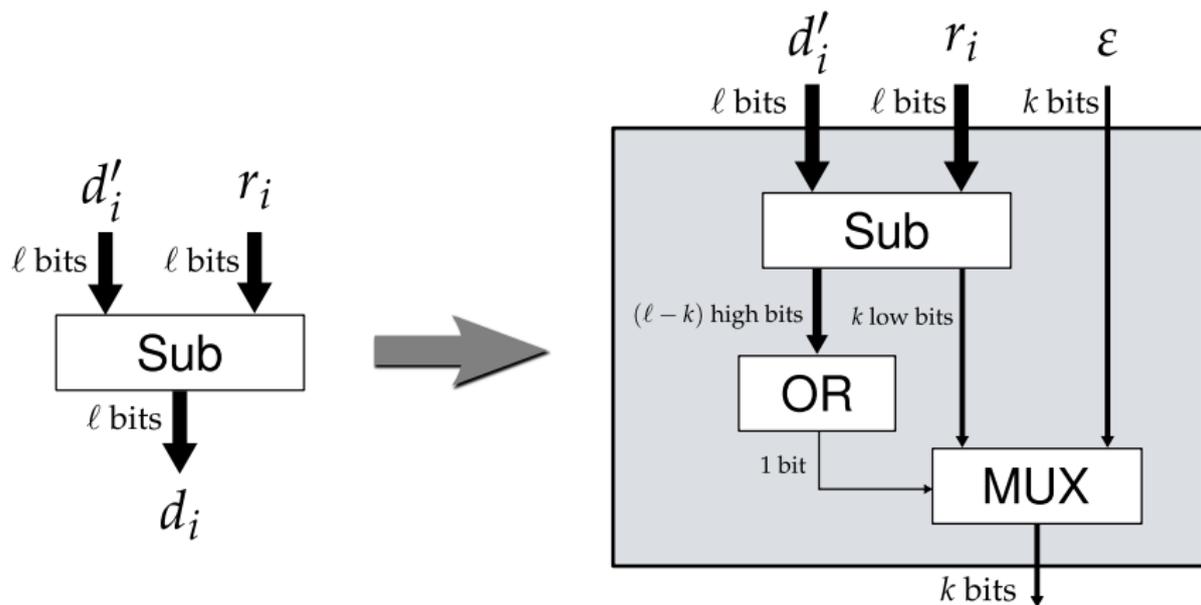
Saves $2M(\ell - k)$ non-free gates in total.

Privacy-preserving Protocol

$$V = \{v_1, v_2, \cdots, v_M\}$$

$$v' = \{v'_1, v'_2, \cdots, v'_N\}$$

Euclidean Distance

Finding Minimum

$$d^* = \min_{1 \le i \le M} (d_i)$$

Retrieve Identity

Backtracking Protocol

Record(i^*), if $d^* = d_{i*} < \varepsilon$;
$\perp$, otherwise.

Finding the Record

- Ultimate goal is to retrieve the record associated with d^*
- Prior work [Kolesnikov et al., 2009] accomplished this by relaying indices throughout the M-to-1 Min circuit
- We achieve this with a *backtracking* protocol
    1. No need to propagate ID numbers
    2. Obtain record without an extra secure information retrieval by ID
    3. Use labels obtained in garbled circuit execution

