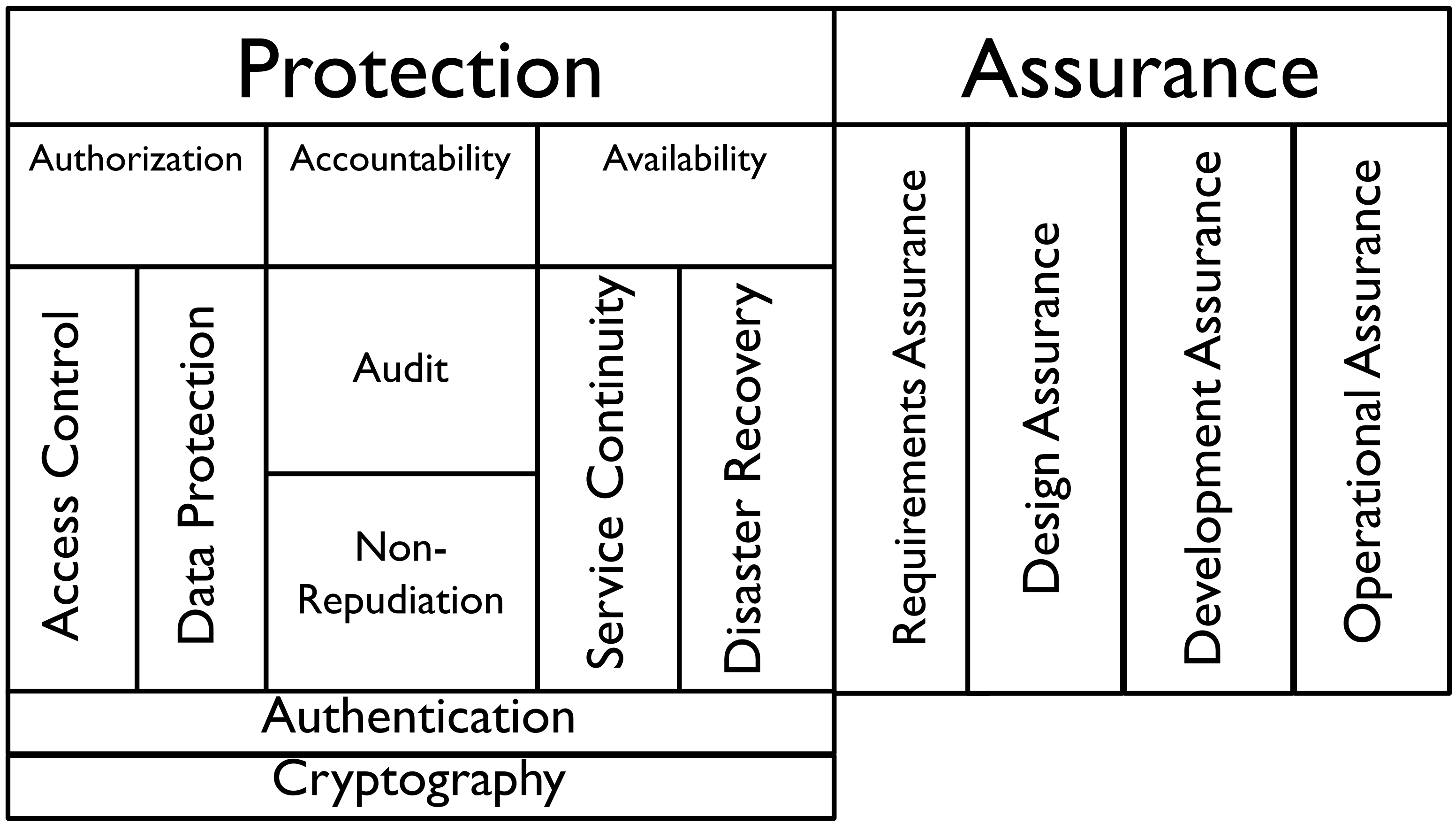
# Key Establishment

EECE 412

# where we are


Protection
Assurance
Authorization
Accountability
Availability
Access Control
Data Protection
Audit
Non-Repudiation
Service Continuity
Disaster Recovery
Requirements Assurance
Design Assurance
Development Assurance
Operational Assurance
Authentication
Cryptography

“The security of a cryptosystem must not depend on keeping secret the crypto-algorithm. The security depends only on keeping secret the key”

Auguste Kerckhoff von Nieuwenhof

Dutch linguist

1883

# session key with mutual authentication using symmetric key

“I’m Alice”, $R_A$ →

$R_B$, E(“Bob”, $R_A$, $K_{AB}$) ←

E(“Alice”, $R_B$, $K_S$, $K_{AB}$) →

Alice

Bob

# FPS session key with mutual authentication using symmetric key

Alice

“I’m Alice”, $R_A$ →

← $R_B$, E(“Bob”, $R_A$, $g^b \bmod p$, $K_{AB}$)

E(“Alice”, $R_B$, $g^a \bmod p$, $K_{AB}$) →

Bob

# Outline

1. Diffie-Hellman key exchange (Stamp 4.4, Anderson 5.7.2.1, 5.7.2.2)
2. mutual authentication in networks (Stamp 9.1-9.3.3, Anderson Chapter 3)
3. perfect forward secrecy (Stamp 9.3.4, 9.3.5, 9.6, 9.7)

# learning objectives for this module

You should be able to

- analyze key establishment and authentication protocols and identify their vulnerabilities
- improve or design new key establishment and authentication protocols

# Notation

- $X \rightarrow Y : \{ Z \,||\, W \}_{k_{X,Y}}$ == $E(Z, W, k_{X,Y})$
  - X sends Y the message produced by concatenating Z and W enciphered by key $k_{X,Y}$, which is shared by users X and Y
- $A \rightarrow T : \{ Z \}_{k_A} \,||\, \{ W \}_{k_{A,T}}$
  - A sends T a message consisting of the concatenation of Z enciphered using $k_A$, A's key, and W enciphered using $k_{A,T}$, the key shared by A and T
- $r_1$, $r_2$ nonces ("nonrepeating" random numbers)

