Network Security

Chapter 7
Cryptographic Protocols

Introduction

- Definition:

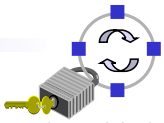
  A *cryptographic protocol* is defined as a series of steps and message exchanges between multiple entities in order to achieve a specific security objective
- Properties of a protocol (in general):
  - Everyone involved in the protocol must know the protocol and all of the steps to follow in advance
  - 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

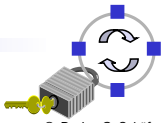
} treated in this course

- Secret splitting (all parts needed for reconstruction)
- Secret sharing (m out of n parts needed for reconstruction)
- 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



Key Exchange

- The Diffie-Hellman protocol introduced in section 2.1.2 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
  - As this pure key exchange without authentication can not even guarantee privacy of a communication following the exchange, it has to be combined with authentication
- 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 *sk* 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 *sk.*



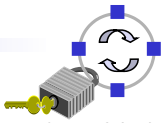
Data Origin Authentication

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 *data integrity*

- 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 encrypting 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

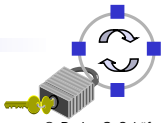


Entity Authentication (1)

Definition:

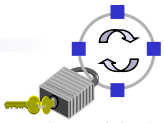
Entity authentication is the security service, that enables communication partners to verify the identity of their peer entities.

- 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 of the above means is difficult or insecure which motivates the need for cryptographic protocols



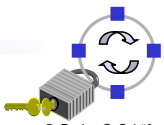
Entity Authentication (2)

- 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



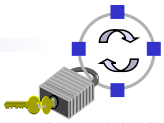
Entity Authentication (3)

- Two main categories of protocols for entity authentication:
  - *Arbitrated authentication:* an arbiter, also called *trusted third party (TTP)* is directly involved in every authentication exchange
    - Advantages:
      - This allows two parties A and B to authenticate to each other without knowing any pre-established secret
      - Even if A and B do not know each other, symmetric cryptography can be used
    - Drawbacks:
      - The TTP can become a bottleneck, 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



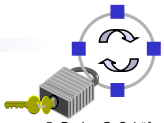
Some Notation...

Notation of Cryptographic Protocols (1)	
Notation	Meaning
A	Name of A, analogous for B, E, TTP, CA
CA_A	Certification Authority of A (explained later)
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
$K_{A, B}$	Secret key, only known to A and B



Some Notation...

Notation of Cryptographic Protocols (2)	
Notation	Meaning
$+K_A$	Public key of A
$-K_A$	Private key of A
$\{m\}_K$	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 $(m, \{H(m)\}_{-K_A})$
$Cert_{-CK_{CA}}(+K_A)$	Certificate of CA for public key $+K_A$ of A, signed with private certification key $-CK_{CA}$ (explained later)
CA<<A>>	Shorthand notation for $Cert_{-CK_{CA}}(+K_A)$



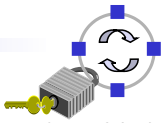
The Needham-Schroeder Protocol (1)

- 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 (2)

- 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 $r_{B\text{-}1}$ is supposed to ensure that an attacker, trying to impersonate Alice, 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!

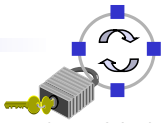
The Otway-Rees Protocol (1)

- 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:

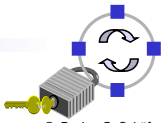
    3.) $TTP \rightarrow B: (i_A, \{r_A, K_{A,B}\}_{K_{A,TTP}}, \{r_B, K_{A,B}\}_{K_{B,TTP}})$



The Otway-Rees Protocol (2)

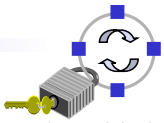
- Otway-Rees protocol definition (continued):
  - Bob decrypts his part of the message, verifies r_B and sends Alice's part of the message to her:

    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.