The 2-to-1 Min
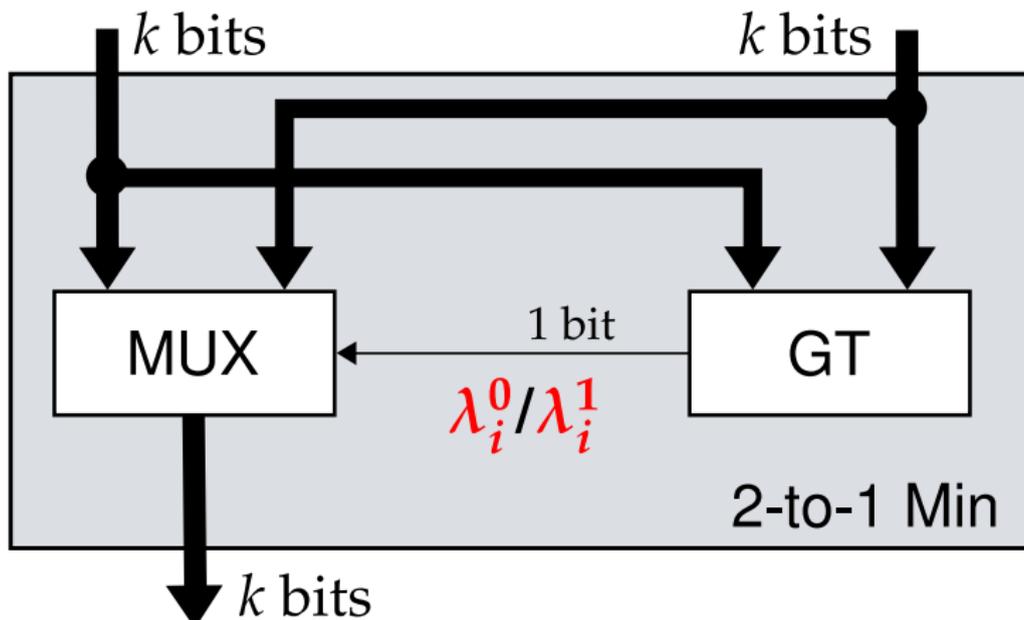
Mini Example — The Server

"Radu" "Adrian" "Doug" "Yan"

Mini Example — The Server
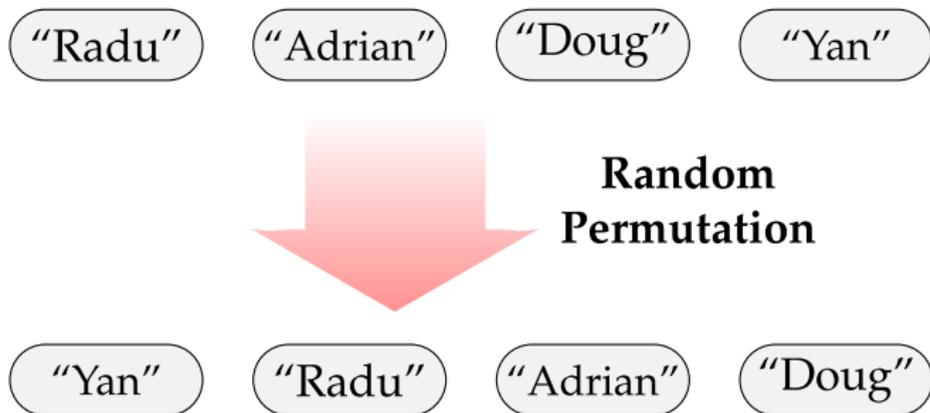
Selection Wires in the M-to-1 Min Tree
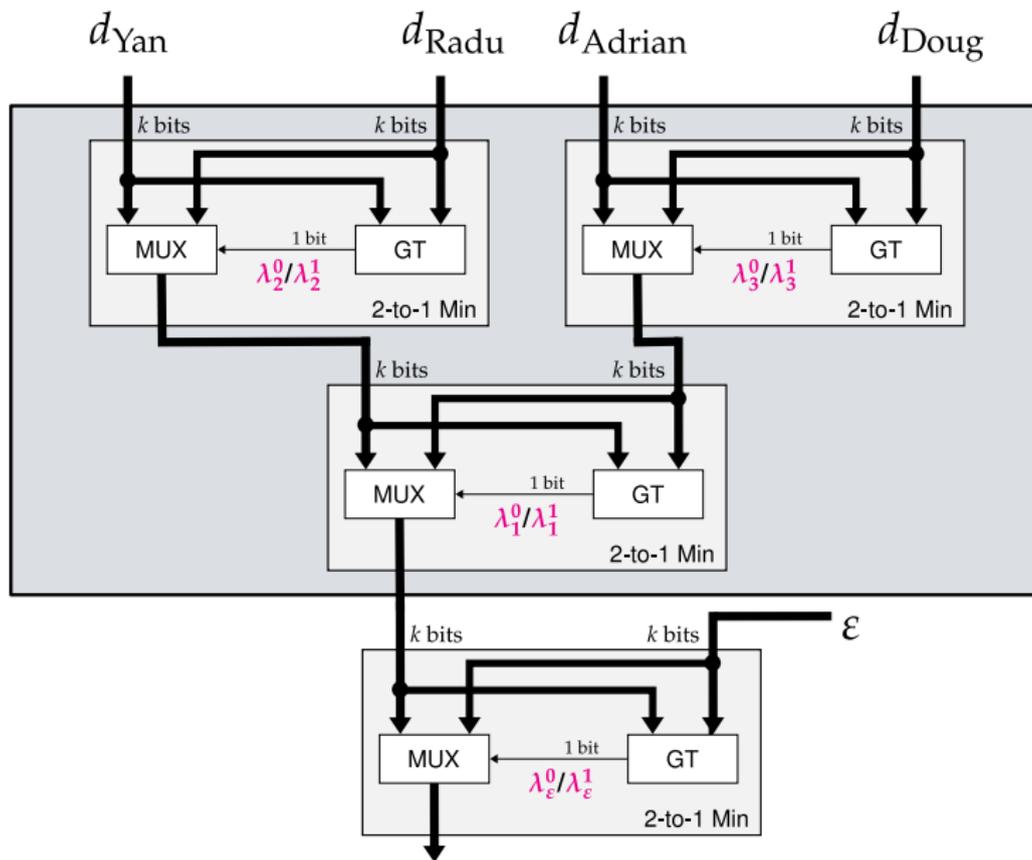
Backtracking — The Sender