# Diffie-Hellman Key Exchange

# important trivia

- Invented by Williamson (GCHQ) and, independently, by D and H (Stanford)
- A "key exchange" algorithm
  - Used to establish a shared symmetric key
- Not for encrypting or signing
- Security rests on difficulty of **discrete log** problem: given $g$, $p$, and $g^k \bmod p$ find $k$

# how it works

- Let $p$ be prime, let $g$ be a **generator**
  - For any $x \in \{1,2,\ldots,p\text{-}1\}$ there is $n$ s.t. $x = g^n \bmod p$

1. Alice selects secret value $a$
2. Bob selects secret value $b$
3. Alice sends $g^a \bmod p$ to Bob
4. Bob sends $g^b \bmod p$ to Alice
5. Both compute shared secret $g^{ab} \bmod p$

- Shared secret can be used as symmetric key

# why it's hard to attack

- Suppose that Bob and Alice use $g^{ab} \bmod p$ as a symmetric key
- Trudy can see $g^a \bmod p$ and $g^b \bmod p$
- Note $g^a g^b \bmod p = g^{a+b} \bmod p \neq g^{ab} \bmod p$
- If Trudy can find $a$ or $b$, system is broken
- If Trudy can solve **discrete log** problem, then she can find $a$ or $b$

# the protocol

- **Public:** g and p
- **Secret:** Alice’s exponent a, Bob’s exponent b

$g^a \bmod p$ →

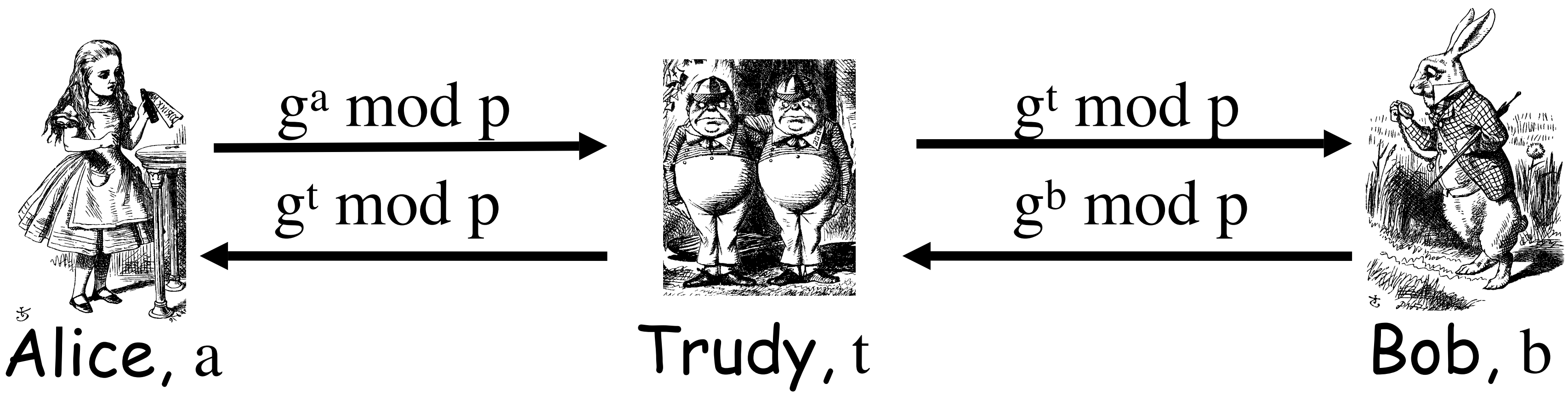
← $g^b \bmod p$

Alice, a

Bob, b

- Alice computes $(g^b)^a = g^{ba} = g^{ab} \bmod p$
- Bob computes $(g^a)^b = g^{ab} \bmod p$
- Could use $K = g^{ab} \bmod p$ as symmetric key

# Man-in-the-Middle Attack




- Trudy shares secret $g^{at}$ mod p with Alice
- Trudy shares secret $g^{bt}$ mod p with Bob
- Alice and Bob don't know Trudy exists!

# how to prevent MiM attack?

- Encrypt DH exchange with symmetric key
- Encrypt DH exchange with public key
- Sign DH values with private key
- Other?

You **MUST** be aware of MiM attack on Diffie-Hellman

# Authentication Protocols

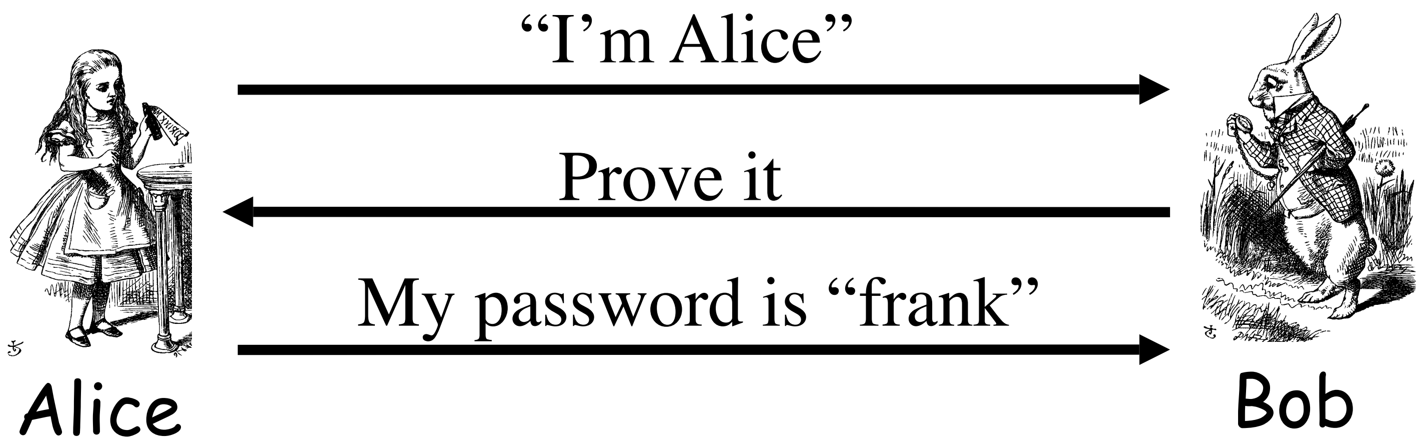
# basics

- Alice must prove her identity to Bob
  - Alice and Bob can be humans or computers
- May also require Bob to prove he's Bob (mutual authentication)
- May also need to establish a session key
- May have other requirements, such as
  - Use only public keys
  - Use only symmetric keys
  - Use only a hash function
  - Anonymity, plausible deniability, etc., etc.

