UNIVERSITÄT PASSAU

Fakultät für Informatik und Mathematik

6090: Security of Computer and Embedded Systems

Week 9: Security Protocols

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This Week’s Outline

- Building A Key Establishment Protocol
- Notation Used In Protocol Modeling
- Protocol Attacks

Motivation

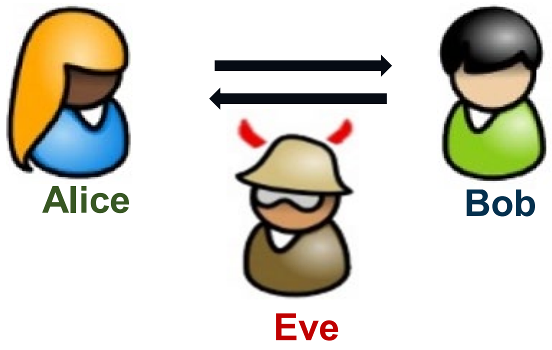
- RSA, AES, etc. provide (probably) very good cryptographic primitives
- How can we construct secure distributed applications with these primitives?
  - Securing Internet connections
  - E-commerce
  - E-banking
  - E-voting
  - Mobile communications
  - Digital contract signing

We will learn that:

Even if cryptography is hard to break, constructing these is not a trivial task!

Establishing An Authentic Channel: NSPK

Alice wants to be sure that she talks to Bob
(authenticity)



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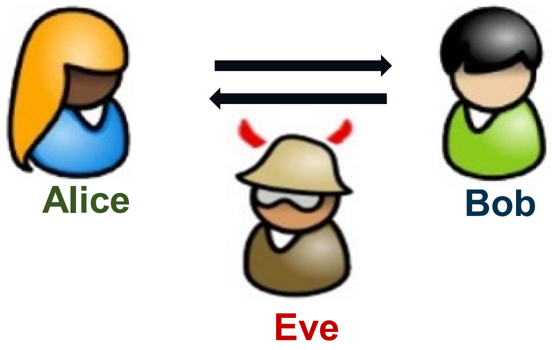

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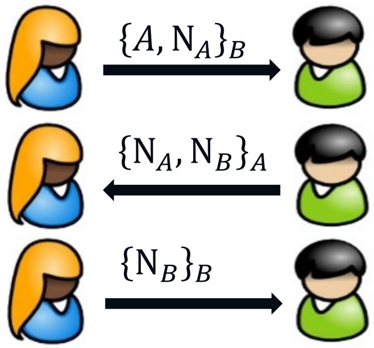

"I am Alice and here is my **nonce** N_A"

"Here is your **nonce** N_A and I have one for you"

"I got it, it is N_B"

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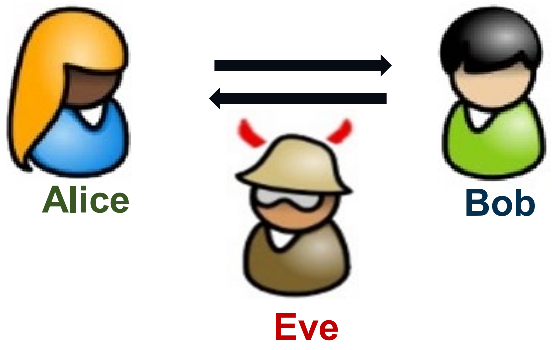

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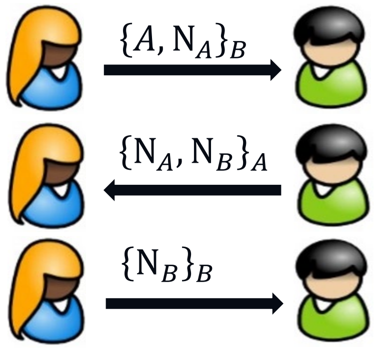

"I am Alice and here is my **nonce** N_A"

"Here is your **nonce** N_A and I have one for you"

"I got it, it is N_B"

* A **nonce** (short for: "number once") is a fresh secret only known to the person generating it

NSPK: Correctness

Goal: *Mutual Authenticity (Two-way Authentication)*
after executing the protocol successfully

Alice and Bob can be sure to talk to each other (and not to somebody else)

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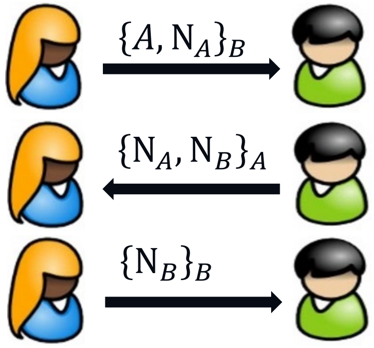
Correctness argument (informal):



"This is Alice and I have chosen a nonce N_A"

"Here is your nonce N_A. Since I could read it, I must be Bob. I also have a challenge N_B for you"

" You sent me N_B.
Since only Alice can read this and she sent it back, you must be Alice"

NSPK: Lowe’s Attack (1996)

Protocols are typically *small* and *convincing* and often wrong!

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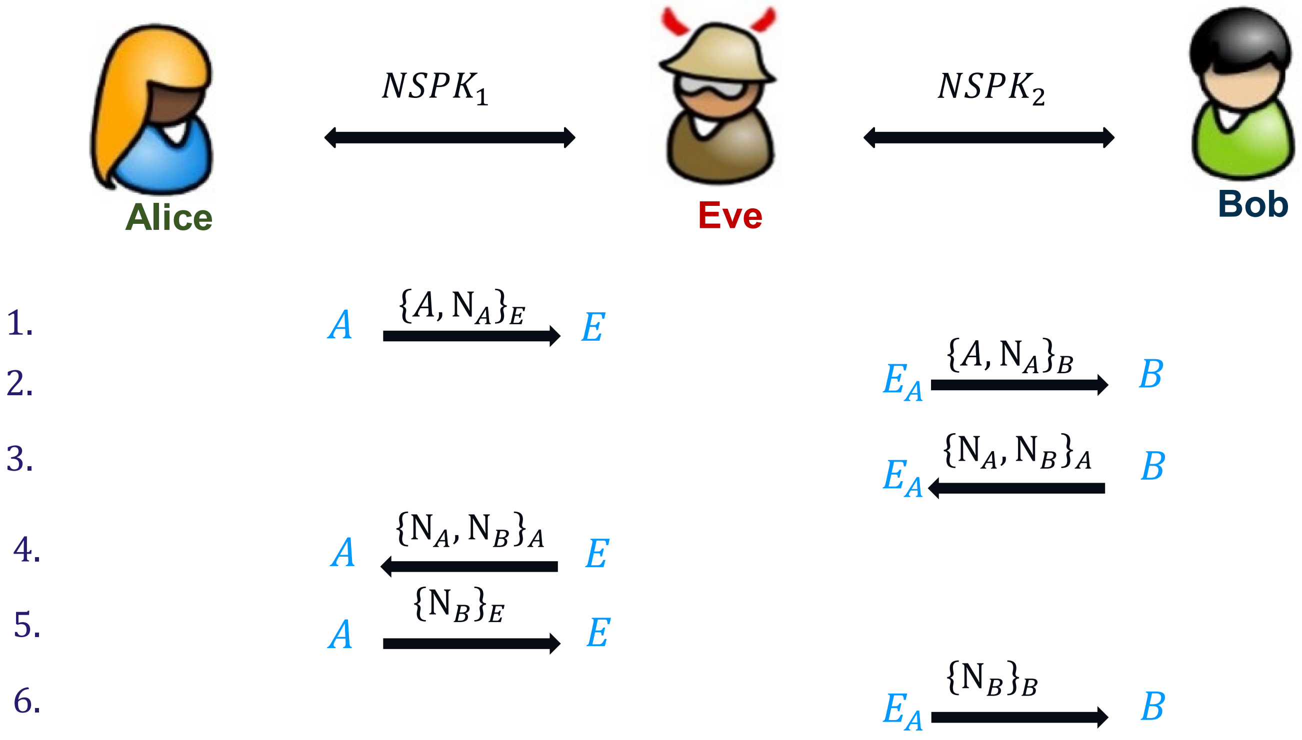


NSPK: Lowe’s Attack (1996)

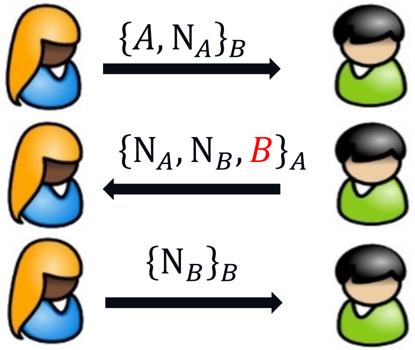
Protocols are typically *small* and *convincing* and often wrong!

