COMx501: Computer Security and Forensics

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COMx501: Computer Security and Forensics
Part 7: Security Protocols

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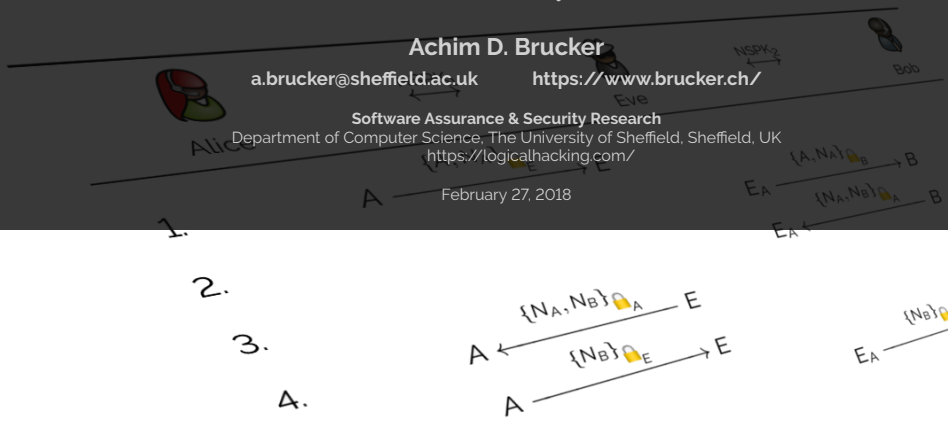


Outline

Motivation

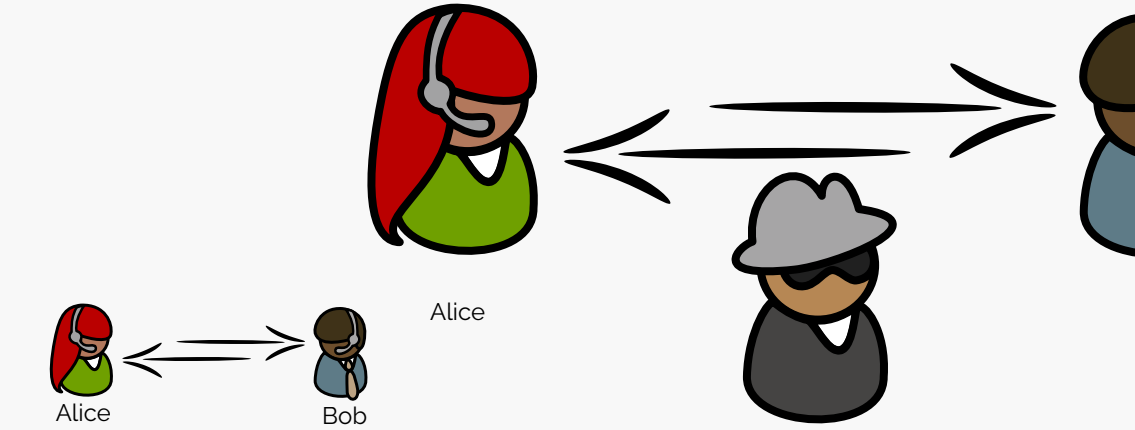
- RSA, AES, etc. provide (probably) very good cryptographic primitives
- How can we construct secure distributed applications with these primitives?
  - Securing Internet connections
  - E-commerce
  - E-banking
  - E-voting
  - Mobile communication
  - Digital contract signing

We will learn:

Even if cryptography is hard to break, this is not a trivial task

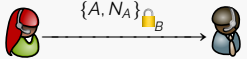
Establishing an Authentic Channel: NSPK

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

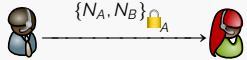


Goal: Mutual Authenticity (Two-way Authentication) After executing the protocol successfully,
Alice and Bob can be sure to talk to each other (and not to somebody else).

