Chapter 7
Cryptographic Protocols

- Authentication
- Key exchange
- Needham-Schroeder / Otway-Rees
- Kerberos
- X.509

Introduction

- Definition: A ***cryptographic protocol*** is defined as a series of steps and message exchanges between multiple entities in order to achieve a specific security objective

- Properties of a protocol (in general):
  - Everyone involved in the protocol must know the protocol and all of the steps to follow in advance
  - Everyone involved in the protocol must agree to follow it
  - The protocol must be unambiguous, that is every step is well defined and there is no chance of misunderstanding
  - The protocol must be complete, i.e. there is a specified action for every possible situation
- Additional property of a cryptographic protocol:
  - It should not be possible to do or learn more than what is specified in the protocol

Applications of Cryptographic Protocols

- Key exchange
- Authentication
  - Data origin authentication
  - Entity authentication
- Combined authentication and key exchange

treated in this course

- Secret splitting
- Secret sharing
- Time-stamping
- Key escrow (ensuring that only an authorized entity can recover keys)
- Zero-Knowledge proofs (proof of knowledge of an information without revealing the information)
- Blind signatures (useful for privacy-preserving time-stamping services)
- Secure elections
- Electronic money

Tasks of Key Management

- *Generation:*
  - It is crucial to security, that keys are generated with a truly random or at least a pseudo-random generation process (see below)
  - Otherwise, an attacker might reproduce the key generation process and easily find the key used to secure a specific communication
- *Distribution:*
  - Distribution of some initial keys usually has to be performed manually / out of band
  - Session key distribution is generally performed during an authentication exchange
  - Examples: Diffie-Hellman, Otway-Rees, Kerberos, X.509
- *Storage:*
  - Keys, especially authentication keys, should be securely stored:
    - either encrypted with a hard-to-guess pass-phrase, or better
    - in a secure device like a smart-card

Tasks of Key Management

- *Recovery:*
    - If a key has been lost (e.g. defect smart-card, floppy, accidentally erased) it should be possible to recover it, in order to avoid loss of data
    - Key recovery is not to be mixed up with key escrow:

      “If I can get my key back it’s key recovery,
      if you can get my key back it’s key escrow...”
- *Revocation:*
    - If a key has been compromised, it should be possible to revoke that key, so that it can no longer be misused (cf. X.509)
- *Destruction:*
    - Keys that are no longer used (e.g. old session keys) should be safely destroyed (cf. media security)
- *Escrow:*
    - Mechanisms and architectures that shall allow government agencies (and only them) to obtain session keys in order to be able to eavesdrop on communications / to read stored data for law enforcement purposes

Key Exchange

- The Diffie-Hellman protocol is our first example of a cryptographic protocol for key exchange
  - Please note, that it does not realize any authentication – neither Alice nor Bob know after a protocol run, with whom they have exchanged a key
  - However, this separation of key exchange and authentication of the exchange has a big advantage, as it allows to guarantee the property of *perfect forward secrecy (PFS)*:
    - If a key exchange ensures PFS, then a compromise of one key in the future will not allow to compromise any data that has been protected with other keys exchanged before that compromise.
    - Example: imagine Alice and Bob both sign the data exchanged to compute s_k with their private keys. Even the compromise of a private key in the future will not allow to decrypt recorded data that has been protected with s_k

Data Origin Authentication

- Definition: ***Data origin authentication*** is the security service that enables entities to verify that a message has been originated by a particular entity and that it has not been altered afterwards; a synonym for this service is ***message authentication***

- The relation of data integrity to cryptographic protocols is twofold:
  - There are cryptographic protocols to ensure data integrity. As a rule they comprise just one protocol step and are, therefore, not very “exciting”:
    - Example 1: assume, that everybody knows Alice’s public RSA key and can be sure to know really Alice’s key, then Alice can insure data integrity of her messages by signing them with her private key
    - Example 2: Alice can as well compute an MDC over her message and append the MDC encrypted with her private key to the message
  - Data integrity of messages exchanged is often an important property in cryptographic protocols, so data integrity is a building block to cryptographic protocols

Entity Authentication

- Definition: ***Entity authentication*** is the security service, that enables communication partners to verify the identity of their peer entities.