1. $A \xrightarrow{\{A, N_A\}_E} E$
2. $E_A \xrightarrow{\{A, N_A\}_B} B$
3. $E_A \xleftarrow{\{N_A, N_B\}_A} B$
4. $A \xleftarrow{\{N_A, N_B\}_A} E$
5. $A \xrightarrow{\{N_B\}_E} E$
6. $E_A \xrightarrow{\{N_B\}_B} B$

Bob believes he is speaking with Alice (but talks to Eve)!

NSPK: Lowe's Fix

Needham-Schroeder with Lowe's fix:



"I am Alice and here is my nonce N_A"

"Here is your nonce N_A and I have one for you and I am Bob."

"I got it! It is N_B"

Definitions

- A **protocol** consists of a set of rules (conventions) that determine the exchange of messages between two or more entities
    - In short, a distributed algorithm with emphasis on communication

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Definitions

- A **protocol** consists of a set of rules (conventions) that determine the exchange of messages between two or more entities
  - In short, a distributed algorithm with emphasis on communication

- **Security (or cryptographic) protocols** use cryptographic mechanisms to achieve security objectives
  - *Example objectives:* Entity or message authentication, key establishment, integrity, timeliness, fair exchange, non-repudiation, …

Questions

1. Is the protocol secure now?

2. How can we detect (and fix) such flaws?

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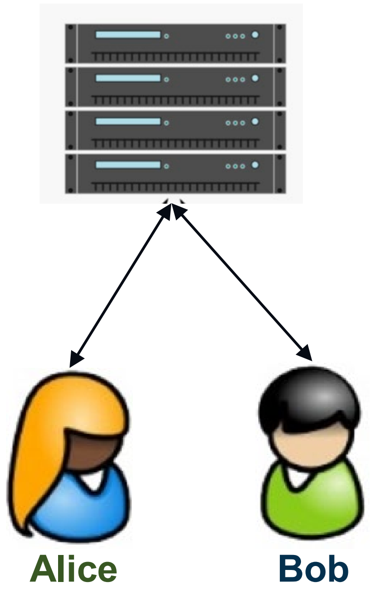
2. How can we detect (and fix) such flaws?

   - We will work on these questions in “formal analysis” as well

Building A Key Establishment Protocol

Scenario: Overview

- An attempt to design a good protocol (from first principles)
- First step: Establish the communications architecture

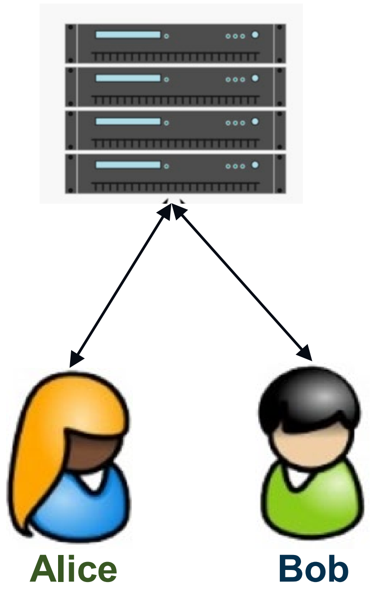


Building A Key Establishment Protocol

Scenario: Overview

- An attempt to design a good protocol (from first principles)
- First step: Establish the communications architecture

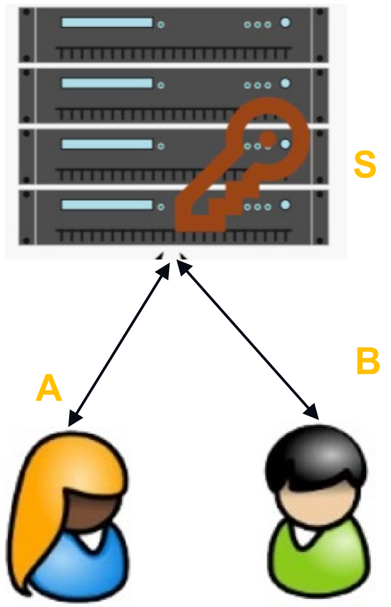
- We choose <u>a common scenario</u> (among many)
    - A set of users, any two of whom may wish to establish a new session key for subsequent secure communications
        - Successful completion of key establishment (& entity authentication) is only the beginning of a secure communications session. Further communication (often also through protocols) may be based on this key.
        - Users are not necessarily honest! (– more on this later)
    - There is <u>an honest server</u>
        - Often called "trusted server", but trust ≠ honesty! We assume that an honest server never cheats and never gives out user secrets



Building A Key Establishment Protocol

Scenario: The Details

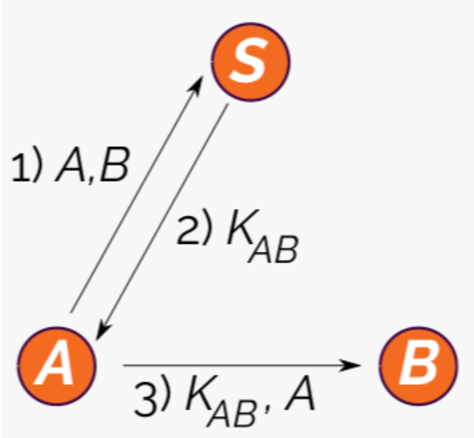
- We thus consider in this scenario protocol with three roles
  1. Initiator role *A* (Alice)
  2. Responder role *B* (Bob)
  3. Server role *S*
- In a concrete execution of a protocol, the roles are played by agents a.k.a. entities a, b, c (Charlie), s, i (Intruder), …
- We use i as the name of the intruder
  Important: No agent in our model knows that i is not honest
- Aims of the protocol
  - At the end of the protocol, K_{AB} should be known to A and B, and possibly to S (who forgets it immediately), but to no other parties
  - A and B can assume that K_{AB} is newly generated
- Formalization of the questions (that we will consider later)
  - How do we formalize the protocol steps and goals?
  - How do we formalize "knowledge", "secrecy", "newly", …?



Building A Key Establishment Protocol

First Attempt: Specification

- Our first attempt: A protocol that consists of three messages
  1. *A* contacts *S* by sending the identities of the two parties who are going to share the session key: *A*, *B*
  2. *S* sends the key K_{AB} to *A*: K_{AB}
  3. *A* passes K_{AB} on to *B*



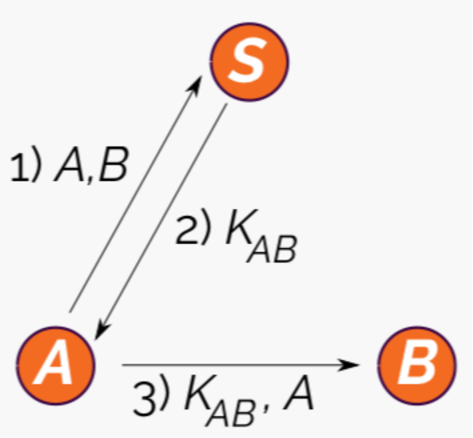
Note:

- K_{AB} does not contain any "information" about *A* or *B*, but is simply a name for the bit-string representing the session key
- Before we examine the (lack of) security of this protocol, note that this is a significantly incomplete protocol specification

Building A Key Establishment Protocol

First Attempt: Discussion (1/2)

- Only messages passed in a successful run are specified
  - No description of what happens in the case that a message of the wrong format is received or that no message is received at all
  - This is often done for security protocols, since error messages are often not relevant for the security
    - But, what about exceptions?