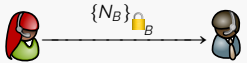
- Correctness argument (informal):



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



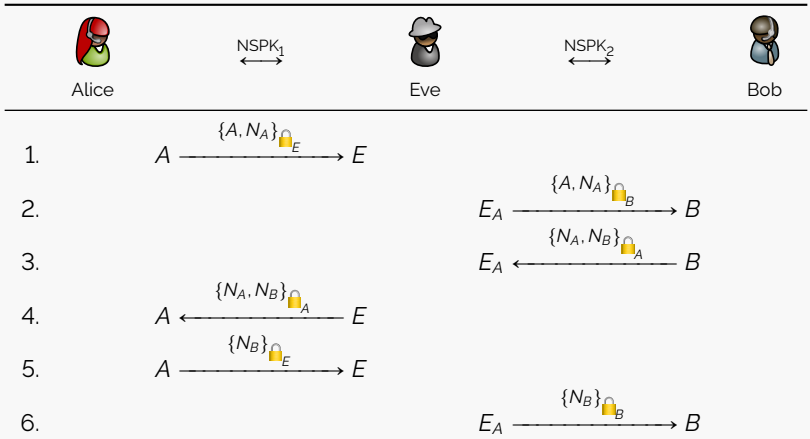
"Here is your nonce N_A. Since I could read it, I must be Bob.
I also have a challenge N_B for you."



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

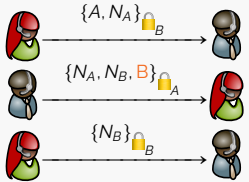
- Protocols are typically *small* and *convincing* … and often wrong!

NSPK: Lowe's attack (1996)



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

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 principals.
  In short, a distributed algorithm with emphasis on communication.
- **Security (or cryptographic) protocols** use cryptographic mechanisms to achieve security objectives.
  Examples: Entity or message authentication, key establishment, integrity, timeliness, fair exchange, non-repudiation, ...
- Analogous to programming Satan's computer

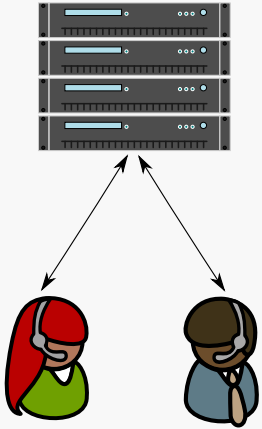
Questions

- Is it secure now?
- How can we detect (and fix) such flaws?
- We work on these questions in the next two weeks (and in the first lab)

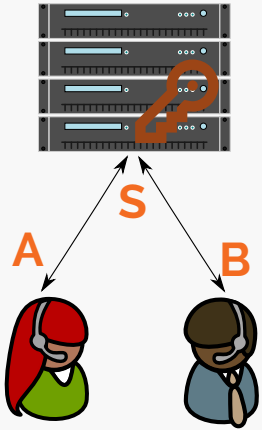
Outline

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

  We choose a common scenario (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 later)
  - There is an honest server.
    - Often called "trusted server", but trust ≠ honesty! We assume that an honest server never cheats and never gives out user secrets



- 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. principals: a, b, c (charly), 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 S (who forgets it immediately), but to no other parties.
  - A and B can assume that K_{AB} is newly generated.
- Formalization questions (that we will consider later):
  - How do we formalize the protocol steps and goals?
  - How do we formalize “knowledge”, “secrecy”, “newly”, …

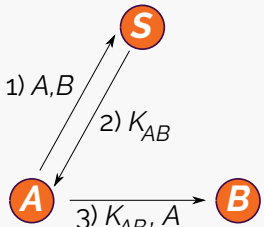


Our first attempt: a protocol that consists of three messages

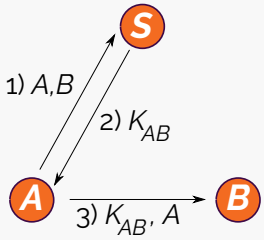
1. A contacts S by sending the identifies of the two parties who are going to share the session key: A, B
2. S sends the key K_{AB} to A: K_{AB}
3. A passes K_{AB} on to B

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

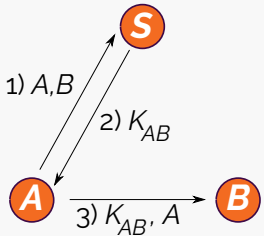


- Only messages passed in a successful run are specified
  - No description of what happens in the case that a message of the wrong format is received or that no message is received at all
  - This is often done for security protocols, since error messages are often not relevant for the security
    (What about Exceptions?)
- No specification of internal actions of principals
  - e.g. "create fresh K_{AB}" and store that it is 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.