- Entity authentication is the most fundamental security service, as all other security services build upon it
- In general it can be accomplished by various means:
  - *Knowledge:* e.g. passwords
  - *Possession:* e.g. physical keys or cards
  - *Immutable characteristic:* e.g. biometric properties like fingerprint, etc.
  - *Location:* evidence is presented that an entity is at a specific place (example: people check rarely the authenticity of agents in a bank)
  - *Delegation of authenticity:* the verifying entity accepts, that somebody who is trusted has already established authentication
- In communication networks, direct verification using the above means is difficult or insecure → need for cryptographic protocols

Entity Authentication

- The main reason, why entity authentication is more than an exchange of (data-origin-) authentic messages is ***timeliness:***
  - Even if Bob receives authentic messages from Alice during a communication, he can not be sure, if:
    - Alice is actually participating in the communication *in this specific moment,* or if
    - Eve is *replaying* old messages from Alice
  - This is of specific significance, when authentication is only performed at connection-setup time:
    - Example: transmission of a (possibly encrypted) PIN when logging in
  - Two principle means to ensure timeliness in cryptographic protocols:
    - *Timestamps* (require more or less synchronized clocks)
    - *Random numbers* (challenge-response exchanges)
- Most authentication protocols do also establish a secret session key for securing the session following the authentication exchange

Entity Authentication - Categories

- ***Arbitrated authentication****:* an arbiter, also called ***trusted third party (TTP)*** is directly involved in every authentication exchange
  - Advantages: allows two parties A and B to authenticate to each other without knowing any pre-established secret and even if A and B do not know each other, symmetric cryptography can be used
  - Drawbacks: TTP can become a bottleneck and availability of TTP is critical; the TTP can monitor all authentication activity

- ***Direct authentication****:* A and B directly authenticate to each other
  - Advantages: no online participation of a third party is required and no possible performance bottleneck is introduced
  - Drawbacks: requires asymmetric cryptography or pre-established secret keys

Some Notation...

Notation	Meaning
r_A	Random value chosen by A
t_A	Timestamp generated by A
$(m_1, ..., m_n)$	Concatenation of messages $m_1, ..., m_n$
$A \rightarrow B: m$	A sends message m to B
$\{m\}_K$	Message m encrypted with key K, synonym for $E(K, m)$
$H(m)$	MDC over message m, computed with function H
$A[m]$	Shorthand notation for $(m, \{H(m)\}_{-K_A})$
CA_A	Certification Authority of A (explained later)
$Cert_{-CK_{CA}}(+K_A)$	Certificate of CA for public key $+K_A$ of A, signed with private certification key $-CK_{CA}$ (explained later)
CA<<A>>	Shorthand notation for $Cert_{-CK_{CA}}(+K_A)$

The Needham-Schroeder Protocol

- Invented in 1978 by Roger Needham and Michael Schroeder [Nee78a]
- The protocol relies on symmetric encryption and makes use of a *trusted third party (TTP)*
- Assume that *TTP* shares secret keys $K_{A,TTP}$ and $K_{B,TTP}$ with Alice and Bob, respectively:
  - *A* generates a random number r_A and sends the following message:

    1.) $A \rightarrow TTP: (A, B, r_A)$
  - *TTP* generates a session key $K_{A,B}$ for secure communication between *A* and *B* and answers to *A*:

    2.) $TTP \rightarrow A: \{r_A, B, K_{A,B}, \{K_{A,B}, A\}_{K_{B,TTP}}\}_{K_{A,TTP}}$
  - A decrypts the message and extracts $K_{A,B}$. She confirms that r_A is identical to the number generated by her in the first step, thus she knows the reply is a fresh reply from TTP. Then she sends to B:

    3.) $A \rightarrow B: \{K_{A,B}, A\}_{K_{B,TTP}}$

The Needham-Schroeder Protocol

- Needham-Schroeder protocol definition (continued):
  - Bob decrypts the message and obtains $K_{A,B}$. He then generates a random number r_B and answers to Alice:

    4.) $B \rightarrow A: \{r_B\}_{K_{A,B}}$
  - Alice decrypts the message, computes r_B - 1 and answers with:

    5.) $A \rightarrow B: \{r_B\text{-}1\}_{K_{A,B}}$
  - Bob decrypts the message and verifies that it contains r_B - 1
- Discussion:
  - The exchange of r_B and r_B-1 is supposed to ensure that an attacker, trying to impersonate Bob, can not perform a full protocol run with replayed messages
  - However, as old session keys $K_{A,B}$ remain valid, an attacker, Eve, who manages to get to know a session key $K_{A,B}$ can later use this to impersonate as Alice:

    1.) $E \rightarrow B: \{K_{A,B}, A\}_{K_{B,TTP}}$

    2.) $B \rightarrow A: \{r_B\}_{K_{A,B}}$ Eve has to intercept this message

    3.) $E \rightarrow B: \{r_B\text{-}1\}_{K_{A,B}}$

    So, even though she doesn't know $K_{A,TTP}$ nor $K_{B,TTP}$ Eve impersonates as Alice!

The Otway-Rees Protocol

- The security problem described above as well as some others were addressed by Needham and Schroeder. Their solution [Nee87a] is essentially the same like the one proposed by Otway and Rees in the same journal [Otw87a]:
  - Alice generates a message containing an index number i_A, her name A, Bobs name B, and the same information plus an additional random number r_A encrypted with the key $K_{A,TTP}$ she shares with TTP, and sends this message to Bob:

    1.) $A \rightarrow B: (i_A, A, B, \{r_A, i_A, A, B\}_{K_{A,TTP}})$
  - Bob generates a random number r_B, encrypts it together with i_A, A, and B using the key $K_{B,TTP}$ he shares with TTP and sends the message to TTP:

    2.) $B \rightarrow TTP: (i_A, A, B, \{r_A, i_A, A, B\}_{K_{A,TTP}}, \{r_B, i_A, A, B\}_{K_{B,TTP}})$
  - TTP generates a new session key $K_{A,B}$ and creates two encrypted messages, one for Alice and one for Bob, and sends them to Bob:

    3.) $TTP \rightarrow B: (i_A, \{r_A, K_{A,B}\}_{K_{A,TTP}}, \{r_B, K_{A,B}\}_{K_{B,TTP}})$

The Otway-Rees Protocol

- Otway-Rees protocol definition (continued):
  - Bob decrypts his part of the message, verifies r_B and sends Alice’s part of the message to her:

    4.) $B \rightarrow A: (i_A, \{r_A, K_{A,B}\}_{K_{A,TTP}})$
  - Alice decrypts the message and checks if i_A and r_A have not changed during the exchange. If not, she can be sure that TTP has send her a fresh session key $K_{A,B}$ for communication with Bob. If she now uses this key in an encrypted communication with Bob, she can be sure of his authenticity.
- Discussion:
  - The index number i_A prevents against replay attacks. However, this requires that TTP checks if i_A is bigger than the last i_A he received from Alice.
  - As TTP will just generate the two messages if both parts of the message he receives contain the same index number i_A and names A, B, Alice and Bob can be sure that both of them have authenticated to TTP during the protocol run.