$\text{Enc}_{n_2, \lambda_2^0}(\text{"Yan"})$ $\text{Enc}_{n_2, \lambda_2^1}(\text{"Radu"})$ $\text{Enc}_{n_3, \lambda_3^0}(\text{"Adrian"})$ $\text{Enc}_{n_3, \lambda_3^1}(\text{"Doug"})$

$\text{Enc}_{n_1, \lambda_1^0}(n_2)$ $\text{Enc}_{n_1, \lambda_1^1}(n_3)$

$\text{Enc}_{\lambda_\varepsilon}(n_1)$
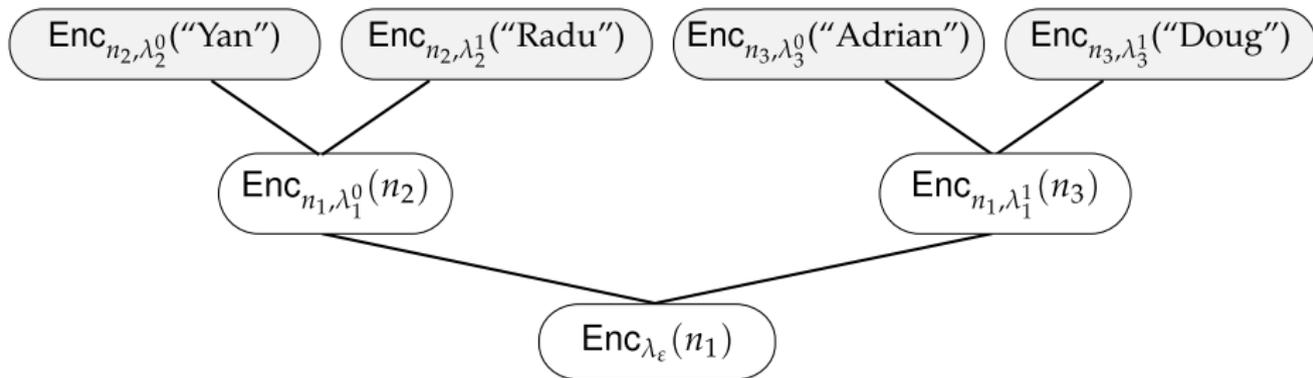
n_1, n_2, n_3 are random nonces known only to the sender.

