CS 166: *Information Security*

Simple Authentication Protocols

Prof. Tom Austin

San José State University

What is a Protocol?

Rules for interaction, which can include:

- Human protocols
  - e.g. raise your hand to ask a question
- Networking protocols
  - rules followed in network communication
  - HTTP, FTP, etc.
- Security protocol
  - communication rules for a security app

How do we tell if a protocol "works"?

1. What guarantees does the protocol provide?
   – Authentication
   – mutual authentication
   – key exchanged
   – and many more …
2. Assume that *everything else works*.
   – No flaws in the crypto
   – No flaws in the implementation
   – Secrets (e.g. keys) stay secret
3. Given the above, can you break the protocol

Protocols

- Protocol flaws can be very **subtle**
- Several well-known security protocols have significant flaws
  - Including WEP, GSM, and IPSec
- Implementation errors can occur
  - IE implementation of SSL
- Not easy to get protocols right…

Ideal Security Protocol

- Must satisfy security requirements
  - Requirements need to be precise
- Efficient
  - Small computational requirement
  - Small bandwidth usage, minimal delays…
- Robust
  - Works when attacker tries to break it
  - Works even if environment changes
- Easy to use & implement, flexible…
- Difficult to satisfy all of these

Secure Entry to NSA

1. Insert badge into reader
2. Enter PIN
3. Correct PIN?

   Yes? Enter

   No? Get shot by security guard

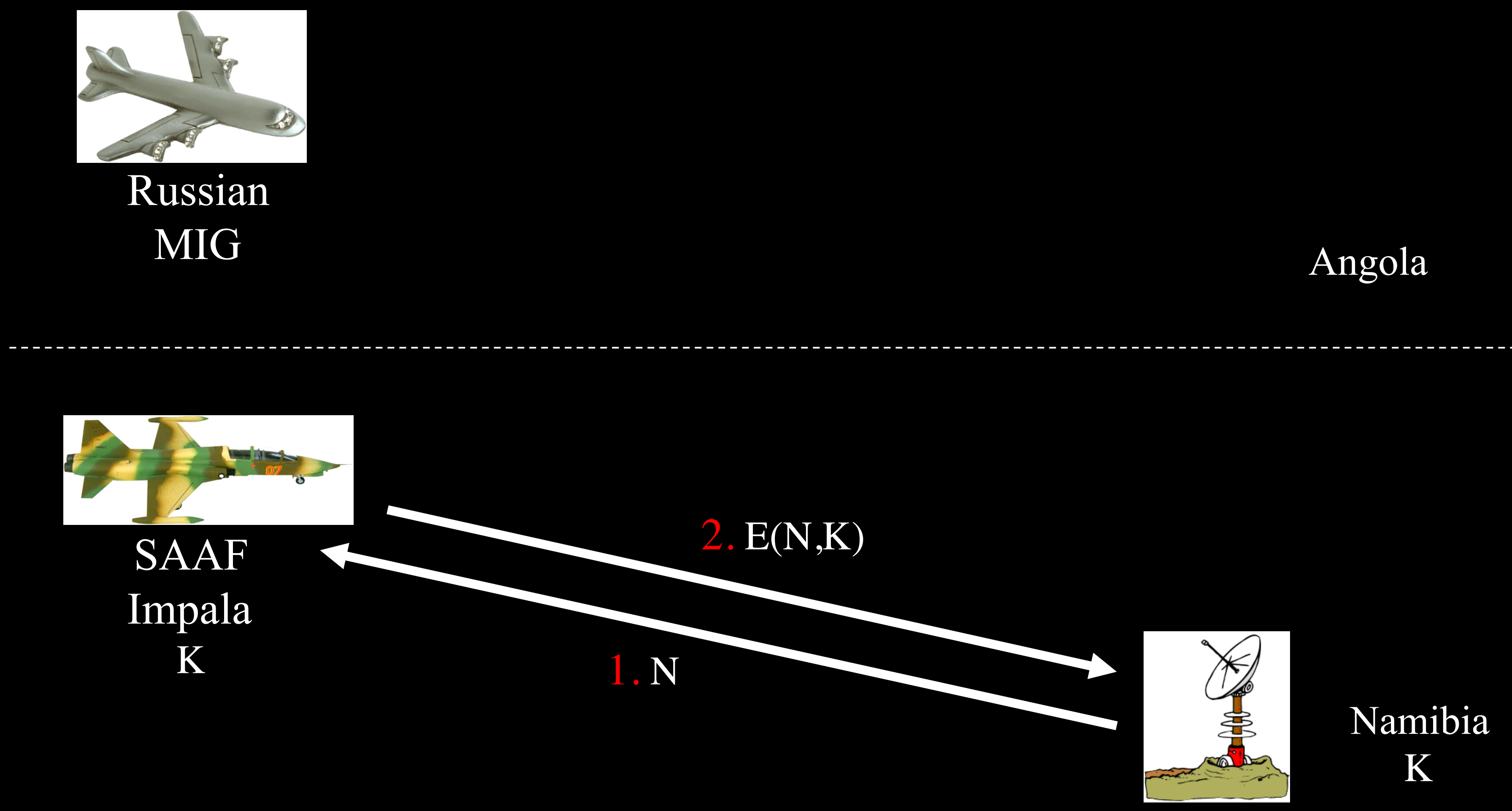
ATM Machine Protocol

1. Insert ATM card
2. Enter PIN
3. Correct PIN?

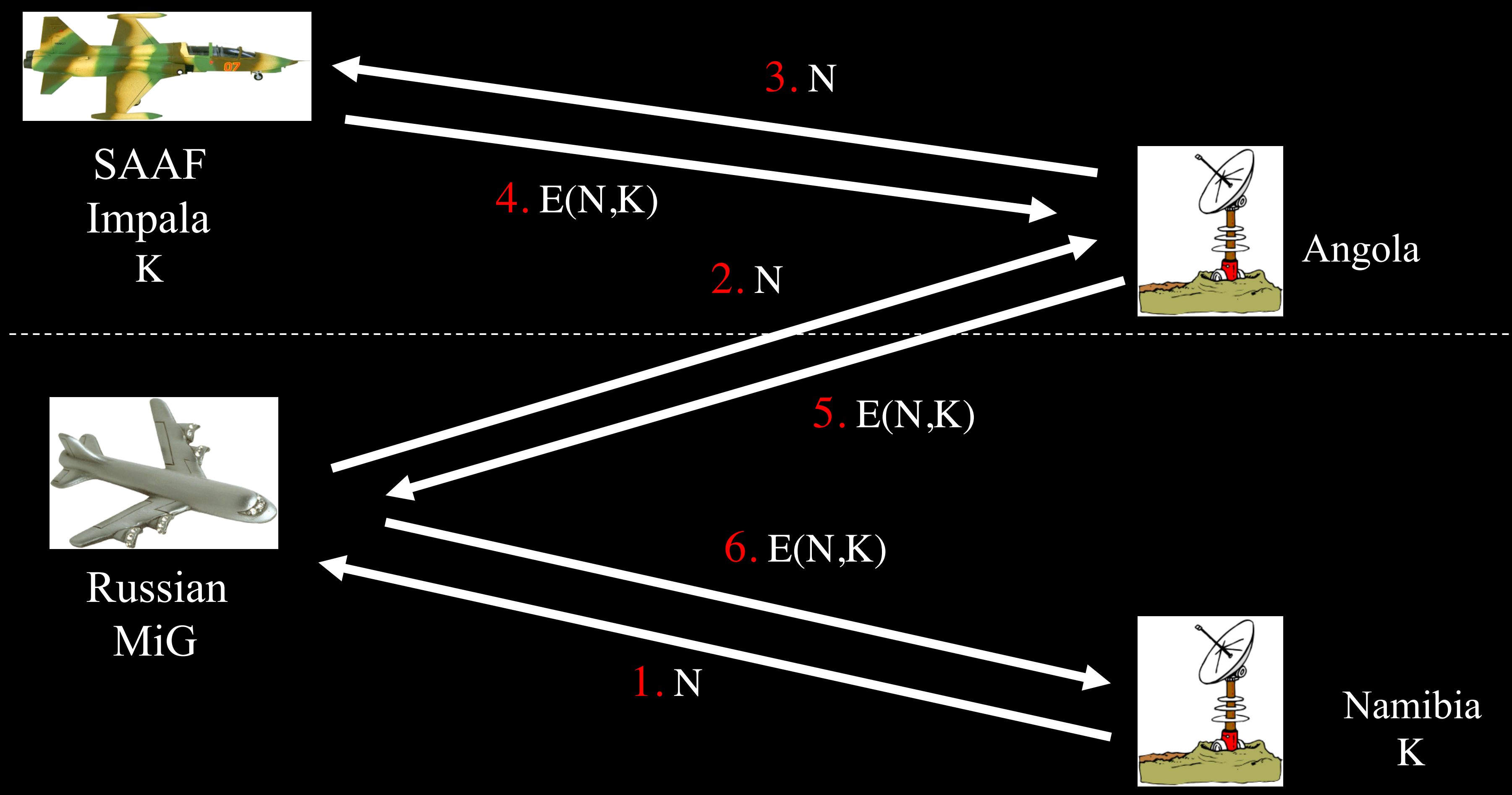
   Yes? Conduct your transaction(s)

   No? Machine (eventually) eats card

Identify Friend or Foe (IFF)



MIG in the Middle



Authentication Protocols

Authentication

- 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
- Probably need to establish a **session key**
- May have other requirements, such as
  - Use public keys
  - Use symmetric keys
  - Use hash functions
  - Anonymity, plausible deniability, etc., etc.

Authentication

- Authentication on a stand-alone computer is relatively simple
  - Hash password with salt
  - “Secure path,” attacks on authentication software, keystroke logging, etc., can be issues
- Authentication over a network is challenging
  - Attacker can passively observe messages
  - Attacker can replay messages
  - Active attacks possible (insert, delete, change)

Simple Authentication

Alice

“I’m Alice”

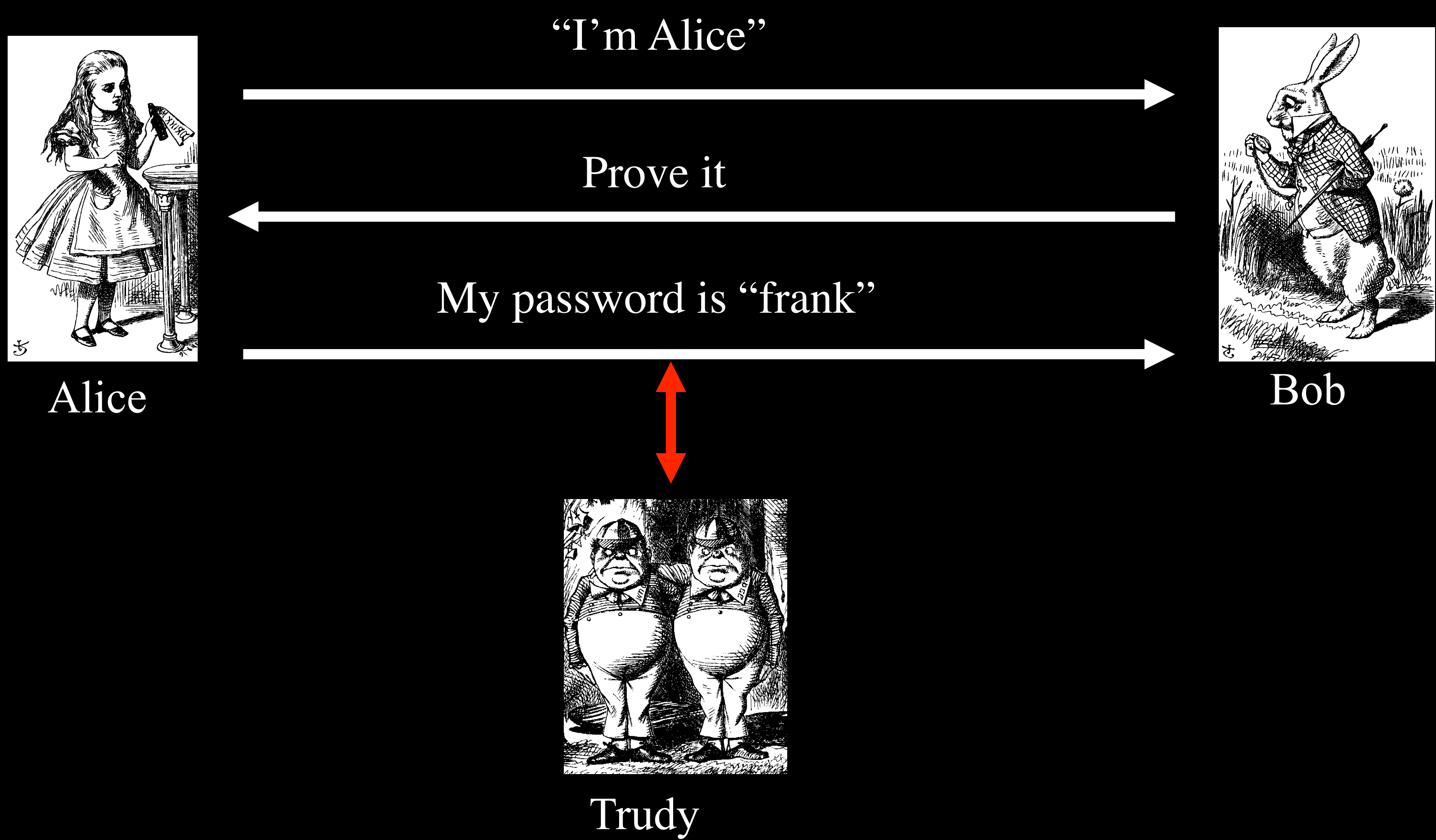
Prove it

My password is “frank”