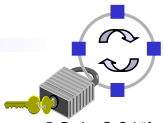
Kerberos (1)

- 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

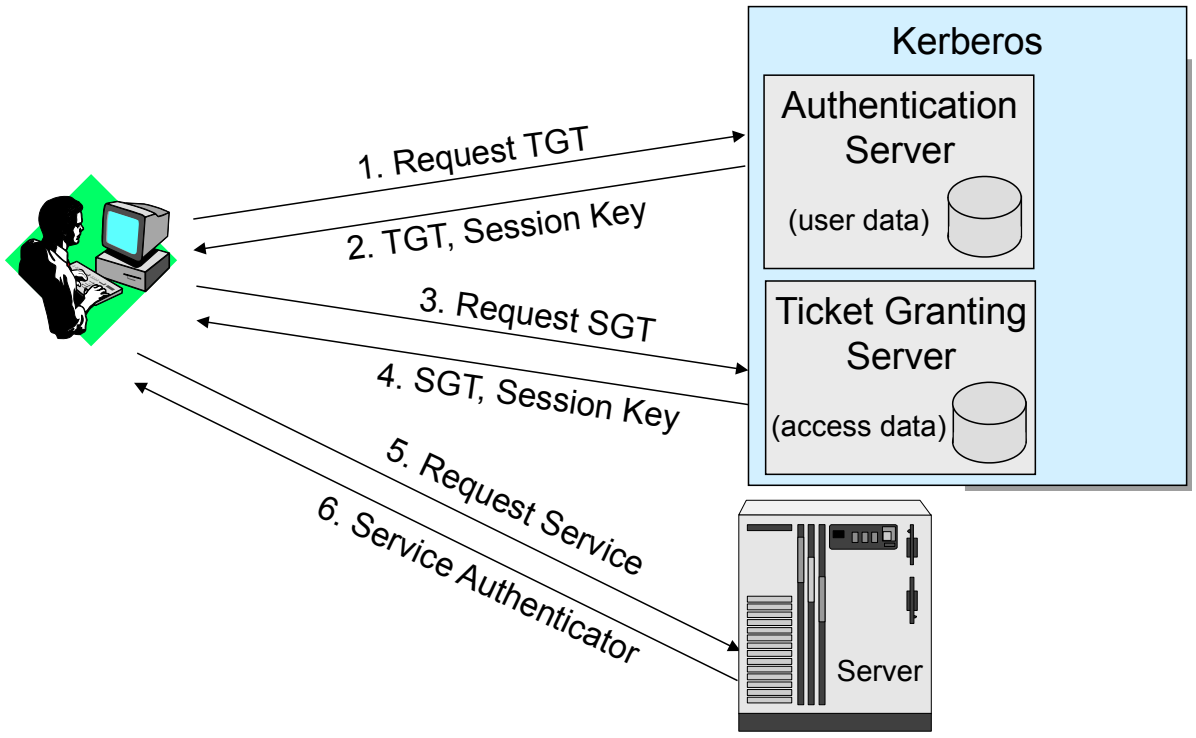


Kerberos (2)

- 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 (3)



Accessing a Service with Kerberos - Protocol Overview

Kerberos Version 4 (4)

- 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 Version 4 (5)

- 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:

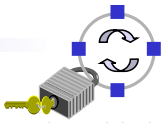
  4.) $TGS \rightarrow A: \{K_{A,S1}, S1, t_{TGS}, Ticket_{S1}\}_{K_{A,TGS}}$

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



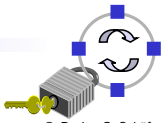
Kerberos Version 4 (6)