- 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:
  1. $A \longrightarrow S: A, B$
  2. $S \longrightarrow A: K_{AB}$
  3. $A \longrightarrow B: K_{AB}, A$

  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).

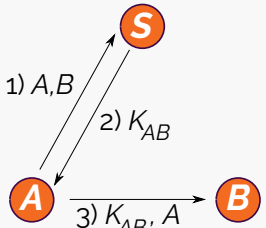


- Problem with this protocol? The session key K AB must be transported to A and B but to no other parties.
- A realistic assumption in typical communication systems such as the Internet and corporate networks:

Security Assumption 1

The intruder is able to eavesdrop on all messages sent in a security protocol.

☞ Use a cryptographic algorithm and associated keys.



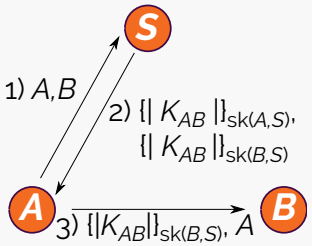
Second attempt:

- 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)
- Problems:
  - Eavesdropping? No.

Perfect Cryptography Assumption

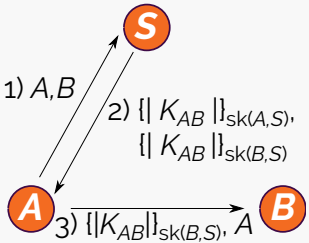
Encrypted messages may only be read by the legitimate recipients who have the keys required to decrypt …



- 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

Security Assumption 2

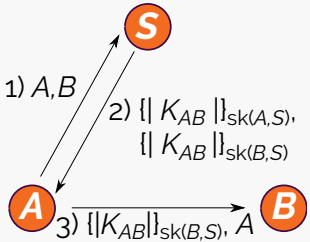
The intruder is able to intercept messages on the network and send messages to anybody (under any sender name).



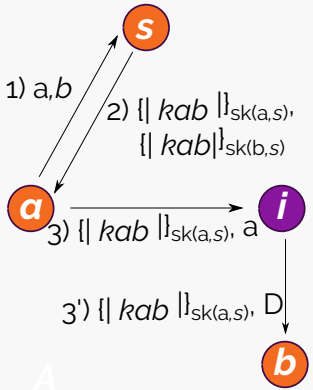
- The intruder has complete control of the channel(s) over which protocol messages flow.

  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



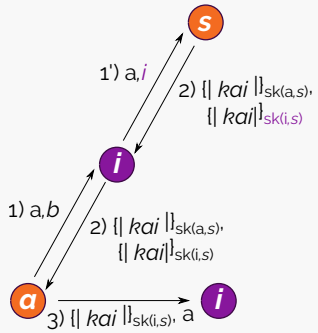
- The intruder *i* simply intercepts the message from *a* to *b* and substitutes *D* for *a*'s identity (*D* is any agent name).
  - → *b* believes that he is sharing the key with *D*, whereas in fact he is sharing it with *a*
- The result of this attack will depend on the scenario in which the protocol is used, but may include such actions as *b* giving away information to *a* which should have been shared only with *D*.
- 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.
- But there is also another (more serious) attack …



Building a Key Establishment Protocol

Second Attempt: Another Attack

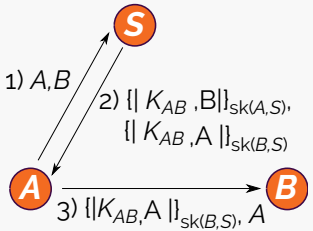
- *i* alters the message from *a* to *s* so that *s* generates *a* key *kai* for *a* and *i* and encrypts it with the key sk(*i*, *s*) of the intruder
- Since *a* cannot distinguish between encrypted messages meant for other principals she will not detect the alteration
  - *kai* is simply *a* formal 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*