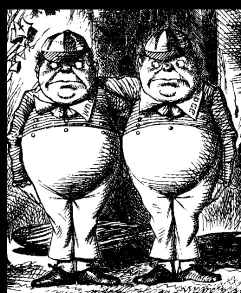
Bob

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

Authentication Attack



Authentication Attack



Trudy

“I’m Alice” →

← Prove it

My password is “frank” →

Bob

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

Simple Authentication

Alice

I’m Alice, my password is “frank”

Bob

- More efficient, but…
- … same problem as previous version

Better Authentication

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

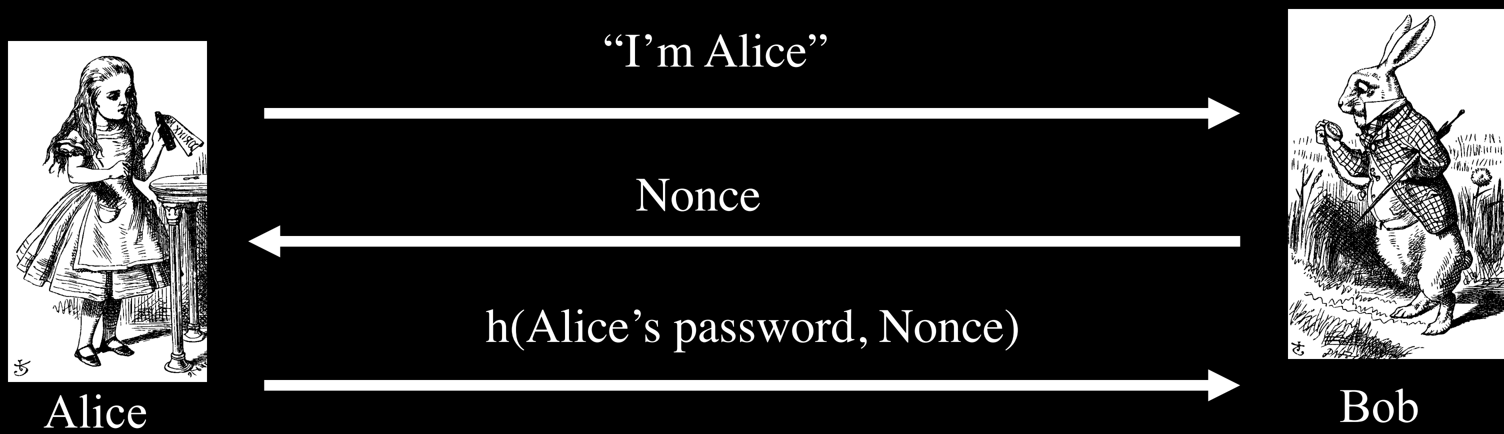
Challenge-Response

- To prevent replay, use ***challenge-response***
  - Goal is to ensure "freshness"
- Suppose Bob wants to authenticate Alice
  - ***Challenge*** sent from Bob to Alice
- Challenge is chosen so that…
  - Replay is not possible
  - Only Alice can provide the correct ***response***
  - Bob can verify the response

Nonce

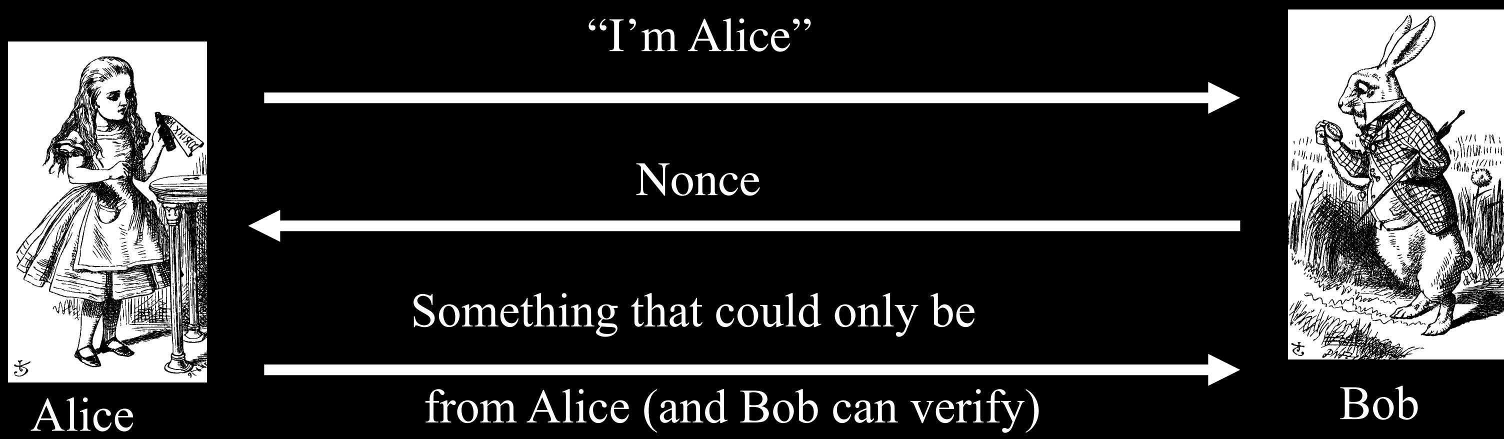
- To ensure freshness, can employ a **nonce**
  - Nonce == **n**umber used **once**
- What to use for nonces?
  - That is, what is the challenge?
- What should Alice do with the nonce?
  - That is, how to compute the response?
- How can Bob verify the response?
- Should we rely on passwords or keys?

Challenge-Response



- Nonce is the challenge
- The hash is the response
- Nonce prevents replay, ensures freshness
- Password is something Alice knows
- Note: Bob must know Alice’s pwd to verify

Generic Challenge-Response



- In practice, how to achieve this?
- Hashed password works, but…
- Encryption is better here (Why?)