# why authentication can be hard?

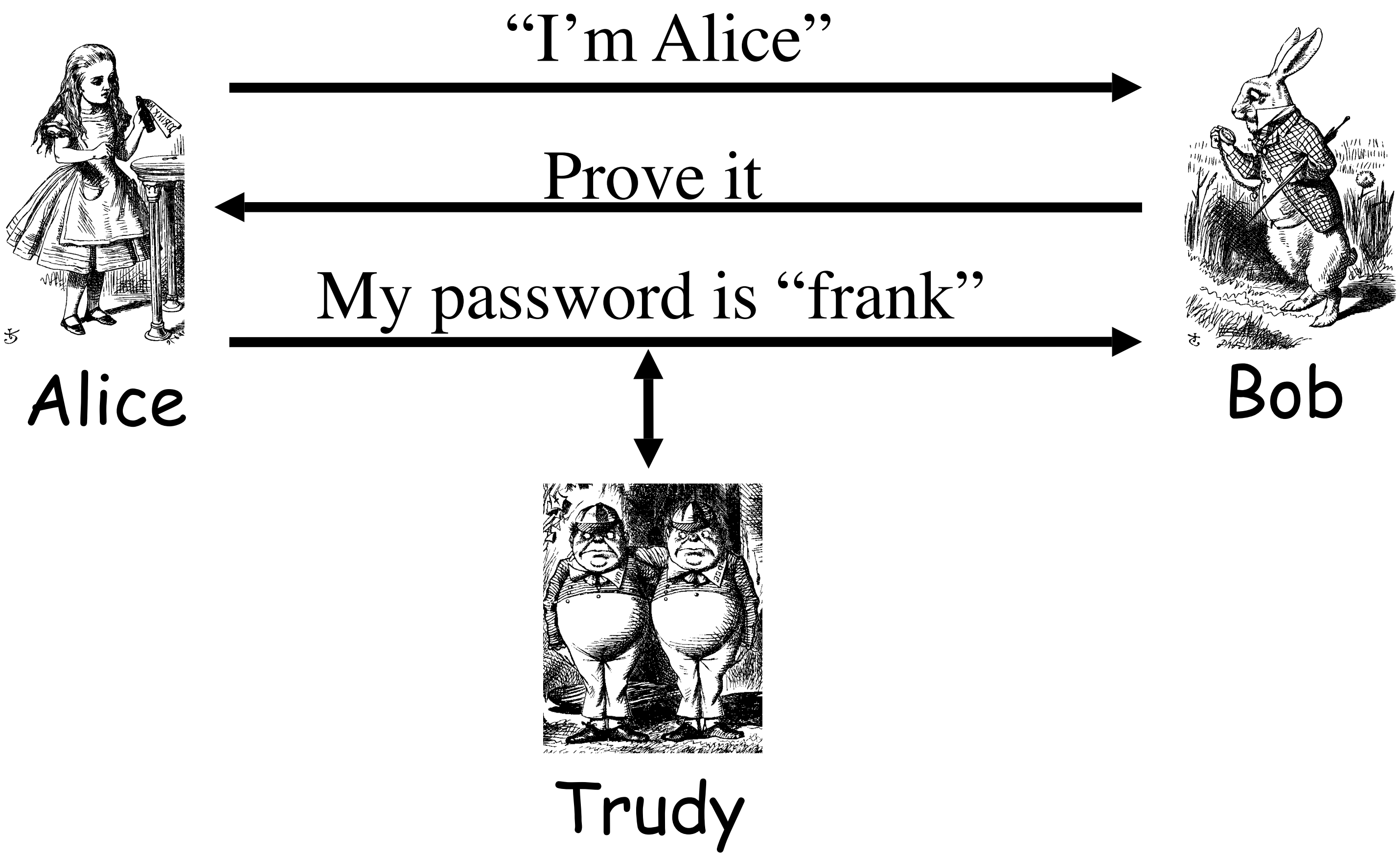
- relatively simple on a stand-alone computer
  - “Secure path” is the primary issue
  - main concern is an attack on authentication software
- much more complex over a network
  - attacker can passively observe messages
  - attacker can replay messages
  - active attacks may be possible (insert, delete, change messages)

# simple authentication

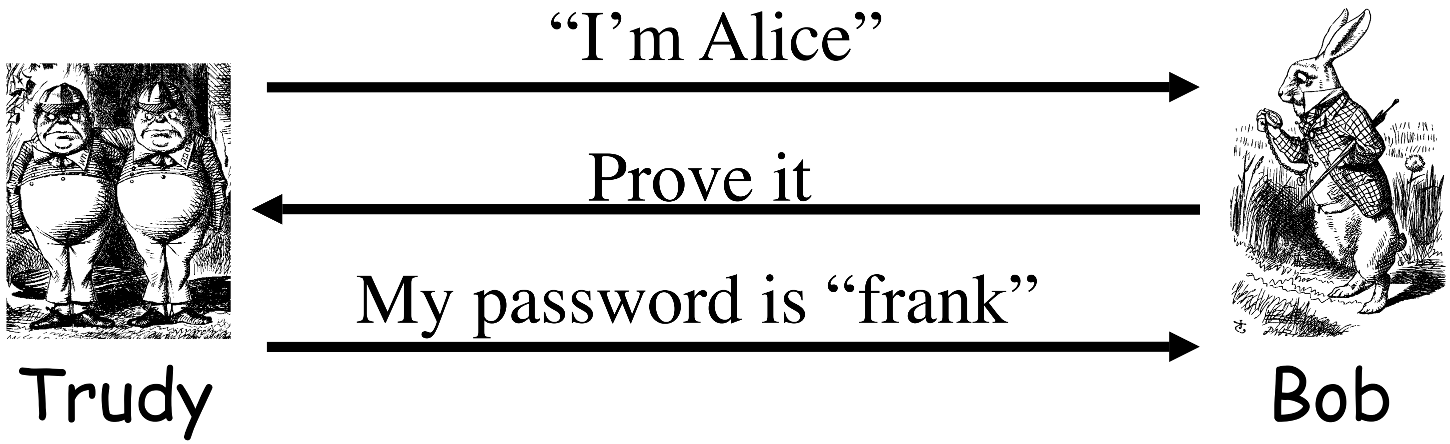



- Simple and may be OK for standalone system
- But insecure for networked system
  - Subject to a replay attack (next 2 slides)
  - Bob must know Alice's password