- 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 $K_{A,S1}$

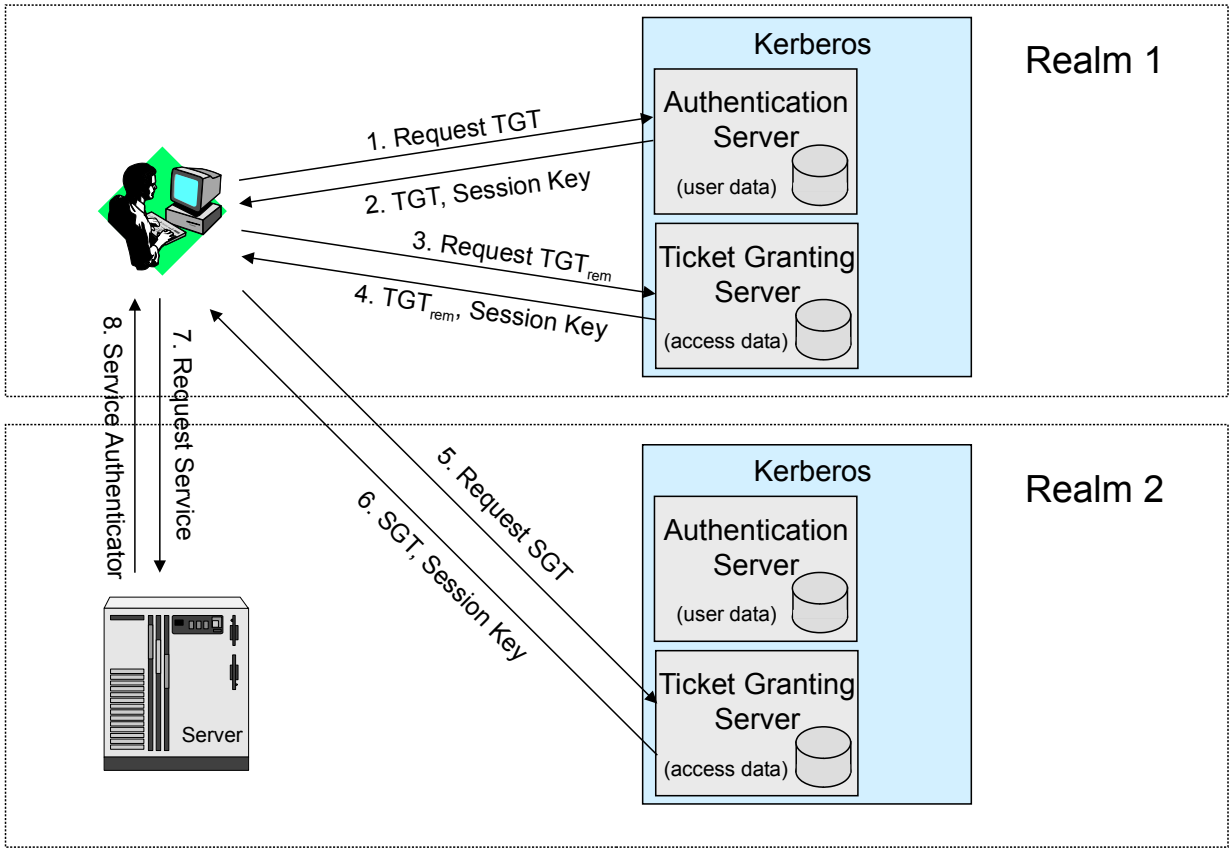
- The protocol described above is the Kerberos Version 4 dialogue.
  - A number of deficiencies have been found in this protocol, so a new Version 5 of the protocol has been defined, which will be discussed later…
  - Where is the problem, by the way?



Multiple Domain Kerberos (1)

- Consider an organization with workstation clusters on two different sites, and imagine that user *A* of site 1 wants to use a server of site 2:
  - If both sites do use their own Kerberos servers and user databases (containing passwords) then there are in fact two different *domains*, also called *realms* in Kerberos terminology.
  - In order to avoid that user A has to be registered in both realms, Kerberos allows to perform an inter-realm authentication.
- Inter-realm authentication requires, that the ticket granting servers of both domains share a secret key $K_{TGS1,TGS2}$
  - The basic idea is, that the TGS of another realm is viewed as a normal server for which the TGS of the local realm can hand out a ticket.
  - After obtaining the ticket for the remote realm, Alice requests a service granting ticket from the remote TGS
  - However, this implies that remote realm has to trust the Kerberos authentication service of the home domain of a “visiting” user!
  - Scalability problem: *n* realms require $n \times (n-1) / 2$ secret keys!