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, attacks on crypto
  - So, we assume crypto algorithms are secure

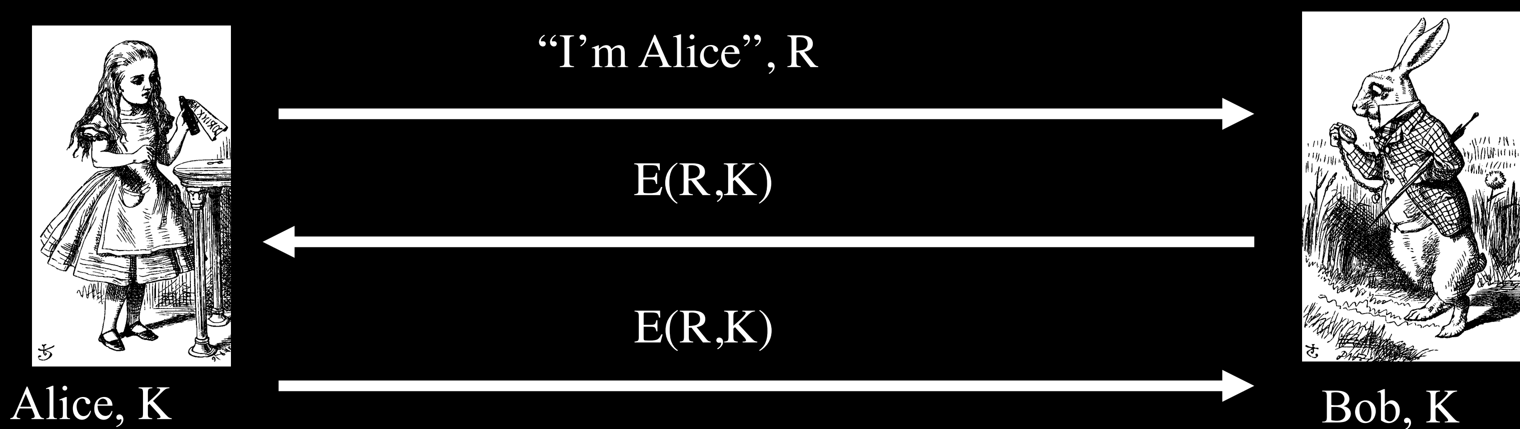
Authentication: Symmetric Key

- Alice and Bob share symmetric key K
- Key K known only to Alice and Bob
- Authenticate by proving knowledge of shared symmetric key
- How to accomplish this?
  - Cannot reveal key, must not allow replay (or other) attack, must be verifiable, …

Authentication with Symmetric Key

- Secure method for Bob to authenticate Alice
- Alice does not authenticate Bob
- So, 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 got to work…

Mutual Authentication

Alice, K

"I'm Alice", R_A

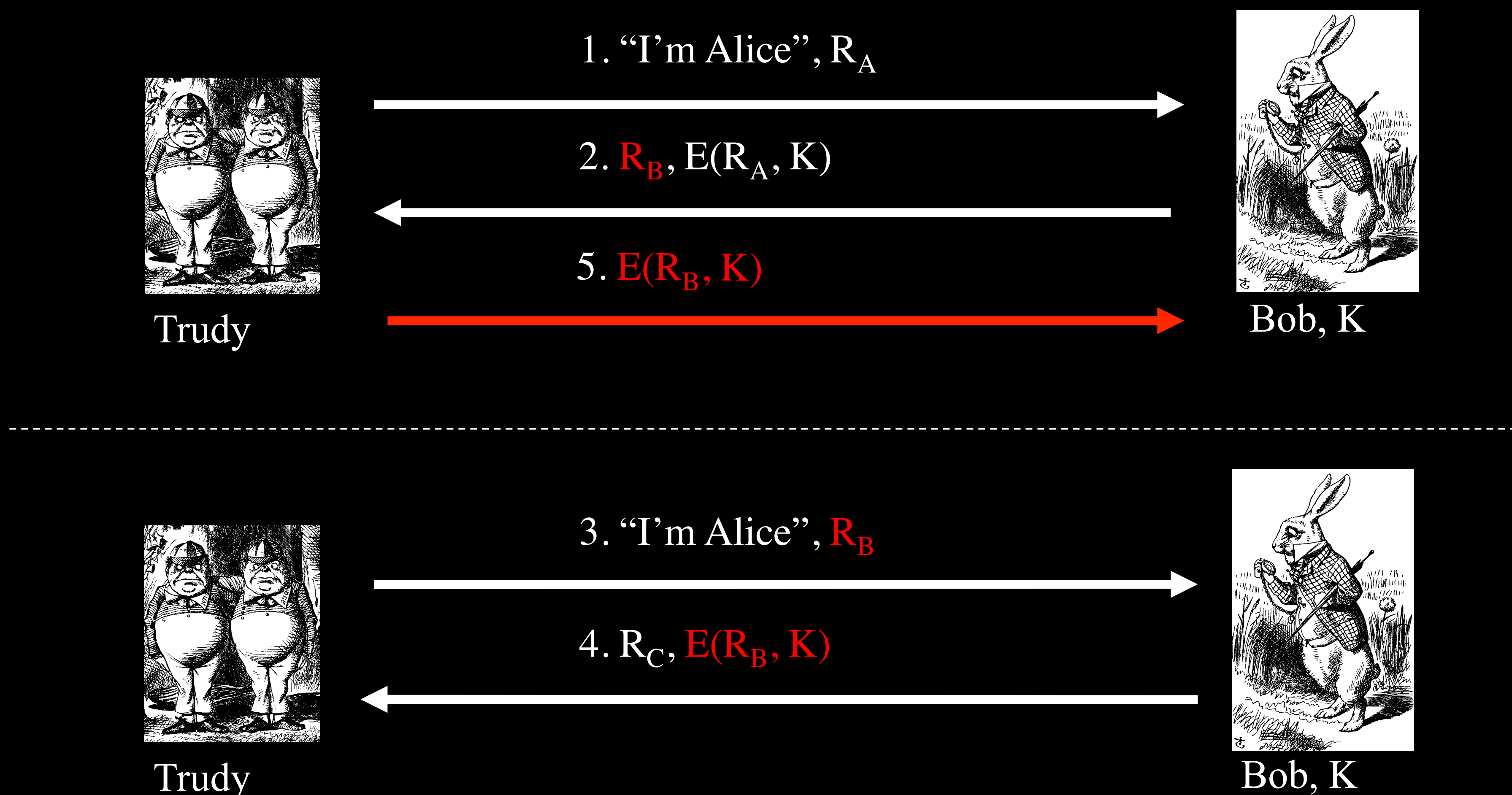
R_B, $E(R_A, K)$

$E(R_B, K)$

Bob, K

- This provides mutual authentication…
- …or does it? See the next slide

Mutual Authentication Attack



Mutual Authentication

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

Symmetric Key Mutual Authentication

Alice, K

"I'm Alice", R_A →

← R_B, E("Bob",R_A,K)

E("Alice",R_B,K) →

Bob, K

- Do these "insignificant" changes help?
- Yes!

