Brief Announcement: Anonymous Credentials Secure to Ephemeral Leakage

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Anonymous credentials

Credentials System

a scheme involving three parties:

- User – proves his attributes,
- Issuer – certifies attributes,
- Verifier – accepts or rejects the proof

Attribures of the user

- age,
- sex,
- citizenship,
- role, ...

User do not reveal its identity.

Camenisch-Lysyanskaya Construction (CL)

Set of attributes

- $m_1, m_2, \ldots, m_l$ denoted as $\{m\}_0^l$

Asymmetric cryptography setup

- $\texttt{Issuer}(x,\ y,\ \{z\}_1^l)$ has a long term **secret key**:
- $\texttt{Verifier}(X, Y, \{Z_i\}_1^l)$ has the **public key**

Zero Knowledge Proof, Unlinkability

- the verifier is convinced,
- gets no information about the user's attributes.
- do not link the protocol runs with the particular user.

Issue Protocol

Four rounds

- **commitment**: the `User` sends a commitment to attributes and to ephemeral values.
- **challenge**: the `Issuer` sends random challenge.
- ***response***: the prover sends the result of some computations over the challenge, the secret and the ephemeral value .
- ***sign***: the `Issuer` sends the signature over the attributes, (certificate).

Proof of knowledge

The first three - proof of knowledge of the attributes

Issue protocol

$\texttt{User}(\{m\}_0^l)$		$\texttt{Issuer}(x,\ y,\ \{z\}_1^l)$
$M = g^{m_0} \Pi_{i=1}^{l} Z_i^{m_i}$		
$(r_0, \ldots r_l) \leftarrow_\$ \mathbb{Z}_q$		
$T = g^{r_0}\ \Pi_{i=1}^{l} Z_i^{r_i}$	$\xrightarrow{M,\ T}$	$c \leftarrow_\$ \mathbb{Z}_q$
	$\xleftarrow{c}$	
$\forall_{i \in \{0,\ldots,l\}}\ s_i = r_i - cm_i$	$\xrightarrow{\{s_i\}_0^l}$	$T \stackrel{?}{=} M^c\ g^{s_0}\ \Pi_{i=1}^{l} Z_i^{s_i}$
		$a_0 \leftarrow_\$ \mathbb{Z}_q,\ A_0 = g^{a_0}$
		$\forall_{i \in \{1,\ldots,l\}}\ A_i = A_0^{z_i}$
		$\forall_{i \in \{0,\ldots,l\}}\ B_i = A_i^{y}$
$\mathrm{Store}(\{A_i\}_0^l,\ \{B_i\}_0^l,\ C)$	$\xleftarrow{\{A_i\}_0^l,\ \{B_i\}_0^l,\ C}$	$C = A_0^x\ M^{a_0 xy}$

Figure: CL system: issuing a credential.

Attribute Verification Protocol

Three rounds

- **commitment**: the `User` sends a commitment to credentials and to ephemeral values.
- **challenge**: the `Verifier` sends random challenge.
- ***response***: the prover sends the result of some computations over the challenge, the credentials and the ephemeral value .

Attribute Verification Protocol

$\mathtt{User}(\{m_i\}_0^l, \{A_i\}_0^l, \{B_i\}_0^l,\ C)$		$\mathtt{Verifier}(X, Y, \{Z_i\}_1^l)$
$(r', r'', r_a, r_0, \dots, r_l) \leftarrow_{\$} \mathbb{Z}_q$		
$\forall_{i\in\{0,\dots,l\}}\ \tilde{A}_i = A_i^{r'}, \tilde{B}_i = B_i^{r'}$		
$\tilde{C} = C^{r'r''}$		
$\hat{t} = \hat{e}(X, \tilde{A}_0)^{r_a}\, \Pi_{i=0}^{l} \hat{e}(X, \tilde{B}_i)^{r_i}$	$\xrightarrow{\{\tilde{A}_i\}_0^l, \{\tilde{B}_i\}_0^l, \tilde{C}, \hat{t}}$	$\forall_{i\in\{1,\dots,l\}} \hat{e}(\tilde{A}_0, Z_i) \stackrel{?}{=} \hat{e}(g, \tilde{A}_i)$
		$\forall_{i\in\{0,\dots,l\}}\ \hat{e}(\tilde{A}_i, Y) \stackrel{?}{=} \hat{e}(g, \tilde{B}_i)$
$s_a = r_a - cr''$	$\xleftarrow{c}$	$c \leftarrow_{\$} \mathbb{Z}_q$
$\forall_{i\in\{0,\dots,l\}}\ s_i = r_i - cm_i r''$	$\xrightarrow{s_a, \{s_i\}_0^l}$	$\hat{t} \stackrel{?}{=} \hat{e}(g, \tilde{C})^c \hat{e}(X, \tilde{A}_0)^{s_a} \Pi_{i=0}^{l} \hat{e}(X, \tilde{B}_i)^{s_i}$

Figure: CL system: attribute verification.