- No specification of internal actions of entities

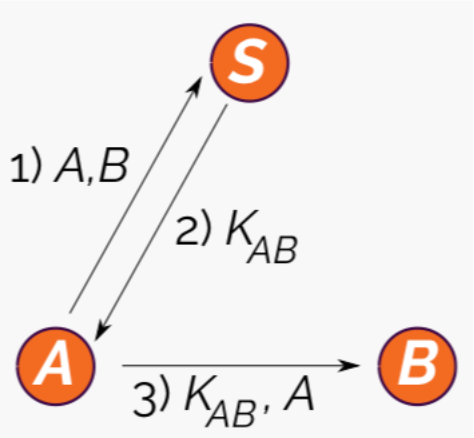
  e.g., "create fresh K_{AB}" and store that as a key for *A* and *B*

- Implicit assumption: *A* and *B* "know" that the received messages are part of the protocol
  - It is common to omit such details which would be required for a networked computer to be able to track the progress of a particular protocol run
  - This may include details of which key should be used to decrypt a received message which has been encrypted

Building A Key Establishment Protocol

First Attempt: Discussion (2/2)

- Despite the obvious limitations associated with specifying protocols by showing only the messages of a successful run, it remains the most popular method of describing security protocols
  - But there are many works that have addressed these problems to "disambiguate" the notations



- An equivalent representation: Alice & Bob notation

$$
\begin{aligned}
&1.\quad A \longrightarrow S : A, B\\
&2.\quad S \longrightarrow A : K_{AB}\\
&3.\quad A \longrightarrow B : K_{AB}, A
\end{aligned}
$$

Note that sender/receiver names (e.g., "$A \longrightarrow B$") are not part of the message and it is not the case that messages automatically reach their destination (securely)

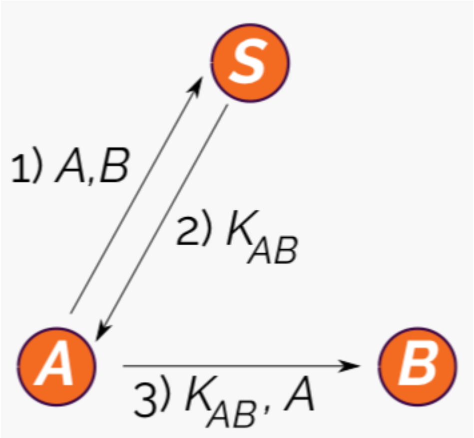
Building A Key Establishment Protocol – Block Examples

First Attempt: A First Problem

- Problem with this protocol?
  - The session key K_{AB} must be transported to A and B but to no other parties

- A realistic assumption in typical communication systems such as the Internet and corporate networks

  Security Assumption 1: ***The intruder is able to eavesdrop on all the messages sent in a security protocol***



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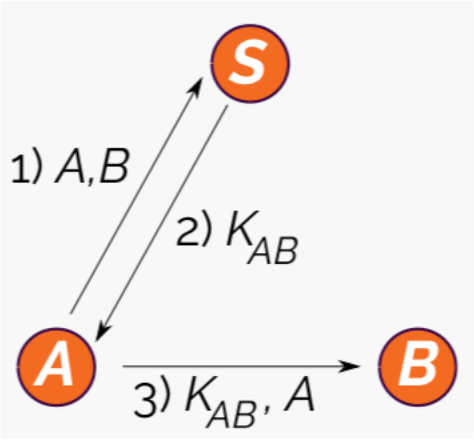
→ Use a cryptographic algorithm and associated keys

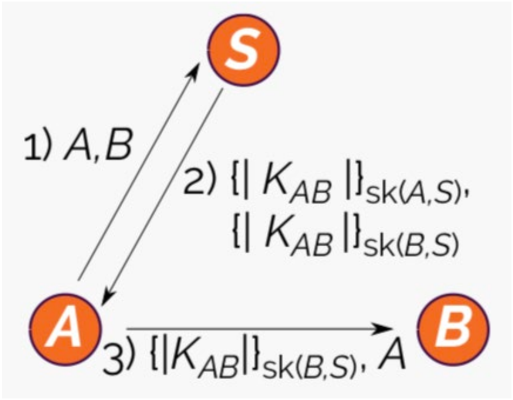


Building A Key Establishment Protocol

Second Attempt: Specification

- Second attempt
  - Assume that S initially shares a secret key $\mathrm{sk}(U, S)$ with each user U of the system
    - $\mathrm{sk}(A, S)$ with *A*
    - $\mathrm{sk}(B, S)$ with *B*

  and *S* encrypts message 2)



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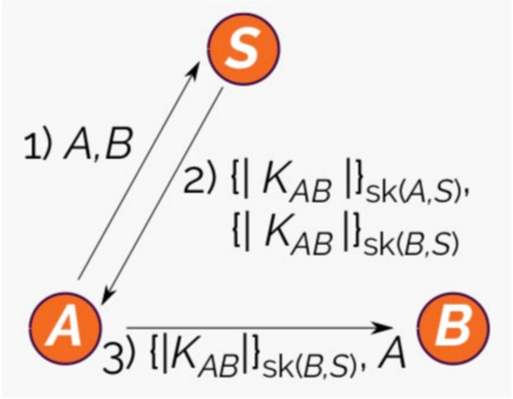

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Building A Key Establishment Protocol

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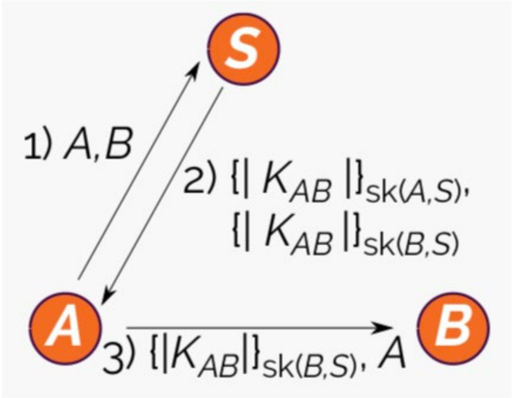

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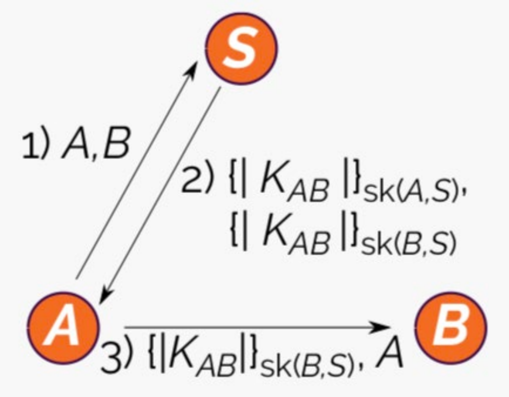
Perfect Cryptography Assumption

Encrypted messages may only be read by the legitimate recipients who have the keys required to decrypt…

Building A Key Establishment Protocol

Second Attempt: Problems (1/2)

- Problem is not that the protocol gives away the secret key K_{AB}, but that the information about who else has K_{AB} is not protected
- Intruder could not only be able to eavesdrop on messages sent, but also to capture messages and alter them



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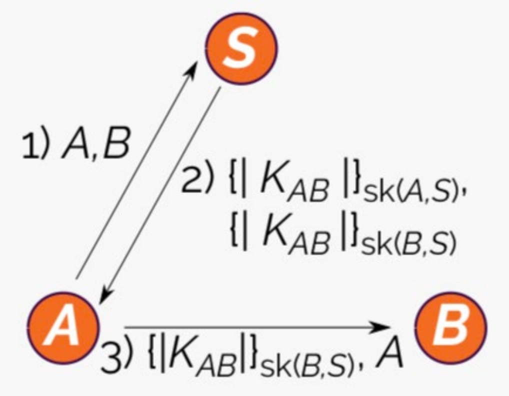


Security Assumption 2

The intruder is able to intercept messages on the network and send messages to anybody (under any sender name)