# authentication attack

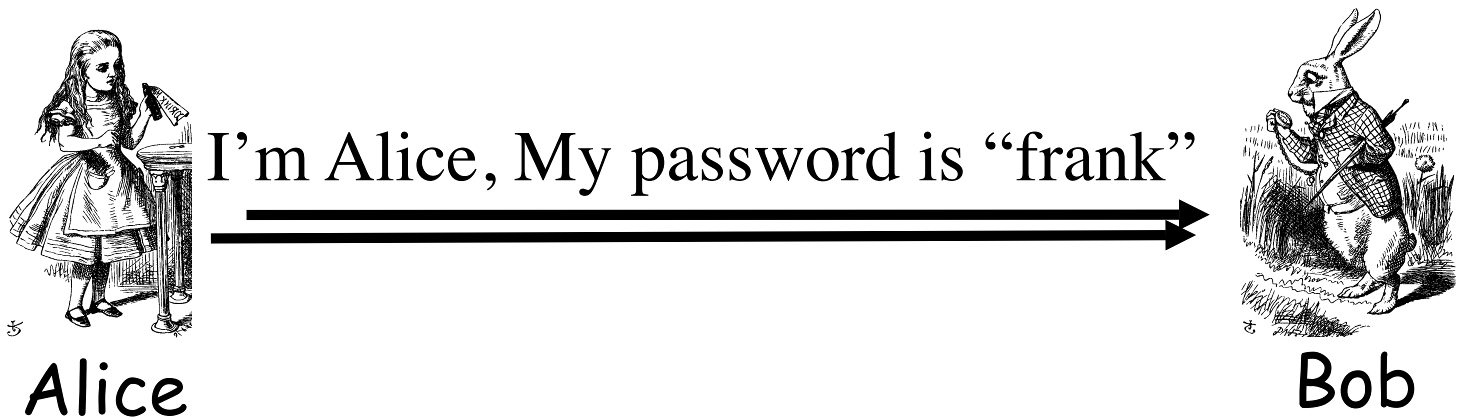


# authentication Attack



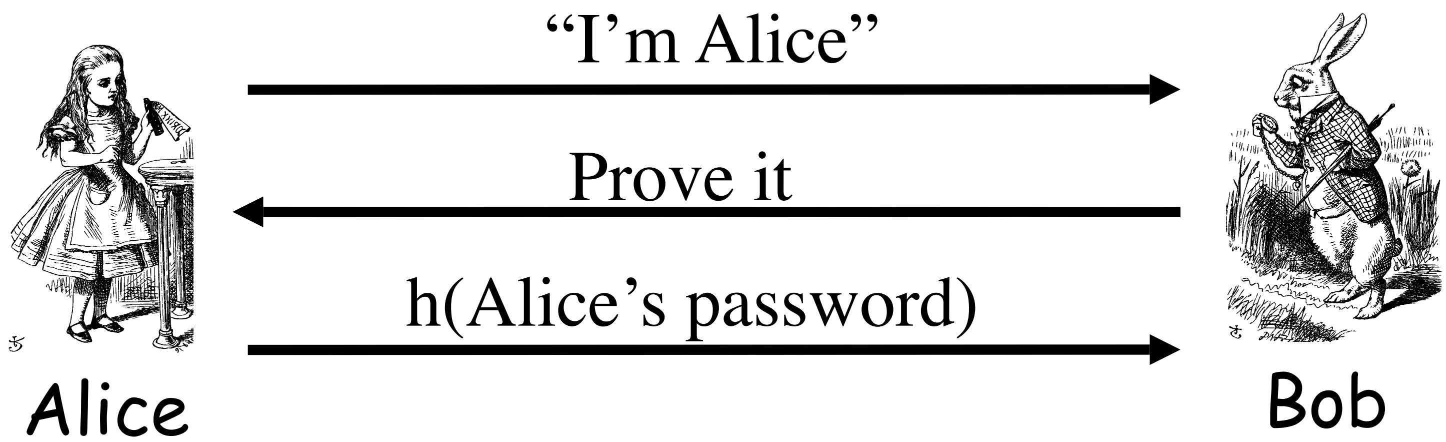

- This is a **replay** attack
- How can we prevent a replay?