Public Key Notation

- Encrypt M with Alice's public key: $\{M\}_{Alice}$
- Sign M with Alice's private key: $[M]_{Alice}$
- Then
  - $[\{M\}_{Alice}]_{Alice} = M$
  - $\{[M]_{Alice}\}_{Alice} = M$
- **Anybody** can use Alice's **public key**
- Only **Alice** can use her **private key**

Public Key Authentication

Alice

"I'm Alice" →

← $\{R\}_{Alice}$

R →

Bob

- Is this secure?
- Trudy can get Alice to decrypt anything!
  - So, should have two key pairs

Public Key Authentication

Alice

“I’m Alice” →

← R

$[R]_{Alice}$ →

Bob

- Is this secure?
- Trudy can get Alice to sign anything!
  - Same as previous — should have two key pairs

Public Keys

- Generally, a bad idea to use the same key pair for encryption and signing
- Instead, should have…
  - …one key pair for encryption/ decryption…
  - …and a different key pair for signing/verifying signatures

Session Key

- Usually, a **session key** is required
  - I.e., a symmetric key for a particular session
  - Used for confidentiality and/or integrity
- How to authenticate and establish a session key (i.e., shared symmetric key)?
  - When authentication completed, want Alice and Bob to share a session key
  - Trudy cannot break the authentication…
  - …and Trudy cannot determine the session key

Authentication & Session Key

Alice

"I'm Alice", R $\rightarrow$

$\leftarrow$ $\{R,K\}_{\text{Alice}}$

$\{R+1,K\}_{\text{Bob}}$ $\rightarrow$

Bob

- Is this secure?
  - Alice is authenticated and session key is secure
  - Alice's "nonce", R, useless to authenticate Bob
  - The key K is acting as Bob's nonce to Alice
- No mutual authentication

Public Key Authentication and Session Key

Alice

"I'm Alice", R

$[R,K]_{Bob}$

$[R+1,K]_{Alice}$

Bob

- Is this secure?
  - Mutual authentication (good), but…
  - … session key is not secret (very bad)

Public Key Authentication and Session Key

Alice

"I'm Alice", R $\rightarrow$

$\leftarrow$ $\{[R,K]_{Bob}\}_{Alice}$

$\{[R+1,K]_{Alice}\}_{Bob}$ $\rightarrow$

Bob

- Is this secure?
- Seems to be OK
- Mutual authentication and session key!

Public Key Authentication and Session Key

Alice

“I’m Alice”, R

$[\{R,K\}_{Alice}]_{Bob}$

$[\{R+1,K\}_{Bob}]_{Alice}$

Bob

- Is this secure?
- Seems to be OK
  - Anyone can see $\{R,K\}_{Alice}$ and $\{R+1,K\}_{Bob}$

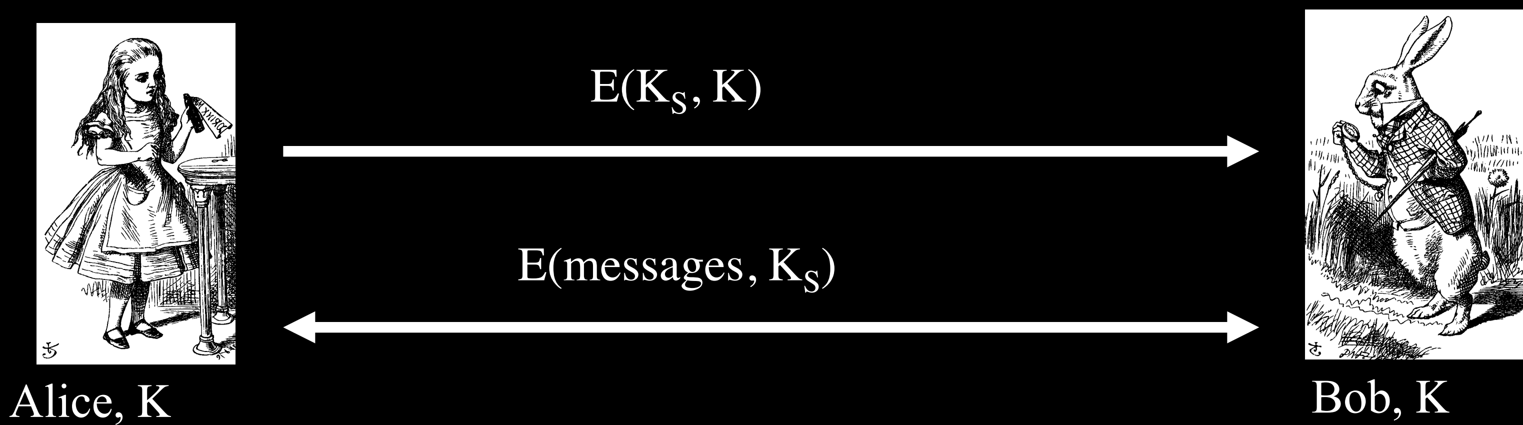
Perfect Forward Secrecy

- Consider this “issue”…
  - Alice encrypts message with shared key K and sends ciphertext to Bob
  - Trudy records ciphertext and later attacks Alice’s (or Bob’s) computer to recover K
  - Then Trudy decrypts recorded messages
- **Perfect forward secrecy (PFS):** Trudy cannot later decrypt recorded ciphertext
  - Even if Trudy gets key K or other secret(s)
- Is PFS possible?

Perfect Forward Secrecy

- Suppose Alice and Bob share key K
- For perfect forward secrecy, Alice and Bob cannot use K to encrypt
- Instead they must use a session key K_S and forget it after it's used
- Can Alice and Bob agree on session key K_S in a way that ensures PFS?

Naïve Session Key Protocol



- Trudy could record $E(K_S, K)$
- If Trudy later gets K then she can get K_S
  - Then Trudy can decrypt recorded messages

Perfect Forward Secrecy

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

g^a mod p →

← g^b mod p

Alice, a

Bob, b

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

Perfect Forward Secrecy

$\xrightarrow{E(g^a \bmod p, K)}$

$\xleftarrow{E(g^b \bmod p, K)}$

Alice: K, a

Bob: K, b

- Session key $K_S = g^{ab} \bmod p$
- Alice **forgets** a, Bob **forgets** b
- So-called **Ephemeral Diffie-Hellman**
- Neither Alice nor Bob can later recover K_S
- Are there other ways to achieve PFS?