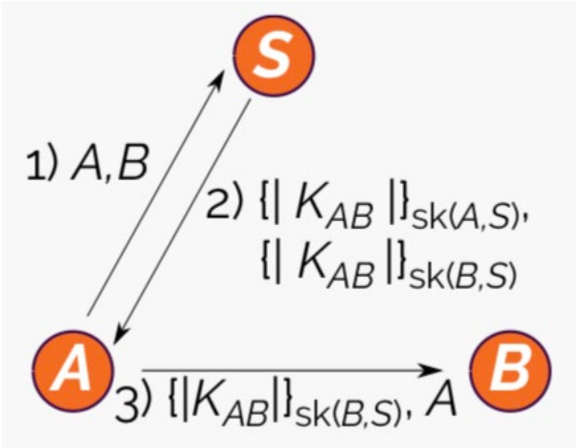
Building A Key Establishment Protocol

Second Attempt: Problems (2/2)

- The intruder has complete control of the channel(s) over which protocol messages flow

The intruder has complete control over the network

- In contrast to ordinary communication protocols, we assume the worst-case of a malicious agent
  - Although there may be no more than 4 or 5 messages involved in a legitimate run of the protocol, there are an infinite number of variations in which the intruder can participate
  - These variations involve an unbounded number of messages and each must satisfy the protocol's security requirements



Building A Key Establishment Protocol

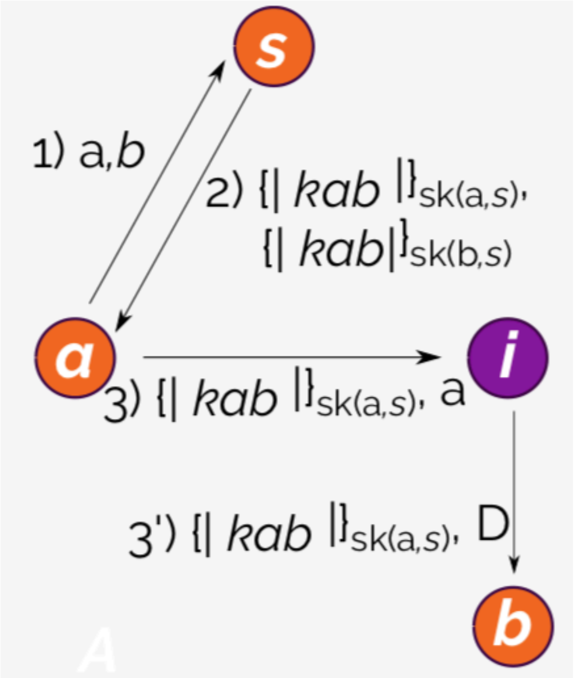
Second Attempt: A Simple Attack

- The intruder *i* simply intercepts the message from *a* to *b* and substitutes *D* for *a*'s identity (*D* is any agent name).

  => *b* believes that he is sharing the key with *a*, whereas in fact he is sharing it with *D*

- The result of this attack will depend on the scenario in which the protocol is used, but may include such actions as *b* giving away information to *D* which should have been shared only with *a*

- Although *i* does not obtain kab, we can still regard the protocol as broken since it does not satisfy the requirement that the users should know who else knows the session key



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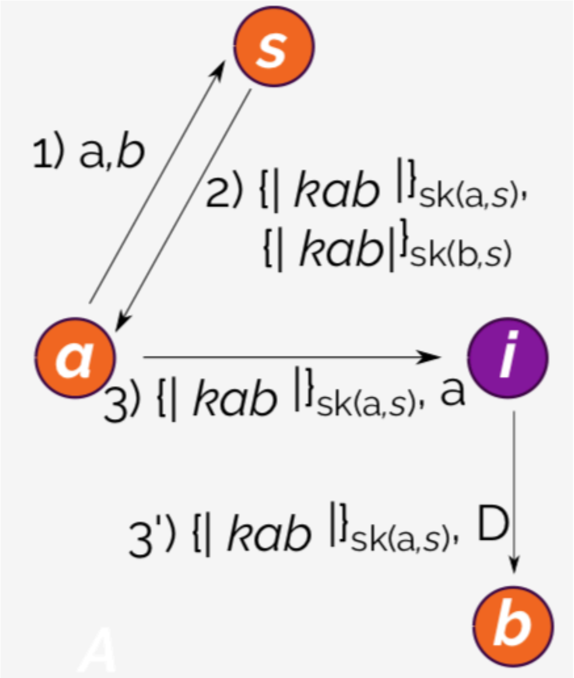
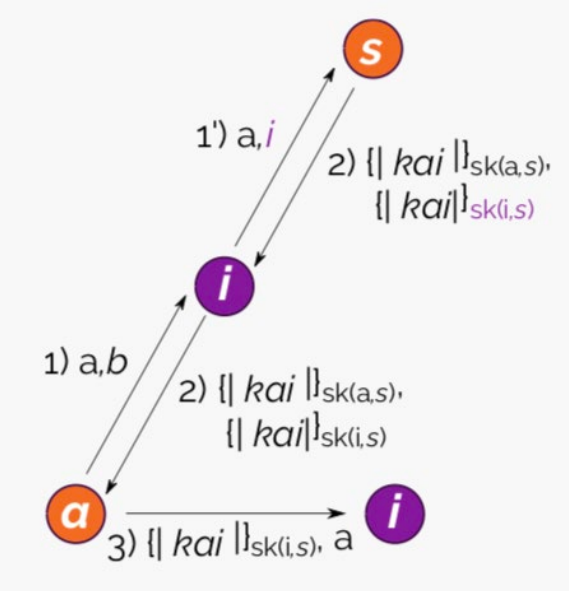
- But there is also another (more serious) attack…



Building A Key Establishment Protocol

Second Attempt: Another Attack

- *i* alters the message from *a* to *s* so that *s* generates *a* key kai for *a* and *i* and encrypts it with the key $\mathrm{sk}(i, s)$of the intruder
- Since *a* cannot distinguish between encrypted messages meant for other principals she will not detect the alteration
    - *kai* is simply a formal name for the bit-string representing the session key, so it will be accepted by *a*
    - *i* intercepts the message from *a* intended for *b* so that *a* will not detect any anomaly
- Hence *a* will believe that the protocol has been successfully completed with *b* whereas *i* knows *kai* and so can masquerade as *b* as well as learn all information that *a* sends intended for *b*
- In contrast to the previous attack, this one will succeed if *i* is a *[legitimate system user]* known to *s*



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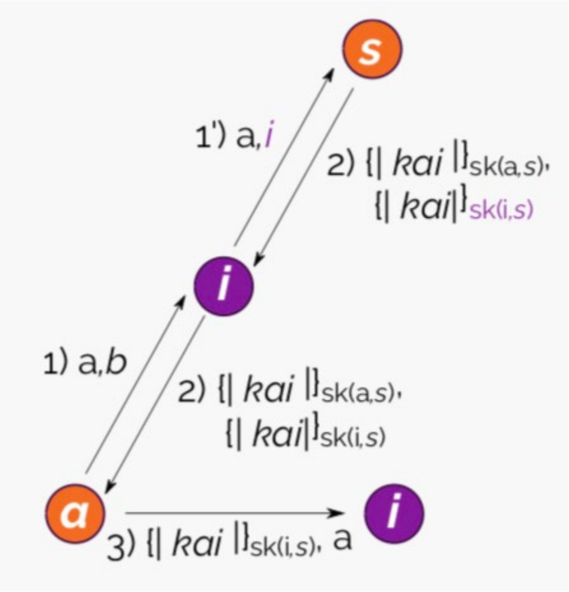


Security Assumption 3

The intruder may be a legitimate protocol participant (an insider), or an external party (an outsider), or a combination of both

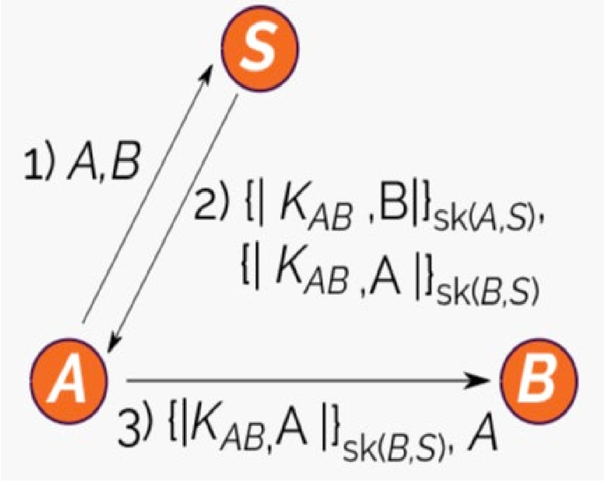
Building A Key Establishment Protocol

Third Attempt: Specification

- To overcome these attacks, the names of the principals who are to share K_{AB} need to be bound cryptographically to the key

