Network Security (NetSec)

IN2101 – WS 17/18

Prof. Dr.-Ing. Georg Carle

Dr. Heiko Niedermayer
Dr. Miguel Pardal
Quirin Scheitle

Acknowledgements: Dr. Cornelius Diekmann

Chair of Network Architectures and Services
Department of Informatics
Technical University of Munich

Chapter 10: Cryptographic Protocols

Introduction

Protocols

Authentication and Key Establishment Protocols

Attack Concepts against Cryptographic Protocols

Desirable Properties of Cryptographic Protocols

Final Protocol, Goals, and Notation

Needham Schroeder Protocol

- Needham Schroeder Symmetric Key Protocol
- Needham Schroeder Public Key Protocol

Conclusions - What have we learned

Chapter 10: Cryptographic Protocols

Introduction

Protocols

Authentication and Key Establishment Protocols

Attack Concepts against Cryptographic Protocols

Desirable Properties of Cryptographic Protocols

Final Protocol, Goals, and Notation

Needham Schroeder Protocol

Conclusions - What have we learned

Explanation Pony and Exercises

- Slides called "- Explanation" and usually marked with 🐴 are not for the lecture, but they contain further explanations for your learning at home.
- Parts called "Exercise" are voluntary exercises for discussion in lecture as well as for your reworking of the slides and learning at home.

Introduction

- Communicate over distance using a network
- Do I speak with the right person?
- Who can read the content?
- How can cryptography be used for that?
- Which keys? From where and when?
- Protocols describe an exchange of messages for a certain purpose (e.g. security goals).

  → Cryptographic Protocols

Learning Goals

- Basic understanding of cryptographic protocols
  - Know the terms and methods and apply them
- Get to know some elementary protocols $\rightarrow$ real-world protocols discussed in later chapters use the basics you learn here
  - Remember and explain them
- You will gain some first thoughts about how to break protocols and learn to think in a way of finding attacks
  - Apply them to find weaknesses
- You will gain some first ideas how to improve protocols
  - Apply them to remove a similar weakness

Stick to the protocol layer (Exercise, Exam)

- When we discuss cryptographic protocols, we assume the following
  - The cryptographic primitives are secure.
    → Insecure primitives or implementations can make a secure protocol insecure[1].
  - The computers, machines, ... are secure.
    → Insecure machines can make the use of a secure protocol insecure.
  - Our reasoning uses the Dolev-Yao attacker model.
    → Attacker = Network
  - Our reasoning focuses on the layer of the cryptographic protocol.
    → Security can be shown by formal methods (model checking of protocol, security proofs, etc.).

[1] Defended by security proofs, code review, formal code analysis, . . .

Stick to the protocol layer (Exercise, Exam)

- When we try to break a protocol, we do this on the layers of the protocol.
  - The reason is that we do not learn anything about weaknesses and security of protocols if we attack them by assuming to hack a computer and steal all data. So, whenever you are asked to analyze or attack a protocol in an exercise, attack on the layer of the protocol and attack its operation. Otherwise you do not learn to understand and evaluate protocols.
- The same is true if we consider mitigations. Fix the protocol by changing its operation, not by adding new requirements like super-secure primitives or machines.

Chapter 10: Cryptographic Protocols

Introduction

Protocols

Authentication and Key Establishment Protocols

Attack Concepts against Cryptographic Protocols

Desirable Properties of Cryptographic Protocols

Final Protocol, Goals, and Notation

Needham Schroeder Protocol

Conclusions - What have we learned

What do we know as of yet?

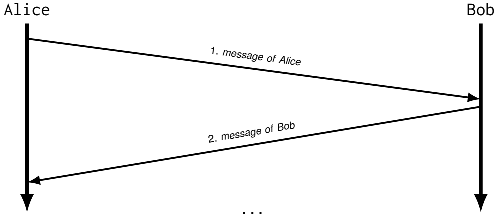
- What do we know?
  - Symmetric encryption and keys
  - Asymmetric encryption and keys
  - Cryptographic hash functions
  - Secure Channel
- To use a secure channel, Alice and Bob need a shared key.
  → A protocol to establish a secure channel needs to establish a shared key.

Protocols, Notation, . . .

- Cryptographic protocols contain:
  - General entities that are normal participants of the protocol. We call them Alice (A), Bob (B), . . .
  - Special-purpose entities that have a special role. Authentication Server (AS), . . .
  - Some synonyms: entity, principle, participant
- Alice-Bob notation: one way to describe cryptographic protocols
  - Protocol messages in sequence (numbering optional):
  - 1. $\mathit{Alice} \rightarrow \mathit{Bob} : \mathit{message\ of\ Alice}$
  - 2. $\mathit{Bob} \rightarrow \mathit{Alice} : \mathit{message\ of\ Bob}$
  - . . .

Protocols, Notation, . . .

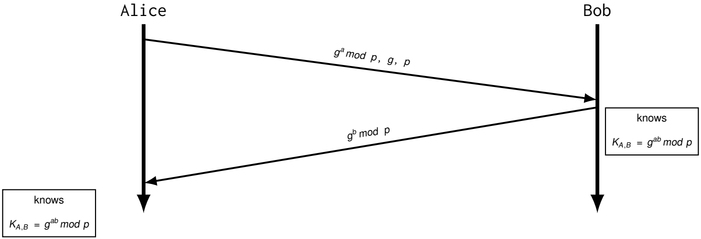
- Or sequence diagram:



- Some Notation:

Notation	Meaning
$A, B, \ldots$	Protocol principles
$K_{A,B}$	Key, here shared key of A and B
$\{m\}_K$	Plaintext m encrypted and integrity-protected with key K

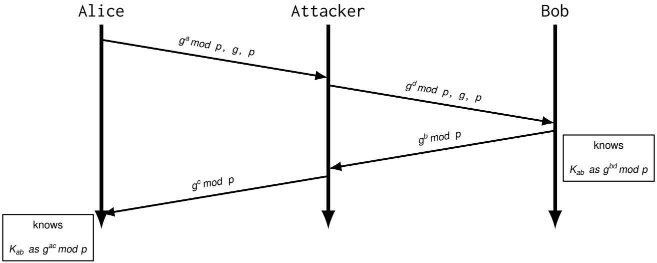
Protocol Try 1 (Textbook Diffie-Hellman)



- Alice and Bob have completed a Diffie-Hellman exhange and established a shared key at the end of the protocol.
- Are we done?

Protocol Try 1 - What goes wrong (Man-in-the-Middle)

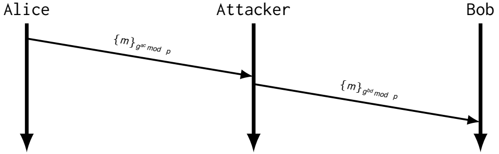
Repetition. This should already be known.



- Attacker now has a shared key K_{ac} with Alice and a shared key K_{bd} with Bob.
- The attacker is called Man-in-the-Middle attacker as it sits in-between any communication between Alice and Bob.

Protocol Try 1 - What goes wrong (Man-in-the-Middle)

When Alice uses the secure channel to send message m:

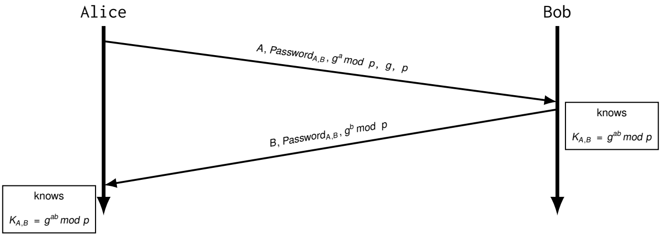


- Despite using the secure channel, the attacker can read, modify, or create message between Alice and Bob.

Protocol Try 1 - What goes wrong (No Authentication)

- The exchange does not contain any authentication.
- Thus, Alice has no way of identifying Bob.
- Bob has no way of identifying Alice.
- An attacker can impersonate whomever it likes.

Protocol Try 2 - Adding a password


Alice
Bob
A, $Password_{A,B}$, g^a mod p, g, p
knows
$K_{A,B} = g^{ab}$ mod p
B, $\text{Password}_{A,B}$, g^b mod p
knows
$K_{A,B} = g^{ab}$ mod p

- Try 2 still fails:
  - Man-in-the-middle still possible
  - Eavesdropper can read password, then impersonation possible
- Why do they already have a password? Lets discuss authentication.

Chapter 10: Cryptographic Protocols

Introduction

Protocols

Authentication and Key Establishment Protocols

Attack Concepts against Cryptographic Protocols

Desirable Properties of Cryptographic Protocols

Final Protocol, Goals, and Notation

Needham Schroeder Protocol

Conclusions - What have we learned

Entity Authentication and Key Establishment

- Entity Authentication
  - Authenticity of an entity is shown
  - An authentication protocol is run and at the end, some protocol participants are ensured of the identity of other participants.
  - Mutual authentication: Authenticity of Alice and Bob is shown to each other
- Key Establishment
  - A key is established between some protocol participants
  - Key Transport: Some entity creates the key and sends it to other entities.
  - Key Agreement: Multiple entities contribute to the generation of the key.