Security Assumption 3

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

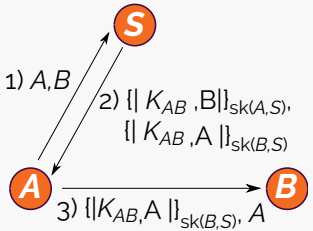
- To overcome these attacks, the names of the principals who are to share K_{AB} need to be bound cryptographically to the key. Neither of two previous attacks succeed on the modified protocol (see right hand side)
- The protocol has improved to the point where an intruder is unable to attack it by eavesdropping or altering the messages sent between honest parties
- 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



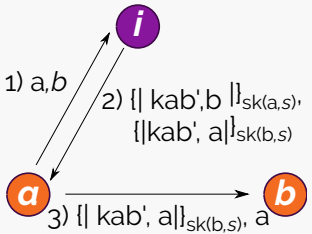
Security Assumption 4

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)

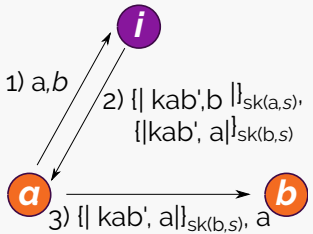
- *i* masquerades as *s*
- Replay:
  kab' is an old key used by *a* and *b* in a previous session
  - By Security Assumption 1, *i* can be expected to know the encrypted messages in which *kab'* was transported to *a* and *b*
  - By Security Assumption 4, *i* can be expected to know the value of *kab'*
  - 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'*



- 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
- Of course: provided that *a* and *b* don't check the key!
  - "Principals don't 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

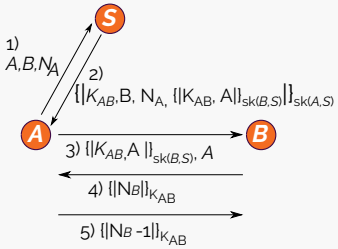
A nonce ("a number used only once") is a random value generated by one principal and returned to that principal to show that a message is newly generated.



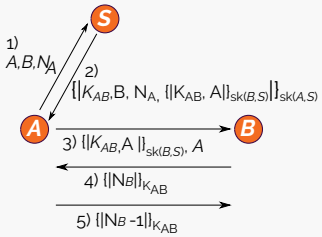
Building a Key Establishment Protocol

Fourth Attempt (1/2)

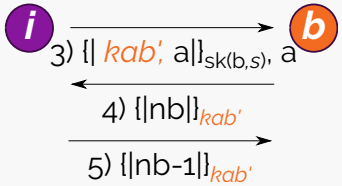
- *A* sends her nonce N_A to *S* with the request for a new key
- If this same value is received with the session key, then *A* can deduce that the key has not been replayed
  (This deduction will be valid as long as session key and nonce are bound together cryptographically in such a way that only S 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 *N*1

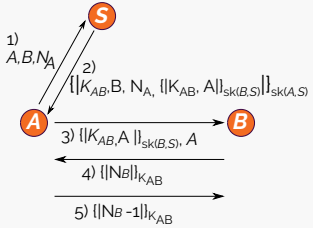


- If the encrypted key for *B* is included in the encrypted part of *A*'s message, then *A* can gain assurance that it is fresh
- It is tempting to believe that *A* may pass this assurance on to *B* in an extra handshake:
  - *B* generates a nonce N_B and sends it to *A* protected by K_{AB} itself
  - *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 due to Denning and Sacco

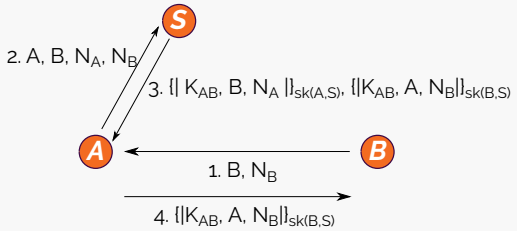


- Problem is assumption that only *A* will be able to form a correct reply to message 4 from *B*
- Since the intruder *i* can be expected to know the value of an old session key, this assumption is unrealistic
- *i* masquerades as *a* and convinces *b* to use old key *kab'*:

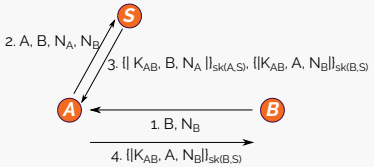




- Idea:
  Let's throw away the assumption that it is inconvenient for both *B* and *A* to send their challenges to *S*
- The protocol is now initiated by *B* who sends his nonce N_B first to *A*
- A adds her nonce N_A and sends both to *S*, who is now able to return K_{AB} in separate messages for *A* and *B*, which can each be verified as fresh by their respective recipients



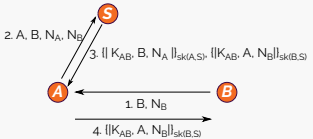
- It may seem that we have achieved more than the previous protocol using fewer messages, but in fact …
  - In the NSCK, *A* could verify that *B* has in fact received the key
  - This property of key confirmation is achieved due to *B*'s use of the key in message 4, assuming that $\{|N_B|\}_{K_{AB}}$ cannot be formed without 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}
    - Is this a Problem?



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
- It would be rash 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

☞ We need means to formalize protocols and goals



Outline

Notation: Messages

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

Agents: a, b, i

Symmetric Keys: K, K_{AB} , ...; $\mathsf{sk}(A, S)$

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

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

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

Asymmetric Encryption: $\{M\}_K$

Signing: $\{M\}_{\mathsf{inv}\,K}$

Nonces: NA, $N1$ fresh data items used for challenge/response.

Sometimes, we may use subscripts, e.g. N_A , but it does not mean that principals can find out that N_A was generated by A

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

Message concatenation: M_1, M_2, M_3

- 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: Protocols

- A typical protocol description combines prose, data type specifications, various kinds of diagrams, ad hoc notations, and message sequences like
  1. $A \longrightarrow B: \ \{NA, A\}_{\mathrm{pk}(B)}$
  2. $B \longrightarrow A: \ \{NA, NB\}_{\mathrm{pk}(A)}$
  3. $A \longrightarrow B: \ \{NB\}_{\mathrm{pk}(B)}$
- 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

Role A:

1. Generate nonce NA, concatenate it with name, and encrypt with $\mathrm{pk}(B)$
   - Send $\{NA, A\}_{\mathrm{pk}(B)}$ to B
2. Receive a message M
   - Decrypt M it with $\mathrm{inv}(\mathrm{pk}(A))$, call it M'. If decryption fails, reject M'
     - Q: how to detect wrong decryption
     - Q: what to do about rejected messages?
   - Split the message into two nonces NA' and NB. If that is not possible, reject M
     - Q: how to check this?
   - Check that $NA' = NA$; if not, reject M
3. Encrypt NB with $\mathrm{pk}(B)$ and send to B

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

Outline

Different Kind of Attacks

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

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

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

- 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
- 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 ...
  - i knows both keys ...
- Prevention: authenticate the half-keys, e.g. with digital signatures
  1. $A \longrightarrow B: \{\exp(g, X)\}_{\mathrm{inv}(\mathrm{pk}(A))}$
  2. $B \longrightarrow A: \{\exp(g, Y)\}_{\mathrm{inv}(\mathrm{pk}(B))}$
- Many protocols are based on Diffie-Hellman, which is not a bad idea!