  Neither of two previous attacks succeed on the modified protocol (see figure)

- The protocol has improved to the point where an intruder is unable to attack it by eavesdropping or altering the messages sent between honest parties



Building A Key Establishment Protocol

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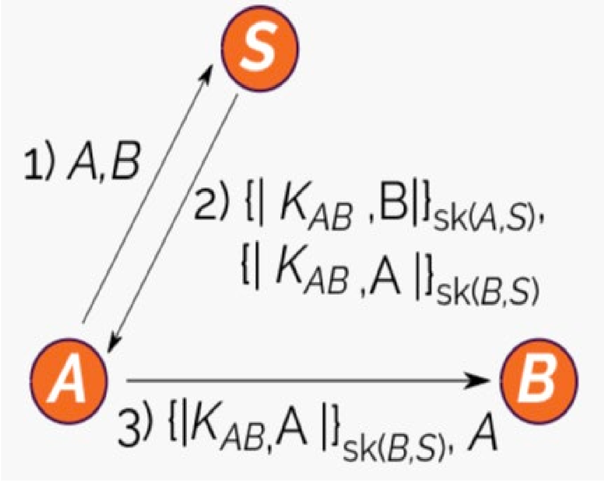
- However, even now the protocol is not good enough to provide security on normal operating conditions



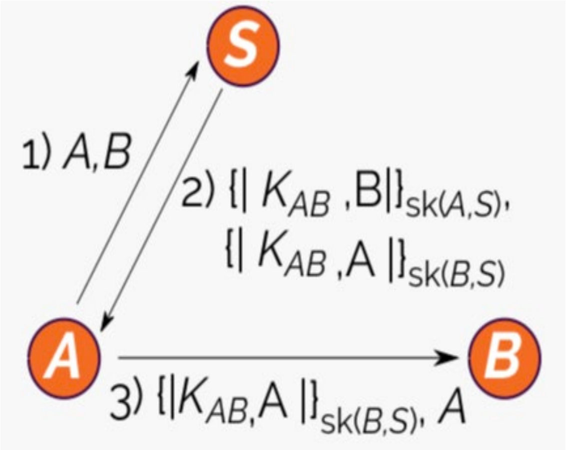
Building A Key Establishment Protocol

Third Attempt: Problem

- The problem stems from the difference in quality between the long-term key-encrypting keys shared initially with S, and the session keys K_{AB} generated for each protocol run

- Reasons for using session keys
  - They are expected to be vulnerable to attack (by cryptanalysis)
  - Communications in different sessions should be separated. In particular, it should not be possible to replay messages from previous sessions

- A whole class of attacks becomes possible when old keys (or other security-relevant data) may be replayed in a subsequent session



Security Assumption 4

The intruder is able to obtain the value of the session key K_{AB} used in any "sufficiently old" previous run of the protocol

Building A Key Establishment Protocol

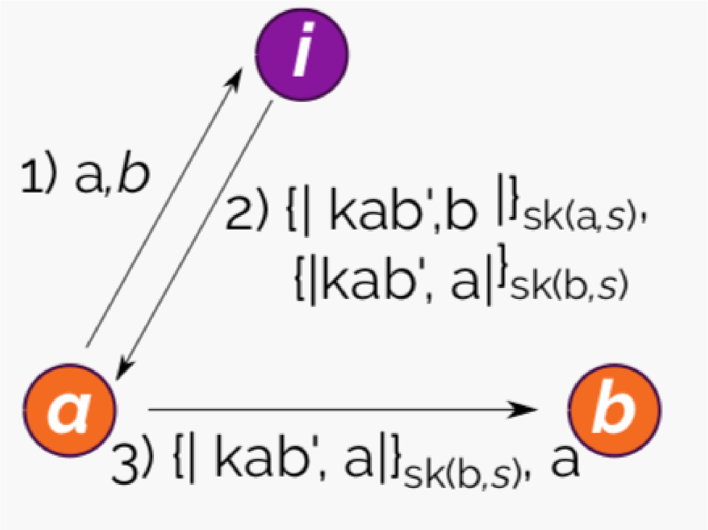
Third Attempt: Attack (1/2)

- *i* masquerades as *s*

- Replay

kab' is an old key used by *a* and *b* in a previous session

  - By Security Assumption 1, *i* can be expected to know the encrypted messages in which kab' was transported to *a* and *b*
  - By Security Assumption 4, *i* can be expected to know the value of kab'
  - Thus, when *a* completes the protocol with *b*, *i* is able to decrypt subsequent information encrypted with kab' or insert or alter messages whose integrity is protected by kab'



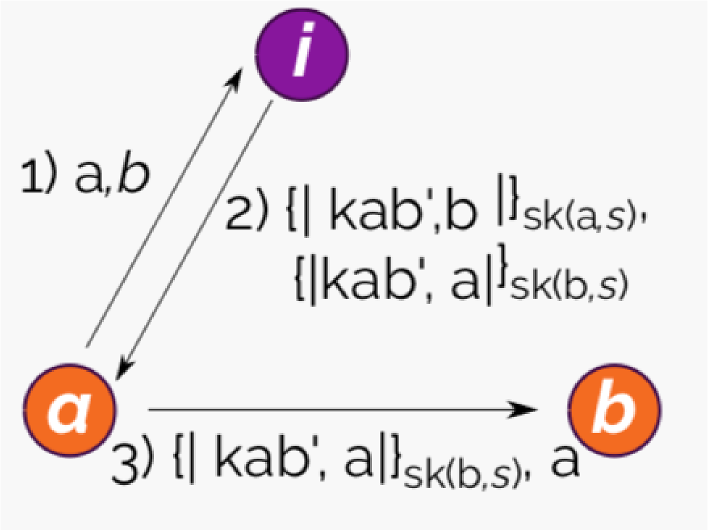
Building A Key Establishment Protocol

Third Attempt: Attack (2/2)

- The replay attack can still be regarded as successful even if *i* has not obtained the value of kab'
  - *i* has succeeded in making *a* and *b* accept an old session key!
  - The attack allows *i* to replay messages protected by kab' which were sent in the previous session

- Happens if *a* and *b* do not check the key!
  - Principals "do not think" but just follow the protocol
  - Various techniques may be used to allow principals to check that session keys have not been replayed

    e.g., the challenge–response method



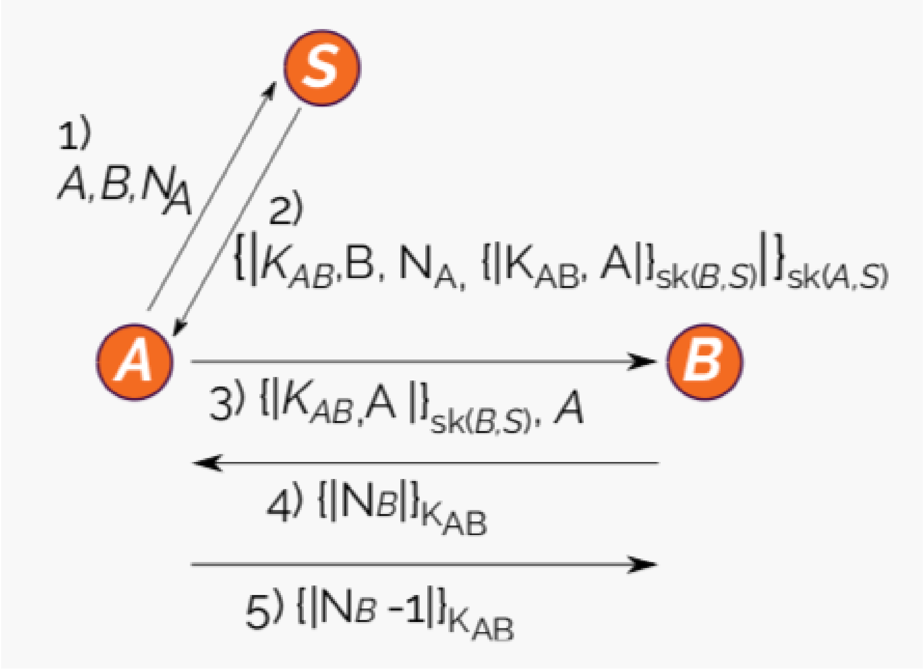
Definition:* *A* *nonce* *("a number used only once") is a random value generated by one principal and returned to that principal to show that a message is newly generated