Entity Authentication and Key Establishment

- Many authentication protocols – as a side effect of the authentication - do establish a shared session key $K_{A,B}$ for securing the session.
- Some opinions about the relationship between authentication and key establishment:
  - "It is accepted that these topics should be considered jointly rather separately" [Diff92]
  - "... authentication is rarely useful in the absence of an associated key distribution" [Bell95]
  - "In our view there are situations when entity authentication by itself may useful, such as when using a physically secured communication channel." [Boyd03]

Key Establishment without Entity Authentication

- Why our first try failed... After a protocol run, neither Alice nor Bob know with whom they actually have exchanged a key.
- Can Key Establishment without Authentication work?
  - If Alice and Bob already have an authenticated channel, then a key exchange over that channel may not need to authenticate.

Entity Authentication without Key Establishment

- Entity Authentication without Key Establishment?
    - In cyber-physical system: something happens in physical world upon authentication.
        - E.g. door opens for Alice. No session key needed.
    - Over the network?
        - If a shared key already exists, only the binding of key and identity (authentication) may be needed.

Entity Authentication and Key Establishment in WWW

- Alice wants to use the online banking service provided by her bank
- Authentication of the web server of the bank:
  - Web browser verifies the identity of the web server via HTTPS using asymmetric encryption
  - A shared session key $K_{A,B}$ is generated as part of the server authentication
  - A secure channel between web browser and web server is established
- Authentication of the client:
  - Uses the secure channel to the web server
  - The web server authenticates Alice based on her PIN number
  - No additional secret key is established

Operation of Cryptographic Protocols

- Initiator
  - The principle (entity) that starts the protocol by sending the first message.
- Responder
  - Principles that did not start the protocol.
- All principles
  - see messages
  - send messages
  - draw conclusions from observations

Authentication = Proof in Formal Logic

- Each principle has its knowledge and beliefs.
- In the operation of the cryptographic protocol it takes certain actions.
- In the operation of the cryptographic protocol it makes observations.
- Reasoning on actions and observation needs to establish the objectives of the protocol.
  - Example (Authenticity of Bob):
    - Sent fresh challenge to Bob.
    - Protected it with public key of Bob.
    - If anyone can read the challenge, then it has to have knowledge of Bob's private key.
    - Value from the challenge is seen again.
    - Thus, Bob participated in the protocol and used his private key.

Where do the keys come from?

- Alice and Bob can have a long-term shared key.
- Alice and Bob can have exchanged their public keys.
- Alice and Bob have exchanged keys with a Trusted Third Party (TTP). The TTP helps.
    - More scalable.
    - Typical names for the TTP: Authentication Server (AS), Certification Authority (CA), . . .
- If no such pre-exchanged keys exist, cryptographic protocols cannot operate securely (Boyd's Theorem).
- More on the issue in a separate chapter on Identity and Public Key Infrastructures.

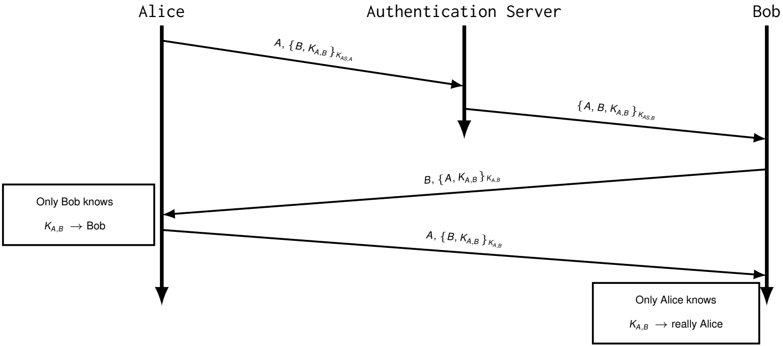
Authentication and Key Establishment Problem Statement - Version 1

Goals: Run a key exchange protocol such that at the end of the protocol:

- Alice and Bob have shared a session key for a secure channel
- Alice (Bob) must be able to verify that Bob (Alice) participated in the protocol run (authentication)

Protocol Try 3 Shared Key with Server

- Using a TTP is more scalable, so lets use a server.
- Alice generates a fresh key and sends it to Bob via the server.
- Btw, when we encrypt, the receiver might need to know who sends the message, at least if it is not the server.



Alice

Authentication Server

Bob

$A, \{B, K_{A,B}\}_{K_{AS,A}}$

$\{A, B, K_{A,B}\}_{K_{AS,B}}$

$B, \{A, K_{A,B}\}_{K_{A,B}}$

$A, \{B, K_{A,B}\}_{K_{A,B}}$

Only Bob knows

$K_{A,B}$ → Bob

Only Alice knows

$K_{A,B}$ → really Alice

Chapter 10: Cryptographic Protocols

Introduction

Protocols

Authentication and Key Establishment Protocols

Attack Concepts against Cryptographic Protocols

Desirable Properties of Cryptographic Protocols

Final Protocol, Goals, and Notation

Needham Schroeder Protocol

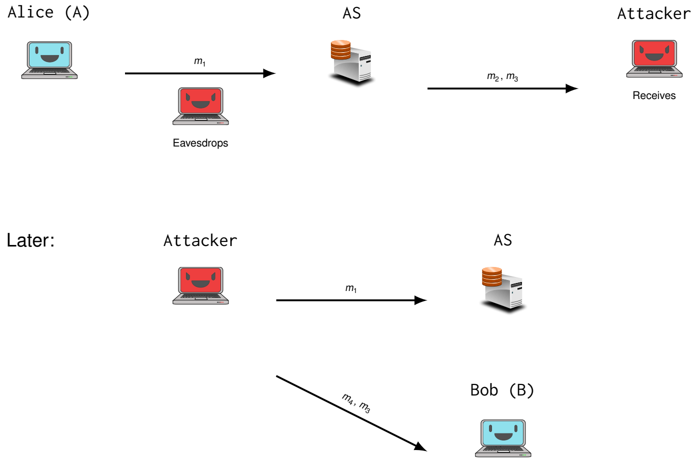
Conclusions - What have we learned

Attacks

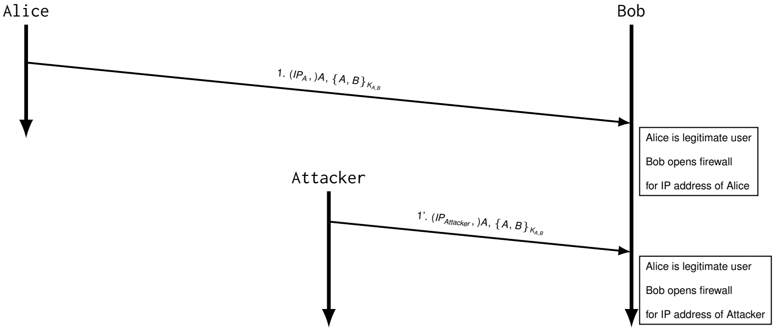
- Already known:
  - Eavesdropping
  - Man-in-the-Middle Attack
  - Cryptanalysis
- Attacker:
  - Can control parts or all of the network (see Dolev-Yao)
  - Eavesdrops and memorizes all it has seen
  - Can initiate protocol run
  - Can interfere with protocol runs
  - Can try to trick principles into running the protocol
  - For protocol analysis, it is usually not able to break crypto and hack the computers.

Replay Attack

- Replay Attack: Receives and eavesdrops messages → later-on send message or part of message to some principle.



Replay Attack - Example



Alice

Bob

1. $(IP_A,)A, \{A, B\}_{K_{A,B}}$

Alice is legitimate user

Bob opens firewall

for IP address of Alice

Attacker

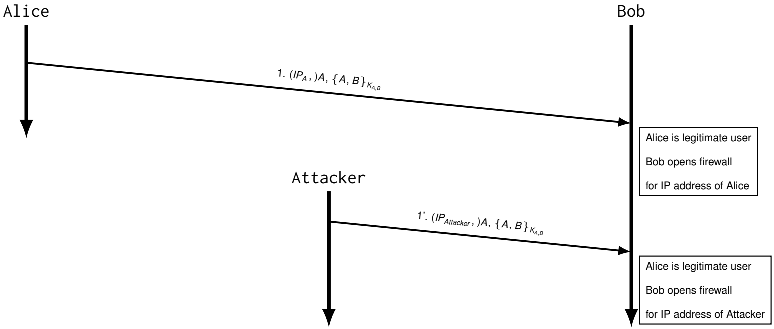
1'. $(IP_{Attacker},)A, \{A, B\}_{K_{A,B}}$

Alice is legitimate user

Bob opens firewall

for IP address of Attacker

Replay Attack - Example


Alice
Bob
1. $(IP_A,)A, \{A, B\}_{K_{A,B}}$
Attacker
1'. $(IP_{Attacker},)A, \{A, B\}_{K_{A,B}}$

Alice is legitimate user

Bob opens firewall

for IP address of Alice

Alice is legitimate user

Bob opens firewall

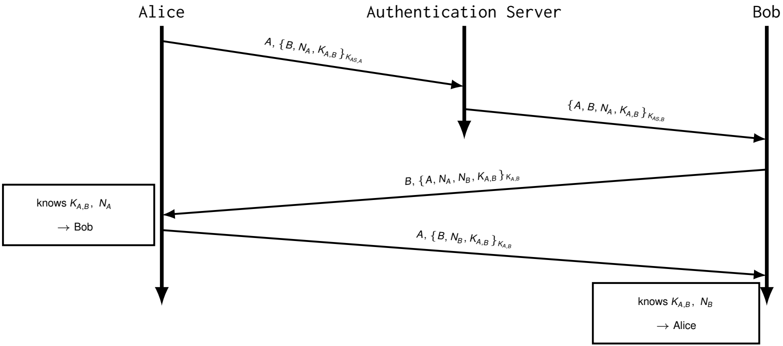
for IP address of Attacker

Bob cannot decide whether the message is fresh or not.