# Simple Authentication




- More efficient…
- But same problem as previous version

# Better Authentication

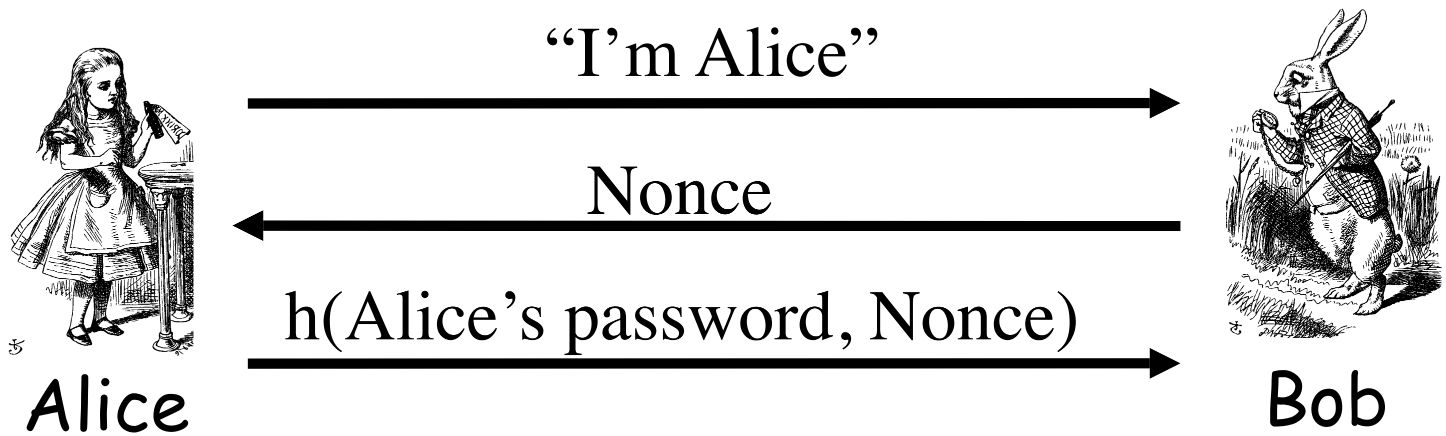



- Better since it hides Alice's password
  - From both Bob and attackers
- But still subject to replay

# challenge-response

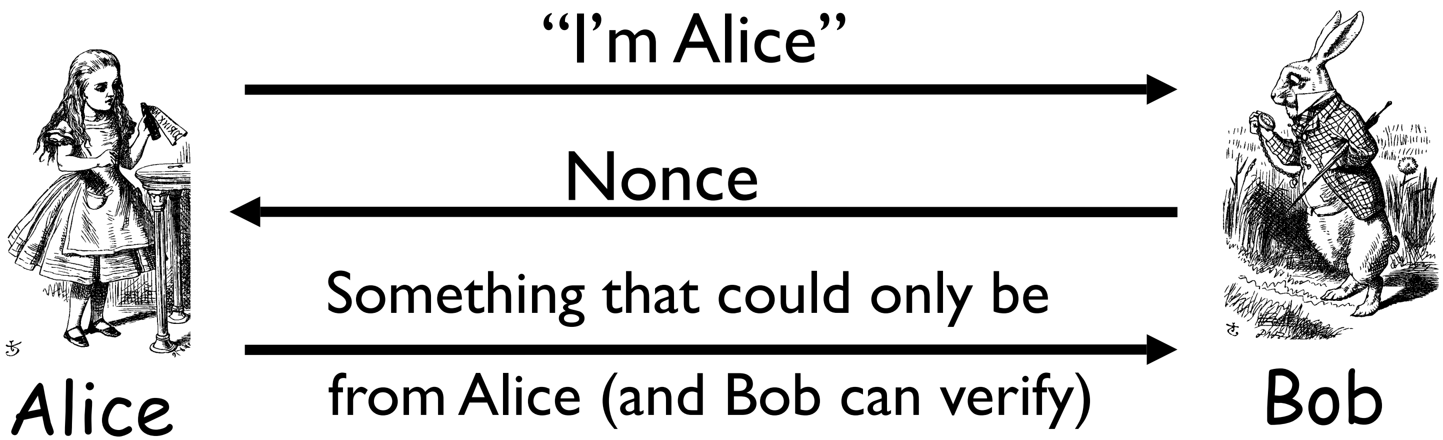
- To prevent replay, challenge-response used
- Suppose Bob wants to authenticate Alice
  - Challenge sent from Bob to Alice
  - Only Alice can provide the correct response
  - Challenge chosen so that replay is not possible
- How to accomplish this?
  - Password is something only Alice should know…
  - For freshness, a “number used once” or **nonce**

# simple challenge-response




- Nonce is the **challenge**
- The hash is the **response**
- Nonce prevents replay, insures freshness
- Password is something Alice knows
- Note that Bob must know Alice's password

# general challenge-response




- What can we use to achieve this?
- Hashed pwd works, crypto might be better

# symmetric key notation

- Encrypt plaintext P with key K

  C = E(P,K)

- Decrypt ciphertext C with key K

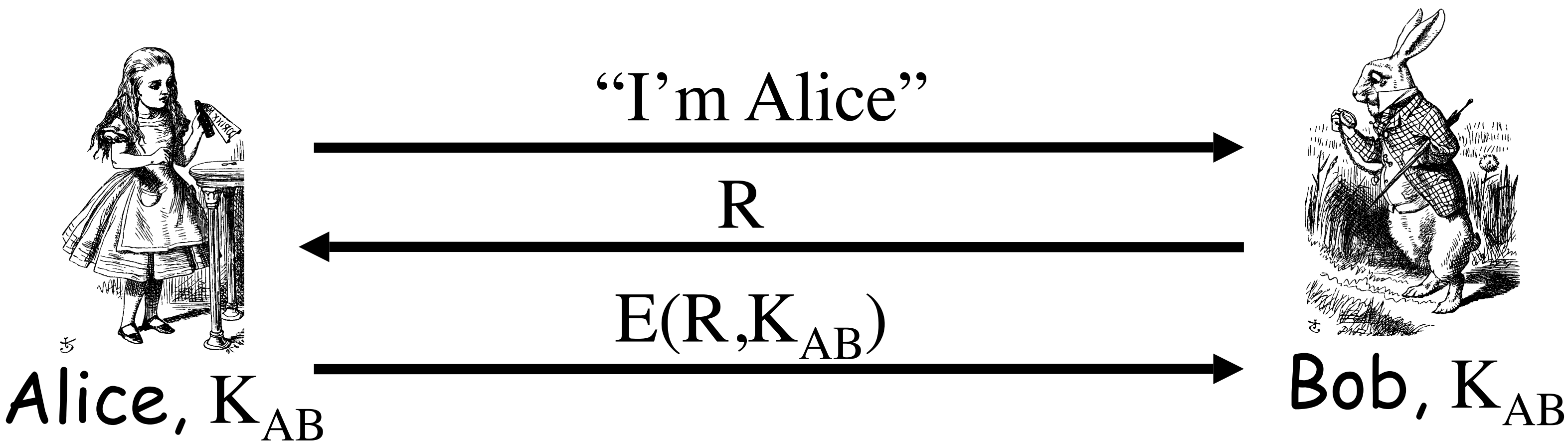
  P = D(C,K)