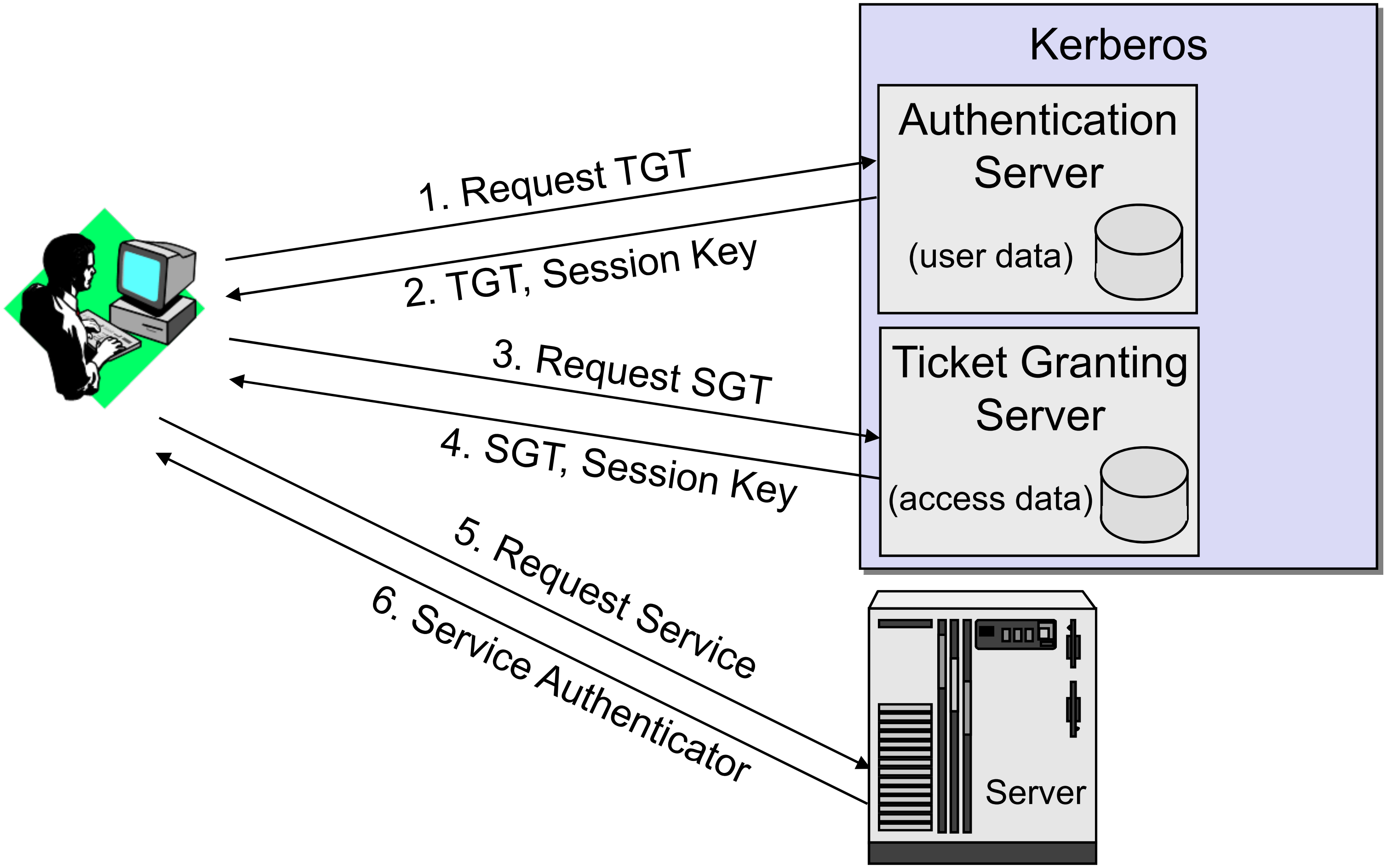
Kerberos

- Kerberos is an authentication and access control service for work-station clusters that was designed at the MIT during the late 1980s
- Design goals:
  - *Security:* eavesdroppers or active attackers should not be able to obtain the necessary information to impersonate a user when accessing a service
  - *Reliability:* as every use of a service requires prior authentication, Kerberos should be highly reliable and available
  - *Transparency:* the authentication process should be transparent to the user beyond the requirement to enter a password
  - *Scalability:* the system should be able to support a large number of clients and servers
- The underlying cryptographic primitive of Kerberos is symmetric encryption (Kerberos V. 4 uses DES, V. 5 allows other algorithms)
- A good tutorial on the reasoning beyond the Kerberos design is given in [Bry88a], that develops the protocol in a series of fictive dialogues

Kerberos – Principles

- The basic usage scenario of Kerberos is a user, *Alice,* who wants to access one or more different services, that are provided by different servers S1, S2, ... connected over an insecure network
- Kerberos deals with the following security aspects of this scenario:
  - *Authentication:* Alice will authenticate to an *authentication server (AS)* who will provide a temporal permit to demand access for services. This permit is called *ticket-granting ticket* (*$Ticket_{TGS}$*) and is comparable to a temporal passport.
  - *Access control:* by presenting her *$Ticket_{TGS}$* Alice can demand a *ticket granting server (TGS)* to obtain access for a service provided by a specific server *S1*. The TGS decides if the access will be permitted and answers with a service granting ticket *$Ticket_{S1}$* for server *S1*.
  - *Key exchange:* the authentication server provides a session key for communication between Alice and TGS and the TGS provides a session key for communication between Alice and *S1*. The use of these session keys also serves for authentication purposes.