Reacting to an old message can result in security compromise!

Protocol Try 4 Replay Attack Defences

- An attacker can replay all messages of protocol try 3. Nonce needs to be fresh.
- Better add a defense → Nonces N_A, N_B, ...


Alice
Authentication Server
Bob
$A, \{B, N_A, K_{A,B}\}_{K_{AS,A}}$
$\{A, B, N_A, K_{A,B}\}_{K_{AS,B}}$
$B, \{A, N_A, N_B, K_{A,B}\}_{K_{A,B}}$
knows $K_{A,B}$, N_A
→ Bob
$A, \{B, N_B, K_{A,B}\}_{K_{A,B}}$
knows $K_{A,B}$, N_B
→ Alice

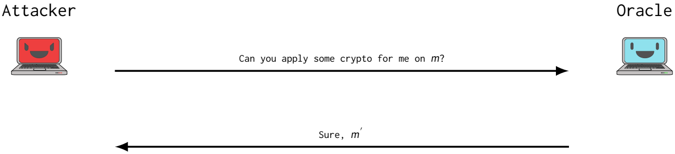
Authentication and Key Establishment Problem Statement - Version 2

Goals:

- Run a key exchange protocol such that at the end of the protocol:
- Alice and Bob have a shared session key for a secure channel
- Alice (Bob) must be able to verify that Bob (Alice) participated in the protocol run (authentication) and that he (she) is “alive” (freshness)

Oracle Attacks

- The attacker cannot break cryptography (assumption[2]).
- Yet maybe there are helpful principles that can help.
  - e.g. because they know the relevant keys
- Oracles are usually entities that can efficiently do something that a normal entity (here our attacker) cannot.



Attacker

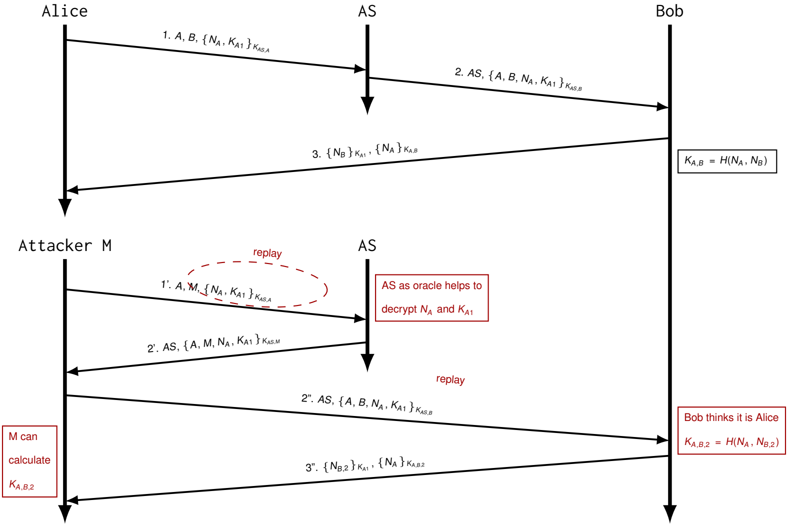
Oracle

Can you apply some crypto for me on m?

Sure, $m^{'}$

[2] see Dolev-Yao Attacker Model

Oracle Attacks - Example


Alice
AS
Bob
1. $A, B, \{N_A, K_{A1}\}_{K_{AS,A}}$
2. $AS, \{A, B, N_A, K_{A1}\}_{K_{AS,B}}$
3. $\{N_B\}_{K_{A1}}, \{N_A\}_{K_{A,B}}$
$K_{A,B} = H(N_A, N_B)$
Attacker M
AS
replay
1'. $A, M, \{N_A, K_{A1}\}_{K_{AS,A}}$
2'. $AS, \{A, M, N_A, K_{A1}\}_{K_{AS,M}}$
replay
2". $AS, \{A, B, N_A, K_{A1}\}_{K_{AS,B}}$
3". $\{N_{B,2}\}_{K_{A1}}, \{N_A\}_{K_{A,B,2}}$

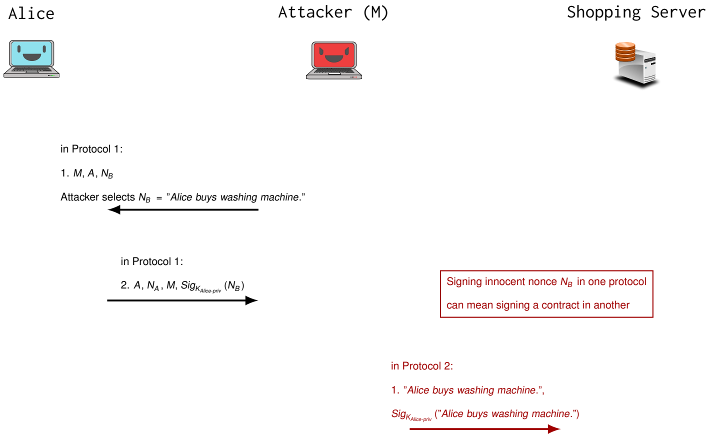
AS as oracle helps to decrypt N_A and K_{A1}

Bob thinks it is Alice $K_{A,B,2} = H(N_A, N_{B,2})$

M can calculate $K_{A,B,2}$

Typing Attack

- Replace (usually encrypted) message field of one type with one of another (usually encrypted) type.



Alice

Attacker (M)

Shopping Server

in Protocol 1:

1. M, A, N_B

Attacker selects N_B = "*Alice buys washing machine*."

in Protocol 1:

2. $A, N_A, M, Sig_{K_{Alice\text{-}priv}}(N_B)$

Signing innocent nonce N_B in one protocol can mean signing a contract in another

in Protocol 2:

1. "*Alice buys washing machine*.",

$Sig_{K_{Alice\text{-}priv}}$ ("*Alice buys washing machine*.")

Other types of attacks

Think about more types of attacks. How would a protocol with a related weakness look like?

Other Types of Protocol Attacks

- Modification: Attacker alters messages sent.
- Preplay: The attacker takes part in a protocol run prior to a protocol run.
- Reflection: The attacker sends back protocol messages to principles who sent them. Related to Oracle attacks.
- Denial of Service: The attacker hinders legitimate principles to complete the protocol.
- Certificate Manipulation: Attacks using manipulated or wrongly-obtained certificates.
- Protocol Interaction: Make one protocol interact with another, e.g. by utilizing that principles use the same long-term keys in both protocols and utilizing that for an attack.

Chapter 10: Cryptographic Protocols

Introduction

Protocols

Authentication and Key Establishment Protocols

Attack Concepts against Cryptographic Protocols

Desirable Properties of Cryptographic Protocols

Final Protocol, Goals, and Notation

Needham Schroeder Protocol

Conclusions - What have we learned

Desirable Properties of Cryptographic Protocols

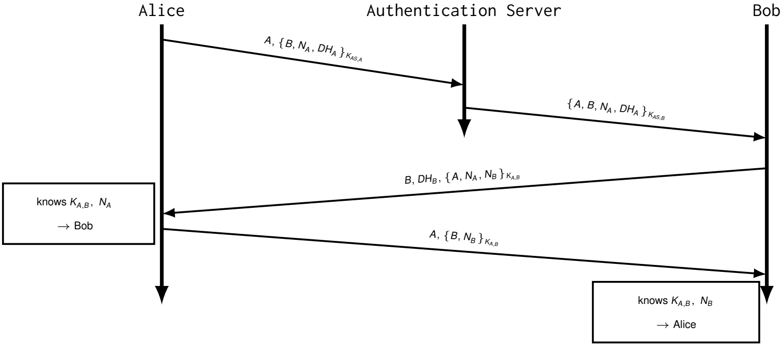
- Desirable Properties = what else we should want
- In this section:
  - Forward Secrecy and Key Agreement
  - Scalability
  - Avoidance of Single-Points-of-Failures
  - Selection of Algorithms
  - Generic Authentication Methods
  - Simplicity

Forward Secrecy (Repetition)