Multiple Domain Kerberos (2)



Multiple Domain Kerberos (3)

- Messages exchanged during a multiple domain protocol run:

1.) $A \rightarrow AS1: (A, TGS1, t_A)$

2.) $AS1 \rightarrow A: \{K_{A,TGS1}, TGS1, t_{AS}, LifetimeTicket_{TGS1}, Ticket_{TGS1}\}_{K_A}$
with $Ticket_{TGS1} = \{K_{A,TGS1}, A, Addr_A, TGS1, t_{AS}, LifetimeTicket_{TGS1}\}_{K_{AS,TGS1}}$

3.) $A \rightarrow TGS1: (TGS2, Ticket_{TGS1}, Authenticator_{A,TGS1})$
with $Authenticator_{A,TGS1} = \{A, Addr_A, t'_A\}_{K_{A,TGS1}}$

4.) $TGS1 \rightarrow A: \{K_{A,TGS2}, TGS2, t_{TGS1}, Ticket_{TGS2}\}_{K_{A,TGS1}}$
with $Ticket_{TGS2} = \{K_{A,TGS2}, A, Addr_A, TGS2, t_{TGS1}, LifetimeTicket_{TGS2}\}_{K_{TGS1,TGS2}}$

5.) $A \rightarrow TGS2: (S2, Ticket_{TGS2}, Authenticator_{A,TGS2})$
with $Authenticator_{A,TGS2} = \{A, Addr_A, t''_A\}_{K_{A,TGS2}}$

6.) $TGS2 \rightarrow A: \{K_{A,S2}, S2, t_{TGS2}, Ticket_{S2}\}_{K_{A,TGS2}}$
with $Ticket_{S2} = \{K_{A,S2}, A, Addr_A, S2, t_{TGS2}, LifetimeTicket_{S2}\}_{K_{TGS2,S2}}$

7.) $A \rightarrow S2: (Ticket_{S2}, Authenticator_{A,S2})$
with $Authenticator_{A,S2} = \{A, Addr_A, t'''_A\}_{K_{A,S2}}$

8.) $S2 \rightarrow A: \{t'''_A + 1\}_{K_{A,S2}}$

Kerberos Version 5 (1)

- Last standard from 2005 (RFC 4120)
- Developed in response to weaknesses that became known to Kerberos v4
  - Includes explicit checksums to verify that messages have not been altered
  - Supports multiple ciphers (others than the insecure DES)
- Unified message format – Messages to authentications server and ticket granting server are very similar
- Flexible ASN.1 encoding of messages, allows later extension
- In the following only a simplified version is shown, way more features are standardized, e.g.:
  - Client-to-Client mutual authentication
  - Pre-authenticated Tickets
  - Renewing Tickets
  - Multidomain Kerberos

Kerberos Version 5 (2)

- The authentication dialog in Kerberos version 5 is similar to version 4
- The Authentication Service Exchange: For initial contact the client A not only sends names and time stamps but also a nonce *n*, which helps to avoid replays if the time changed; it is also possible to claim multiple addresses

  1.) $A \rightarrow AS: (A, TGS, t_{start}, t_{end}, n, Addr_{A, ..})$
- The response includes a plaintext ticket and encrypted information:

  2.) $AS \rightarrow A: (A, Ticket_{TGS}, \{K_{A,TGS}, LastRequest, n, t_{expire}, t_{AS}, t_{start}, t_{end}, t_{renew}, TGS, Addr_A\}_{K_A})$

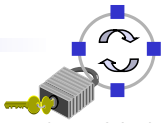
  $Ticket_{TGS} = (TGS, \{K_{A,TGS}, A, transited, t_{AS}, t_{start}, t_{end}, t_{renew}, Addr_A, restrictions\}_{K_{AS,TGS}})$

  LastRequest indicates the last login to be presented to the user

  transited contains the trust chain Multidomain Kerberos

  restrictions for the user may be handed to the TGS and servers

  t_{expire} and t_{end} contain different times to allow for renewing of tickets (in which the start and end time may simply be updated



Kerberos Version 5 (3)

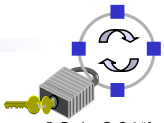
- The dialog to the TGS is harmonized with the initial dialog: It additionally contains tickets and an authenticator that proves that A knows $K_{A,TGS}$

  3.) $A \rightarrow TGS: (A, S1, t_{start}, t_{end}, n', Addr_A, Authenticator_{A,TGS}, Tickets, \ldots)$

  with $Authenticator_{A,TGS} = \{ A, CheckSum, t_A', K_{A,TGS}', Seq\#, \ldots\}_{K_{A,TGS}}$