Backtracking — The Receiver

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$\text{Enc}_{n_2, \lambda_2^0}(\text{"Yan"})$ $\text{Enc}_{n_2, \lambda_2^1}(\text{"Radu"})$ $\text{Enc}_{n_3, \lambda_3^0}(\text{"Adrian"})$ $\text{Enc}_{n_3, \lambda_3^1}(\text{"Doug"})$

$\text{Enc}_{n_1, \lambda_1^0}(n_2)$ $\text{Enc}_{n_1, \lambda_1^1}(n_3)$

$\text{Enc}_{\lambda_\varepsilon}(n_1)$
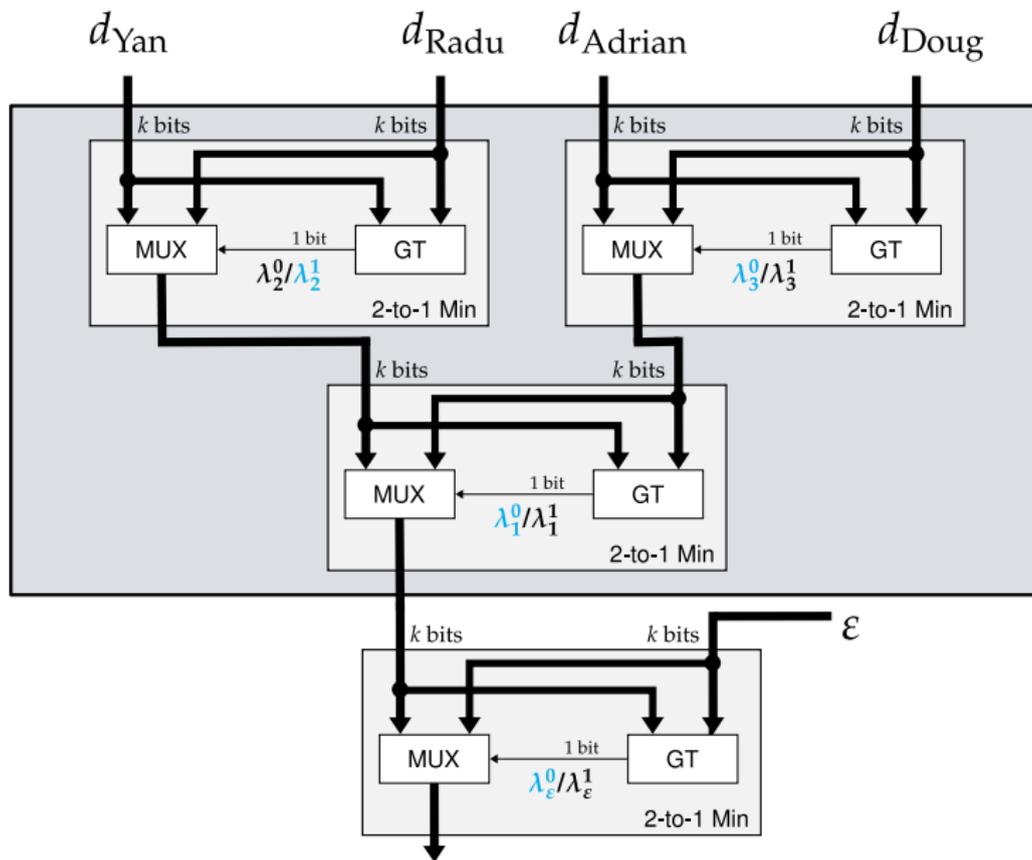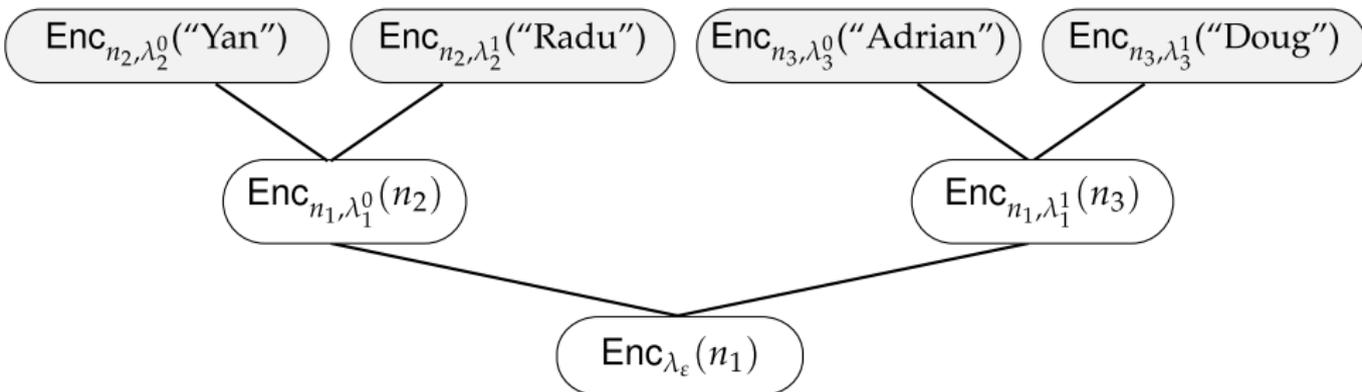
Client knows $\lambda_\varepsilon^0, \lambda_1^0, \lambda_2^1, \lambda_3^0$ from circuit evaluation,