- Forward Secrecy (Repetition)
  - If long-term key is compromised, attacker cannot find out session key for older sessions.
  - If session key is compromised, other sessions and long-term key not affected.
- Can be achieved via Diffie-Hellman exchange.
  - DH_A is Diffie-Hellman information provided by Alice (e.g. in Textbook DH: g, p, g^a mod p)
  - DH_B is Diffie-Hellman information provided by Bob

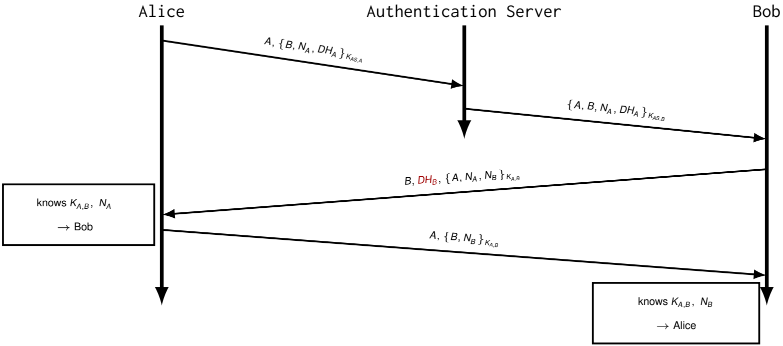
Protocol Try 5 Adding Forward Secrecy

- Session key $K_{A,B}$ derived from DH_A and DH_B


Alice
Authentication Server
Bob
$A, \{B, N_A, DH_A\}_{K_{AS,A}}$
$\{A, B, N_A, DH_A\}_{K_{AS,B}}$
$B, DH_B, \{A, N_A, N_B\}_{K_{A,B}}$
knows $K_{A,B}$, N_A
→ Bob
$A, \{B, N_B\}_{K_{A,B}}$
knows $K_{A,B}$, N_B
→ Alice

Protocol Try 5 Adding Forward Secrecy

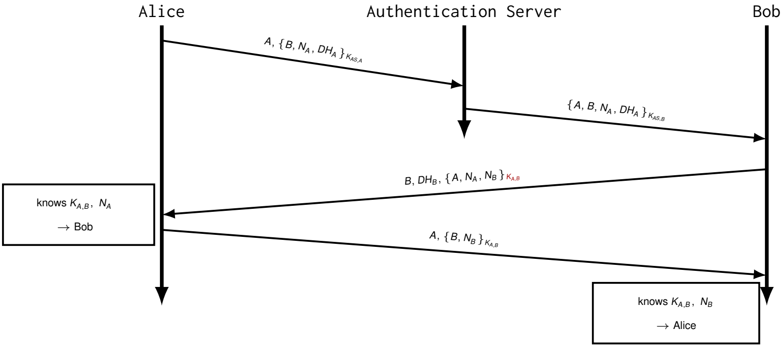
- Session key $K_{A,B}$ derived from DH_A and DH_B


Alice
Authentication Server
Bob
$A, \{B, N_A, DH_A\}_{K_{AS,A}}$
$\{A, B, N_A, DH_A\}_{K_{AS,B}}$
$B, DH_B, \{A, N_A, N_B\}_{K_{A,B}}$
knows $K_{A,B}$, N_A
→ Bob
$A, \{B, N_B\}_{K_{A,B}}$
knows $K_{A,B}$, N_B
→ Alice

- Note: DH_B is integrity protected by $\{A, N_A, N_B\}_{K_{A,B}}$. Why?

Protocol Try 5 Adding Forward Secrecy

- Session key $K_{A,B}$ derived from DH_A and DH_B



Alice
Authentication Server
Bob
$A, \{B, N_A, DH_A\}_{K_{AS,A}}$
$\{A, B, N_A, DH_A\}_{K_{AS,B}}$
$B, DH_B, \{A, N_A, N_B\}_{K_{A,B}}$
knows $K_{A,B}$, N_A
→ Bob
$A, \{B, N_B\}_{K_{A,B}}$
knows $K_{A,B}$, N_B
→ Alice

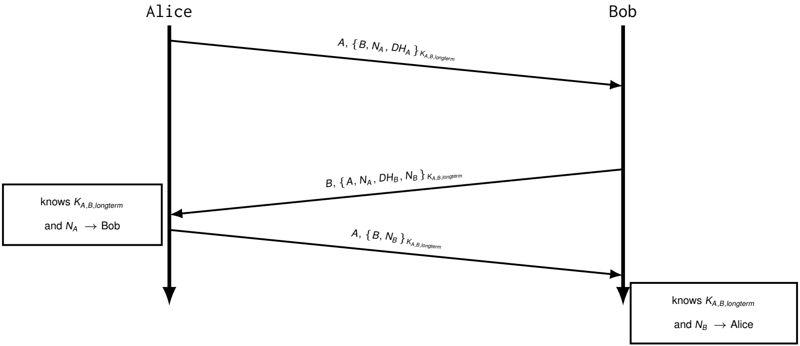
- Note: DH_B is integrity protected by $\{A, N_A, N_B\}_{K_{A,B}}$. Why?

Scalability - revisted

- Scalability of keys $\rightarrow$ Authentication Server
- But having a central server is a single point of failure
- ... and bad for scalability of service
- Thus, good if server need not be contacted within a protocol run.
- While server may have provided keys or certificates (identity-key binding) beforehand.

Protocol Try 6 Removing Authentication Server

- Session key $K_{A,B}$ derived from Diffie-Hellman


Alice
Bob
$A, \{B, N_A, DH_A\}_{K_{A,B,longterm}}$
$B, \{A, N_A, DH_B, N_B\}_{K_{A,B,longterm}}$
knows $K_{A,B,longterm}$
and N_A → Bob
$A, \{B, N_B\}_{K_{A,B,longterm}}$
knows $K_{A,B,longterm}$
and N_B → Alice

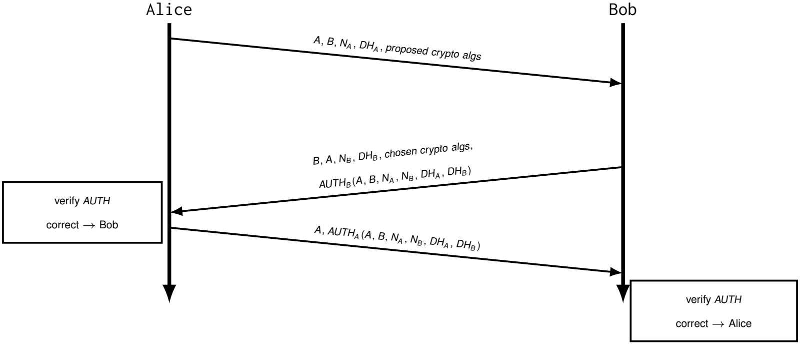
Selection of Used Algorithms

- Can we adapt the protocol, so that public key cryptography could be used?
- In practise, one might also want that all kinds of algorithms can be exchanged over time. → Do not become outdated!
- Concept:
    - Generic $Auth_X()$ function that can be realized with a suitable authentication function given either a public or shared key of X.
      Example:
        - Alice and Bob share a symmetric key
        - Bob: $Auth_B(m) = MAC_{K_{A,B}}(m)$
        - Alice: $Vrfy_{K_{A,B}}(m, Auth_B(m))$

        - Alice and Bob know each other's public key
        - Bob: $Auth_B(m) = Sig_{K_{B\text{-}priv}}(m)$
        - Alice: $Vrfy_{K_{B\text{-}pub}}(m, Auth_B(m))$
    - Alice and Bob have to agree on this function and used algorithms, e.g.
        - Alice proposes a set of functions and algoritms
        - Bob selects the ones that are then used

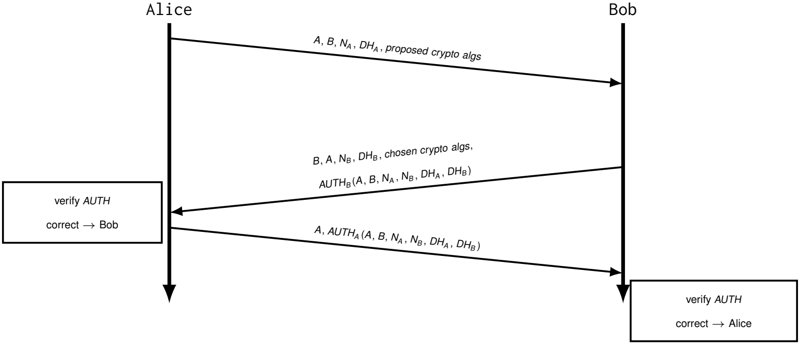
Protocol Try 7 Generic AUTH payload and Selection of Algorithms

- Session key $K_{A,B}$ derived from Diffie-Hellman


Alice
Bob
A, B, N_A, DH_A, proposed crypto algs
B, A, N_B, DH_B, chosen crypto algs,
$AUTH_B(A, B, N_A, N_B, DH_A, DH_B)$
verify AUTH
correct → Bob
$A, AUTH_A(A, B, N_A, N_B, DH_A, DH_B)$
verify AUTH
correct → Alice

