(Remarks on) Security Proofs of Certificateless Signature Schemes

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Outline

Certificateless Signature Schemes

- Certificateless Public-Key Cryptography [Al-Riyami and Paterson, 2003]
- Main design goal: compromise between ID-Based Cryptography and traditional "PKI-Based" Cryptography:
  - Avoid IBC's key escrow
  - Avoid certificates altogether
- CL-PKC is a form of implicit key certification [Girault, 1991]

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- The original motivation was certificateless *encryption*:
  - Kept a few of IBC's features, such as "encryption into the future"
  - Certificateless signatures were presented as a "by-product"
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Certificateless Signature Schemes - Definition

- **Setup.** Run by the KGC to initialize the system. Given a security parameter 1^k, returns master keys, public and secret (mpk, msk).
- **PartialKeyGen.** Takes as input (mpk, msk) and the identity $ID \in \{0,1\}^*$, and outputs the partial private key D_{ID}.
- **UserKeysGen.** Takes as input mpk and generates the user's public key P_{ID} and corresponding secret value, x_{ID}.
- **CL-Sign.** Takes as input mpk, ID, (D_{ID}, x_{ID}) and a message M. Outputs a signature σ on M.
- **CL-Verify.** Takes as input mpk, ID, P_{ID}, M and the signature σ, and outputs `ACCEPT` if and only if σ is a valid signature by user U_{ID}, under public key P_{ID}, on M.

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Security of CLS Schemes

- No explicit certification $\rightarrow$ keys can be replaced.
- KGC is assumed not to replace public keys.
- Must take two types of adversaries into consideration:
  - **Type I.** Arbitrary adversaries that are able to replace public keys;
  - **Type II.** the KGC, who has access to the master secret.
- Formalized through two very similar games.

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Definition

Basic Game: Let $\mathcal{C}$ be the challenger algorithm and k be a security parameter:

1. $\mathcal{C}$ executes `Setup`(1^k) and obtains (mpk, msk);
2. $\mathcal{C}$ runs $\mathcal{A}$ on 1^k and mpk. During its run, $\mathcal{A}$ has access to the following oracles: `RevealPublicKey`, `RevealPartialKey`, `RevealSecretValue`, `ReplacePublicKey`, `QueryHash`, `Sign`;
3. $\mathcal{A}$ outputs (ID^*, M^*, σ^*).

$\mathcal{A}$ wins the game if the verification procedure of the CLS scheme accepts (ID^*, M^*, σ^*).

Security of CLS Schemes

Additional conditions to win the game:

- **Type I Adversaries.** $\mathcal{A}_I$ wins the game if both conditions below hold:
  - `Sign`(ID^*,M^*) was never queried;
  - `RevealPartialKey`(ID^*) was also never queried.
- **Type II Adversaries.** $\mathcal{A}_{II}$ wins the game if all conditions below hold:
  - `Sign`(ID^*,M^*) was never queried;
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Remark #1: *How do adversaries replace public keys?*

- Many schemes make the assumption that when $\mathcal{A}$ replaces a public key, it knows the corresponding secret value:
  - [Goya, 2006], [Huang et al., 2005], [Yap et al., 2006], [Du and Wen, 2007], [Choi et al., 2007].
- Deriving the secret value from the public key is hard.
- Therefore, this assumption implies that the only way to compute public keys is the "naive" way:
  1. Choose a secret value;
  2. compute a valid public key from the secret value, using the prescribed procedure for the scheme.
- This does not allow adversaries to pick a public key of their choice.

