

Network Security (NetSec)

IN2101 – WS 16/17

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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

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Conclusions - What have we learned

- This course is based to some extent on slides provided by Günter Schäfer, author of the book "Netzicherheit - Algorithmische Grundlagen und Protokolle", available in German from dpunkt Verlag.
- The English version of the book is entitled "Security in Fixed and Wireless Networks: An Introduction to Securing Data Communications" and is published by Wiley is also available. We gratefully acknowledge his support.
- The slide set has been reworked by Heiko Niedermayer, Ali Fessi, Ralph Holz, Cornelius Diekmann, and Georg Carle.

- 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.

- 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

- Basic understanding of cryptographic protocols
 - Know the terms and methods and apply them
- Get to know some elementary protocols → 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

- When we discuss cryptographic protocols, we assume the following
 - The cryptographic primitives are secure.
 - Insecure primitives or implementations can make a secure protocol insecure¹.
 - 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, ...

- 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.

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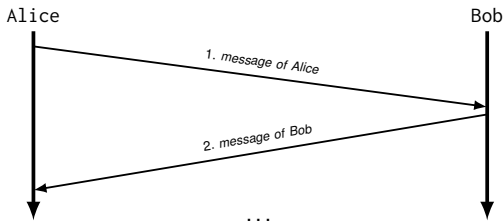
Needham Schroeder Protocol

Conclusions - What have we learned

- 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.

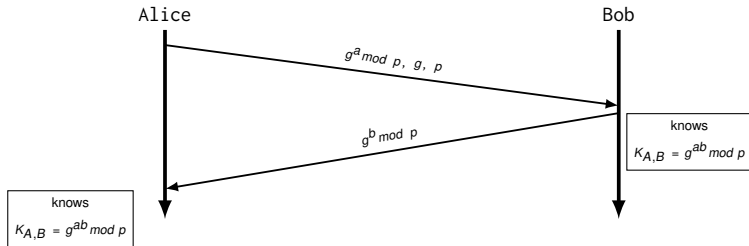
- Cryptographic protocols contain:
 - General entities that are normal participants of the protocol. We call them Alice (A), Bob (B), ...
 - Special-purpose entities that have a special role. Authentication Server (AS), ...
 - Some synonyms: entity, principle, participant
- Alice-Bob notation: one way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

- Or sequence diagram:



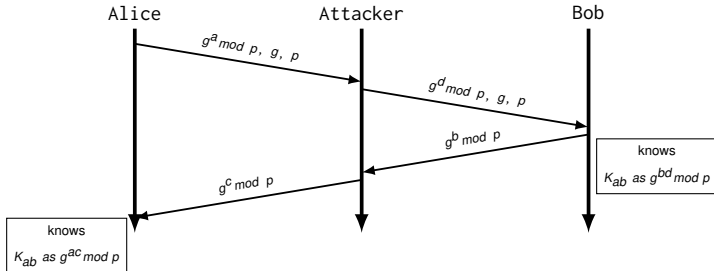
- Some Notation:

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



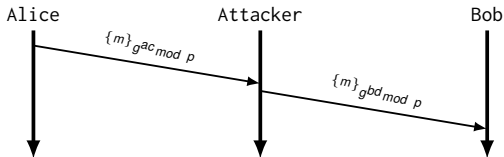
- Alice and Bob have completed a Diffie-Hellman exchange and established a shared key at the end of the protocol.
- Are we done?

Repetition. This should already be known.



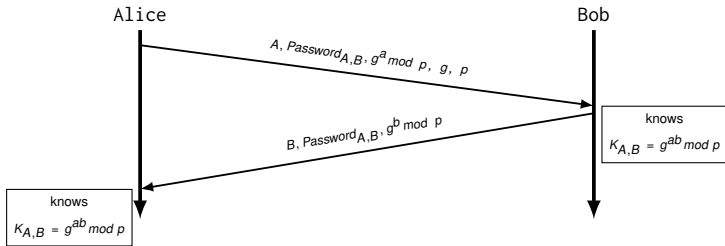
- Attacker now has a shared key K_{ac} with Alice and a shared key K_{bd} with Bob.
- The attacker is called Man-in-the-Middle attacker as it sits in-between any communication between Alice and Bob.

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.

- 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.



- 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.

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Conclusions - What have we learned

- 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.

- 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]

- 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?
 - 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.

- 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

- 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

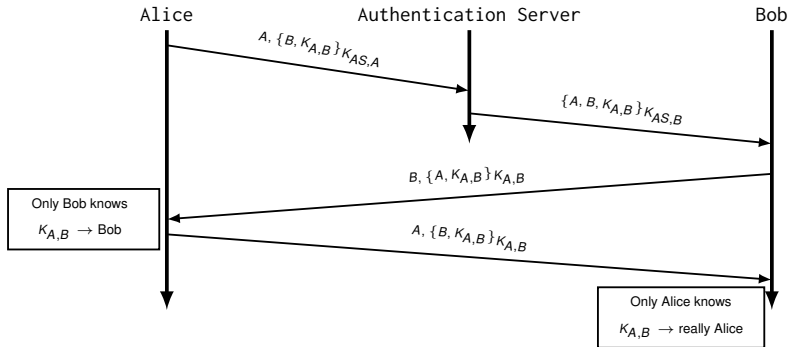
- Each principle has its knowledge and beliefs.
- In the operation of the cryptographic protocol it takes certain actions.
- In the operation of the cryptographic protocol it makes observations.
- Reasoning on actions and observation needs to establish the objectives of the protocol.
 - Example (Authenticity 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.