Protocol Try 7 Generic AUTH payload and Selection of Algorithms

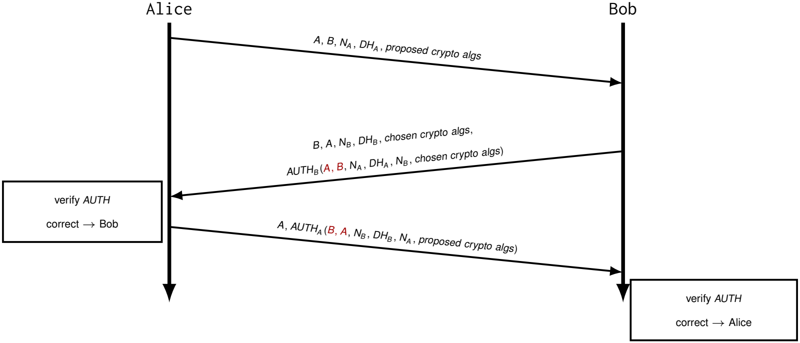
- Session key $K_{A,B}$ derived from Diffie-Hellman


Alice
Bob
A, B, N_A, DH_A, proposed crypto algs
B, A, N_B, DH_B, chosen crypto algs,
$AUTH_B(A, B, N_A, N_B, DH_A, DH_B)$
verify AUTH
correct → Bob
$A, AUTH_A(A, B, N_A, N_B, DH_A, DH_B)$
verify AUTH
correct → Alice

- AUTH playload could be $MAC_{K_{A,B,longterm}}$. Then, Alice and Bob authenticate on identical messages → replay attack possible!

Protocol Try 8 AUTH Payload rework

- Session key $K_{A,B}$ derived from Diffie-Hellman



Alice
Bob
A, B, N_A, DH_A, *proposed crypto algs*
B, A, N_B, DH_B, *chosen crypto algs*,
$AUTH_B$(A, B, N_A, DH_A, N_B, *chosen crypto algs*)
verify *AUTH*
correct → Bob
A, $AUTH_A$(B, A, N_B, DH_B, N_A, *proposed crypto algs*)
verify *AUTH*
correct → Alice

- AUTH playloads are different and contain information provided by both principles.

Simplicity

- Cryptographic protocols should be kept as simple as possible (but not any simpler)
- Complexity makes analysis harder and increases attack surface.
- Design Concept: Request-Response Pairs
  - $A \longrightarrow B : \mathit{Request}1$
  - $B \longrightarrow A : \mathit{Response}1$
  - ...

DoS Protection

- Cryptography is expensive (in particular asymmetric cryptography)
- Denial-of-Service attacker
  - Make victim do expensive operations
  - The attacker does not have to generate valid ciphertext, simple random numbers can work.
- Defense
  - Avoid expensive operations unless other principle has shown willingness to participate by replying with valid messages.
    - In final protocol try, we will avoid crypto until message 3.
  - Cookie mechanisms like TCP SYN Cookies could be used to avoid holding of state.

Chapter 10: Cryptographic Protocols

Introduction

Protocols

Authentication and Key Establishment Protocols

Attack Concepts against Cryptographic Protocols

Desirable Properties of Cryptographic Protocols

Final Protocol, Goals, and Notation

Needham Schroeder Protocol

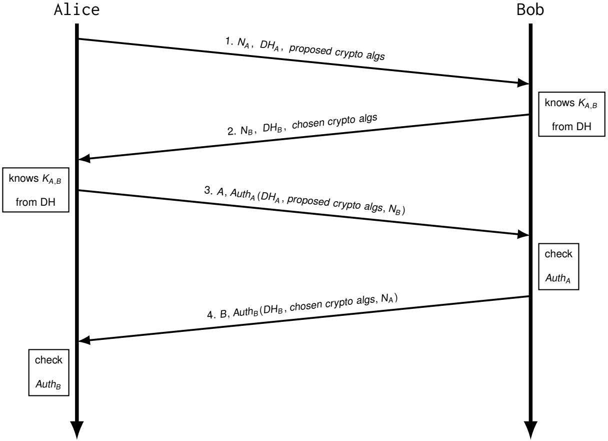
Conclusions - What have we learned

Authentication and Key Establishment Problem Statement - Version 3 (FINAL)

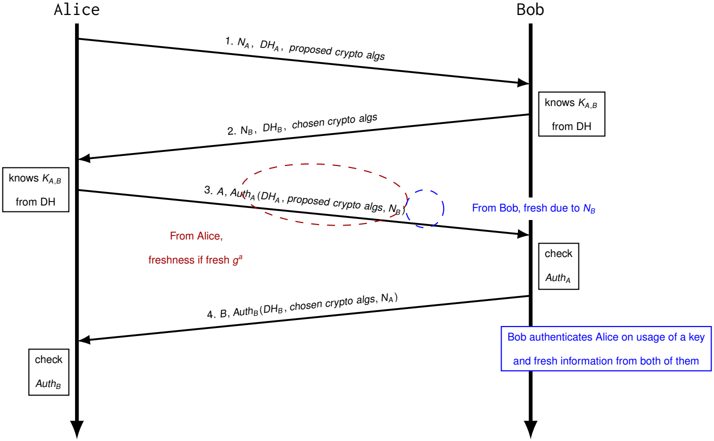
Goals:

- Run a key exchange protocol such that at the end of the protocol:
- Alice and Bob have a shared session key for a secure channel
- Alice and Bob have agreed on the cryptographic algorithms to be used for the secure channel
- Alice (Bob) must be able to verify that Bob (Alice) participated in the protocol run (authentication) and that he (she) is “alive” (freshness)
- Alice and Bob must know that $K_{A,B}$ is newly generated

Final Protocol


Alice
Bob
1. N_A, DH_A, proposed crypto algs
knows $K_{A,B}$ from DH
2. N_B, DH_B, chosen crypto algs
knows $K_{A,B}$ from DH
3. A, $Auth_A(DH_A$, proposed crypto algs, $N_B)$
check $Auth_A$
4. B, $Auth_B(DH_B$, chosen crypto algs, $N_A)$
check $Auth_B$

Final Protocol



Alice

Bob

1. N_A, DH_A, *proposed crypto algs*

knows $K_{A,B}$ from DH

2. N_B, DH_B, *chosen crypto algs*

knows $K_{A,B}$ from DH

3. A, $Auth_A(DH_A$, *proposed crypto algs*, $N_B)$

From Bob, fresh due to N_B

From Alice,

freshness if fresh g^a

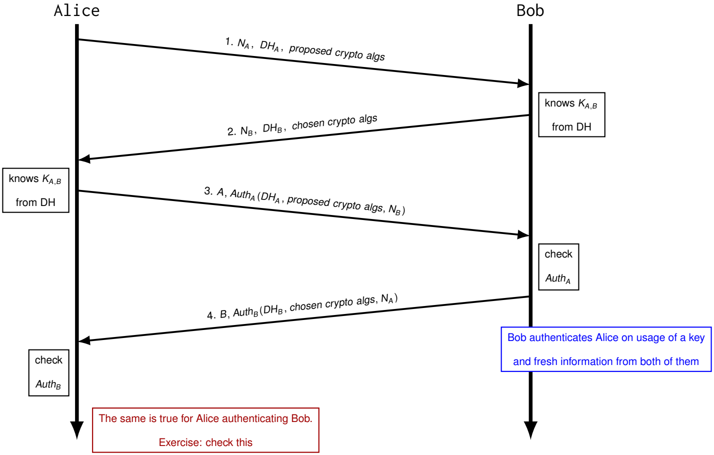
check $Auth_A$

4. B, $Auth_B(DH_B$, *chosen crypto algs*, $N_A)$

Bob authenticates Alice on usage of a key and fresh information from both of them

check $Auth_B$

Final Protocol



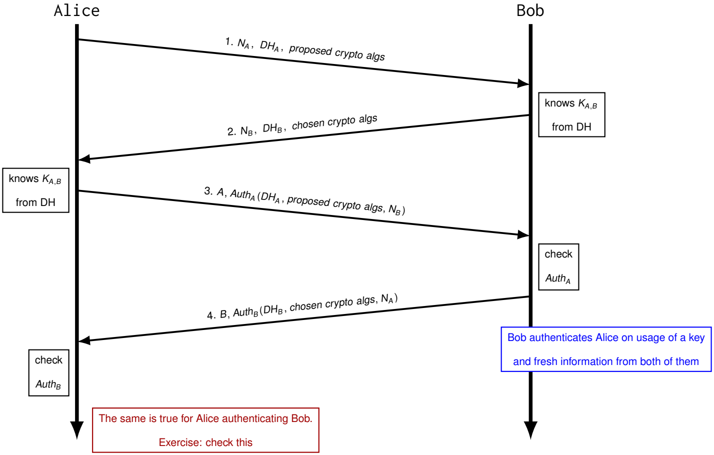
Alice
Bob
1. N_A, DH_A, *proposed crypto algs*
knows $K_{A,B}$ from DH
2. N_B, DH_B, *chosen crypto algs*
knows $K_{A,B}$ from DH
3. A, $Auth_A(DH_A$, *proposed crypto algs*, $N_B)$
check $Auth_A$
4. B, $Auth_B(DH_B$, *chosen crypto algs*, $N_A)$
check $Auth_B$

Bob authenticates Alice on usage of a key and fresh information from both of them

The same is true for Alice authenticating Bob.