Mutual Authentication, Session Key and PFS

Alice

“I’m Alice”, R_A →

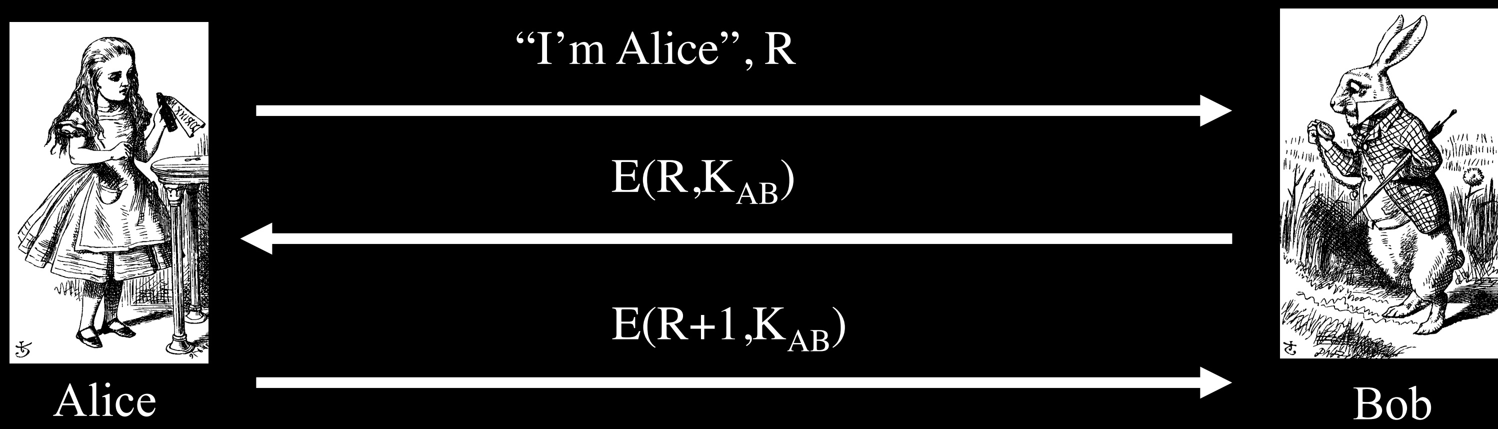
← R_B, $[\{R_A, g^b \bmod p\}_{Alice}]_{Bob}$

$[\{R_B, g^a \bmod p\}_{Bob}]_{Alice}$ →

Bob

- Session key is $K = g^{ab} \bmod p$
- Alice forgets a and Bob forgets b
- If Trudy later gets Bob’s and Alice’s secrets, she cannot recover session key K

Protocol Lab

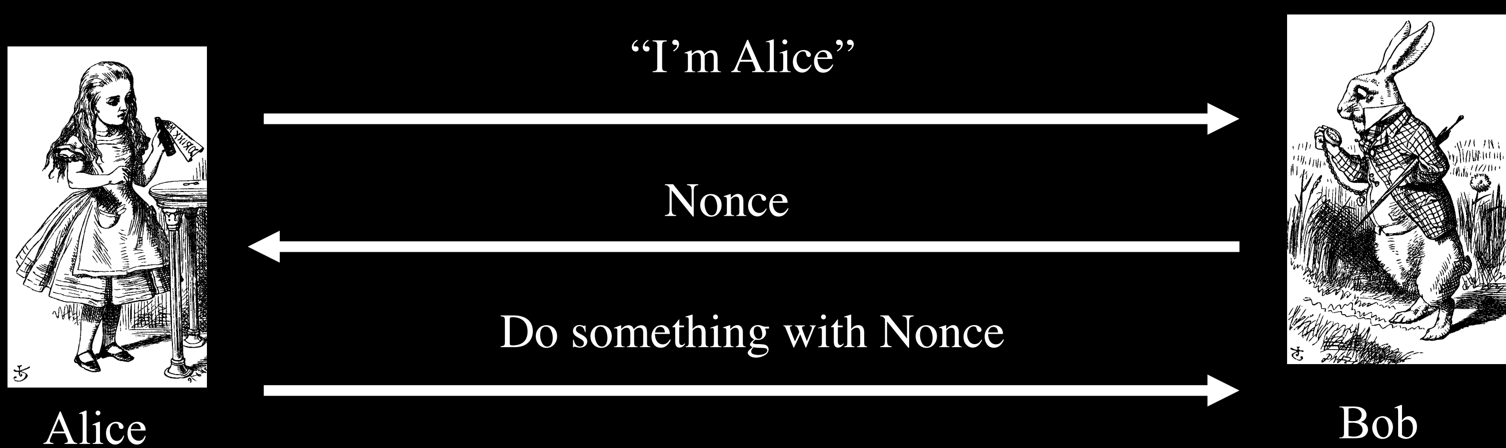


Note that K_{AB} is a shared symmetric key used only for mutual authentication.

1. Find 2 attacks Trudy can use to convince Bob that she is really Alice.
2. Fix this protocol so that it is secure.

Reducing the Number of Messages

Out protocols so far use *nonces* as a challenge. Unfortunately, that requires 3 messages.



Can we do the same thing in one message?

Timestamps instead of nonces

Timestamps can be used instead of nonces.

- Alice sends the time she performed her calculation and Bob accepts if within the *clock skew.*

- The good: we reduce the number of messages.
- The bad: time is now a security-critical property

Clock Skew

- Clocks are never exactly synchronized.
  - We must accept "about the same time"
- How much clock skew is enough?
  - Too much, Trudy can do a replay.
  - Too little, the protocol will be unusable.

Timestamp Example, High Level

Alice

I’m Alice, T, do something with T

Bob

1. Alice gets the time T and performs her calculations
2. Alice sends her message along with the timestamp T
3. Bob checks the time and verifies it is within the skew
4. If so, Bob verifies Alice's calculations

Public Key Authentication with Timestamp T

Alice

“I’m Alice”, $\{[T, K]_{Alice}\}_{Bob}$ →

← $\{[T+1, K]_{Bob}\}_{Alice}$

Bob

- Secure mutual authentication?
- Session key?
- Seems to be OK

Public Key Authentication with Timestamp T

Alice

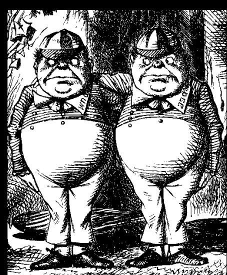
“I’m Alice”, $[\{T, K\}_{Bob}]_{Alice}$

$[\{T+1, K\}_{Alice}]_{Bob}$

Bob

- Secure authentication and session key?
- Trudy can use Alice’s public key to find $\{T, K\}_{Bob}$ and then…

Public Key Authentication with Timestamp T



Trudy

“I’m Trudy”, $[\{T, K\}_{Bob}]_{Trudy}$

$[\{T+1, K\}_{Trudy}]_{Bob}$

Bob

- Trudy obtains Alice-Bob session key K
- Note: Trudy must act within clock skew

Public Key Authentication

- Sign and encrypt with nonce…
  - **Secure**
- Encrypt and sign with nonce…
  - **Secure**
- Sign and encrypt with timestamp…
  - **Secure**
- Encrypt and sign with timestamp…
  - **Insecure**
- Protocols can be subtle!