- 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.

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)

- 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.



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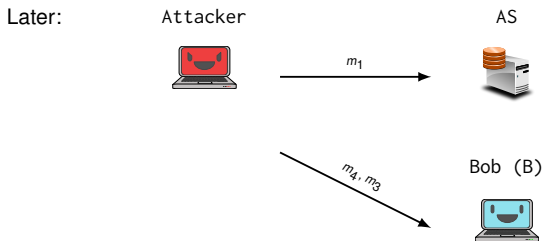
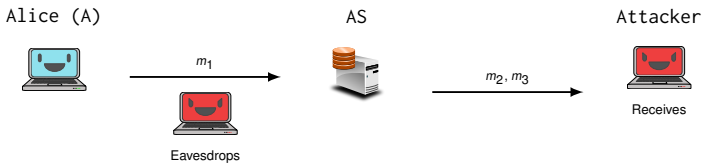
Final Protocol, Goals, and Notation

Needham Schroeder Protocol

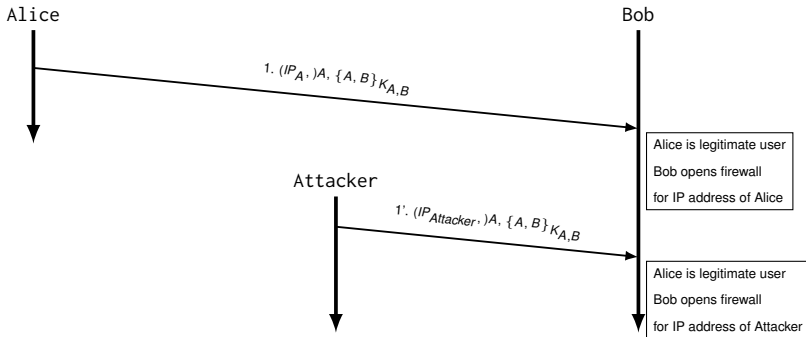
Conclusions - What have we learned

- 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.

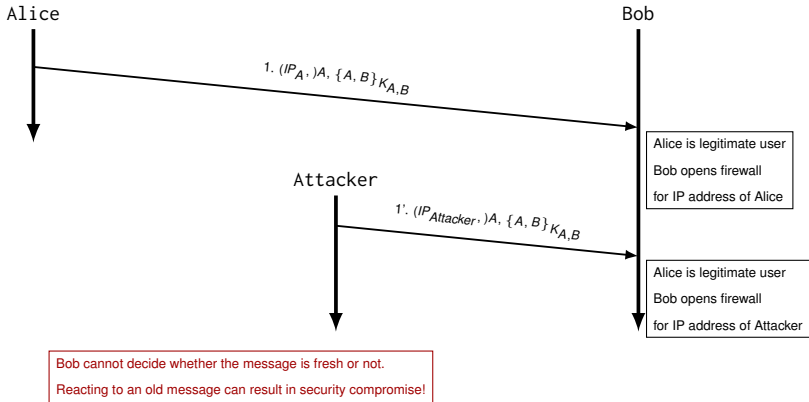
- Replay Attack: Receives and eavesdrops messages → later-on send message or part of message to some principle.



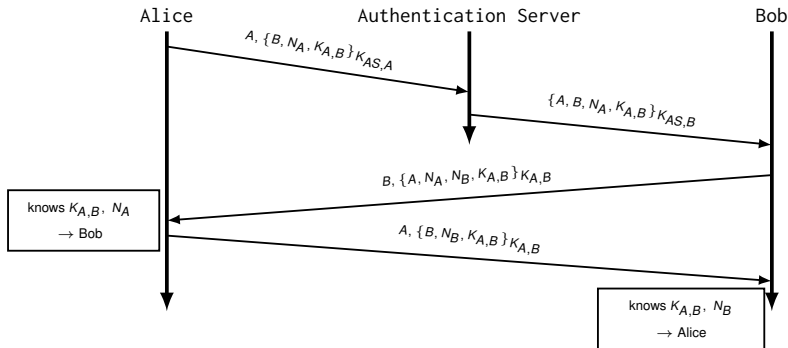
Replay Attack - Example



Replay Attack - Example



- An attacker can replay all messages of protocol try 3. None needs to be fresh.
- Better add a defense \rightarrow Nonces N_A, N_B, \dots



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)

- The attacker cannot break cryptography (assumption²).
- 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

