Secure digital certificates with a blockchain protocol

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Trento, 10^{th} February 2017

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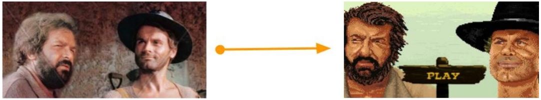
Digital identities

In the digital world real people are identified with digital identities.



In a PKI (Public Key Infrastructure), to every digital identy corresponds a pair of cryptographic keys:

- the PUBLIC KEY, which is publicly known;
- the PRIVATE KEY, which must be kept secret.

Digital certificates

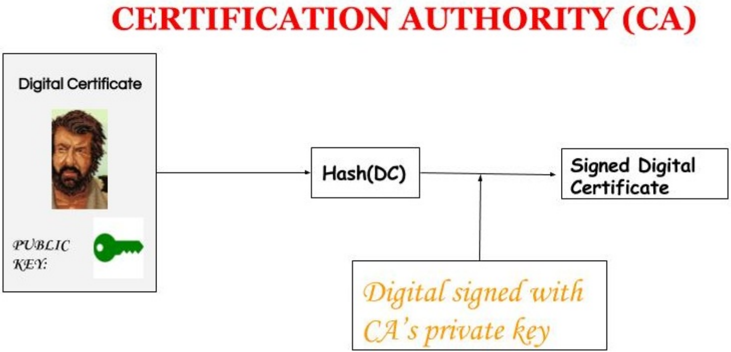
Digital identities are bound with corresponding public keys through **digital certificates**.

PKI

A PKI is a set of roles, policies, and procedures needed to create, manage, distribute, use, store, and revoke digital certificates.

X.509

X.509 is a widespread standard to manage digital certificates.



Mutually untrusted parties communicate through a **centralized system**.

Blockchain technology

The **Blockchain technology** is suitable for decentralized systems with mutually untrusted parties.

In 2015 Prof. Sead Muftic (KTH) proposed a blockchain-based protocol that allows distribution and management of digital certificates (linking a subject with his public key) without the need of CAs.

Muftic, Sead. "*Bix certificates: Cryptographic tokens for anonymous transactions based on certificates public ledger.* Ledger 1 (2016): 19-37.

BIX Certification Infrastructure (BCI)

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2. during the registration, a new user receives a **unique identifier**, called *BIX Identifier*;
3. after the registration, a new user interacts with the system via a *BCI Agent*, a **PC or smartphone application**.

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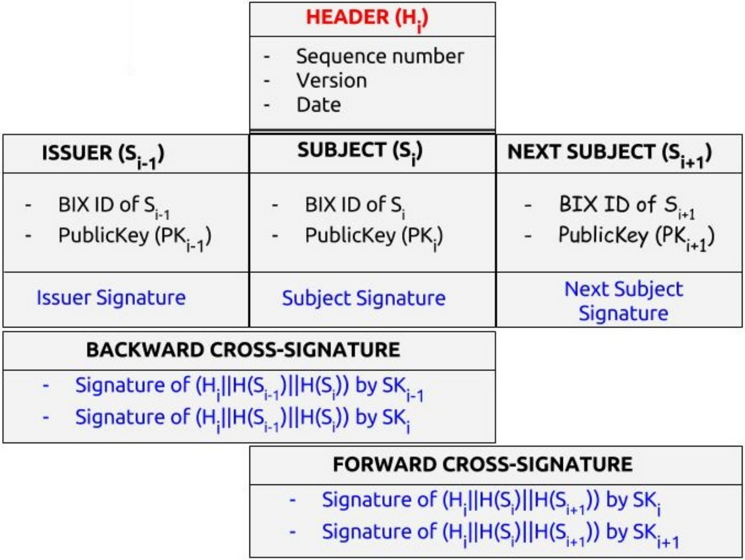
After the registration, a new user can request the **issuing of a BIX certificate**, to be added to a preexisting *BCL* or to a new one.

BIX Certificates



Header (H_i)

- **Sequence number**: certificate's identification number, i, of the certificate (position in the BCL);
- **Version**: code designating the type of the BIX certificate;
- **Date/time**: date and time of issuance of the certificate.

Issuer, Subject and Next-Subject

Subject (S_i)

- **Subject BIX ID**: BIX Identifier of the user who owns the certificate;
- **Date/time**: date and time of creation of user's public/private key pair;
- **Algorithm identifier**: kind of asymmetric cryptographic scheme;
- **Public key**: cryptographic public key, PK_i, of the owner of the certificate.

Subject signature: digital signature over the Subject field via the private key SK_i associated to PK_i.

The Issuer (S_{i-1}) and the Next-Subject (S_{i+1}) are the Subject of the previous and the next certificate in the BCL.

Backward and Forward cross-signatures

BIX certificates are bound together through the:

- **Backward cross-signature**: contains two signatures, created by
  1. the Issuer S_{i-1},
  2. the Subject S_i,

  over the concatenation of the Header H_i, the hash of the Issuer $H(S_{i-1})$ and the hash of the Subject $H(S_i)$.

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- **Forward cross-signature**: contains two signatures, created by
  1. the Subject S_i,
  2. the Next Subject S_{i+1},

  over the concatenation of the Header H_i, the hash of the Subject $H(S_i)$ and the hash of the Next Subject $H(S_{i+1})$.

Special Certificates

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Tail certificate

- last certificate of a specific *BCL*;
- same structure of a standard certificate, but some fields are not populated (next user is still unknown).

The user that owns the tail certificate will become the issuer for the next certificate.

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4. the new user receives three certificates, completes them and requests all the *BCL* to the system in order to check its integrity;
5. he broadcasts to the system the completed certificates.

Certificate exchange

When a user S_i wants to perform a secure communication/transaction with a second user S_j, he sends his certificate c_i to S_j and requests her certificate c_j.