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To illustrate this issue, we use Goya & Terada's scheme:

- **Setup**
  1. Choose $e : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_T$.
  2. generators $P \in \mathbb{G}_1$, $Q \in \mathbb{G}_2$ such that $P = \psi(Q)$;
  3. compute $g = e(P, Q)$; choose $s \overset{R}{\leftarrow} \mathbb{Z}_p^*$; compute $Q_{pub} = sQ$;
  4. choose hash functions $H_1 : \{0,1\}^* \rightarrow \mathbb{Z}_p^*$ and $H_2 : \{0,1\}^* \times \{0,1\}^* \times \mathbb{G}_T \times \mathbb{G}_T \rightarrow \mathbb{Z}_p^*$.
- **PartialKeyGen.** $D_A = \frac{1}{H_1(ID_A)+s} P$.
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- **CL-Sign.** Pick a random $r \in \mathbb{Z}_p^*$; compute $U = g^r \in \mathbb{G}_T$; compute $h = H_2(M, ID_A, N_A, U) \in \mathbb{Z}_p^*$, and $S = (r + ht_A)D_A \in \mathbb{G}_1$. The signature is $\sigma = (S, h)$.
- **CL-Verify.** Compute $U' = e[S, H_1(ID_A)Q + Q_{pub}](N_A)^{-h}$; accept if and only if

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- Correctness of the scheme:

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&= e[(r + ht_A)D_A, h_1 Q + Q_{pub}](N_A)^{-h} \\
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&= e[P, Q]^{r + ht_A} g^{-t_A h} \\
&= g^r g^{ht_A} g^{-t_A h} = g^r = U
\end{aligned}
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- Based on Barreto et al.'s IBS [Barreto et al., 2005]
- Very efficient: only one pairing for verification
- Thought to be provably secure:
  - Actually insecure as the following attack shows

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Forging Goya/Terada Signatures.

- Given the target identity ID_A:
  1. Choose a random $t_A \xleftarrow{r} \mathbb{Z}_q^*$ and compute
     $$N_A = (e(P, Q_{pub})g^{H_1(ID_A)})^{t_A} = (g^s g^{H_1(ID_A)})^{t_A} = g^{t_A(s+H_1(ID_A))};$$
  2. Replace ID_A's public key with N_A
- Now, to a sign message M:
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- $\mathcal{A}$ does not know x, $N_A = g^x$

Remark #1: *How do adversaries replace public keys?*

Forging Goya/Terada Signatures.

- Given the target identity ID_A:
  1. Choose a random $t_A \xleftarrow{r} \mathbb{Z}_q^*$ and compute
  $$N_A = (e(P, Q_{pub})g^{H_1(ID_A)})^{t_A} = (g^s g^{H_1(ID_A)})^{t_A} = g^{t_A(s+H_1(ID_A))};$$
  2. Replace ID_A's public key with N_A
- Now, to a sign message M:
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Remark #2: *The Oracle Replay Technique and CLS*

- The Oracle Replay Technique was proposed in [Pointcheval and Stern, 2000] to prove the security of *generic* signature schemes:
  - Schnorr, variants of ElGamal, schemes from Fiat-Shamir heuristics.
- A signature scheme $\mathcal{S}$ is said to be generic if, given the input message m, it produces triples (r, h, σ), where:
  - r takes its value randomly within a large set;
  - h is the hash value of m, r;
  - σ depends only on r, m and h.
- **Forking Lemma.** If an adversary $\mathcal{A}$ can forge signatures then it's possible to replay a successful execution and (with non-negligible probability) obtain a pair of related forgeries (r, h, σ) and (r, h', σ') where $h' \neq h$.

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- A pair of signatures (r, h, σ) and (r, h', σ') where $h' \neq h$ is usually enough to compute private keys (in generic schemes).
  - A Schnorr signature is $\sigma = k + hx \mod q$, and $r = g^k$.
  - If we also know $\sigma' = k + h'x \mod q$, then:

$$\begin{aligned}(\sigma' - \sigma)(h' - h)^{-1} &= (k + h'x - k - hx)((h' - h)^{-1}) \\ &= x(h' - h)(h' - h)^{-1} \\ &= x \mod q,\end{aligned}$$