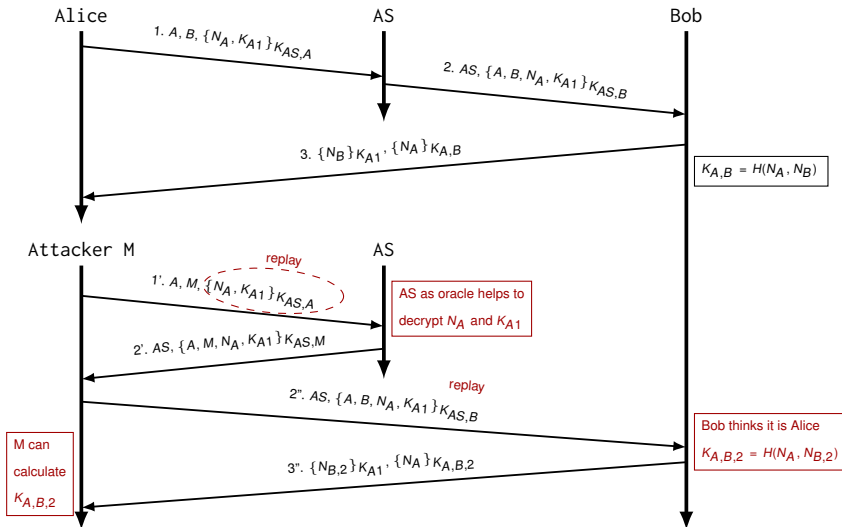
Can you apply some crypto for me on m ?

Oracle

Sure, m'

²see Dolev-Yao Attacker Model

Oracle Attacks - Example



- 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 $N_B = \text{"Alice buys washing machine."}$



in Protocol 1:

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



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

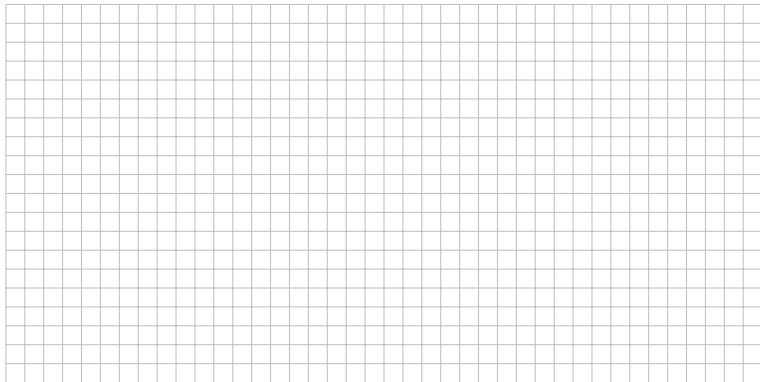
in Protocol 2:

1. "Alice buys washing machine.",

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



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



- 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.

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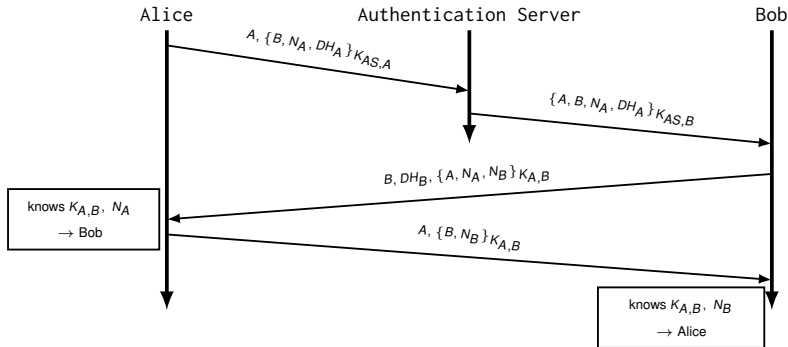
Needham Schroeder Protocol

Conclusions - What have we learned

- 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)
 - 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: $g, p, g^a \bmod p$)
 - DH_B is Diffie-Hellman information provided by Bob

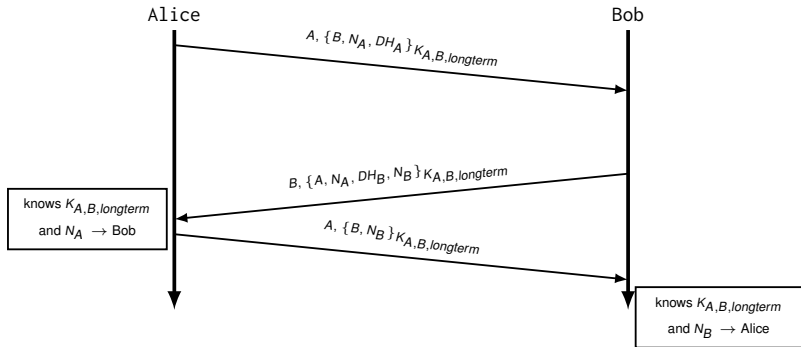
- Session key $K_{A,B}$ derived from DH_A and DH_B



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

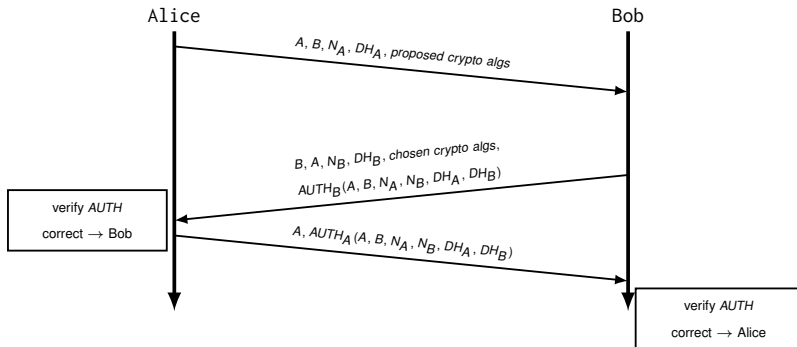
- Scalability of keys → Authentication Server
- But having a central server is a single point of failure
- ... and bad for scalability of service
- Thus, good if server need not be contacted within a protocol run.
- While server may have provided keys or certificates (identity-key binding) beforehand.