Public Key Authentication with Timestamp T

Alice

“I’m Alice”, $[\{T, K\}_{Bob}]_{Alice}$ $\longrightarrow$

$\longleftarrow$ $[\{T + 1\}_{Alice}]_{Bob}$

Bob

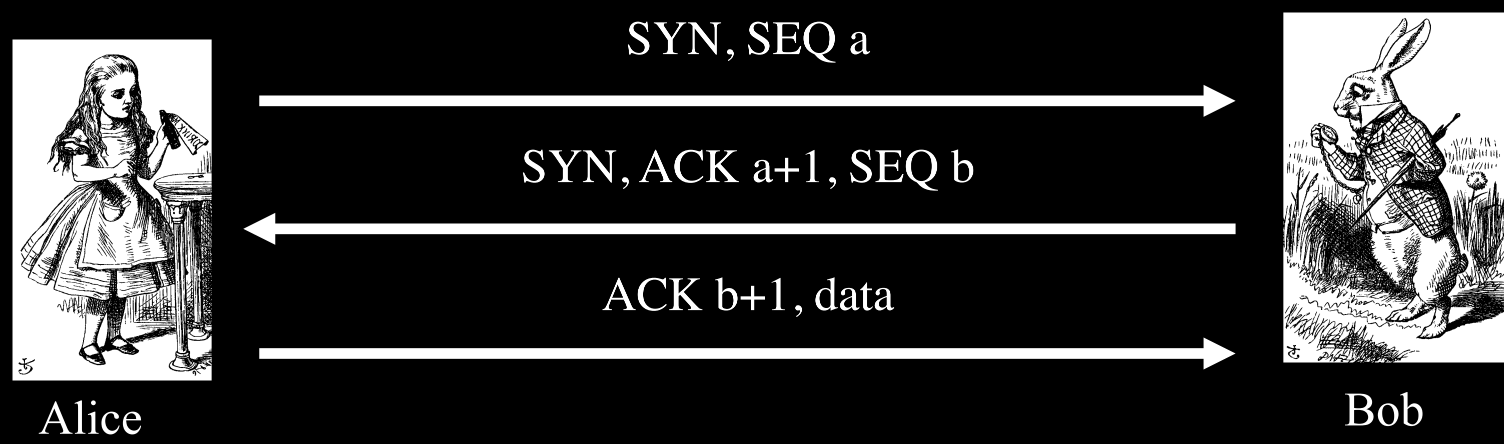
- Is this “encrypt and sign” secure?
  - Yes, seems to be OK
- Does “sign and encrypt” also work here?

Authentication and TCP

TCP-based Authentication

- TCP not intended for use as an authentication protocol
- But IP address in TCP connection often used for authentication
- One mode of IPSec relies on IP address for authentication

TCP 3-way Handshake

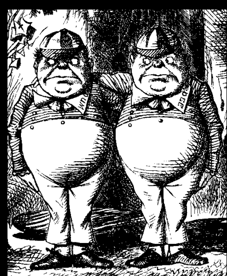


- Recall the TCP three way handshake
- Initial sequence numbers: SEQ a and SEQ b
  - Supposed to be selected at random
- If not…

TCP Authentication Attack

1. SYN, SEQ = t (as Trudy)

2. SYN, ACK = t+1, SEQ = b_1



Trudy

Bob

⋮

3. SYN, SEQ = t (as Alice)

5. ACK = b_2+1, data

4. SYN, ACK = t+1, SEQ = b_2

5.

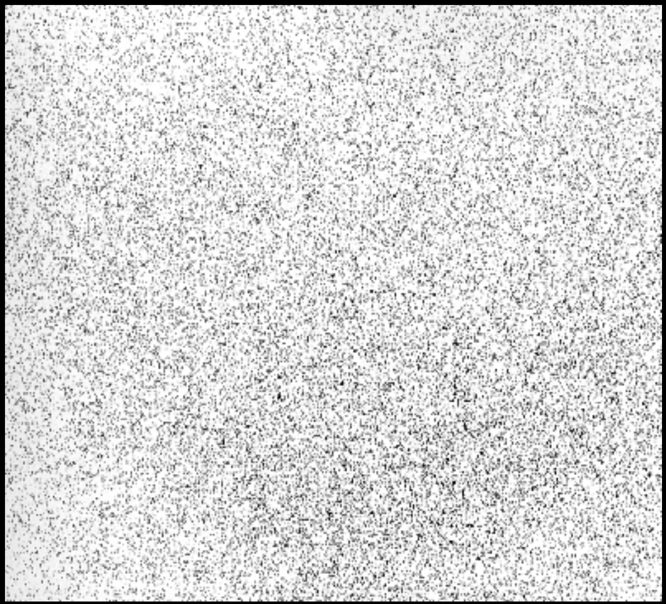
5.

5.

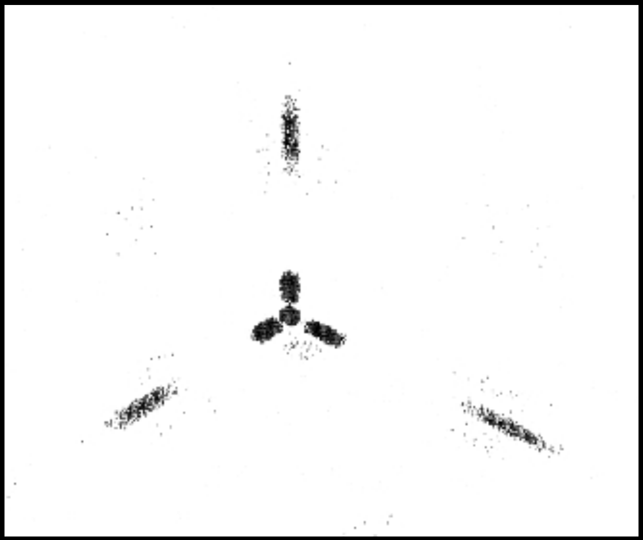
5.

Alice

TCP Authentication Attack



Random SEQ numbers



Initial SEQ numbers
Mac OS X

- If initial SEQ numbers not very random…
- …possible to guess initial SEQ number…
- …and previous attack will succeed

TCP Authentication Attack

- Trudy cannot see what Bob sends, but she can send packets to Bob, while posing as **Alice**
- Trudy must prevent Alice from receiving Bob's packets (or else connection will terminate)
- If **password** (or other authentication) required, this attack fails
- If TCP connection is relied on for authentication, then attack can succeed
- **Bad idea to rely on TCP for authentication**

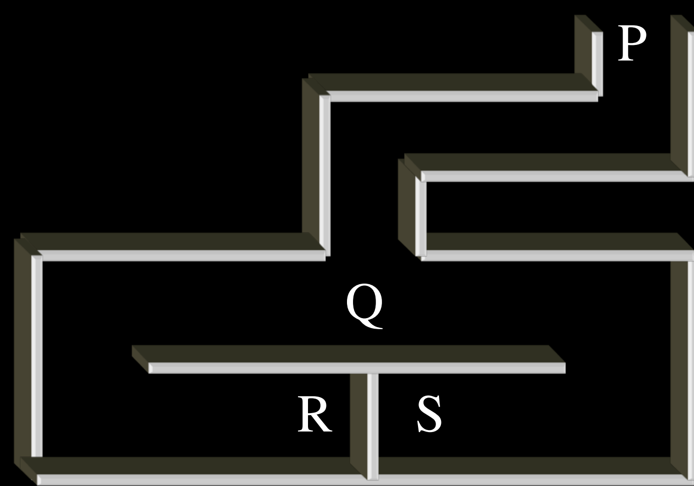
Zero Knowledge Proofs

Zero Knowledge Proof (ZKP)