Device based authentication

Device

Small hardware which *securely* store the authentication keys inside (e.g smartcards).

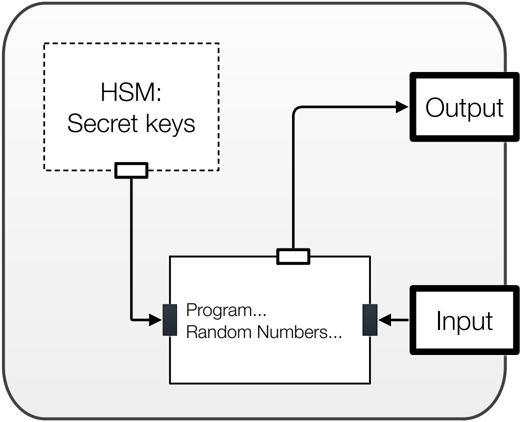
Adversaries Attacks

- tries to extract what was put inside,
- tries to manipulate what is inside,
- ...

Common threats:

- invasive attack,
- power analysis,
- emission of radiation,
- ...

Typical Device Architecture
Device Monolitic Architecture



Regular CL

Ephemeral Setup Attack

Attack on Issue Protocol

- set r_i,
- capture $s_i = r_i - cm_i$
- extract m_i

Attack on Verification Protocol

- set r_i, r'',
- capture $s_i = r_i - cm_i r''$
- extract m_i

Chosen Prover Ephemeral

Model

Security experiment

The experiment $\mathtt{Exp}_{\mathsf{IS}}^{\mathsf{CPE},\lambda,\ell}$:

Init stage System setup.

Query stage $\mathcal{A}$ runs a polynomial number ℓ of $\pi(\mathtt{User}^{\bar{x}}, ...)$ collecting view v, where $\bar{x}_i \in \{\bar{x}_1, \ldots, \bar{x}_\ell\}$ are injected

Impersonation stage $\mathcal{A}$ runs the protocol $\pi(\mathcal{A}(\mathsf{pk}, v), ...)$

Adversary advantage

The advantage of $\mathcal{A}$ in the experiment $\mathtt{Exp}_{\mathsf{IS}}^{\mathsf{CPE},\lambda,\ell}$ as **probability of acceptance** in the *impersonation stage*:

$$\mathbf{Adv}(\mathcal{A}, \mathtt{Exp}_{\mathsf{IS}}^{\mathsf{CPE},\lambda,\ell}) = \Pr[\pi(\mathcal{A}(\mathsf{pk}, v), \ldots) \to 1].$$

The identification scheme is secure if it is negligible in λ.

Security of identification scheme

$\mathcal{A}$ **probability of acceptance** is negligible in λ.

Solution
Shifting computation into exponent

Issue Protocol

instead

$$s_i = r_i - cm_i$$

we compute

$$S_i = \tilde{g}^{r_i - cm_i}$$

for

$$\tilde{g} = g^{\omega}$$

Verification Protocol

instead

$$s_i = r_i - cm_i r''$$

we compute

$$S_i = \overline{X}^{\,r_i - cm_i r''}$$

for

$$\overline{X} = X^{\omega}$$

Modified CL scheme

$\mathtt{User}(\{m_i\}_0^l)$		$\mathtt{Issuer}(x, y, \{z_i\}_1^l)$
$M = g^{m_0} \Pi_{i=1}^l Z_i^{m_i}$ $(r_0, \ldots, r_l) \leftarrow_\$ \mathbb{Z}_q$ $T = g^{r_0} \Pi_{i=1}^l Z_i^{r_i}$	$\xrightarrow{M,\ T}$	$(c, \omega) \leftarrow_\$ \mathbb{Z}_q,\ \tilde{g} = g^\omega$
	$\xleftarrow{c, \tilde{g}}$	
$\forall_{i \in \{0,\ldots,l\}}\ S_i = \tilde{g}^{r_i - c m_i}$	$\xrightarrow{\{S_i\}_0^l}$	$\widehat{e}(\tilde{g}, T/M^c) \stackrel{?}{=} \widehat{e}(S_0, g)\ \prod_{i=1}^l \widehat{e}(S_i, Z_i)$ $a_0 \leftarrow_\$ \mathbb{Z}_q,\ A_0 = g^{a_0}$ $\forall_{i \in \{1,\ldots,l\}}\ A_i = A_0^{z_i}$ $\forall_{i \in \{0,\ldots,l\}}\ B_i = A_i^y$
$\mathrm{Store}(\{A_i\}_0^l,\ \{B_i\}_0^l,\ C)$	$\xleftarrow{\{A_i\}_0^l,\ \{B_i\}_0^l,\ C}$	$C = A_0^x\ M^{a_0 xy}$

Figure: Credential issuance protocol for the modified system.