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

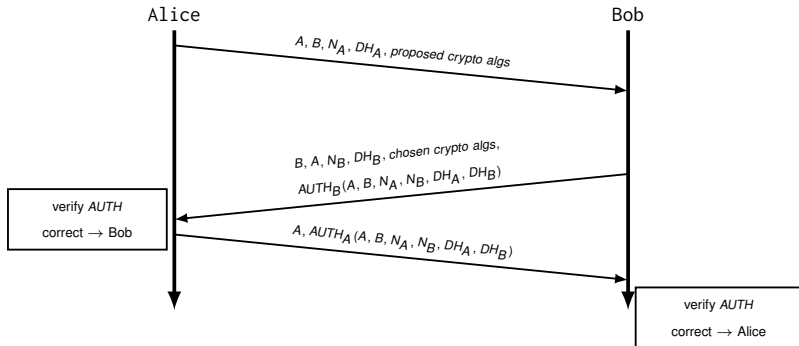


- Can we adapt the protocol, so that public key cryptography could be used?
- In practise, one might also want that all kinds of algorithms can be exchanged over time. → Do not become outdated!
- Concept:
 - Generic $Auth_X()$ function that can be realized with a suitable authentication function given 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: $Auth_B(m) = Sig_{K_{B-priv}}(m)$
 - Alice: $Vrfy_{K_{B-pub}}(m, Auth_B(m))$
 - Alice and Bob have to agree on this function and used algorithms, e.g.
 - Alice proposes a set of functions and algorithms
 - Bob selects the ones that are then used

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

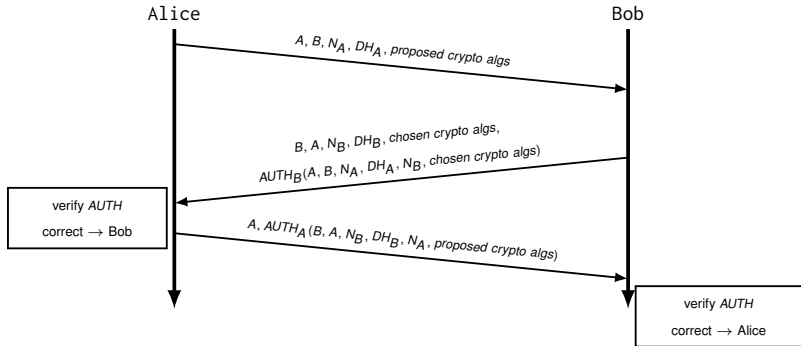


- Session key $K_{A,B}$ derived from Diffie-Hellman



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

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



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

- 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
 - $A \rightarrow B$: *Request*₁
 - $B \rightarrow A$: *Response*₁
 - ...

- 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.

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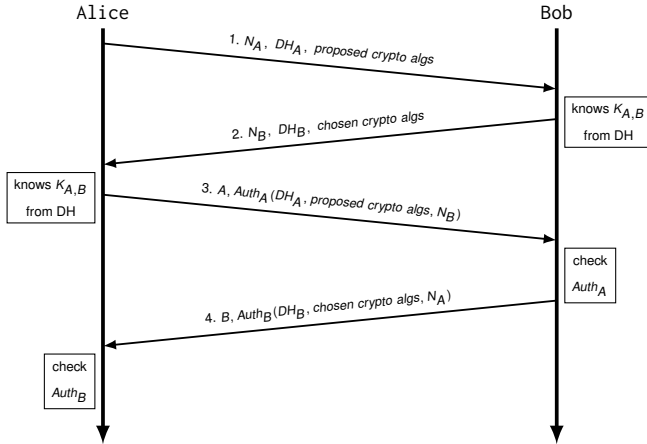
Needham Schroeder Protocol

Conclusions - What have we learned

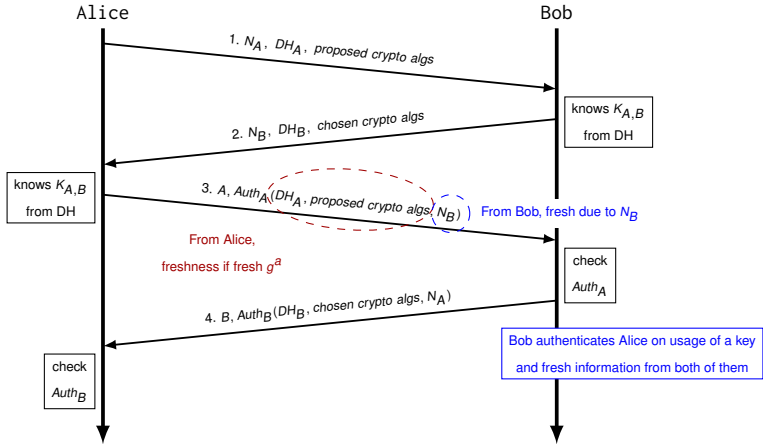
Goals:

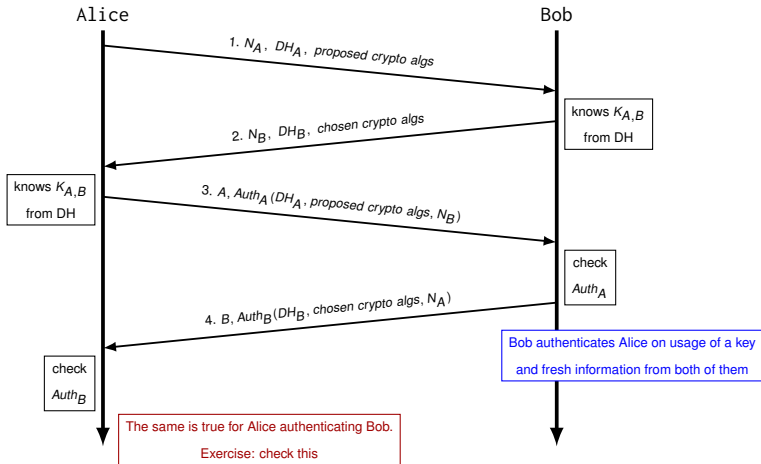
- Run a key exchange protocol such that at the end of the protocol:
- Alice and Bob have a shared session key for a secure channel
- Alice and Bob have agreed on the cryptographic algorithms to be used for the secure channel
- Alice (Bob) must be able to verify that Bob (Alice) participated in the protocol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

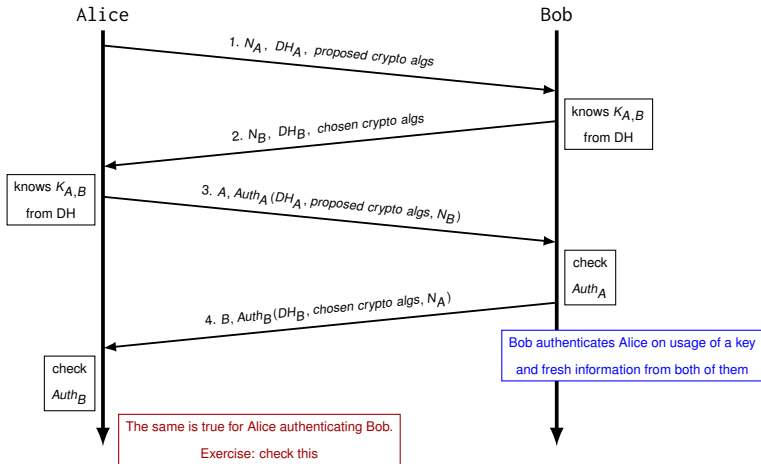
Final Protocol



Final Protocol





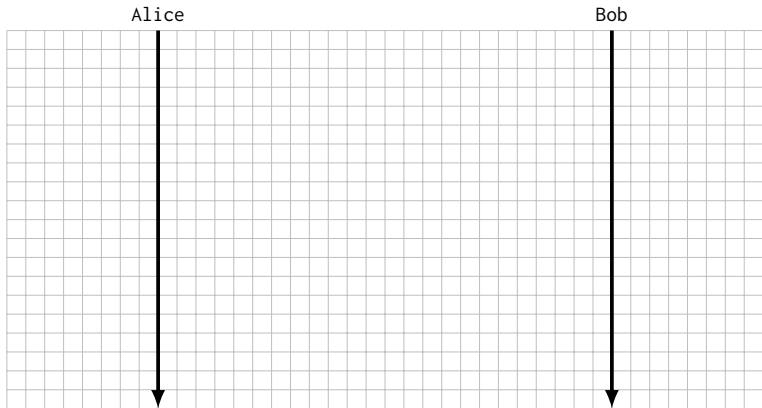


- AUTH payload is generated with pre-shared information!