  Note: The authenticator contains a cryptographic checksum now!
- The reply to A is entirely analog to message 2:

  4.) $TGS \rightarrow A: (A, Ticket_{S1}, \{K_{A,S1}, LastRequest, n', t_{expire}, t_{TGS}, t_{start}, t_{end}, t_{renew}, S1, Addr_A\}_{K_{A,TGS}})$



Kerberos Version 5 (4)

- The exchange with the server is also similar to Version 4, but with the authenticator an explicit checksum possible:

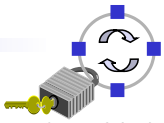
  5.) $A \rightarrow S1$: $(Ticket_{S1}, Authenticator_{A,S1})$

  with $Authenticator_{A,S1} = \{A, CheckSum, t_A'', K_{A,S1}', Seq\#, ..\}_{K_{A,S1}}$

- 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:

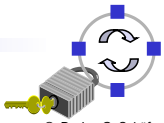
  6.) $S1 \rightarrow A$: $\{t_{S1}, K_{A,S1}', Seq\#, \ldots\}_{K_{A,S1}}$

- All in all the dialog fixes several potential vulnerabilities, while others remain:
  - Sequence numbers and nonces allow for additional replay checking if time base changes
  - Explicit checksums prevent modification of data within tickets
  - Central servers are still potential single-points-of-failure
  - Still some time synchronization is required for initial exchanges



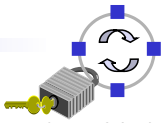
Advanced methods for password authentication (1)

- All shown protocols have a common weakness:
  - Passwords must be easy to remember and easy to enter
  - ➡ Low entropy
  - Attackers may quick try all possible combinations
  - Offline, using graphic cards, cloud computers, special hardware…
  - Asymmetric situation
- Possible solutions:
  - Key derivation functions
    - Make brute-force attacks more difficult by hashing extremely often
    - Requires also effort by legitimate devices
    - Only linear security gain
    - Better functions use a lot of memory to render attacks with graphic cards and special hardware infeasible
  - Password Authenticated Key Exchange (PAKE)
    - Covered in the following



Advanced methods for password authentication (2)

- Password Authenticated Key Exchange (PAKE) - Fundamental idea
  - Perform a key exchange with asymmetric cryptography
  - Authenticate peers with a password using a Zero Knowledge Proof
  - Peers are only able to tell that passwords matched or not
  - No further information to perform efficient bruteforce searches on
    - Would require solving difficult problems, e.g. some sort of DH problem
    - Renders offline attacks infeasible
  - Online attacks possible, but may be discovered



PAKE schemes: EKE (1)

- A simple first protocol is Encrypted Key Exchange (EKE) [BM92]
- Dialog starts with A generating a single use private/public key pair and sending the public key $+K_{ar}$ encrypted with the password $K_{A,B}$ to B

  1.) $A \rightarrow B: A, \{ +K_{ar} \}_{K_{A,B}}$

- B choses a symmetric session key K_r and sends it encrypted with the public key and the password back to A

  2.) $B \rightarrow A: \{\{ K_r \}_{+K_{ar}} \}_{K_{A,B}}$

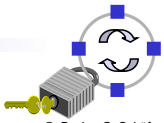
- A and B now share a common session key and proof knowledge about it by exchanging nonces

  3.) $A \rightarrow B: \{ r_A \}_{K_r}$

  4.) $A \rightarrow B: \{ r_A, r_B \}_{K_r}$

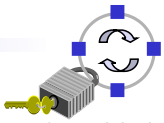
  5.) $A \rightarrow B: \{ r_B \}_{K_r}$

- After this step it is assured that both must have known $K_{A,B}$ and there has been no man-in-the-middle attack