User S_i **checks certificate** c_j in two steps:

1. he verifies the Subject signature, the Issuer signature and also the Backward Cross-Signature of her certificate c_j.
2. S_i verifies that c_j is in the BCL, which is available in his local storage or must be updated.

Attack scenario - 1

An attacker tries to attach its certificate to a preexisting *BCL* without interacting properly with the last user of the *BCL*.

Attack scenario - 2

An attacker tries to corrupt a *BCL* built upon a root certificate of a preexisting *BCL*, resulting in another *BCL* that may re-distribute as a proper one.

Security of cryptographic schemes

Cryptographic schemes base their security upon the computational difficulty of solving some well-known mathematical problems.

Example
The RSA scheme bases its security upon the difficult to efficiently factorize huge integers.

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The fact that to break a cryptographic scheme is **necessary to solve** a well-known mathematical problem is tipically only an unproven assumption.

Formal proof of security of a protocol

Goal

Model the possible attacks on the protocol and prove that a succesfull breach implies the solution of a hard, well-known mathematical problem.

If the mathematical problem cannot be solved, a **contradiction is reached** and the protocol is secure.

Some protocol's parameters must be chosen in such a way the problem guaranteeing the security becomes almost impossible to be solved in reasonable time.

Formal proof of security of a protocol

Adversary (A)

He tries to break the protocol making queries to C

Challenger (C)

They run the algorithm of the protocol.

Queries: private keys, encryption of specific plaintexts, decryption of specific ciphertexts...

Adversary's target

Recover a key, forge a digital signature,...

Formal proof of security of a protocol

General path

1. an *Assumption* is made: there is no polynomial-time algorithm solving a mathematical problem P with non-negligible probability;
2. the problem to break the protocol is reduced to solve the problem P;
3. if A breaks the protocol, then he is able to solve with non-negligible probability p_1 the mathematical problem.
    - a simulator S is build;
    - given an istance of P, S runs a challenger C that interacts with A, simulating the protocol correctly with non-negligible probability p_2;
    - S solves P with non-negligible probability (usually $p_1 p_2$).

Hash functions

Messages to be signed, seen as binary strings, are compressed via hash functions.

Definition (Hash functions)

A hash function H is a function of the form:

$$\begin{array}{rccc} H: & \{0,1\}^* & \to & \{0,1\}^\ell \\ & m & \mapsto & H(m) \end{array}$$

The image $H(m)$ is called *digest*.

Cryptographic hash functions

A hash function H is said cryptographic if some security assumptions holds. For example:

Definition (Collision resistance for R)

A hash function H is collision resistance if, given $R \subset \{0,1\}^r$, there is no polynomial-time algorithm finding distinct $m_1, m_2 \in L$ such that $H(m_1) = H(m_2)$ with non-negligible probability.

Examples

- SHA256, with digests of 256 bits;

ECDSA

The **Elliptic Curve Digital Signature Algorithm** (ECDSA) is a Digital Signature Scheme, i.e. an assymetric cryptographic scheme for producing and verifying digital signatures.

It consists of three algorithms:

1. *Key Generation*
2. *Signing*
3. *Verifying*

Key Generation

$$KeyGen(\kappa) \rightarrow (SK, PK)$$

Given

- a **security parameter** κ

it generates:

- a **public key** PK, that is published,
- a **secret key** SK.

Signing

$$Sign(m, SK) \rightarrow s$$

Given

- a **message** m,
- the **secret key** SK

it computes

- a **digital signature** s of m.

Verifying

$$Ver(m, s, PK) \rightarrow r$$

Given

- a **message** m,
- a **signature** s,
- the **public key** PK

it outputs

- the **result** $r \in \{True, False\}$ that says whether or not s is a valid signature of m computed by the secret key corresponding to PK.

Assumption on ECDSA

Definition (Security of a Digital Signature Scheme)

A Digital Signature Scheme DSS is said **secure** if an adversary A, given a public key PK - corresponding to a secret key SK - and some digital signatures $s_i = Sign(m_i, SK)$, is not able to identify a message $m \neq m_i \ \forall i$ and compute s such that $Ver(m, s, PK) = True$ in polynomial-time complexity with non-negligible probability.

We assume that ECDSA is **secure** since it bases its security upon the **Elliptic Curve Discrete Logarithm Problem** (ECDLP).

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Nowadays, there is not a polynomial-time algorithm for solving the ECDLP.

Theorem 1

Theorem (Longo, _ , Sala, Rinaldo - 2016)

Let A be an adversary that manages to succesfully perform the **first attack** *with probability ϵ, then a simulator S might be built that, with probability at least ϵ, either solves the Collision Problem for the hash function relatively to the set L of all possible Subject fields, or breaks the Digital Signature Scheme.*

Corollary 1

Corollary (Longo, _ , Sala, Rinaldo - 2016)

If the Digital Signature Scheme used in Muftic's protocol is secure and the hash function is collision resistant for the set L, where L is the set of all possible Header fields, then the BIX protocol is secure against the first attack.

Theorem 2

Theorem (Longo, _ , Sala, Rinaldo - 2016)

Let A be an adversary that manages to succesfully perform the **second attack** *with probability ϵ, then a simulator S might be built that with probability at least $\frac{\epsilon}{n-1}$ either solves the Collision Problem for the hash function relatively to the set L of all possible Subject fields, or breaks the Digital Signature Scheme, where n is the length of the BCL that S gives to A.*

Corollary 2

Corollary (Longo, _ , Sala, Rinaldo - 2016)

If the Digital Signature Scheme used in Mutftic's protocol is secure and the hash function is collision resistant for the set L of all possible Subject fields, then the BIX protocol is secure against the second attack.

Thanks for your attention!