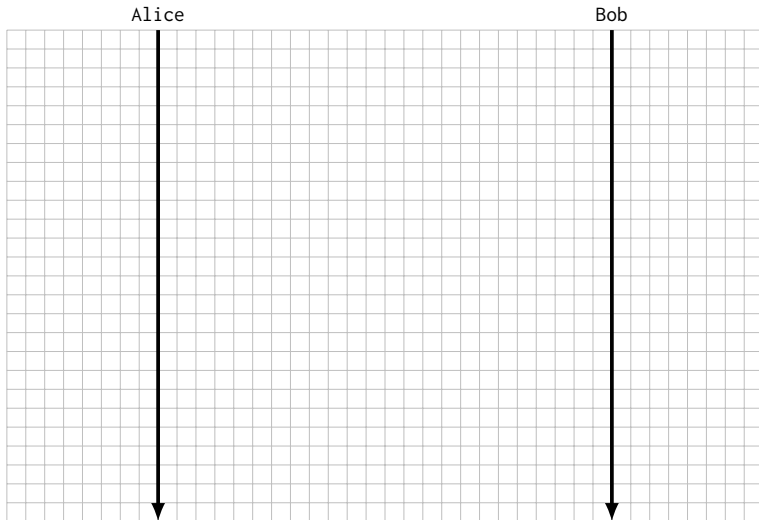


- Explanation
 - Messages 1 and 2 form a request-response pair where only information is exchanged.
 - Messages 3 and 4 form the authentication request-response pair with identity information and authentication.
 - Alice or Bob need to stop the communication when authentication fails or a wrong entity 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)

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



Exercise: Final Protocol with Timestamps instead of Nonces?



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, \dots, m_n)	Concatenation of m_1, \dots, m_n
$A \rightarrow B : m$	A sends message m to B

Notation	Meaning
K_{A-pub}	Public Key of A
K_{A-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-pub} of A, signed by the private key of CA

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Roger Needham



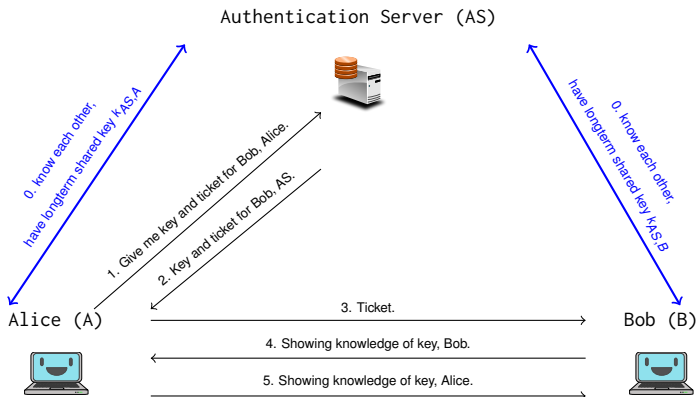
Michael Schroeder

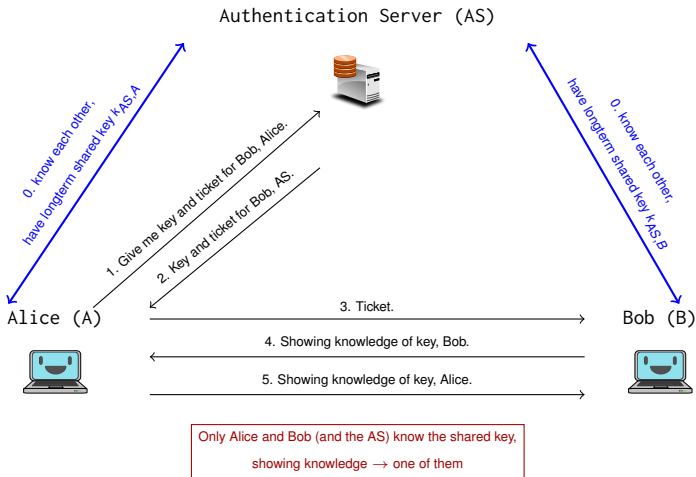
- Invented in 1978 by Roger Needham and Michael Schroeder [Nee78]
- The Needham-Schroeder Protocol is a protocol for mutual authentication and key establishment
- It aims to establish a session key between two users (or a user and an application server, e.g. email server) over an insecure network

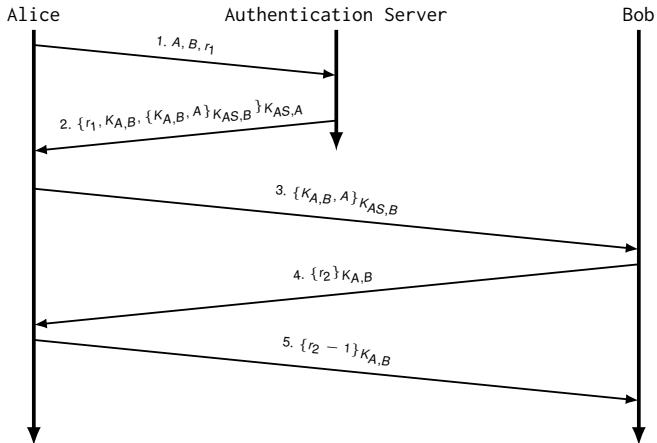
- The protocol has 2 versions:
 - The Needham Schroeder [Symmetric Key Protocol](#): based on symmetric encryption, forms the basis for the Kerberos protocol
 - The Needham Schroeder [Public Key Protocol](#): uses public key cryptography. A flaw in this protocol was published by Gavin Lowe [Lowe95] 17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

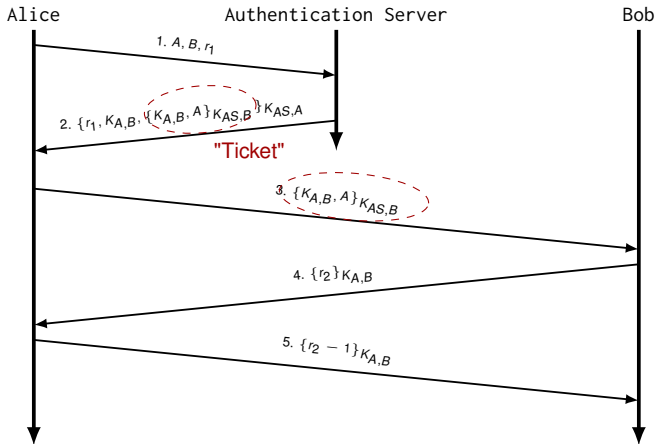


Gavin Lowe











- 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.