- Alice wants to prove that she knows a secret without revealing **any** info about it
- Bob must verify that Alice knows secret
  - But, Bob gains no info about the secret
- Process is probabilistic
  - Bob can verify that Alice knows the secret to an arbitrarily high probability
- An "interactive proof system"

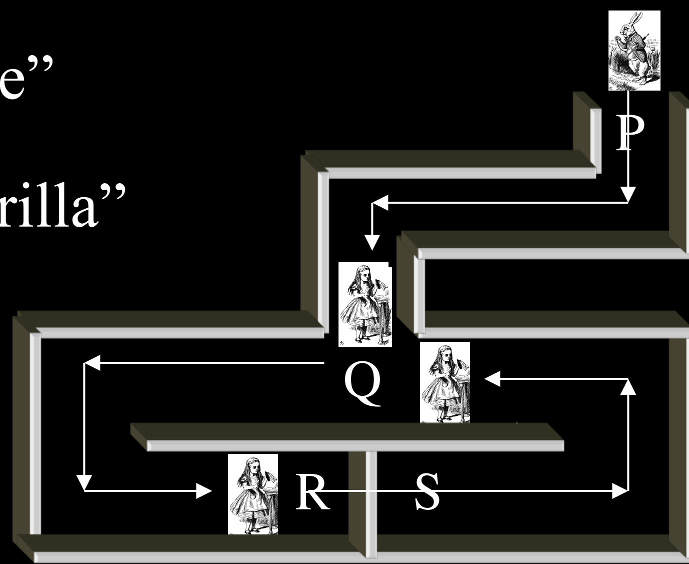
Bob's Cave

- Alice knows secret phrase to open path between R and S ("open sarsaparilla")
- Can she convince Bob that she knows the secret without revealing phrase?



Bob’s Cave

- Bob: “Alice come out on S side”
- Alice (quietly): “Open sarsaparilla”
- If Alice does not know the secret…
- …then Alice could come out from the correct side with probability 1/2
- If Bob repeats this n times, then Alice (who does not know secret) can only fool Bob with probability $1/2^n$



Fiat-Shamir Protocol

- Cave-based protocols are inconvenient
  - Can we achieve same effect without the cave?
- Finding square roots modulo N is difficult
  - Equivalent to factoring
- Suppose N = pq, where p and q prime
- Alice has a secret S
- N and $v = S^2 \bmod N$ are **public**, S is **secret**
- Alice must convince Bob that she knows S without revealing any information about S

Fiat-Shamir

Alice
secret S
random r

$x = r^2 \bmod N$ →

← $e \in \{0,1\}$

$y = r \cdot S^e \bmod N$ →

Bob
random e

$$N \text{ and } v = S^2 \bmod N$$

- Alice selects random r, Bob chooses $e \in \{0,1\}$
- Bob verifies: $\mathbf{y^2 = x \cdot v^e \bmod N}$
  - Why? Because… $y^2 = r^2 \cdot S^{2e} = r^2 \cdot (S^2)^e = x \cdot v^e \bmod N$

Fiat-Shamir: e = 1

Alice
secret S
random r

$x = r^2 \bmod N$ →

← $e = 1$

$y = r \cdot S \bmod N$ →

Bob
random e

N and $v = S^2 \bmod N$

- Alice selects random r, Bob chooses e =1
- If $y^2 = x \cdot v \bmod N$ then Bob accepts it
  - I.e., "Alice" passes this iteration of the protocol
- Note that Alice must know S in this case

Fiat-Shamir: $e = 0$

$x = r^2 \bmod N$

$e = 0$

$y = r \bmod N$

Alice
secret S
random r

Bob
random e

to know S in this case!

Fiat-Shamir

- **Public:** modulus N and $v = S^2 \bmod N$
- **Secret:** Alice knows S
- Alice selects random r and **commits** to r by sending $x = r^2 \bmod N$ to Bob
- Bob sends **challenge** $e \in \{0,1\}$ to Alice
- Alice **responds** with $y = r \cdot S^e \bmod N$
- Bob checks whether $y^2 = x \cdot v^e \bmod N$
  - Does this prove response is from Alice?

Does Fiat-Shamir Work?

- If everyone follows protocol, math works:
  - Public: $v = S^2 \bmod N$
  - Alice to Bob: $x = r^2 \bmod N$ and $y = r \cdot S^e \bmod N$
  - Bob verifies: $y^2 = x \cdot v^e \bmod N$
- Can Trudy convince Bob she is Alice?
  - If Trudy expects $e = 0$, she sends $x = r^2$ in msg 1 and $y = r$ in msg 3 (i.e., follow the protocol)
  - If Trudy expects $e = 1$, sends $x = r^2 \cdot v^{-1}$ in msg 1 and $y = r$ in msg 3
- If Bob chooses $e \in \{0,1\}$ at random, Trudy can only trick Bob with probability 1/2

Fiat-Shamir Facts

- Trudy can trick Bob with probability 1/2, but…
  - …after n iterations, the probability that Trudy can convince Bob that she is Alice is only $1/2^n$
  - Just like Bob's cave!
- Bob's $e \in \{0,1\}$ must be unpredictable
- Alice must use new r each iteration, or else…
  - If $e = 0$, Alice sends $r \bmod N$ in message 3
  - If $e = 1$, Alice sends $r \cdot S \bmod N$ in message 3
  - Anyone can find S given $r \bmod N$ and $r \cdot S \bmod N$

Fiat-Shamir Zero Knowledge?

- Zero knowledge means that nobody learns ***anything*** about the secret S
  - **Public:** $v = S^2 \bmod N$
  - Trudy sees $r^2 \bmod N$ in message 1
  - Trudy sees $r \cdot S \bmod N$ in message 3 (if $e = 1$)
- If Trudy can find r from $r^2 \bmod N$, gets S
  - But that requires modular square root
  - If Trudy could find modular square roots, she could get S from **public** v
- Protocol does not seem to "help" to find S

ZKP in the Real World

- Public key certificates identify users
  - No anonymity if certificates sent in plaintext
- ZKP offers a way to authenticate without revealing identities
- ZKP supported in MS's Next Generation Secure Computing Base (NGSCB), where…
  - …ZKP used to authenticate software "without revealing machine identifying data"
- ZKP is **not** just pointless mathematics!

Best Authentication Protocol?

- It depends on…
  - The sensitivity of the application/data
  - The delay that is tolerable
  - The cost (computation) that is tolerable
  - What crypto is supported (public key, symmetric key, …)
  - Whether mutual authentication is required
  - Whether PFS, anonymity, etc., are concern
- …and possibly other factors