Exercise: check this

Final Protocol


Alice
Bob
1. N_A, DH_A, *proposed crypto algs*
knows $K_{A,B}$ from DH
2. $\mathrm{N_B}$, DH_B, *chosen crypto algs*
knows $K_{A,B}$ from DH
3. A, $Auth_A(DH_A$, *proposed crypto algs*, $N_B)$
check $Auth_A$
4. B, $Auth_B(DH_B$, *chosen crypto algs*, $\mathrm{N_A})$
check $Auth_B$

Bob authenticates Alice on usage of a key and fresh information from both of them

The same is true for Alice authenticating Bob.

Exercise: check this

- AUTH playload is generated with pre-shared information!

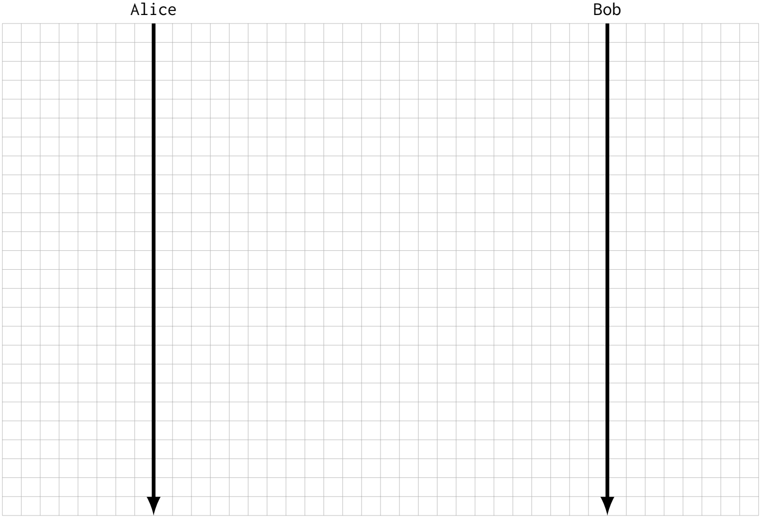
Final Protocol Explanations

- Explanation
  - Messages 1 and 2 form a request-response pair where only information is exchanged.
  - Messages 3 and 4 form the authentication request-response pair with identity information and authentication.
  - Alice or Bob need to stop the communication when authentication fails or a wrong entity authenticates.
  - Message 3: Alice authenticates on her first message and on the nonce N_B provided by Bob.
  - Message 4: Bob authenticates on his first message and on the nonce N_A provided by Alice.
- Final protocol is a simplified version of the IKEv2 protocol (IKE_SA_Init plus IKE_Auth Exchange) of IPSec (see IPSec chapter)

Repetition Exercise (later once we discussed IPSec): Compare with IKEv2

Write down "Final Protocol" in the terminology / fields used in IPSec.

Exercise: Final Protocol with Timestamps instead of Nonces?



Notation

Notation	Meaning
A	Name of principle A (Alice), analogous for B, E, TTP, CA
CA_A	Certification Authority of A
r_A	Random value chosen by A
N_A	Nonce (number used once) chosen by A
t_A	Timestamp generated by A
$(m_1, .., m_n)$	Concatenation of m_1, ..., m_n
$A \rightarrow B : m$	A sends message m to B

Notation

Notation	Meaning
$K_{A\text{-}pub}$	Public Key of A
$K_{A\text{-}priv}$	Private Key of A
$K_{A,B}$	Shared symmetric key of A and B, only known to A and B
$H(m)$	Cryptographic hash value over m
$Enc_K(m)$	Encrypt m with key K, K can be symmetric or asymmetric
$Dec_K(c)$	Decrypt c with key K, K can be symmetric or asymmetric
$Sig_K(m)$	Signature of message m with key K, K is a private asymmetric key
$MAC_K(m)$	Message Authentication Code of m with key K, K is symmetric key
$\{m\}_K$	Message m encrypted and integrity-protected with symmetric key K
$[m]_K$	m integrity-protected with key K
$Cert_{CA}(A)$	Certificate of CA for public key $K_{A\text{-}pub}$ of A, signed by the private key of CA

Chapter 10: Cryptographic Protocols

Introduction

Protocols

Authentication and Key Establishment Protocols

Attack Concepts against Cryptographic Protocols

Desirable Properties of Cryptographic Protocols

Final Protocol, Goals, and Notation

Needham Schroeder Protocol

- Needham Schroeder Symmetric Key Protocol
- Needham Schroeder Public Key Protocol

Conclusions - What have we learned

Needham Schroeder Protocol

Roger Needham

Michael Schroeder

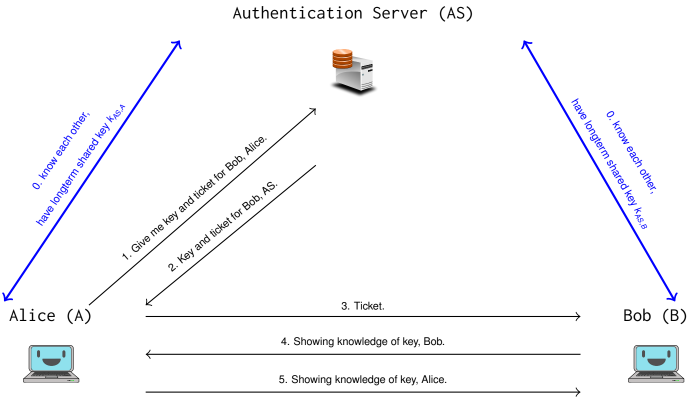
- Invented in 1978 by Roger Needham and Michael Schroeder [Nee78]
- The Needham-Schroeder Protocol is a protocol for mutual authentication and key establishment
- It aims to establish a session key between two users (or a user and an application server, e.g. email server) over an insecure network

Needham Schroeder Protocol

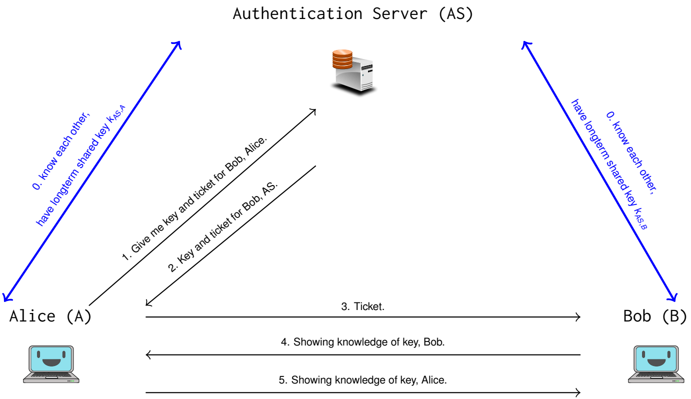
- The protocol has 2 versions:
  - The Needham Schroeder Symmetric Key Protocol:
    based on symmetric encryption, forms the basis for the Kerberos protocol
  - The Needham Schroeder Public Key Protocol:
    uses public key cryptography. A flaw in this protocol was published by Gavin Lowe [Lowe95] 17 years later! Lowe proposes also a way to fix the flaw in [Lowe95]

Gavin Lowe

Needham Schroeder Symmetric Key Protocol


Authentication Server (AS)
0. know each other,
have longterm shared key $k_{AS,A}$
0. know each other,
have longterm shared key $k_{AS,B}$
1. Give me key and ticket for Bob, Alice.
2. Key and ticket for Bob, AS.
Alice (A)
Bob (B)
3. Ticket.
4. Showing knowledge of key, Bob.
5. Showing knowledge of key, Alice.

Needham Schroeder Symmetric Key Protocol



Authentication Server (AS)

0. know each other, have longterm shared key $k_{AS,A}$

1. Give me key and ticket for Bob, Alice.

2. Key and ticket for Bob, AS.

0. know each other, have longterm shared key $k_{AS,B}$

Alice (A)

Bob (B)

3. Ticket.

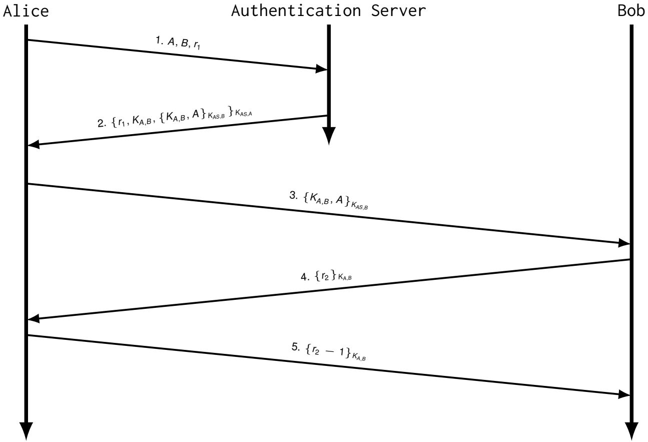
4. Showing knowledge of key, Bob.