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Attribute Verification Protocol

User$(\{m_i\}_0^l, \{A_i\}_0^l, \{B_i\}_0^l, C)$ — **Verifier**$(X, Y, \{Z_i\}_1^l)$

$$(r', r'', r_a, r_0, \ldots, r_l) \leftarrow_\$ \mathbb{Z}_q$$
$$\forall_{i \in \{0,\ldots,l\}}\ \tilde{A}_i = A_i^{r'}$$
$$\forall_{i \in \{0,\ldots,l\}}\ \tilde{B}_i = B_i^{r'}$$
$$\tilde{C} = C^{r'r''}$$
$$\hat{t} = \widehat{e}(X, \tilde{A}_0)^{r_a} \Pi_{i=0}^{l} \widehat{e}(X, \tilde{B}_i)^{r_i}$$

User → Verifier: $\{\tilde{A}_i\}_0^l, \{\tilde{B}_i\}_0^l, \tilde{C}, \hat{t}$

Verifier:

$$\forall_{i \in \{1,\ldots,l\}}\ \widehat{e}(\tilde{A}_0, Z_i) \stackrel{?}{=} \widehat{e}(g, \tilde{A}_i)$$
$$\forall_{i \in \{0,\ldots,l\}}\ \widehat{e}(\tilde{A}_i, Y) \stackrel{?}{=} \widehat{e}(g, \tilde{B}_i)$$
$$(\omega, c) \leftarrow_\$ \mathbb{Z}_q$$
$$\overline{X} = X^{\omega}$$

Verifier → User: $c, \overline{X}$

$$s_a = r_a - cr''$$
$$\forall_{i \in \{0,\ldots,l\}}\ S_i = \overline{X}^{\,r_i - cm_i r''}$$

User → Verifier: $s_a, \{S_i\}_0^l$

Verifier:

$$\hat{t}^{\omega} \stackrel{?}{=} \widehat{e}(g^{\omega c}, \tilde{C})\widehat{e}(\overline{X}, \tilde{A}_0)^{s_a} \Pi_{i=0}^{l} \widehat{e}(S_i, \tilde{B}_i)$$

Figure: CL system: attribute verification.

Security Assumption

Assumption (modLRSW Assumption)

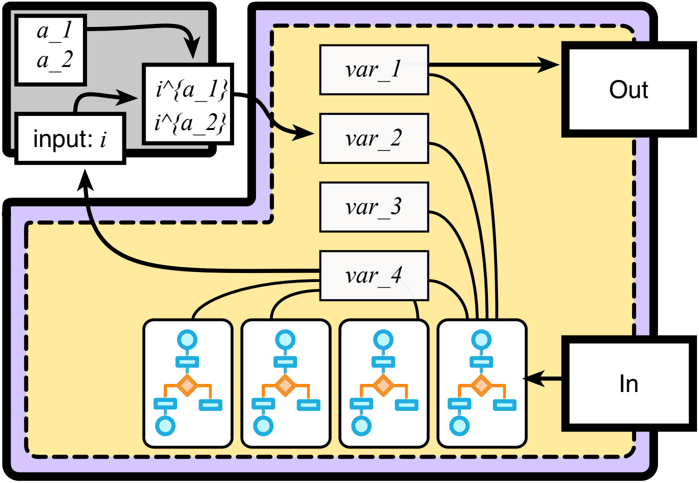
Let $\mathbb{G}$ *be a cyclic group with generator* g *and prime order* q*. Let* $A = g^a, B = g^b \in \mathbb{G}$*. Let* $\mathrm{Par} = (\mathbb{G}, g, q, A, B)$ *denote public parameters. Let* $\mathcal{O}_{AB}(\cdot)$ *be an oracle that on input* $m \in \mathbb{Z}_q$ *outputs* $(r,\ r^b,\ r^{a+mab})$*, where* r *is a random* $\mathbb{G}$ *element.*

$$\Pr\left[\begin{array}{c}(h^{m'}, (x,\ y,\ z)) \leftarrow \mathcal{A}^{\mathcal{O}_{AB}(\cdot)}(\mathrm{Par}, h) \\ \text{s.t. } m' \notin Q \wedge x \in \mathbb{G} \wedge y = x^b \wedge z = x^{a+m'ab}\end{array}\right] < \epsilon,$$

where $Q = \{m_i\}$ *denotes the set of messages* m_i *queried to* $\mathcal{O}_{A,B}(\cdot)$ *oracle.*

Device model

HSM with minimal functionality



Computations with unreliable devices

Possible Advantages

”Gray” Secure Module

1. user retain ”Gray” Secure Module
2. ”Gray” Secure Module – black box

”Yellow” Insecure Module

1. yellow part can be outsourced to unreliable devices
2. yellow part – white box

Adversary cannot:

- extract long term secret keys,
- impersonate user

Thanks

Thank You