Backtracking — The Receiver

$\text{Enc}_{n_2,\lambda_2^0}(\text{"Yan"})$ $\text{Enc}_{n_2,\lambda_2^1}(\text{"Radu"})$ $\text{Enc}_{n_3,\lambda_3^0}(\text{"Adrian"})$ $\text{Enc}_{n_3,\lambda_3^1}(\text{"Doug"})$

$\text{Enc}_{n_1,\lambda_1^0}(n_2)$ $\text{Enc}_{n_1,\lambda_1^1}(n_3)$

$\text{Enc}_{\lambda_\varepsilon}(n_1)$
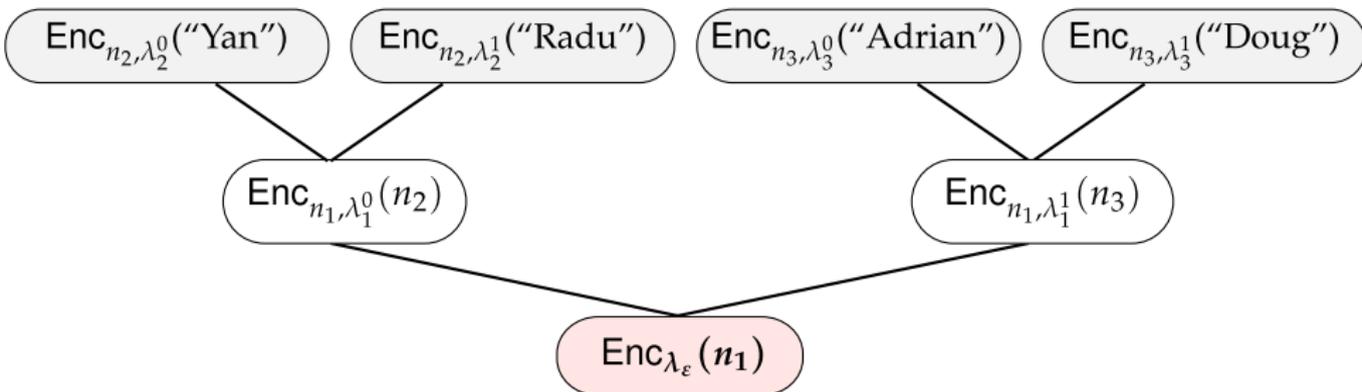
Client knows $\lambda_\varepsilon^0, \lambda_1^0, \lambda_2^1, \lambda_3^0$ from circuit evaluation, so is able to infer n_1

Backtracking — The Receiver

$\text{Enc}_{n_2, \lambda_2^0}(\text{"Yan"})$ $\text{Enc}_{n_2, \lambda_2^1}(\text{"Radu"})$ $\text{Enc}_{n_3, \lambda_3^0}(\text{"Adrian"})$ $\text{Enc}_{n_3, \lambda_3^1}(\text{"Doug"})$