- Here, we are concerned with attacks on **protocols**, not directly on the crypto
- We assume that crypto algorithm is secure

# authentication with symmetric key

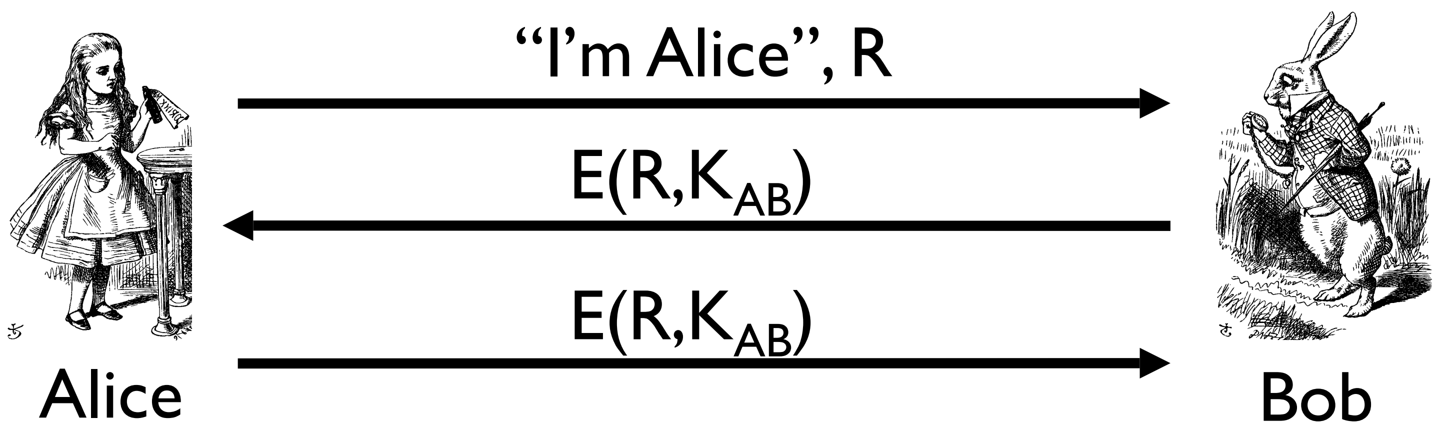
- Alice and Bob share symmetric key $K_{AB}$
- key $K_{AB}$ known only to Alice and Bob
- authenticate by proving knowledge of shared symmetric key
- how to accomplish this?
  - must not reveal key
  - must not allow replay attack

# authentication with symmetric key




- Secure method for Bob to authenticate Alice
- Alice does not authenticate Bob
- Can we achieve mutual authentication?

# mutual authentication?

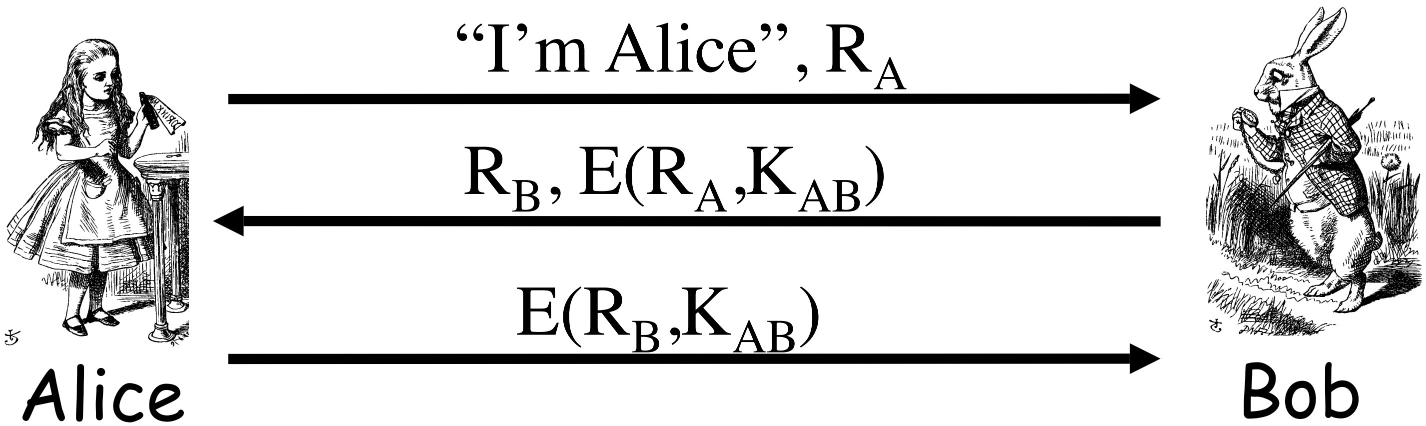



- What's wrong with this picture?
- "Alice" could be Trudy (or anybody else)!

# Mutual Authentication

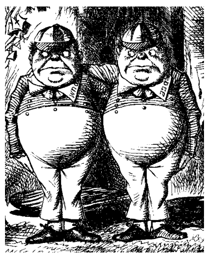
- Since we have a secure one-way authentication protocol…
- The obvious thing to do is to use the protocol twice
  - Once for Bob to authenticate Alice
  - Once for Alice to authenticate Bob
- This has to work…