5. Showing knowledge of key, Alice.

Only Alice and Bob (and the AS) know the shared key,

showing knowledge → one of them

Needham Schroeder Symmetric Key Protocol



Alice

Authentication Server

Bob

1. A, B, r_1

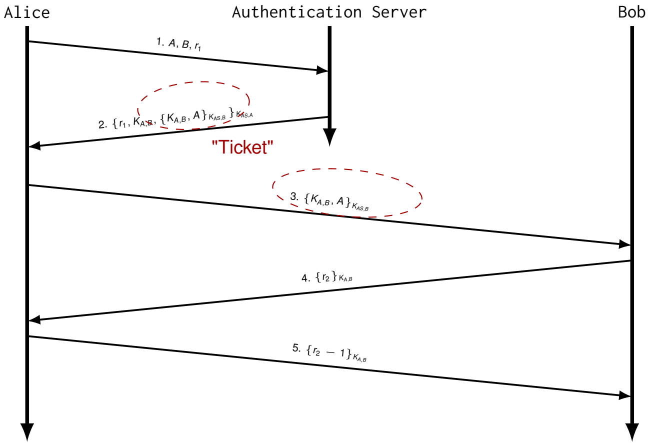
2. $\{r_1, K_{A,B}, \{K_{A,B}, A\}_{K_{AS,B}}\}_{K_{AS,A}}$

3. $\{K_{A,B}, A\}_{K_{AS,B}}$

4. $\{r_2\}_{K_{A,B}}$

5. $\{r_2 - 1\}_{K_{A,B}}$

Needham Schroeder Symmetric Key Protocol


Alice
Authentication Server
Bob
1. A, B, r_1
2. $\{r_1, K_{A,B}, \{K_{A,B}, A\}_{K_{AS,B}}\}_{K_{AS,A}}$
"Ticket"
3. $\{K_{A,B}, A\}_{K_{AS,B}}$
4. $\{r_2\}_{K_{A,B}}$
5. $\{r_2 - 1\}_{K_{A,B}}$

Needham Schroeder Symmetric Key Protocol

- 1. $A \rightarrow AS : A, B, r_1$
  - Alice informs AS that she (A) wants to contact Bob (B).
  - Random number r_1 is used as nonce to identify the session.
  - Notice, the AS cannot tell whether it is Alice or someone else. Still, this is ok as answer will be protected.
- 2. $AS \rightarrow A : \{r_1, K_{A,B}, \{K_{A,B}, A\}_{K_{AS,B}}\}_{K_{AS,A}}$
  - The AS encrypts the message with key $K_{AS,A}$ so that only Alice can read the message.
  - Alice notices nonce r_1 and assumes answer to be fresh.
  - Alice gets to know session key $K_{A,B}$ which is also part of the ticket.
  - Alice also gets to know the ticket $\{K_{A,B}, A\}_{K_{AS,B}}$.
  - Alice cannot read or modify ticket as it is protected with key $K_{AS,B}$ unknown to her.

Needham Schroeder Symmetric Key Protocol

- 3. $A \rightarrow B : \{K_{A,B}, A\}_{K_{AS,B}}$
  - Bob can decrypt the ticket and learns that Alice (A) wants to contact him.
  - Furthermore, he learns the session key $K_{A,B}$
- 4. $B \rightarrow A : \{r_2\}_{K_{A,B}}$
  - Bob sends nonce r_2 to Alice encrypted with the session key $K_{A,B}$
  - While Alice does not know about r_2, she knows $K_{A,B}$ as new session key. Integrity shows knowledge of session key by B, which means that B is Bob as only Bob (and the AS) also knows the session key.
- 5. $A \rightarrow B : \{r_2 - 1\}_{K_{A,B}}$
  - Alice sends nonce $r_2 - 1$ to Bob encrypted with the new session key $K_{A,B}$.
  - Since only Alice also knows r_2, this A must be Alice.
  - Notice, the change from r_2 to $r_2 - 1$ is to make messages 4 and 5 different to avoid e.g. replay attacks.
    - Modern encryption modes with Initialization Vectors (IV) also ensure this if both messages 4 and 5 would be $\{r_2\}_{K_{A,B}}$. However, an attacker could replay with the same IV and then the modified protocol would fail unless it takes further measures to forbid and prevent repeated IVs.

Needham Schroeder Symmetric Key Protocol

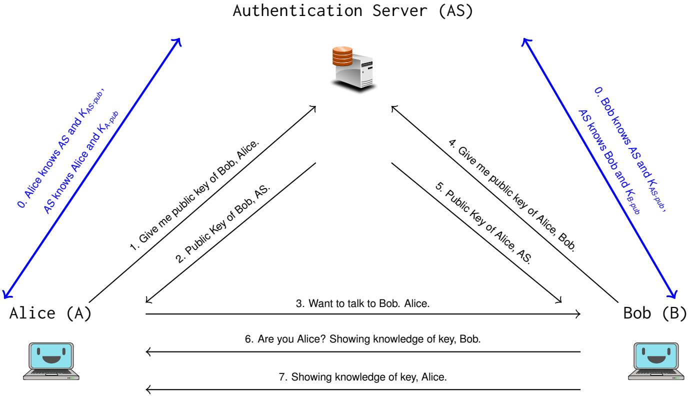
Ticket and Ticket Reuse

- Needham and Schroeder do not speak of tickets in their protocol, but from a modern point of view (relating to Kerberos) $\{K_{A,B}, A\}_{K_{AS,B}}$ is called a ticket.
- If Alice still trusts the ticket she has, Needham and Schroeder propose a shortened protocol:
  - 1. (3'.) $A \rightarrow B : \{K_{A,B}, A\}_{K_{AS,B}}, \{r_2\}_{K_{A,B}}$
  - 2. (4'.) $B \rightarrow A : \{r_3, r_2 - 1\}_{K_{A,B}}$
  - 3. (5'.) $A \rightarrow B : \{r_3 - 1\}_{K_{A,B}}$
- As the session key is not fresh anymore, Alice challenges Bob with r_2 and Bob Alice with r_3.

Ticket Reuse Issues and Forward Secrecy

- If an attacker learns about session key $K_{A,B}$ and observed the related ticket in a previous protocol run, then the attacker can impersonate Alice.
  - 1. (3'.) $Attacker \rightarrow B : \{K_{A,B}, A\}_{K_{AS,B}}, \{r_2\}_{K_{A,B}}$
  - 2. (4'.) $B \rightarrow A : \{r_3, r_2 - 1\}_{K_{A,B}}$ needs to be intercepted and decrypted by attacker.
  - 3. (5'.) $Attacker \rightarrow B : \{r_3 - 1\}_{K_{A,B}}$
- Thus, breaking session key $K_{A,B}$ would allow to impersonate Alice in the future.
- Also, the Needham Schroeder Protocols do not provide any forward secrecy.

Needham Schroeder Public Key Protocol



Authentication Server (AS)

0. Alice knows AS and $K_{AS\text{-}pub}$, AS knows Alice and $K_{A\text{-}pub}$

0. Bob knows AS and $K_{AS\text{-}pub}$, AS knows Bob and $K_{B\text{-}pub}$

1. Give me public key of Bob, Alice.

2. Public Key of Bob, AS.

3. Want to talk to Bob. Alice.

4. Give me public key of Alice, Bob.

5. Public Key of Alice, AS.

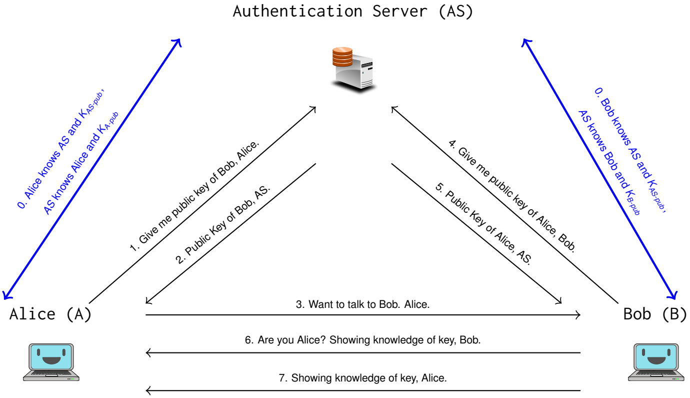
6. Are you Alice? Showing knowledge of key, Bob.

