Malleable SNARKs and Their Applications

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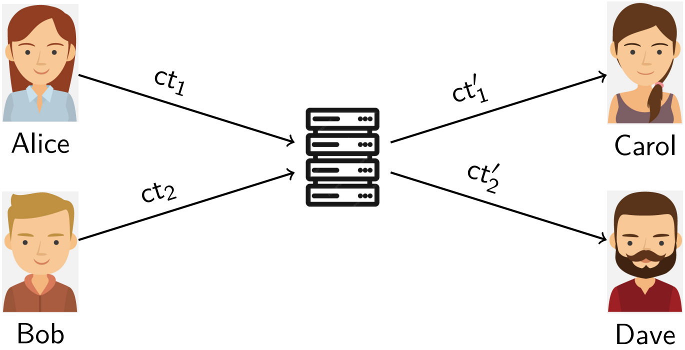
Motivation: Mix-Nets (over-simplified)



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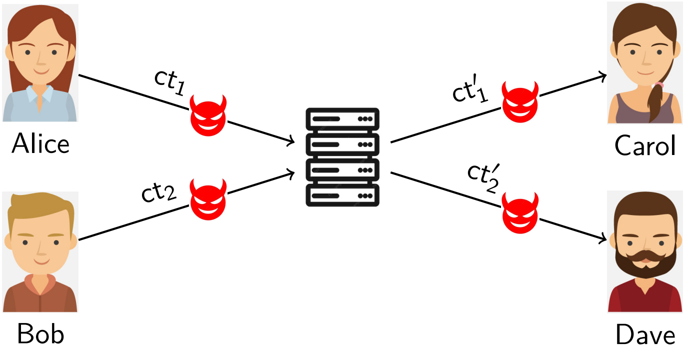
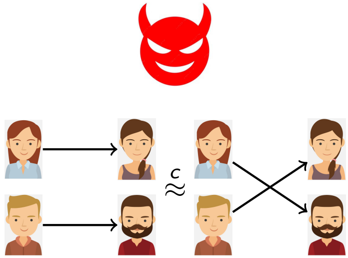


Security:



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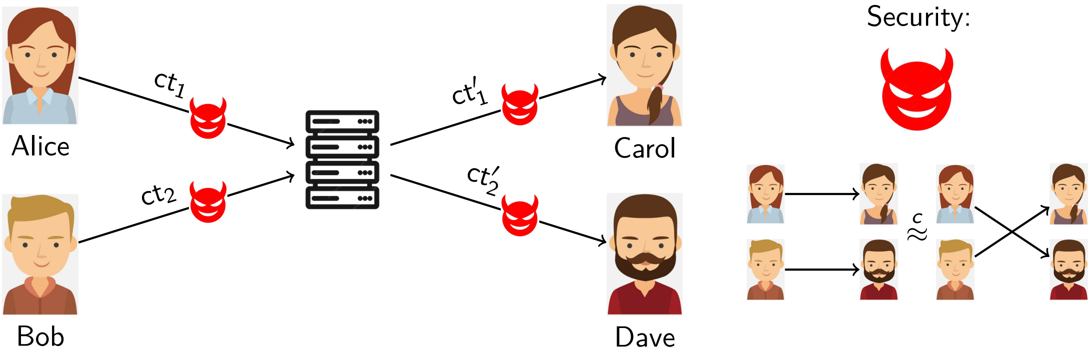

Solution:  rerandomizes ciphertexts (+ anonymity of the encryption scheme)

IND-RCCA secure rerandomizable PKE

Given: IND-CPA secure rerandomizable PKE
Needed: IND-RCCA secure rerandomizable PKE

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Dec oracle returns $\diamond$ if ciphertext decrypts to $m_0^\star$ or $m_1^\star$

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Naor-Yung transform [NY90]
$\mathsf{ct}' = (\mathsf{ct}_1, \mathsf{ct}_2, \pi)$

ct_1 and ct_2 encrypt the same message

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c

Proof system must support:

- rerandomization
- adapt the statement to rerandomized ciphertexts

sage

IND-RCCA rerandomizable PKE

Malleable NIZKs [CKLM12]

- NP relation $\mathcal{R}$
- Allowed transformations $\mathcal{T}$

such that

$$\forall (x, w) \in \mathcal{R}, (T_x, T_w) \in \mathcal{T} \rightarrow (T_x(x), T_w(w)) \in \mathcal{R}$$

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- a NIZK for $\mathcal{R}$
- with the following extra feature

$$\pi \xrightarrow{(T_x, T_w)} \pi'$$

$\boxed{x \text{ is true}}$ $\boxed{T_x(x) \text{ is true}}$

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Simulation-soundness: Takes into account that simulated statements can be modified with $\mathcal{T}$

Instantiations of malleable NIZKs

Groth-Sahai proofs [CKLM12]:

- ✓ Very efficient
- ✗ Only for a specific $\mathcal{R}$ (pairing-product equations)
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Generically from SNARKs [our work]:

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Malleable NIZKs from SNARKs

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Recursive usage of SNARKs

- succinctness avoids blow-up of proof size/verification time
- ✓zero-knowledge ✓derivation private (by zero-knowledge of the SNARK)
- also used for incrementally verifiable computation (IVC), proof carrying data (PCD), blockchains (to compress proofs)

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$\boxed{\text{Main technical challenge}}$