Kerberos – An example session



Accessing a Service with Kerberos Version 4 - Protocol Overview

Kerberos – An example session

- The user logs on his workstation and requests to access a service:
  - The workstation represents him in the Kerberos protocol and sends the first message to the authentication server *AS,* containing his name, the name of an appropriate ticket granting server *TGS* and a timestamp t_A:

    1.) $A \rightarrow AS: (A, TGS, t_A)$
- The AS verifies, that A may authenticate itself to access services, generates the key K_A out of A's password (which is known to him), extracts the workstation address $Addr_A$ of the request, creates a ticket granting ticket $Ticket_{TGS}$ and a session key $K_{A,TGS}$, and sends the following message to A:

  2.) $AS \rightarrow A: \{K_{A,TGS}, TGS, t_{AS}, LifetimeTicket_{TGS}, Ticket_{TGS}\}_{K_A}$

  with $Ticket_{TGS} = \{K_{A,TGS}, A, Addr_A, TGS, t_{AS}, LifetimeTicket_{TGS}\}_{K_{AS,TGS}}$
- Upon receipt of this message, the workstation asks Alice to type in her password, computes the key K_A from it, and uses this key to decrypt the message. If Alice does not provide her "authentic" password, the extracted values will be "garbage" and the rest of the protocol will fail

Kerberos – An example session

- Alice creates a so-called *authenticator* and sends it together with the ticket-granting ticket and the name of server S1 to TGS:

  3.) $A \rightarrow TGS: (S1, Ticket_{TGS}, Authenticator_{A,TGS})$

  with $Authenticator_{A,TGS} = \{A, Addr_A, t'_A\}_{K_{A,TGS}}$

- Upon receipt, *TGS* decrypts $Ticket_{TGS}$, extracts the key $K_{A,TGS}$ from it and uses this key to decrypt $Authenticator_{A,TGS}$. If the name and address of the authenticator and the ticket are matching and the timestamp t'_A is still fresh, it checks if A may access the service S1 and creates the following message:

  4.) $TGS \rightarrow A: \{K_{A,S1}, S1, t_{TGS}, Ticket_{S1}\}_{K_{A,TGS}}$

  with $Ticket_{S1} = \{K_{A,S1}, A, Addr_A, S1, t_{TGS}, LifetimeTicket_{S1}\}_{K_{TGS,S1}}$

- Alice decrypts the message and does now hold a session key for secure communication with *S1*. She now sends a message to *S1* to show him her ticket and a new authenticator:

  5.) $A \rightarrow S1: (Ticket_{S1}, Authenticator_{A,S1})$

  with $Authenticator_{A,S1} = \{A, Addr_A, t''_A\}_{K_{A,S1}}$

Kerberos – An example session

- Upon receipt, *S1* decrypts the ticket with the key $K_{TGS,S1}$ he shares with *TGS* and obtains the session key $K_{A,S1}$ for secure communication with A. Using this key he checks the authenticator and responds to A:

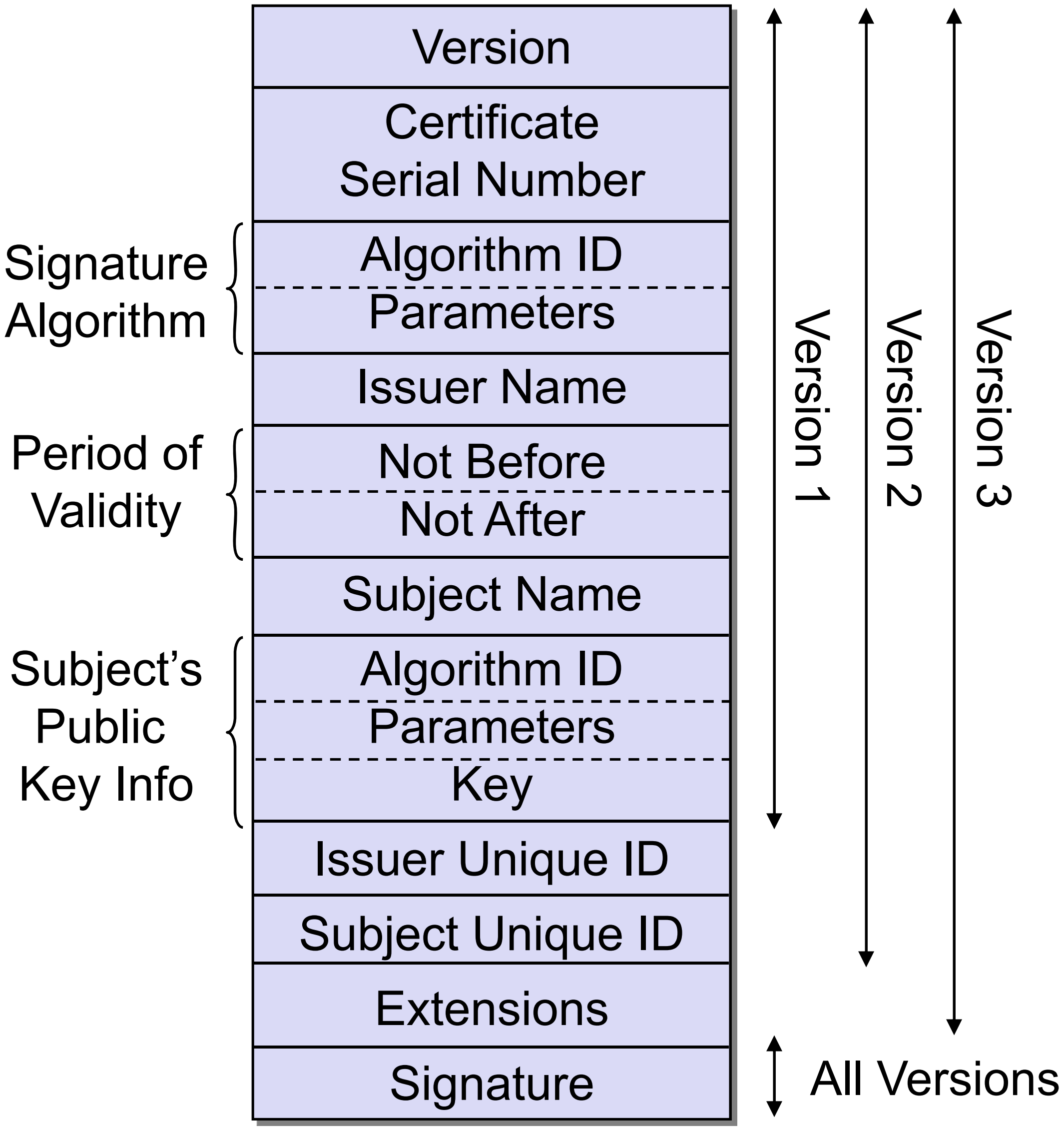
  6.) $S1 \rightarrow A: \{t''_A + 1\}_{K_{A,S1}}$

- By decrypting this message and checking the contained value, Alice can verify, that she is really communicating with *S1*, as only he (besides *TGS*) knows the key $K_{TGS,S1}$ to decrypt $Ticket_{S1}$ which contains the session key $K_{A,S1}$, and so only he is able to decrypt $Authenticator_{A,S1}$ and to answer with $t''_A + 1$ encrypted with $K_{A,S1}$

X.509 – Introduction

- X.509 is an international recommendation of ITU-T and is part of the X.500-series defining directory services:
  - The first version of X.509 was standardized in 1988
  - A second version standardized 1993 resolved some security concerns
  - A third version was drafted in 1995
- X.509 defines a framework for provision of authentication services, comprising:
  - ***Certification*** of public keys and certificate handling:
    - Certificate format
    - Certificate hierarchy
    - Certificate revocation lists
  - Three different dialogues for direct ***authentication***:
    - One-way authentication, requires synchronized clocks
    - Two-way mutual authentication, still requires synchronized clocks
    - Three-way mutual authentication entirely based on random numbers

X.509 – Public Key Certificates



Version

Certificate Serial Number

Signature Algorithm: Algorithm ID, Parameters

Issuer Name

Period of Validity: Not Before, Not After

Subject Name

Subject's Public Key Info: Algorithm ID, Parameters, Key

Issuer Unique ID

Subject Unique ID

Extensions

Signature

Version 1

Version 2

Version 3

All Versions

- A *public key certificate* is some sort of passport, certifying that a public key belongs to a specific name
- Certificates are issued by *certification authorities (CA)*
- If all users know for sure the public key of the CA, every user can check every certificate issued by this CA
- Certificates can avoid online-participation of a TTP
- The security of the private key of the CA is crucial to the security of all users!