Building A Key Establishment Protocol
Fourth Attempt (1/2)

- *A* sends her nonce N_A to *S* with the request for a new key

- If this same value is received with the session key, then *A* can deduce that the key has not been replayed
  (This deduction will be valid as long as session key and nonce are bound together cryptographically in such a way that only S could have formed such a message)

- Note, N_A is just a number
  - There is nothing in N_A that identifies who has created it
  - Hence, we will also write NA or even better N_1 or $N1$



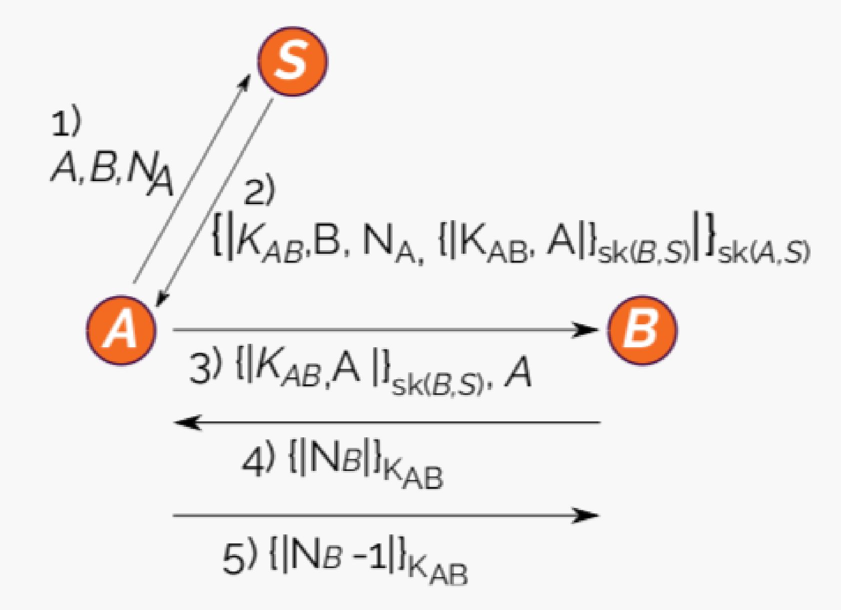
Building A Key Establishment Protocol

Fourth Attempt (2/2)

- If the encrypted key for *B* is included in the encrypted part of *A*'s message, then *A* can gain assurance that it is fresh

- It is tempting to believe that *A* may pass this assurance on to *B* in an extra handshake
  - *B* generates a nonce N_B and sends it to *A* protected by K_{AB} itself
  - *A* uses K_{AB} to reply to *B* ("–1" to avoid replay of message 4)

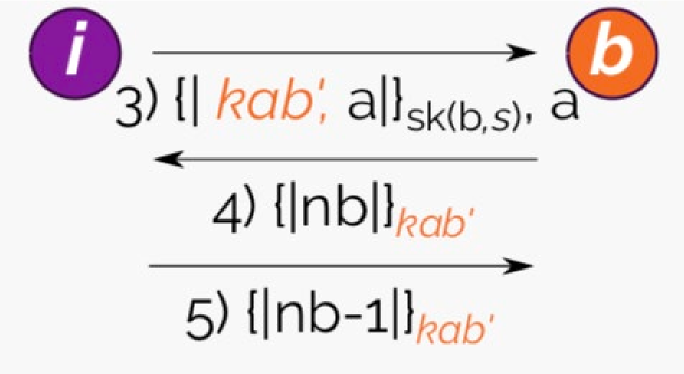
- This is actually a famous security protocol
  - Needham Schroeder with Conventional Keys (NSCK)
  - Published by Needham and Schroeder in 1978, it has been the basis for a whole class of related protocols
  - Unfortunately, this protocol is vulnerable to a famous attack as shown by Denning and Sacco

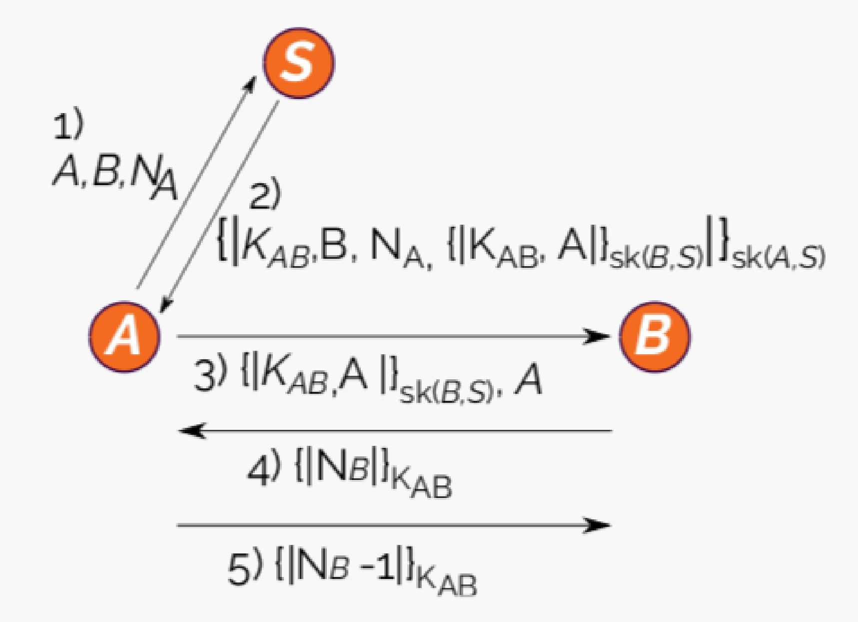


Building A Key Establishment Protocol

Fourth Attempt: Attack

- The problem is the assumption that only *A* will be able to form a correct reply to message 4 from *B*
- Since the intruder *i* can be expected to know the value of an old session key, this assumption is unrealistic
- *i* masquerades as *a* and convinces *b* to use old key kab'





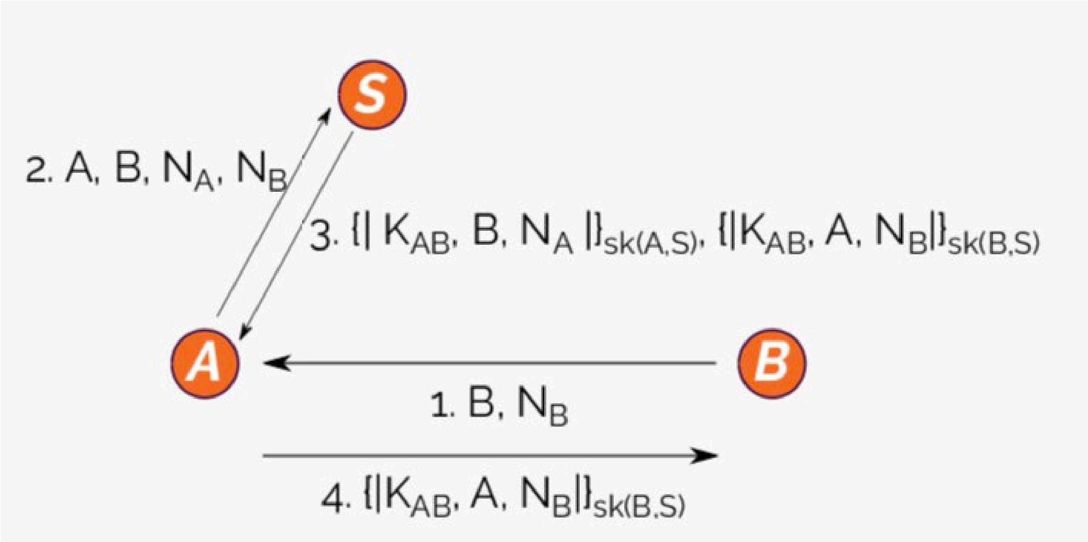
Building A Key Establishment Protocol

Fifth Attempt

- **Idea**
  Let's throw away the assumption that it is inconvenient for both *B* and *A* to send their challenges to *S*