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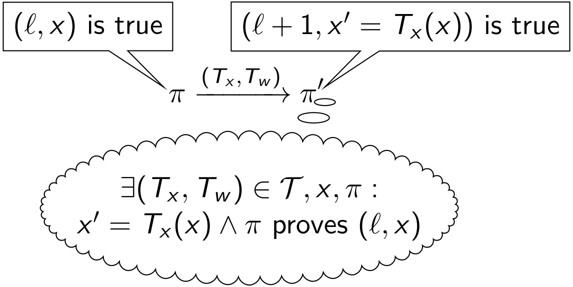

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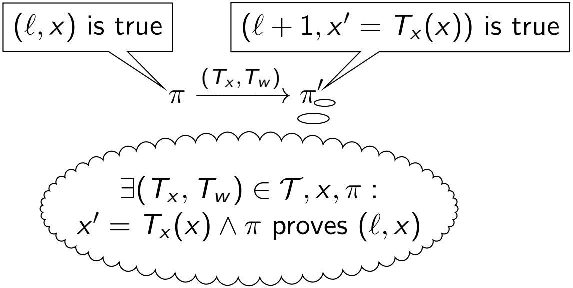

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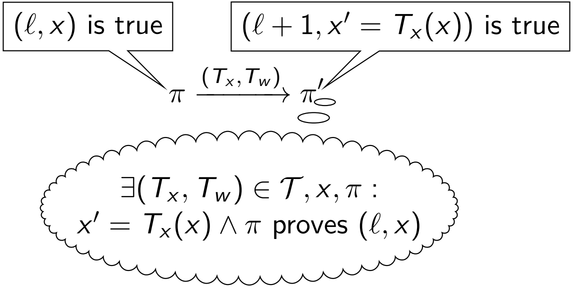

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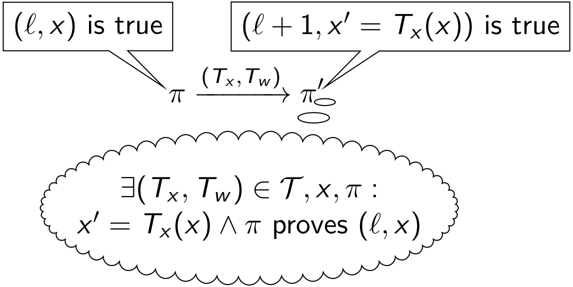

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✗ Only bounded number of recursions

Non-solution: One-way permutation

OWP $f : X \to X$

Counter ℓ is replaced by $\xi \in X$

- Initially: $\xi \leftarrow X$
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Idea: Extractor would have to break one-wayness if

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We need a variant of OWF that is secure if the adversary chooses the value x to invert.

Adversarial one-way functions (AOWFs)

Stateful 2-stage adversary $(\mathcal{A}_1, \mathcal{A}_2)$

1^{st} attempt: $\begin{array}{l} \mathcal{A}_1 \text{ outputs } y \\ \mathcal{A}_2 \text{ outputs } x \end{array}$ $(\mathcal{A}_1, \mathcal{A}_2)$ wins if $f(x) = y$

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If

- f is only <u>sequentially</u> computable
- n depends on the runtime of $\mathcal{A}_1$ $(\mathrm{Time}_{\mathcal{A}_1} < n \cdot \mathrm{Time}_{f(\cdot)})$

there is no trivial attack!

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  - For our candidate this can be achieved by inputting additional random bits in the hash function

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Requires assumption specific to the underlying HE scheme

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- Good candidates for SNARKs with fast extraction

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Pictures

Alice, Bob, and other faces, Server: freepik.com
Matryoshka doll: holz-leute.de

Transformations with arity ≥ 2

$\boxed{x_1 \text{ is true}}$

$$\begin{matrix}\pi_1 \\ \pi_2\end{matrix} \xrightarrow{(T_x, T_w)} \pi'$$

$\boxed{x_2 \text{ is true}}$

Transformations with arity ≥ 2

x_1 is true

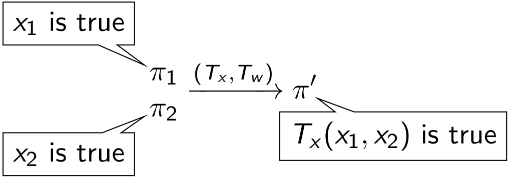
$$\begin{matrix} \pi_1 \\ \pi_2 \end{matrix} \xrightarrow{(T_x, T_w)} \pi'$$

x_2 is true

$T_x(x_1, x_2)$ is true

Counter-based approach: $\begin{matrix} (\ell_1, \pi_1) \\ (\ell_2, \pi_2) \end{matrix} \xrightarrow{(T_x, T_w)} (\max\{\ell_1, \ell_2\} + 1, \pi')$

Transformations with arity ≥ 2



Counter-based approach: $\begin{matrix}(\ell_1, \pi_1)\\(\ell_2, \pi_2)\end{matrix} \xrightarrow{(T_x, T_w)} (\max\{\ell_1, \ell_2\} + 1, \pi')$

- ✗ Only for constant-depth

Transformations with arity ≥ 2

x_1 is true

$$\begin{matrix} \pi_1 \\ \pi_2 \end{matrix} \xrightarrow{(T_x, T_w)} \pi'$$

x_2 is true

$T_x(x_1, x_2)$ is true

Counter-based approach: $\begin{matrix} (\ell_1, \pi_1) \\ (\ell_2, \pi_2) \end{matrix} \xrightarrow{(T_x, T_w)} (\max\{\ell_1, \ell_2\} + 1, \pi')$

- ✗ Only for constant-depth

AOWF-based approach:

- ✓ Unbounded depth
- Needs higher arity variant of AOWFs (works for hash functions)
- Statements and proofs must be input to the AOWF
- Extractor must cache extracted SNARKs