X.509 – Public Key Certificates

- Notation of a certificate binding a public key $+K_A$ to user A issued by certification authority CA using its private key $-CK_{CA}$:
  - $Cert_{-CK_{CA}}(+K_A) = CA[V, SN, AI, CA, T_{CA}, A, +K_A]$

    with: V = version number

    SN = serial number

    AI = algorithm identifier of signature algorithm used

    CA = name of certification authority

    T_{CA} = period of validity of this certificate

    A = name to which the public key in this certificate is bound

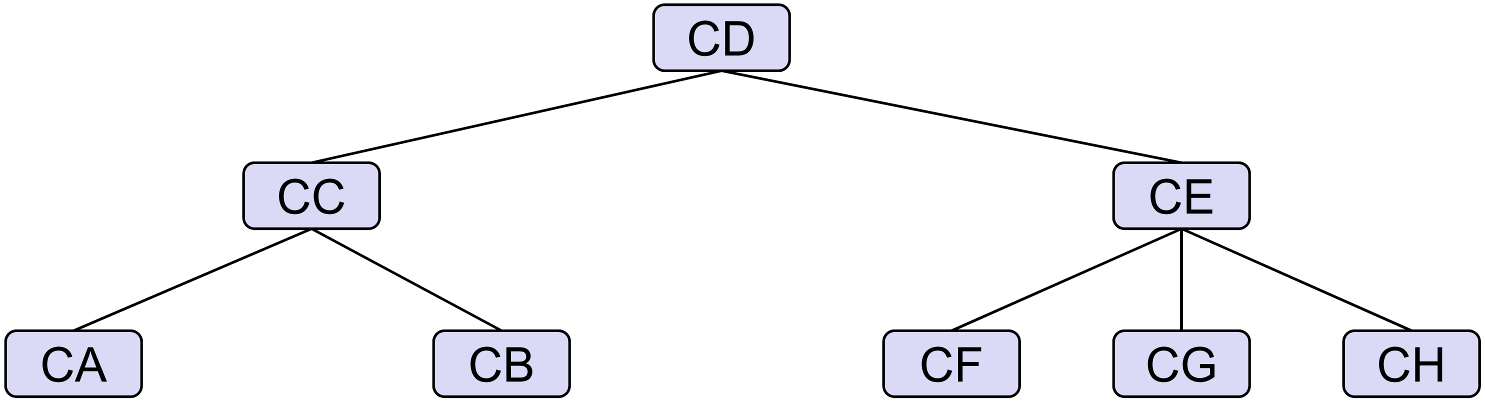
    $+K_A$ = public to be bound to a name
  - The shorthand notation $CA[m]$ stands for $(m, \{H(m)\}_{-CKCA})$
  - Another shorthand notation for $Cert_{-CK_{CA}}(+K_A)$ is CA<<A>>

X.509 – Certificate Chains & Certificate Hierarchy

- Consider now two users Alice and Bob, living in different countries, who want to communicate securely:
  - Chances are quite high, that their public keys are certified by different CAs
  - Let's call Alice's certification authority *CA* and Bob's *CB*
  - If Alice does not trust or even know *CB* then Bob's certificate *CB<<B>>* is useless to her, the same applies in the other direction
- A solution to this problem is constructing *certificate chains*:
  - Imagine for a moment that *CA* and *CB* know and trust each other
    - A real world example for this concept is the mutual trust between countries considering their passport issuing authorities
  - If *CA* certifies *CB*'s public key with a certificate *CA<<CB>>* and *CB* certifies *CA*'s public key with a certificate *CB<<CA>>*, then *A* and *B* can check their certificates by checking a certificate chain:
    - Upon being presented *CB<<B>>* Alice tries to look up if there is a certificate *CA<<CB>>*
    - She then checks the chain: *CA<<CB>>, CB<<B>>*