- The protocol is now initiated by *B* who sends his nonce N_B first to *A*

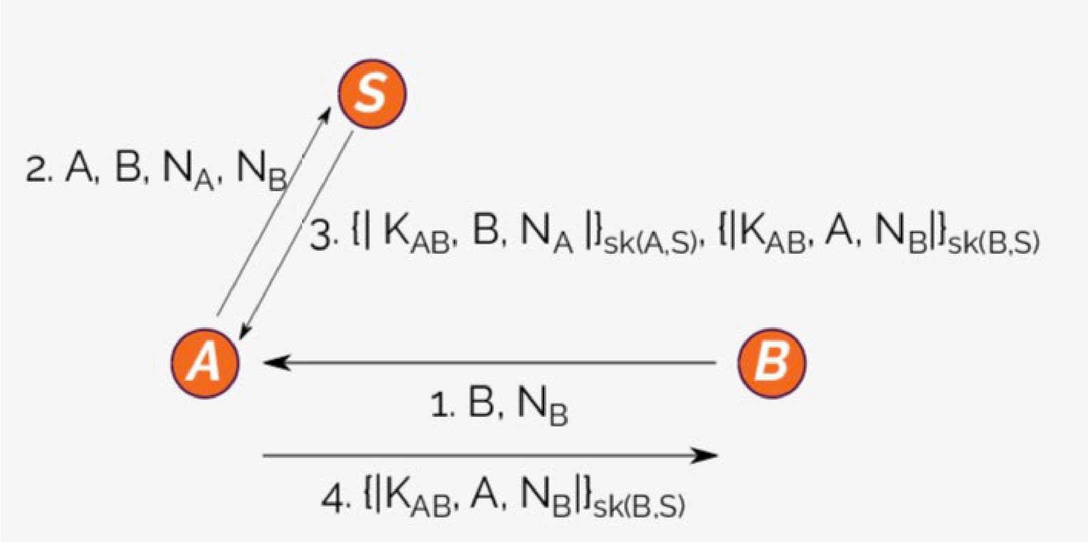
- *A* adds her nonce N_A and sends both to *S*, who is now able to return K_{AB} in separate messages for *A* and *B*, which can each be verified as fresh by their respective recipients



Building A Key Establishment Protocol

Fifth Attempt: Observations

- It may seem that we have achieved more than the previous protocol using fewer messages, but in fact…
  - In the NSCK, *A* could verify that *B* has in fact received the key
  - This property of key confirmation is achieved due to *B*'s use of the key in message 4, assuming that $\{|\mathrm{N}_B|\}_{K_{AB}}$ cannot be formed without the knowledge of K_{AB}
  - In our final protocol, neither *A* nor *B* can deduce at the end of a successful protocol run that the other has actually received K_{AB}



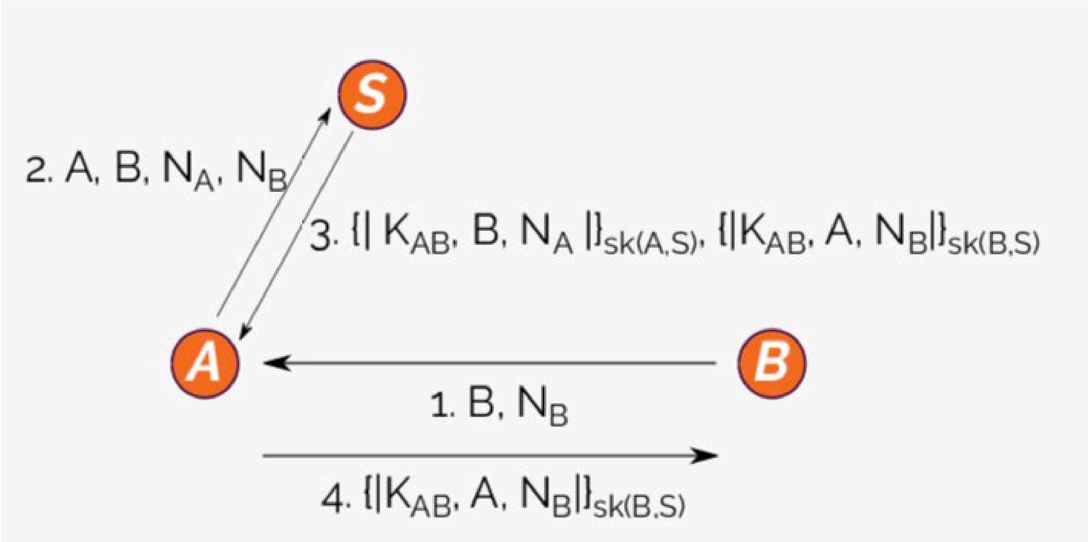
Building A Key Establishment Protocol

Summary

- This protocol avoids all the attacks that we have seen so far, as long as the cryptographic algorithm used provides the properties of both confidentiality and integrity, and the server *S* acts correctly

- No rush to claim that this protocol is secure before giving a precise meaning to that term!

- The security of a protocol must always be considered relative to its goals



Building A Key Establishment Protocol
Summary

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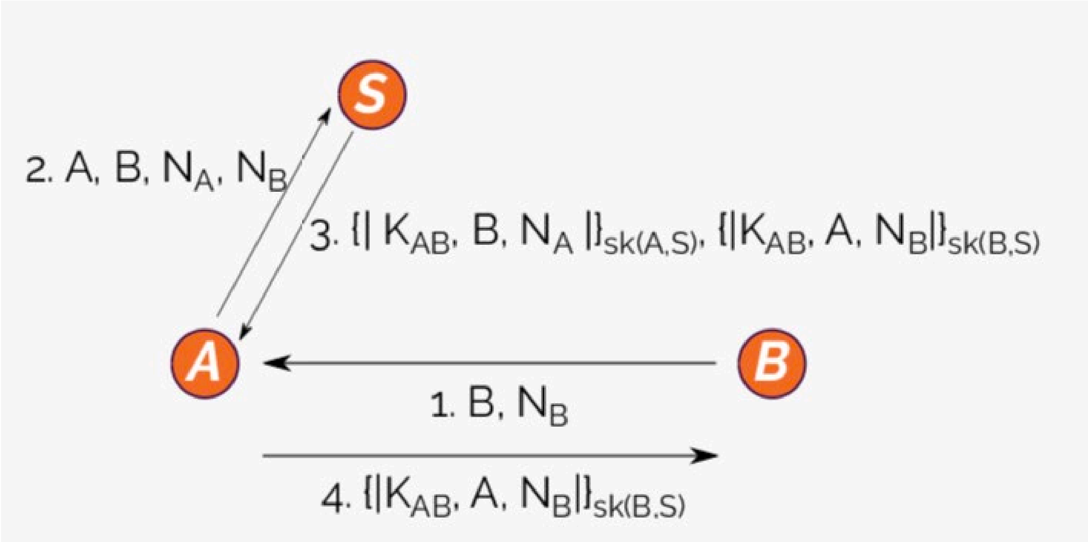
➡ We need “means” to formalize protocols and goals



Notation Used In Protocol Modeling

Notation: Messages

Roles: *A*, *B* or *Alice*, *Bob*

Agents: *a*, *b*, *i*

Symmetric Keys: *K*, K_{AB}, …; $\mathrm{sk}(A, S)$

Symmetric Encryption: $\{|M|\}_K$

Public Keys: $K, \mathrm{pk}(A)$

Private Keys: $\mathrm{inv}(K),\ \mathrm{inv}(\mathrm{pk}(A))$

Asymmetric Encryption: $\{M\}_K$

Signing: $\{M\}_{\mathrm{inv}\ K}$

Nonces: $\mathrm{N}A$, $\mathrm{N}1$ fresh data items used for challenge/response

Timestamps: *T* denotes time, e.g., used for key expiration

Message concatenation: M_1, M_2, M_3

Notation Used In Protocol Modeling

Notation: Communication

- Fundamental event is communication between principals

$$A \longrightarrow B : \{A, T_1, K_{AB}\}_{\mathrm{pk}(B)}$$

- *A* and *B* name roles
  Can be instantiated by any principal playing in the role

- Communication is asynchronous

- Sender/receiver names "$A \longrightarrow B$" are not part of the message

- Protocol specifies actions of principals
  Alternatively, protocol defines a set of event sequences (traces)

Notation Used In Protocol Modeling

Notation: Protocols

- A typical protocol description combines prose, data type specifications, various kinds of diagrams, ad hoc notations, and message sequences like

  1. $A \longrightarrow B : \{\mathrm{N}A, A\}_{\mathrm{pk}(B)}$
  2. $\mathrm{B} \longrightarrow A : \{\mathrm{N}A, \mathrm{N}B\}_{\mathrm{pk}(A)}$
  3. $A \longrightarrow B : \{\mathrm{N}B\}_{\mathrm{pk}(B)}$

- They often include informal statements concerning the properties of the protocol and why they should hold

- What does a message $A \longrightarrow B : M$ actually mean?