$\text{Enc}_{n_1, \lambda_1^0}(n_2)$ $\text{Enc}_{n_1, \lambda_1^1}(n_3)$

$\text{Enc}_{\lambda_\varepsilon}(n_1)$
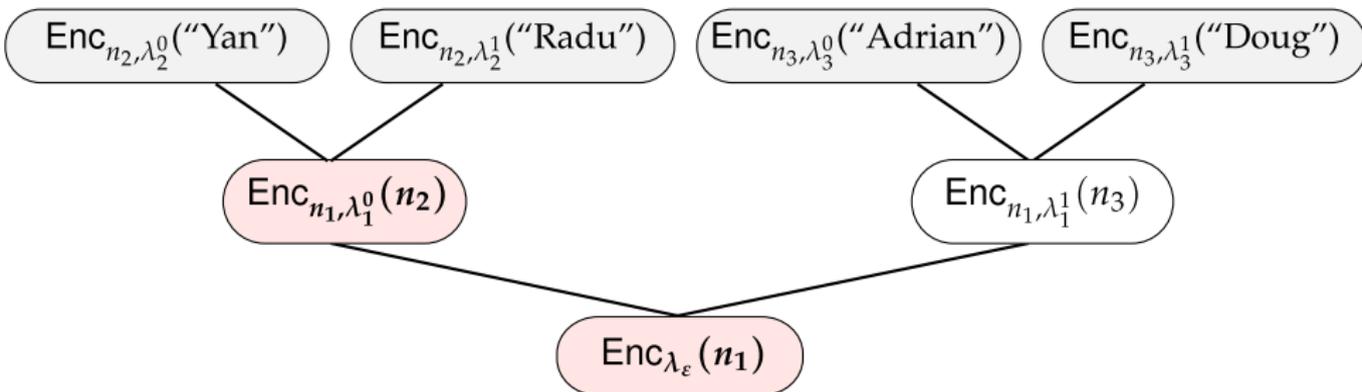
Client knows $\lambda_\varepsilon^0, \lambda_1^0, \lambda_2^1, \lambda_3^0$ from circuit evaluation, so is able to infer n_1, n_2

Backtracking — The Receiver

$\text{Enc}_{n_2, \lambda_2^0}(\text{"Yan"})$ $\text{Enc}_{n_2, \lambda_2^1}(\textbf{"Radu"})$ $\text{Enc}_{n_3, \lambda_3^0}(\text{"Adrian"})$ $\text{Enc}_{n_3, \lambda_3^1}(\text{"Doug"})$

$\text{Enc}_{n_1, \lambda_1^0}(n_2)$ $\text{Enc}_{n_1, \lambda_1^1}(n_3)$

$\text{Enc}_{\lambda_\varepsilon}(n_1)$
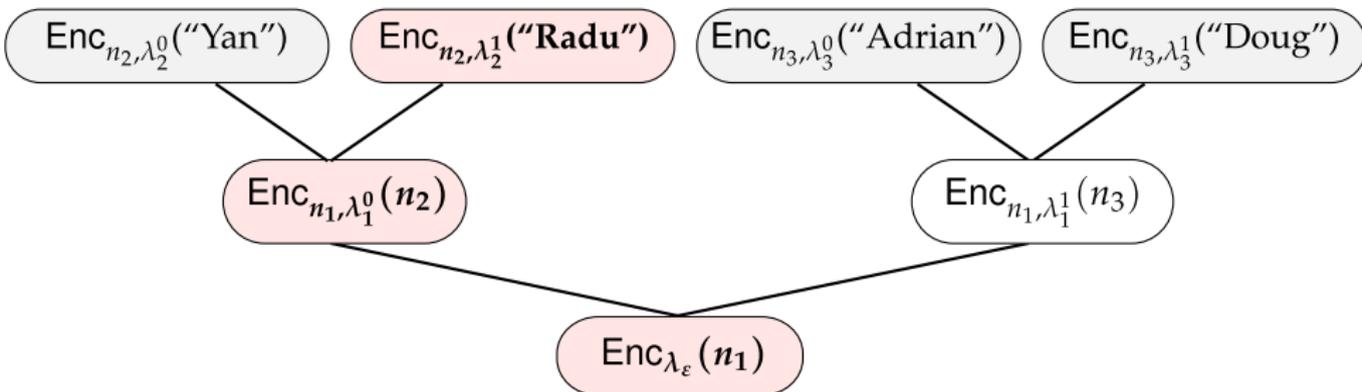
Client knows $\lambda_\varepsilon^0, \lambda_1^0, \lambda_2^1, \lambda_3^0$ from circuit evaluation, so is able to infer n_1, n_2, and **Radu**.