PAKE schemes: EKE (2) – Security discussion

- Resistance against offline attacks depends on $+K_{ar}$ being indistinguishable from random numbers
  - What does this mean for ECC?
  - For RSA authors suggest e being encrypted, n being send in plaintext
    - n has no small prime factors and is therefore distinguishable from random numbers
    - Still insecure against man-in-the-middle attacks as attackers may choose n with special properties (e.g. p – 1 and q – 1 divisible by 3)
    - Answer from B is distinguishable from random numbers
    - Details can be found in [Par97] or [SR14]
- Does not offer perfect forward secrecy…
- But there is another protocol by the authors called DH-EKE



PAKE schemes: DH-EKE (1)

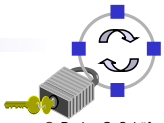
- DH-EKE is basically DH exchange with clever authentication
- A sends DH exchange encrypted with the password $K_{A,B}$

  1.) $A \rightarrow B: \{ g^{ra} \bmod p \}_{K_{A,B}}$
- B answers with his part of the DH exchange (encrypted with the password $K_{A,B}$) and uses the session key $K_S = g^{ra \cdot rb} \bmod p$ to send an encrypted nonce c_b

  2.) $B \rightarrow A: \{ g^{rb} \bmod p \}_{K_{A,B}} \{ c_b \}_{K_s}$
- Both parties proof their knowledge of K_S

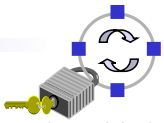
  3.) $A \rightarrow B: \{ c_a \,||\, c_b \}_{K_s}$

  4.) $B \rightarrow A: \{ c_a \}_{K_s}$



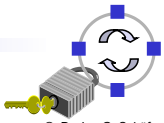
PAKE schemes: DH-EKE (2) – Security discussion

- Again encrypted data must be indistinguishable from random data
  - The value p must be chosen wisely, i.e., s.t. p - 1 is close to $2^{8 \cdot n}$ for sufficiently large natural numbers n
  - To easily prevent small group attacks (p – 1) / 2 should also be prime
  - ECC is still difficult to realize
- Offers perfect forward secrecy
- All in all nice scheme, but used to be patented
  - No wide adaptation
  - Led to the development of numerous different schemes



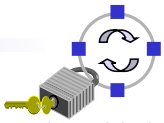
PAKE schemes: SRP (1)

- Most widely available protocol today: Secure Remote Password (SRP)
- Multiple versions: Here SRP-6a [Wu02]
- Initialization:
  - Server B chooses a random number $s_{A,B}$
  - calculates $x = H(s_{A,B} \,||\, username \,||\, password)$ and $v = g^x \bmod p$
  - Users are authenticated by ($username$, $s_{A,B}$, v)
  - Server does not need store the password ➡ cannot easily be obtained if server is compromised!
  - Server can also not use these values to impersonate user at other servers
  - Property is called *augmented* PAKE scheme



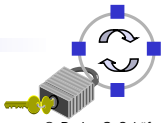
PAKE schemes: SRP (2) - Dialogue

- A initiates connection by sending its username
  1.) $A \rightarrow B: A$
- B answers with chosen cryptographic parameters and a verifier v that is "blinded" by a DH exchange
  2.) $B \rightarrow A: p, g, s_{A,B}, \underbrace{(H(g \,||\, p) \cdot v + g^{rb}) \bmod p}_{Y_B}$
- A calculates the common session key by $K_S = (Y_B - H(g \,||\, p) \cdot g^x)^{ra+u \cdot x} \bmod p$, with $u = H(Y_A \,||\, Y_B)$, and sends back its part of the DH exchange and a verification that it knows K_S
  3.) $A \rightarrow B: \underbrace{g^{ra} \bmod p}_{Y_A}, H(Y_A, Y_B, K_S)$
- B calculates $K_S' = (Y_A v^u)^{rb} \bmod p$ and proofs knowledge
  4.) $B \rightarrow A: H(Y_A, H(Y_A, Y_B, K_S), K_S')$
- K_S' and K_S match if there has been no man-in-the-middle attack



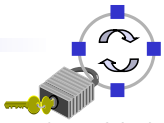
PAKE schemes: SRP (3) - Discussion

- Secure scheme
  - **Mutual** authentication between server and client
  - Augmentation increases security in client/server scenarios
  - No support for ECC as it requires field arithmetic
- Patented, but free to use
- Support for TLS, IPsec, …