7. Showing knowledge of key, Alice.

Alice (A)

Bob (B)

Needham Schroeder Public Key Protocol

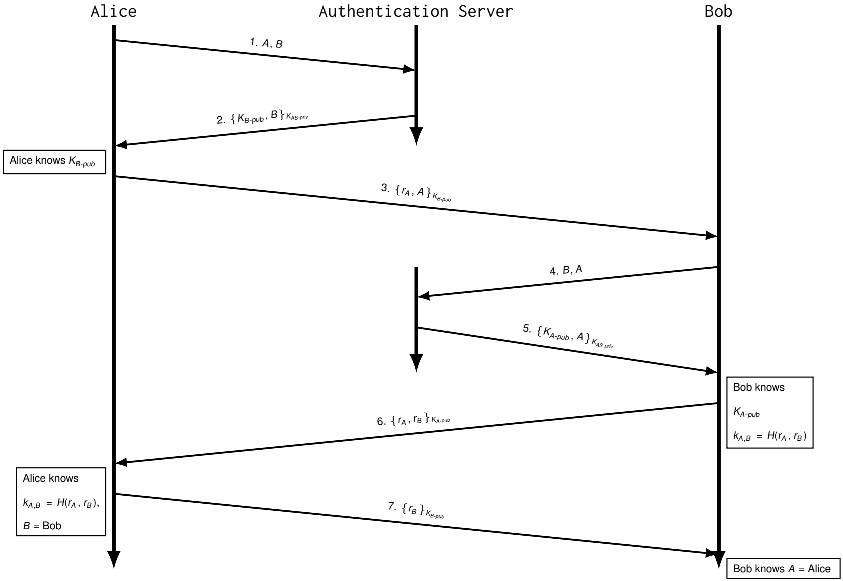


Authentication Server (AS)
0. Alice knows AS and $K_{AS\text{-pub}}$,
AS knows Alice and $K_{A\text{-pub}}$
0. Bob knows AS and $K_{AS\text{-pub}}$,
AS knows Bob and $K_{B\text{-pub}}$
1. Give me public key of Bob, Alice.
2. Public Key of Bob, AS.
4. Give me public key of Alice, Bob.
5. Public Key of Alice, AS.
Alice (A)
Bob (B)
3. Want to talk to Bob. Alice.
6. Are you Alice? Showing knowledge of key, Bob.
7. Showing knowledge of key, Alice.

AS asserts relationship public key ↔ person (Alice or Bob),

showing knowledge of the related private key → related person

Needham Schroeder Public Key Protocol



Alice

Authentication Server

Bob

1. A, B

2. $\{K_{B\text{-pub}}, B\}_{K_{AS\text{-priv}}}$

Alice knows $K_{B\text{-pub}}$

3. $\{r_A, A\}_{K_{B\text{-pub}}}$

4. B, A

5. $\{K_{A\text{-pub}}, A\}_{K_{AS\text{-priv}}}$

Bob knows

$K_{A\text{-pub}}$

$k_{A,B} = H(r_A, r_B)$

6. $\{r_A, r_B\}_{K_{A\text{-pub}}}$

Alice knows

$k_{A,B} = H(r_A, r_B)$,

B = Bob

7. $\{r_B\}_{K_{B\text{-pub}}}$

Bob knows A = Alice

As a one-time exception, we will use $\{\cdot\}$ with asymmetric keys (for historic reasons). Never mix up encryption/signing in practice!!!

Needham Schroeder Public Key Protocol

- 1. $A \rightarrow AS : A, B$
- 2. $AS \rightarrow A : \{K_{B\text{-}pub}, B\}_{K_{AS\text{-}priv}}$
  - In this exchange, Alice asks for the public key of Bob. Her identity is irrelevant. Anyone can ask for Bob's public key.
  - AS encrypts $K_{B\text{-}pub}, B$ with its private key. Anyone can decrypt, but only the AS can generate this "signature".
- 3. $A \rightarrow B : \{r_A, A\}_{K_{B\text{-}pub}}$
  - Alice sends Bob a challenge r_A and the identity A that she claims to be (not yet proven!).
  - Only Bob can decrypt the message with his private key, so only he can know r_A later-on.
- 4. $B \rightarrow AS : B, A$
- 5. $AS \rightarrow B : \{K_{A\text{-}pub}, A\}_{K_{AS\text{-}priv}}$
  - 4. and 5. are the same as 1. and 2.

Needham Schroeder Public Key Protocol

- 6. $B \rightarrow A : \{r_A, r_B\}_{K_{A\text{-}pub}}$
  - Bob answers Alice's challenge r_A. So, Alice knows he is Bob.
  - Bob challenges Alice with r_A. As her public key is used, only she can decrypt the message and know r_B.
  - The shared session key is $K_{A,B} = H(r_A, r_B)$, with H being a cryptographic hash function. As r_A and r_B are only sent encrypted with the public key of either Alice or Bob, no other entity knows r_A, r_B, and thus $K_{A,B}$.
- 7. $A \rightarrow B : \{r_B\}_{K_{B\text{-}pub}}$
  - Alice answers Bob's challenge r_B. So, Bob knows she is Alice.

Exercise: Proper usage of Encryption and Signing

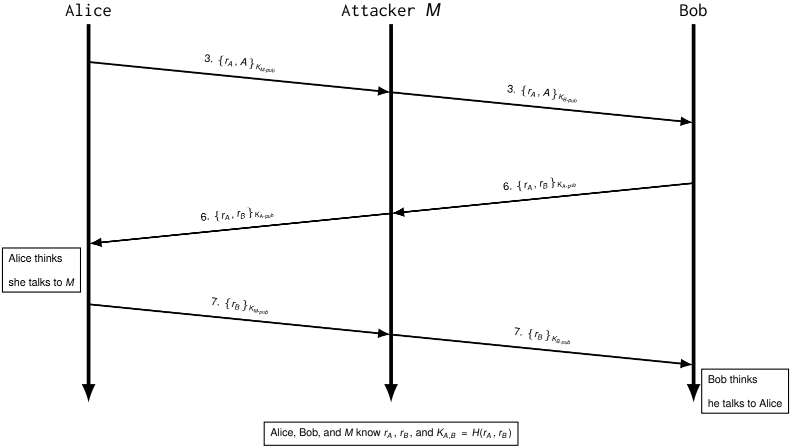
On the previous slides, we used $\{\cdot\}$ with asymmetric keys. It should combine $\mathit{Enc}_k(\cdot)$ and $\mathit{Sig}_k(\cdot)$. Why is this a bad idea in practice? How should the protocol look with only using $\mathit{Enc}_k(\cdot)$ and $\mathit{Sig}_k(\cdot)$?

Needham Schroeder Public Key Protocol - Attack

- In 1995, Lowe found a man-in-the-middle attack on the Needham Schroeder Public Key Protocol.
- Assumption: Attacker *M* can trick Alice *A* into a communication with him. So, Alice starts a communication session with *M*.
- Idea: make Bob believe, he talks to Alice instead of the attacker.

Needham Schroeder Public Key Protocol - Attack

- We skip the exchanges with the AS to obtain the public keys.


Alice
Attacker M
Bob
3. $\{r_A, A\}_{K_{M\text{-}pub}}$
3. $\{r_A, A\}_{K_{B\text{-}pub}}$
6. $\{r_A, r_B\}_{K_{A\text{-}pub}}$
6. $\{r_A, r_B\}_{K_{A\text{-}pub}}$
Alice thinks she talks to M
7. $\{r_B\}_{K_{M\text{-}pub}}$
7. $\{r_B\}_{K_{B\text{-}pub}}$
Bob thinks he talks to Alice
Alice, Bob, and M know r_A, r_B, and $K_{A,B} = H(r_A, r_B)$

Needham Schroeder Public Key Protocol - Attack Resolution

- The attack fails when message 6 is modified to:
  6. $B \rightarrow A : \{r_A, r_B, B\}_{K_{A\text{-}pub}}$
- Exercise: Verify that the attack will now fail.

Chapter 10: Cryptographic Protocols

Introduction

Protocols

Authentication and Key Establishment Protocols

Attack Concepts against Cryptographic Protocols

Desirable Properties of Cryptographic Protocols

Final Protocol, Goals, and Notation

Needham Schroeder Protocol

Conclusions - What have we learned

Conclusions - What have we learned
What have we learned

- Authentication and Key Establishment
  - Related to Formal Reasoning
  - Secure Authentication needs some pre-established keys, also see PKI chapter
  - Protocol weaknesses can be tricky
  - Learned to attack protocols on conceptual level
  - Learned some protocols, remember the ones with actual names[3]
  - Learned how authenticity and key establishment can be achieved
- Analyze protocols on the layers they operate
- Analyze complete systems over all layers

[3] "Try *N*" is not a name

Literature

- C. Boyd, A. Mathuria. *Protocols for Authentication and Key Establishment*, Springer, 2003.
- G. Schäfer. *Netzsicherheit - Algorithmische Grundlagen und Protokolle*, dpunkt Verlag, 2003.
- N. Ferguson, B. Schneier. *Practical Cryptography*, John Wiley & Sons, 2003.
- G. Lowe. *An Attack on the Needham-Schroeder Public-Key Authentication Protocol*, Information Processing Letters, volume 56, number 3, pages 131-133, 1995.
- R. Needham, M. Schroeder. *Using Encryption for Authentication in Large Networks of Computers.*, Communications of the ACM, Vol. 21, No. 12, 1978.