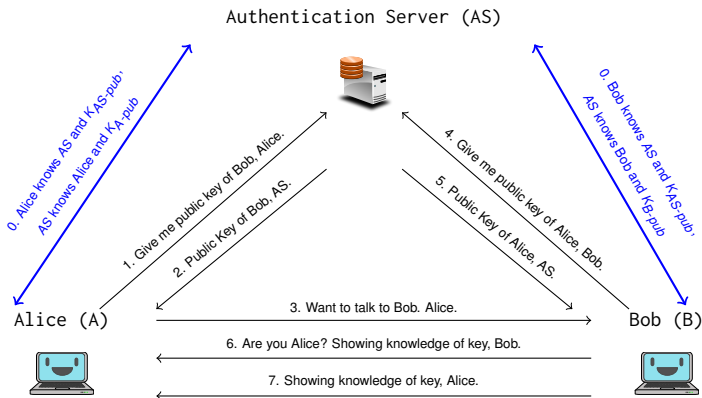
- 3. $A \rightarrow B : \{K_{A,B}, A\}_{K_{AS,B}}$
 - Bob can decrypt the ticket and learns that Alice (A) wants to contact him.
 - Furthermore, he learns the session key $K_{A,B}$
- 4. $B \rightarrow A : \{r_2\}_{K_{A,B}}$
 - Bob sends nonce r_2 to Alice encrypted with the session key $K_{A,B}$
 - While 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.

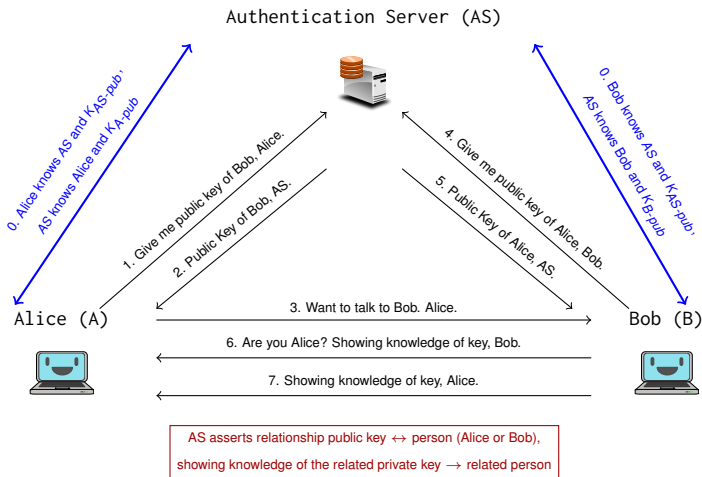
- Needham and Schroeder do not speak of tickets in their protocol, but from a modern point of view (relating to Kerberos) $\{K_{A,B}, A\}_{K_{AS,B}}$ is called a ticket.
- If Alice still trusts the ticket she has, Needham and Schroeder propose a shortened protocol:
 - 1. (3'.) $A \rightarrow B : \{K_{A,B},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