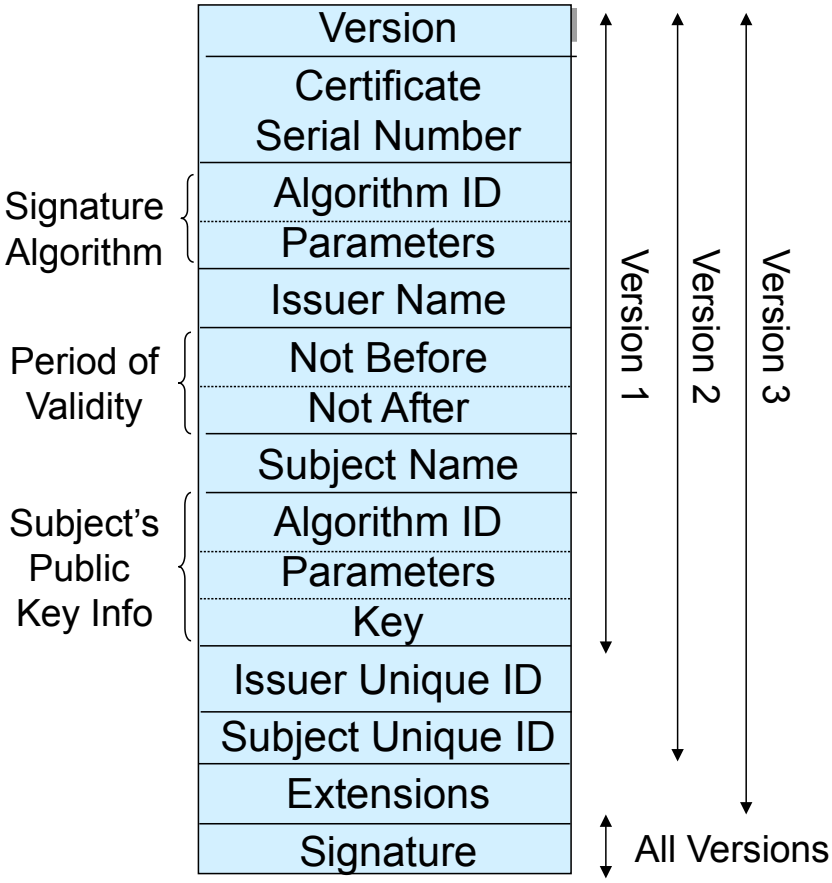


X.509 – Introduction

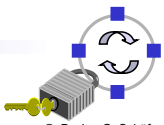
- X.509 is an international recommendation of ITU-T and is part of the X.500-series defining directory services:
  - The first version of X.509 was standardized in 1988
  - A second version standardized 1993 resolved some security concerns
  - A third version of X.509 is currently maintained by IETF in RFC 4211
- 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 (1)



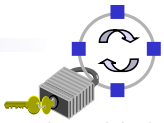
- A *public key certificate* is some sort of passport, certifying that a public key belongs to a specific name
- Certificates are issued by *certification authorities (CA)*
- If all users know for sure the public key of the CA, every user can check every certificate issued by this CA
- Certificates can 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 (2)

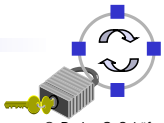
- Notation of a certificate binding a public key $+K_A$ to user *A* issued by certification authority *CA* using its private key $-CK_{CA}$:
  - $Cert_{-CK_{CA}}(+K_A) = CA[V, SN, AI, CA, T_{CA}, A, +K_A]$

    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 key 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>>