Type Flaw Attacks

- 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. $A \longrightarrow B: \; M, A, B, \{|NA, M, A, B|\}_{sk(A,S)}$
  2. $B \longrightarrow S: \; M, A, B, \{|NA, M, A, B|\}_{sk(A,S)}, \{|NB, M, A, B|\}_{sk(B,S)}$
  3. $S \longrightarrow B: \; M, \{|NA, K_{AB}|\}_{sk(A,S)}, \{|NB, K_{AB}|\}_{sk(B,S)}$
  4. $B \longrightarrow A: \; M, \{|NA, K_{AB}|\}_{sk(A,S)}$

  Server keys already known and M is a session id (e.g., an integer)
- Now suppose $|M, A, B| = |K_{AB}|$ (e.g., $|M| = 32$ Bit, $|A| = 32$ Bit, $|B| = 32$ Bit, and $|K_{AB}| = 64$ Bit
- Attack 1 (reflection/type-flaw):
  i replays parts of message 1 as message 4 (omitting steps 2 and 3)
  1. $a \longrightarrow i(b): \; m, a, b, \{|na, m, a, b|\}_{sk(a,s)}$
  4. $i(b) \longrightarrow a: \; m, \{|na, \underbrace{m, a, b}_{\text{mistaken as } kab} |\}_{sk(a,s)}$

Type Flaw Attacks: The Otway-Rees Protocol (2/2)

- Otway-Rees:
  1. $A \longrightarrow B: \; M, A, B, \{|NA, M, A, B|\}_{sk(A,S)}$
  2. $B \longrightarrow S: \; M, A, B, \{|NA, M, A, B|\}_{sk(A,S)}, \{|NB, M, A, B|\}_{sk(B,S)}$
  3. $S \longrightarrow B: \; M, \{|NA, K_{AB}|\}_{sk(A,S)}, \{|NB, K_{AB}|\}_{sk(B,S)}$
  4. $B \longrightarrow A: \; M, \{|NA, K_{AB}|\}_{sk(A,S)}$

  Server keys already known and M is a session id (e.g., an integer)
- Now suppose $|M, A, B| = |K_{AB}|$ (e.g., $|M| = 32$ Bit, $|A| = 32$ Bit, $|B| = 32$ Bit, and $|K_{AB}| = 64$ Bit
- Attack 2 (reflection/type-flaw): The intruder can play the role of S in 2 and 3 by reflecting the encrypted components of 2 back to B
  1. $a \longrightarrow b: \; m, a, b, \{|na, m, a, b|\}_{sk(a,s)}$
  2. $b \longrightarrow i(s): \; m, a, b, \{|na, m, a, b|\}_{sk(a,s)}, \{|na, m, a, b|\}_{sk(b,s)}$
  3. $i(s) \longrightarrow b: \; m, \{|na, \underbrace{m, a, b}_{kab}|\}_{sk(a,s)}, \{|nb, \underbrace{m, a, b}_{kab}|\}_{sk(b,s)}$
  4. $b \longrightarrow a: \; m, \{|na, \underbrace{m, a, b}_{kab}|\}_{sk(a,s)}$

  👉 a and b accept the wrong key and i can decrypt their subsequent communication (key authentication and secrecy fails)

Example of a Binding Attack

- The protocol
  1. $A \longrightarrow S: \; A, B, NA$
  2. $S \longrightarrow A: \; S, \{S, A, NA, K_B\}_{\mathsf{inv}(\mathsf{pk}(S))}$

  admits a binding attack:

  1.1 $a \longrightarrow i(s): \; a, b, na$
  2.1 $i(a) \longrightarrow s: \; a, i, na$
  2.2 $s \longrightarrow i(a): \; s, \{s, a, na, ki\}_{\mathsf{inv}(\mathsf{pk}(S))}$
  1.2 $i(s) \longrightarrow s: \; s, \{s, a, na, ki\}_{\mathsf{inv}(\mathsf{pk}(S))}$
- Fix: include thename of B in 2.

Outline

- 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, …
    (e.g. $\{X, Y\}_{\mathsf{inv}(K)}$ versus $\{X\}_{\mathsf{inv}(K)}, \{Y\}_{\mathsf{inv}(K)}$)
  - Be clear on what properties you are assuming.
  - Beware of clock variations (for timestamps).
  - etc.
- 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?
  - etc.

Conclusion

- 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
  - annot 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)

Thank you for your attention!
Any questions or remarks?

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