System Recap

$$V = \{v_1, v_2, \cdots, v_M\}$$

$$v' = \{v'_1, v'_2, \cdots, v'_N\}$$

Euclidean Distance — Distance

$$d = \{d_1, d_2, \cdots, d_M\}$$

Finding Minimum — OT, Circuit

$$d^* = \min_{1 \leq i \leq M} (d_i)$$

Retrieve Identity — Backtracking

$$\mathbf{Record}(i^*), \text{ if } d^* = d_{i*} < \varepsilon;$$
$$\perp, \text{ otherwise.}$$

Results — Online Performance

Time

Bandwidth

OT | Circuit | Distance | Backtracking
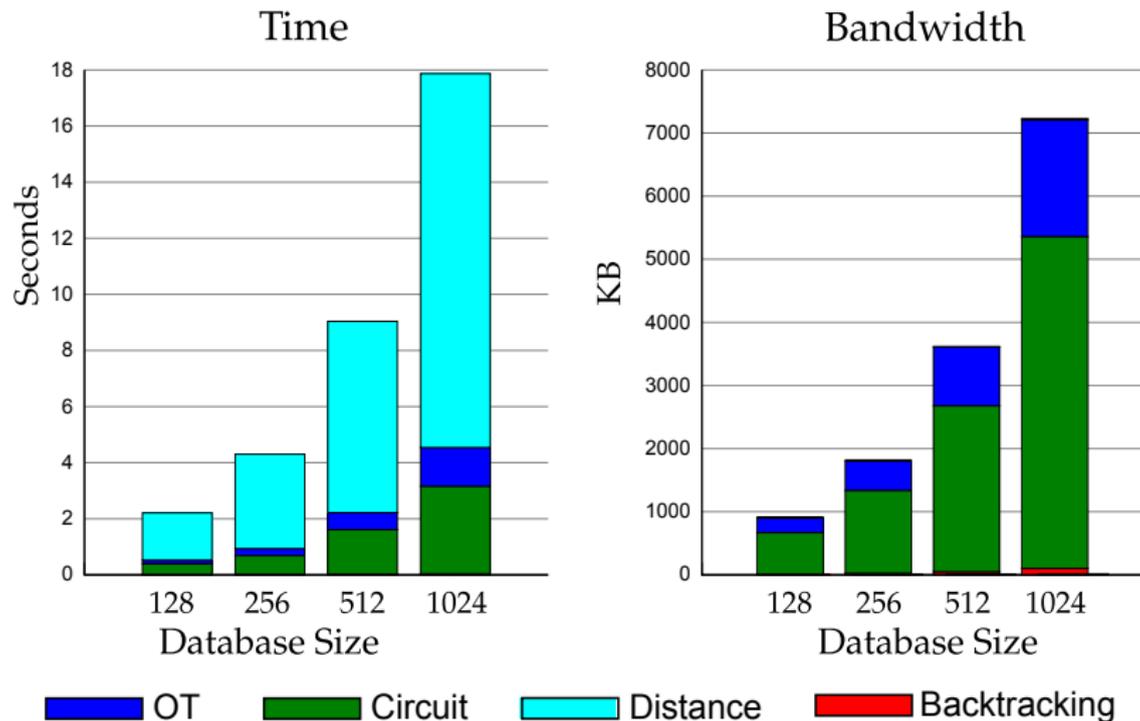
$4.6\times$ faster and uses 58% less bandwidth than Barni et al. [2010], even though we compute the global minimum

Thank you!

Software available for download at:
     http://www.mightbeevil.org/secure-biometrics/

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