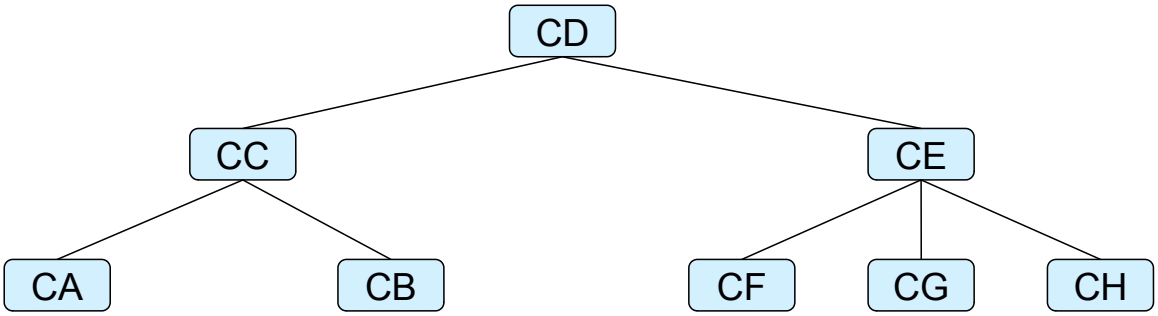
X.509 – Certificate Chains & Certificate Hierarchy (1)

- 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 (2)

- 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 Chains & Certification Hierarchy (3)

- Remaining issue:
  - Certification paths may become rather long
  - Compromise of single intermediate certificate suffices to break security
- Leads to two developments
  - Cross-certification:
    - Allows to sign root certificates among each other
    - But also allow "shortcuts" in the certificate forest
    - Makes navigation more complex, but potentially multipath verification
  - Certificate pinning:
    - Allows applications, e.g., web browsers, to learn that peers use certificates only from a certain CA
    - Used by Google Chrome for example, after man-in-the-middle attacks on google.com became known

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, or extensions may point to URL
  - 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 (1)

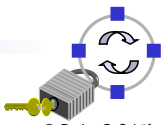
- One-way authentication:
  - If only Alice wants to authenticate herself to Bob she sends the following message to Bob:

    1.) $(A[t_A, r_A, B, sgnData_A, \{K_{A,B}\}_{+K_B}], CA\langle\langle A\rangle\rangle)$

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

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

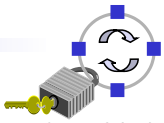
    the contained timestamp t_B is not really required, as Alice can check if the signed message contains the random number r_A



X.509 – Authentication Protocols (2)

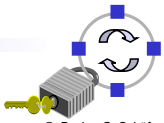
- Three-way authentication:
  - If Alice and Bob are not sure if they have synchronous clocks, Alice sends the following message to Bob:

    3.) $A[r_B]$
  - So, the timeliness of Alice's participation in the authentication dialogue is proven by signing the "fresh" random number r_B
- Note on the signature algorithm:
  - As obvious from the use of certificates, X.509 suggests to sign the authentication messages using asymmetric cryptography
  - However, the authentication protocol itself can also be deployed using symmetric cryptography:
    - In this case, A and B need to have agreed upon a secret *authentication key* $AK_{A,B}$ prior to any protocol run, and
    - the messages are signed by appending a MAC computed with that key.



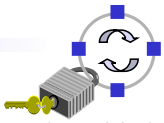
Formal Validation of Cryptographic Protocols (1)

- As we have seen from the 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
    - An early version of the X.509 standard contained a flaw which was similar to the flaw in the Needham-Schroeder 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-machine based approaches, first-order predicate calculus, general purpose specification languages
    - Main Drawback: security differs significantly from correctness as for the later one does not need to assume malicious manipulation



Formal Validation of Cryptographic Protocols (2)

- Categories of formal validation methods for cryptographic protocols:
  - *Expert system based approaches:*
    - Knowledge of human experts is formalized into deductive rules that can be used by a protocol designer to investigate different scenarios
    - Main drawback: not well suited to find flaws in cryptographic protocols that are based on unknown attacking techniques
  - *Algebraic approaches:*
    - Cryptographic protocols are specified as algebraic systems
    - Analysis is conducted by examining algebraic term-rewriting properties of the model and inspecting if the model can attain certain desirable or undesirable states
  - *Specific logic based approaches:*
    - Approaches of this class define a set of predicates and a mapping of messages exchanged during a protocol run into to a set of formula
    - A generic set of rules allows then to analyze the *knowledge* and *belief* that is obtained by the peer entities of a cryptographic protocol during a protocol run (quite successful approach: GNY logic [GNY90a])



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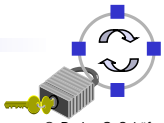

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