# Mutual Authentication




- This provides mutual authentication
- Is it secure? See the next slide…

# attack on mutual authentication



Trudy

1. "I'm Alice", $R_A$

2. $R_B$, $E(R_A, K_{AB})$

5. $E(R_B, K_{AB})$

Bob

---

Trudy

3. "I'm Alice", $R_B$

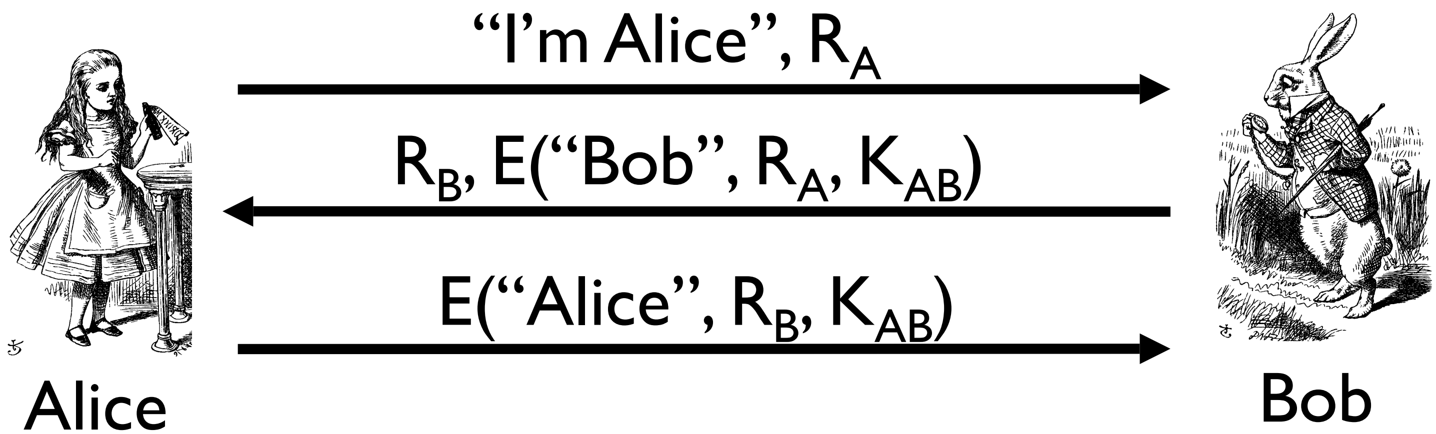
4. $R_C$, $E(R_B, K_{AB})$

Bob

# Notes on Mutual Authentication

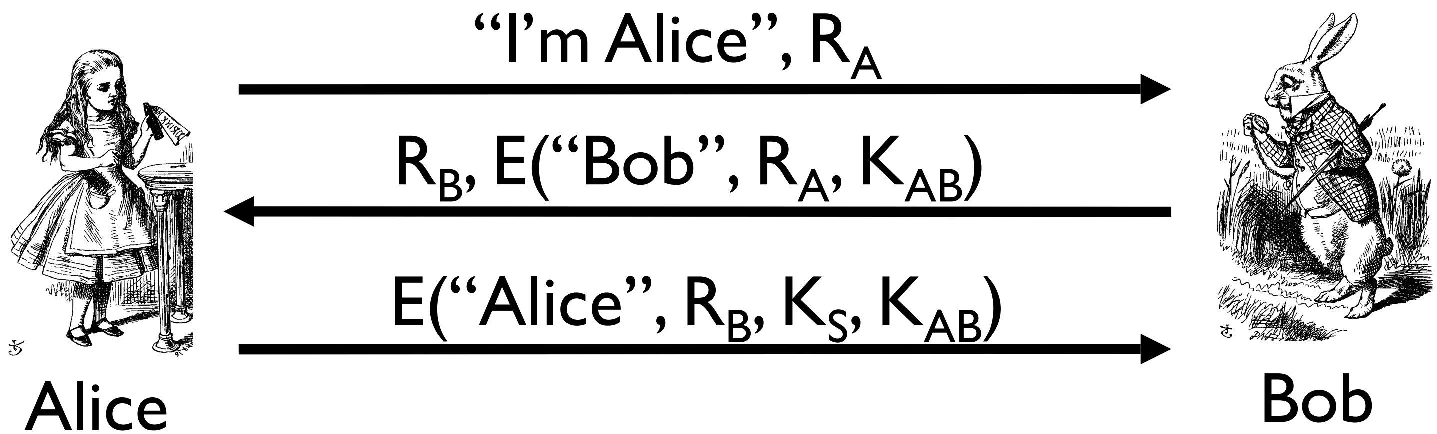
- Our one-way authentication protocol **not** secure for mutual authentication
- Protocols are subtle!
- The "obvious" thing may not be secure
- Also, if assumptions or environment changes, protocol may not work
  - This is a common source of security failure
  - For example, Internet protocols

# mutual authentication with symmetric key




- Do these “insignificant” changes help?
- Yes!

# session key with mutual authentication using symmetric key



# Perfect Forward Secrecy

# Perfect Forward Secrecy

- The concern…
  - Alice encrypts message with shared key $K_{AB}$ and sends ciphertext to Bob
  - Trudy records ciphertext and later attacks Alice's (or Bob's) computer to find $K_{AB}$
  - Then Trudy decrypts recorded messages

**Perfect forward secrecy (PFS):** Trudy cannot later decrypt recorded ciphertext

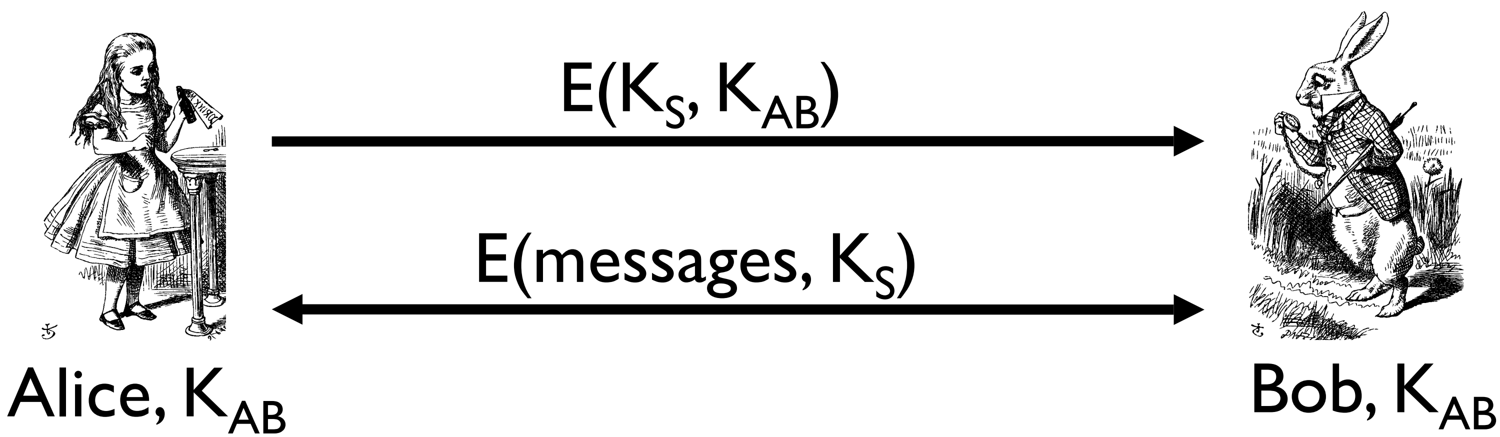
  - Even if Trudy gets key $K_{AB}$ or other secret(s)

- Is PFS possible?