"We assume that an intruder can interpose a computer in all communication paths, and thus can alter or copy parts of messages, replay messages, or emit false material.

We also assume that each principal has a secure environment in which to compute such as is provided by a personal computer…"

Needham and Schroeder

Protocol Execution

- Role A:

1. $A \longrightarrow B : \{\mathrm{N}A, A\}_{\mathrm{pk}(B)}$
2. $B \longrightarrow A : \{\mathrm{N}A, \mathrm{N}B\}_{\mathrm{pk}(A)}$
3. $A \longrightarrow B : \{\mathrm{N}B\}_{\mathrm{pk}(B)}$

1. Generate nonce N*A*, concatenate it with name, and encrypt with pk(B)
2. Receive a message *M*
   1. Decrypt *M* with inv(pk*(A))*, call it *M'*. If decryption fails, reject *M'*
   2. Split the message into two nonces N*A'* and N*B*. If that is not possible, reject *M*
   3. Check that N*A'* = N*A; if not*, reject *M*
3. Encrypt N*B* with pk*(B)* and send to B

Protocol Attacks

Different Kind of Attacks

Man-in-the-middle (or parallel sessions) attack: $A \leftrightarrow i \leftrightarrow B$

Replay (or freshness) attack: Reuse parts of previous messages

Masquerading attack: Pretend to be another principal

Reflection attack: Send transmitted information back to originator

Oracle attack: Take advantage of normal protocol responses as encryption and decryption "services"

Binding attack: Using messages in a different context/for a different purpose than originally intended

Type flaw attack: Substitute a different type of message field

Protocol Attacks

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* These attack types are not formally defined and there may be overlaps between these types

Man-in-the-Middle Attack

Diffie-Hellman (1/3)

- **Diffie-Hellman Key Exchange**
  - A and B agree on a DH group (g, p)
  - A generates large x and sends half-key $X = g^x \; mod \; p$ to B
  - B generates large y and sends half-key $Y = g^y \; mod \; p$ to A
  - A and B compute key $k = Y^x \; mod \; p = X^y mod \; p$

Security depends on the difficulty of computing the discrete logarithm of an exponentiated number modulo a large prime number

Man-in-the-Middle Attack

Diffie-Hellman (2/3)

- **Diffie-Hellman** (without authentication of the half-keys) can be attacked

1. $a \longrightarrow i\ (b): \exp(g, x)$
    1. $i\ (a) \longrightarrow b : \exp\ (g, z)$
    2. $b \longrightarrow i\ (a): \exp\ (g, y)$
2. $i(b) \longrightarrow i\ (a): \exp(g, z)$

a believes to share key $\exp(\exp(g, x), z)$ with b,
b believes to share key $\exp(\exp(g, y), z)$ with a,
i knows both keys…

Man-in-the-Middle Attack

Diffie-Hellman (3/3)

- **Prevention:** Authenticate the half keys, e.g., with digital signatures
  1. $A \longrightarrow B$: $\exp(g, x)_{\mathrm{inv}(\mathrm{pk}(A))}$
  2. $B \longrightarrow A$: $\exp(g, y)_{\mathrm{inv}\,(\mathrm{pk}(B))}$

Today many protocols are based on Diffie-Hellman, which is not a bad idea!

Type Flaw Attacks
Definition

- A message consists of a sequence of sub-messages, e.g., a principal's name, a nonce, a key, …

- Real messages are bit strings without type information, e.g.,

  1011 0110 0010 1110 0011 0111 1010 0000

- Type flaw is when $A \longrightarrow B : M$ and B accepts M as valid but parses it differently

  ⟹ B interprets the bits differently than A

Type Flaw Attacks

The Otway-Rees Protocol (1/2)

- Server-based protocol providing authenticated key distribution (with key authentication and key freshness) but without entity authentication or key confirmation

  1. $A \rightarrow B : M, A, B, \{|\mathrm{N}A, M, A, B|\}_{\mathrm{sk}(A,S)}$
  2. $B \rightarrow S : M, A, B, \{|\mathrm{N}A, M, A, B|\}_{\mathrm{sk}(A,S)}, \{|\mathrm{N}B, M, A, B|\}_{\mathrm{sk}(B,S)}$
  3. $S \rightarrow B : M, \{|\mathrm{N}A, K_{AB}|\}_{\mathrm{sk}(A,S)}, \{|\mathrm{N}B, K_{AB}|\}_{\mathrm{sk}(B,S)}$
  4. $B \rightarrow A : M, \{|\mathrm{N}A, K_{AB}|\}_{\mathrm{sk}(A,S)}$

- Server keys already known and M is a session id (e.g., an integer)

Type Flaw Attacks

The Otway-Rees Protocol (2/2)

- Suppose that $|M, A, B| = |K_{AB}|$

- Possible Attack (reflection/type flaw)

i replays parts of message 1 as message 4 (omitting steps 2 and 3)

1. $a \rightarrow i(b) : m, a, b, \{|na\ m, a, b|\}_{\mathrm{sk}(a,s)}$
2. $i(b) \rightarrow a : m, \{|na, \underbrace{m, a, b}_{\text{mistaken as } kab}|\}_{\mathrm{sk}(a,s)}$

Prudent Engineering of Security Protocols

- Principles proposed by Abadi and Needham (1994, 1995)
  - Every message should say what it means
  - Specify clearly conditions for a message to be acted on
  - Mention names explicitly if they are essential to the meaning
  - Be clear as to why encryption is being done: Confidentiality, message authentication, binding of messages, …
  - Be clear on what properties you are assuming
  - Beware of clock variations (for timestamps)
  - And other necessary things…

- Good advice, but
  - Is the protocol guaranteed to be secure then?
  - Is it optimal and/or minimal then?
  - Have you considered all types of attacks?
  - So on…

Summary

- Theses
  - A protocol without clear goals (and assumptions) is useless
  - A protocol without a proof of correctness is probably wrong

- Assumptions/Intruder model (following Dolev and Yao)
  - Can control the network
  - Can participate in the protocol
  - Can compose/decompose messages with the keys he has
  - Cannot break cryptography

  => Worst case assumption of an intruder

- Goals: What the protocol should achieve, e.g.,
  - Authenticate messages, binding them to their originator
  - Ensure timeliness of messages (recent, fresh, …)
  - Guarantee secrecy of certain items (e.g., generated keys, …)

Reading List

- Ross J. Anderson. Security Engineering: A Guide to Building Dependable Distributed Systems. John Wiley & Sons, Inc., New York, NY, USA, 1st edition, 2001.
  - The complete book is available at: http://www.cl.cam.ac.uk/~rja14/book.html
- Alfred J. Menezes, Scott A. Vanstone, and Paul C. Van Oorschot. Handbook of Applied Cryptography. CRC Press, Inc., Boca Raton, FL, USA, 5th edition, 2001.
  - The complete book is available at: http://cacr.uwaterloo.ca/hac/
- Bruce Schneier. Applied Cryptography. John Wiley & Sons, Inc., 2nd edition, 1996.

Thanks for your attention!

- Any questions or remarks?