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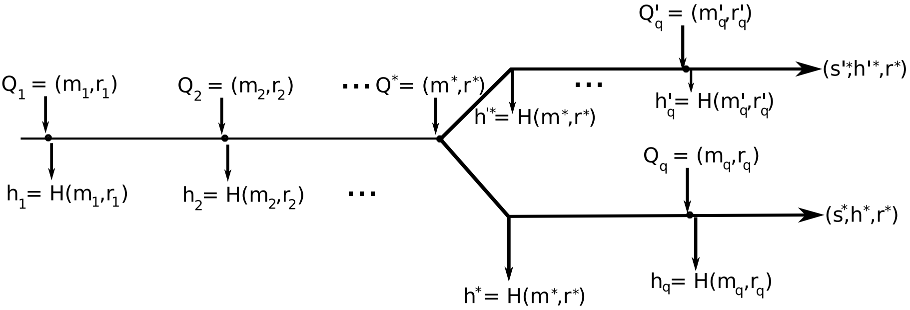
The Oracle Replay Technique can be illustrated as follows:



- (s^*, h^*, r^*) is the first forgery, $(s^{*'}, h^{*'}, r^*)$ is the second.

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- What guarantees that r will be the same in both forgeries?
  - It's in the $\mathcal{Q}^*$ hash query so it must be chosen before the execution "forks"
- But in CLS keys can be replaced
- So, in a CLS, what guarantees that the public key will be the same in both executions?
  - Nothing, *unless it is also in the hash query*
- Thus, we define the notion of *CL-Generic* Signature scheme:
- A CLS scheme $\mathcal{S}$ is said to be CL-Generic if, given the input message M, it produces triples (r, h, σ), where:
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  - Later found insecure by Huang et al.
- Signing procedure: $r \xleftarrow{r} \mathbb{Z}_p^*$; $u = e(rP, P)$; $S = H_2(M, u)t_A D_A + rP$.
  - *Insecure.*
- Change to: $r \xleftarrow{r} \mathbb{Z}_p^*$; $u = e(rP, P)$; $S = H_2(M, u, \boxed{PK_{ID}})t_A D_A + rP$.
  - *Secure.* Proof by the Oracle Replay Technique.
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Summary of CLS Schemes

Scheme	Sign	Verify	Status
[Al-Riyami and Paterson, 2003]	1	4	*Broken*
[Huang et al., 2005]	2	5	**OK**
[Castro and Dahab, 2007]	1	4	**OK**
[Li et al., 2005]	0	4	**OK**
[Gorantla and Saxena, 2005]	0	2	*Broken*
[Yap et al., 2006]	0	2	*Broken*
[Zhang et al., 2006]	0	4	**OK**
[Goya, 2006]	0	1	*Broken*
[Liu et al., 2006]	0	6	**OK**
[Choi et al., 2007]	0	1	*Unknown*
[Choi et al., 2007]	0	2	*Unknown*
[Du and Wen, 2007]	0	1	*Unknown*
Castro & Dahab [soon on ePrint]	0	3	**OK**

The cost of signing and verifying is expressed in number of pairings.

Concluding Remarks

We discussed two common pitfalls in the security proofs of CLS schemes:

1. **Knowledge of secret values related to replaced public-keys:**
   - Assumption used in the proofs of too many schemes
   - Leads to attack on Goya/Terada
   - Puts security of [Du and Wen, 2007] and [Choi et al., 2007] in doubt
2. **The use of the Replay Technique:**
   - Efficient, provably secure, correction of Al-Riyami/Paterson
   - Security proofs of a previously unproven scheme [Li et al., 2005]
   - General guideline for constructing CLS schemes

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Crypto at UNICAMP

- R. Dahab and Julio López.
- Efficient implementation of elliptic curve algorithms, pairings, crypto for sensor networks, formal methods.
- National (Barreto, van de Graaf) and international collaboration (Menezes, Hankerson, Scott, Koç).
- Yearly Workshop on Crypto Algorithms and Protocols (WCAP).
- National PKI working groups.