# Perfect Forward Secrecy

- For perfect forward secrecy, Alice and Bob cannot use $K_{AB}$ to encrypt
- Instead they must use a **session key** $K_S$ and forget it after it's used
- Problem: How can Alice and Bob agree on session key $K_S$ and insure PFS?

# naïve session key protocol




- Trudy could also record $E(K_S,K_{AB})$
- If Trudy gets $K_{AB}$, she gets $K_S$

# perfect forward secrecy

- Can use **Diffie-Hellman** for PFS
- Recall Diffie-Hellman: public g and p

$g^a \bmod p$ →

← $g^b \bmod p$

Alice, a

Bob, b

- But Diffie-Hellman is subject to MiM
- How to get PFS and prevent MiM?

# PFS session key via DH

$E(g^a \bmod p, K_{AB})$ →

← $E(g^b \bmod p, K_{AB})$

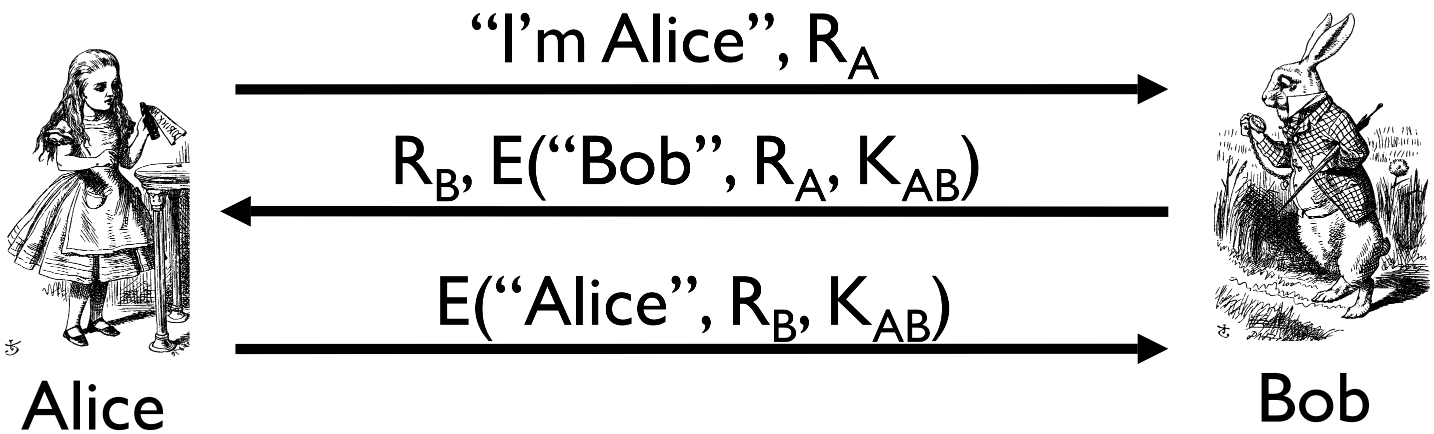
Alice, a Bob, b

- Session key $K_S = g^{ab} \bmod p$
- Alice forgets a, Bob forgets b

**Ephemeral Diffie-Hellman**

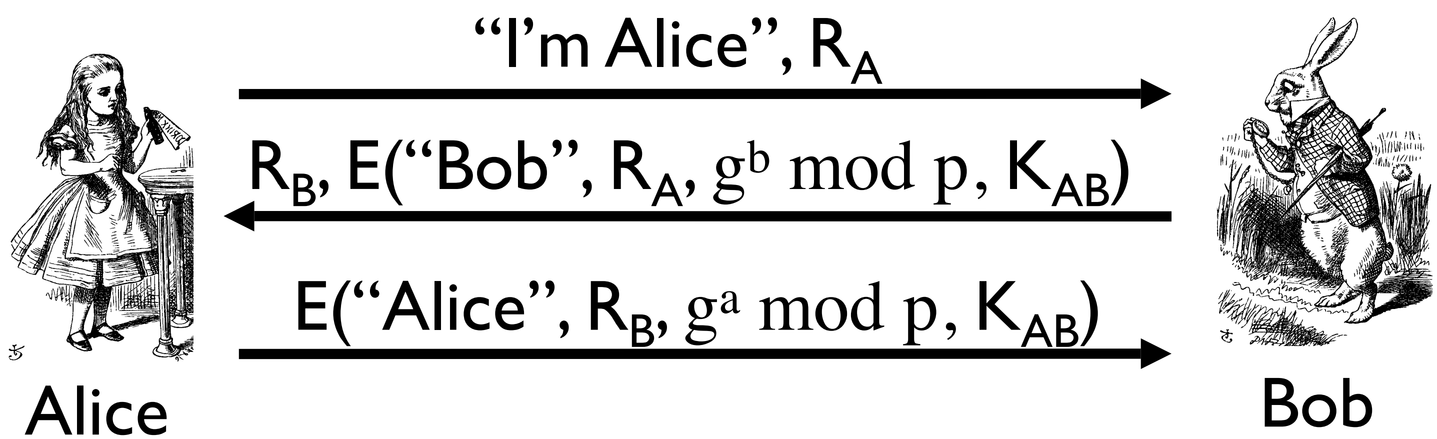
- Not even Alice and Bob can later recover $K_S$
- Other ways to do PFS?

# mutual authentication with symmetric key




- Do these “insignificant” changes help?
- Yes!

# FPS session key with mutual authentication using symmetric key



# Outline

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2. mutual authentication in networks (Stamp 9.1-9.3.3)
3. perfect forward secrecy (Stamp 9.3.4, 9.3.5)

# learning objectives for this module

You should be able to

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