Needham Schroeder Symmetric Key Protocol

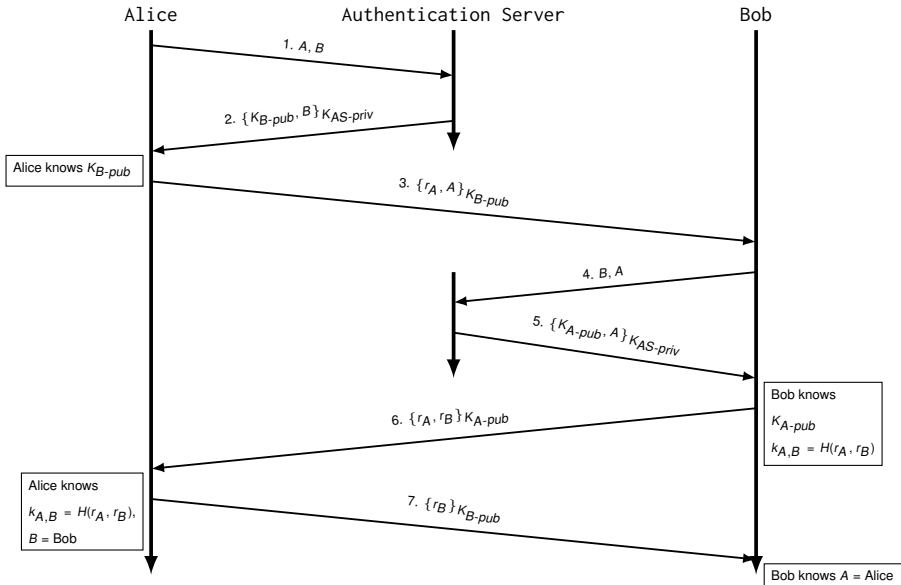
Ticket Reuse Issues and Forward Secrecy

- 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



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



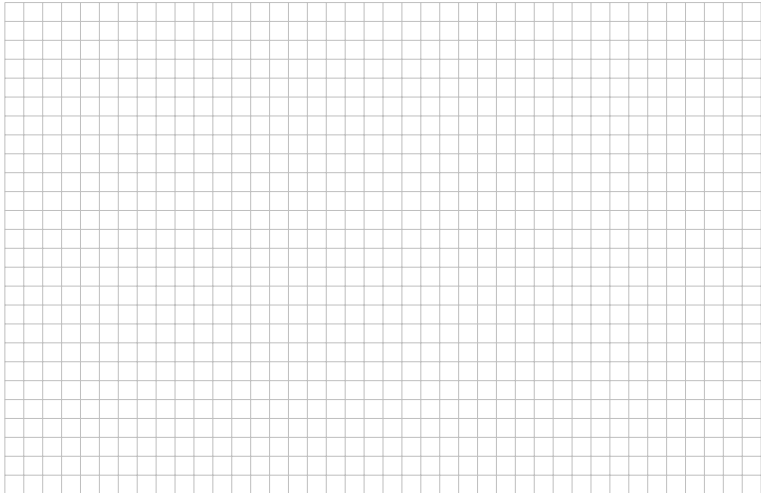
- 1. $A \rightarrow AS : A, B$
- 2. $AS \rightarrow A : \{K_{B-pub}, B\}_{K_{AS-priv}}$
 - In this exchange, Alice asks for the public key of Bob. Her identity is irrelevant. Anyone can ask for Bob's public key.
 - AS encrypts K_{B-pub}, B with its private key. Anyone can decrypt, but only the AS can generate this "signature".
- 3. $A \rightarrow B : \{r_A, A\}_{K_{B-pub}}$
 - 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. $AS \rightarrow B : \{K_{A-pub}, A\}_{K_{AS-priv}}$
 - 4. and 5. are the same as 1. and 2.



- 6. $B \rightarrow A : \{r_A, r_B\}_{K_{A-pub}}$
 - 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. $A \rightarrow B : \{r_B\}_{K_{B-pub}}$
 - Alice answers Bob's challenge r_B . So, Bob knows she is Alice.

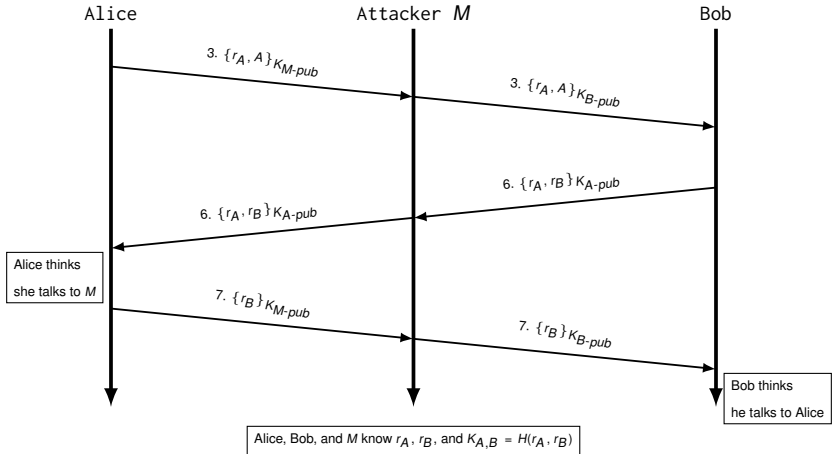
Exercise: Proper usage of Encryption and Signing

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

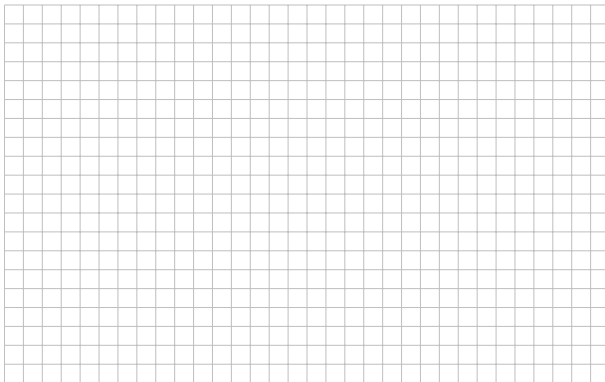


- In 1995, Lowe found a man-in-the-middle attack on the Needham Schroeder Public Key Protocol.
- Assumption: Attacker M can trick Alice A into a communication with him. So, Alice starts a communication session with M .
- Idea: make Bob believe, he talks to Alice instead of the attacker.

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



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



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
 - 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 names³
 - 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^o is not a name

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- G. Schäfer. *Netzicherheit - 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.