X.509 – Certificate Chains & Certification Hierarchy

- Certificate chains need not to be limited to a length of two certificates:
  - CA<<CC>>, CC<<CD>>, CD<<CE>>, CE<<CG>>, CG<<G>
    would permit Alice to check the certificate of user G issued by CG even if she just knows and trusts her own certification authority CA
  - In fact, A's trust in the key $+K_G$ is established by a *chain of trust* between certification authorities
  - However, if Alice is presented *CG<<G>>*, it is not obvious which certificates she needs for checking it
- X.509 therefore suggests that authorities are arranged in a *certification hierarchy*, so that navigation is straightforward:



X.509 – Certificate Revocation

- Consider now that the private key of Alice is compromised, e.g. because Eve broke into her computer read her private key from a file and cracked the password she used to protect the private key:
  - If Alice detects the compromise of her private key, she would definitely like to ask for *revocation* of the corresponding public key certificate
  - If the certificate is not revoked, then Eve could continue to impersonate Alice up to the end of the certificate's validity period
- An even worse situation occurs, when the private key of a certification authority is compromised:
  - This implies, that all certificates signed with this key have to be revoked!
- Certificate revocation is realized by maintaining *certificate revocation lists (CRL)*:
  - CRLs are stored in the X.500 directory
  - When checking a certificate, it has also to be checked that the certificate has not yet been revoked (search for the certificate in the CRL)

→ Certificate revocation is a relatively slow and expensive operation

X.509 – Authentication Protocols

- ***One-way authentication:***
  - If only Alice wants to authenticate herself to Bob she sends the following message to Bob:

    1.) $$(A\underbrace{[t_A, r_A, B, sgnData_A, \{K_{A,B}\}_{+K_B}]}_{\text{Signed with } -K_A}, \underbrace{CA{<}{<}A{>}{>}}_{\text{Contains } +K_A})$$

    with $sgnData_A$ representing optional data to be signed by A, $\{K_{A,B}\}_{+K_B}$ being an optional session key encrypted with Bob's public key, and CA<<A>> being optional as well

  - Upon reception of this message, Bob verifies with $+K_{CA}$ the contained certificate, extracts Alice's public key, checks Alice's signature of the message and the timeliness of the message (t_A), and optionally decrypts the contained session key $K_{A,B}$ Alice has proposed

X.509 – Authentication Protocols

- ***Two-way authentication:***
  - If mutual authentication is desired, then Bob creates a similar message:

    2.) $(B[t_B, r_B, A, r_A, sgnData_B, \{K_{B,A}\}_{+K_A}], CA{<<}B{>>})$

    the contained timestamp t_B is not really required, as Alice can check if the signed message contains the random number r_A

- ***Three-way authentication:***
  - If Alice and Bob are not sure if they have synchronous clocks, Alice sends the following message to Bob:

    3.) $A[r_B, B]$
  - So, the timeliness of Alice’s participation in the authentication dialogue is proven by signing the “fresh” random number r_B

Formal Validation of Cryptographic Protocols

- As we have seen from the Needham-Schroeder protocol, the security of a cryptographic protocol is not obvious to assess:
  - There are many more examples of *protocol flaws* in cryptographic protocols, which sometimes were discovered not until years after the publication of the protocol
  - This motivates the need for *formal methods* for analyzing the properties of cryptographic protocols
- Categories of formal validation methods for cryptographic protocols:
  - General approaches for analysis of specific protocol properties:
    - Examples: finite-state-machines, specification languages (SDL, UML)
    - Main Drawback: security differs significantly from correctness as for the later one does not need to assume malicious manipulation
  - Expert system based approaches
  - Algebraic approaches
  - Specific logic based approaches

Summary (what do I need to know)

- Authentication
  - Entity authentication
  - Message authentication

- Security protocols
  - Support for authentication and key exchange

- Using a TTP
  - Needham-Schroeder
  - Otway-Rees
  - Kerberos

- Direct authentication
  - X.509

Additional References

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