Cryptanalysis

Protocols and Random Numbers

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Random Numbers

- Critical in Cryptographic Algorithms
- No single test
  - Unpredictability
  - Statistical Tests
- Random Number weaknesses and Key management are greatest points of attack for otherwise “safe” cryptosystem.
- Can’t generate enough Random bits so use Pseudo Random Number Generators

- Reference
  - J. Kelsey, B. Schneier, D. Wagner, and C. Hall, *“Cryptanalytic Attacks on Pseudorandom Number Generators”*, Fast Software Encryption, Fifth International Workshop Proceedings (March 1998), Springer-Verlag, 1998, pp. 168-188.

Random Numbers

- Requirements
- Attacks
- Entropy
- Mixing
- PRNG
- 800-90

Cryptographic Random Numbers

- Requirements
  - $Pr([x_1,x_2,\ldots,x_n]= [a_1,a_2,\ldots,a_n])=2^{-n}$. $Pr([x_1,x_2,\ldots,x_n]=$
  - $H(\mathbf{x}=[x_1,x_2,\ldots,x_n])= n$
  - $Pr([x_1,x_2,\ldots,x_n]= [a_1,a_2,\ldots,a_n])= Pr(x_1=a_1)\cdot Pr(x_2=a_2) \cdot\ldots\cdot Pr(x_n=a_{n\cdot})$
  - $Pr([x_1,x_2,\ldots,x_n] | [,x_2,\ldots,x_n])=Pr(x_1)$
  - Guessing values at random with equal probability is as well as you can do

- Failure tests
  - Frequency tests
  - Hidden Markov modeling

Remember: H for the key distributions

- Distribution A: H(X)= ¼ lg(4) + ¼ lg(4) + ¼ lg(4) +1/4 lg(4) = 2 bits
- Distribution B: H(X)= 16x(1/16) lg(16)= 4 bits
- Distribution C: H(X)= 2^nx(1/2^n) lg(2^n) = n bits
  - Expected time for key search is ~ 2^n.

- Distribution A': H(X) = ½ lg(2) + 3 x(1/6 lg(6))= 1.79 bits
- Distribution B': H(X) = ½ lg(2) + 15 x(1/30 lg(30))= 2.95 bits
- Distribution C': H(X) = ½ lg(2) + ½(2^n-1)x(1/(2^n-1) lg(2^n-1))= n/2+1 bits
  - Expected time for key search is ~ $2^{n/2}$+1.

Sources of Entropy

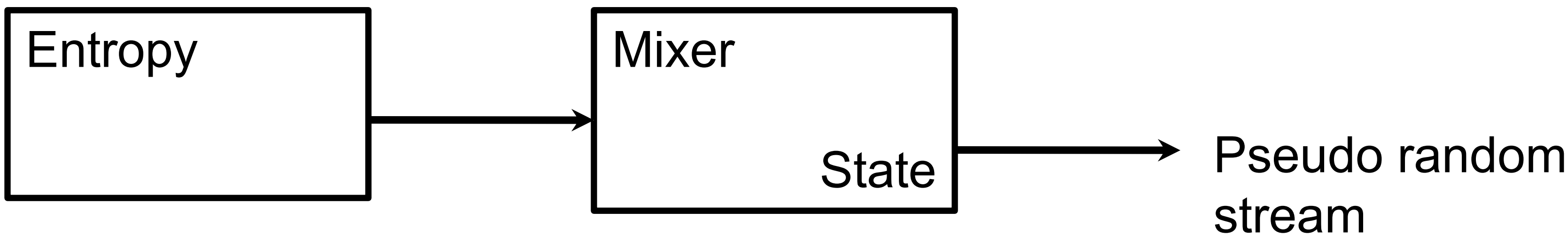
- Coin Tosses
- Radioactive decay
- Typing Speed
- Thermal noise
- Ring Oscillator
- Lava Lamps
- Noisy diode
- Disk arm speed variation

- Process id, thread id
- Drift between clock and timer interrupts
- Ticks since boot
- Memory stats
- Disk Free
- Cursor
- Counters
- Execution time (Jitter)

Some entropy source calculations

- Fair coin toss:
  - Each coin toss adds 1 bit of entropy
- Biased (but independent) coin tosses
  - Pr(x=1)= 1/4, Pr(x=0)= 3/4.
  - Entropy: -1/4 lg(1/4)-3/4 lg(3/4)= 1/2 + 1/4 lg(3) ≈ .85 bit
- If John wears red shoes, x_i=1 otherwise x_i=0. $x_{i+1}=x_i \oplus 1$
  - Even if John wears red shoes randomly with p=1/2, every 2n bits only have n bits of entropy.
  - Calculate entropy with a different "wear red shoes" distribution"

Pseudo random number generation



- Smooth and stretch entropy
- Must first estimate entropy input and maintain sufficient entropy
- Idea is to generate n bit key state should maintain n bits of entropy

Pseudo-Random Generators (PRNGs)

- "Anyone discussing deterministic generation of random number is, strictly speaking, already in a state of sin" – von Neuman.
- Output of pseudo-random number generators must produce output that looks random
  - Start with a fixed state S and collect inputs with high entropy
- Generators can be built using
  - Block ciphers
  - Hash functions
  - Stream Cipher

Guidelines for PRNG

- Base the PRNG on something strong.
- Make sure the whole PRNG state changes over time..
- Do “catastrophic reseeding” of the PRNG.
- Resist backtracking.
- Resist Chosen-Input Attacks.
- Recover from Compromises Quickly
- Use a hash function to protect vulnerable PRNG outputs and entropy mixing.
- Hash PRNG inputs with a counter or timestamp before use.
- Occasionally generate a new starting PRNG state.

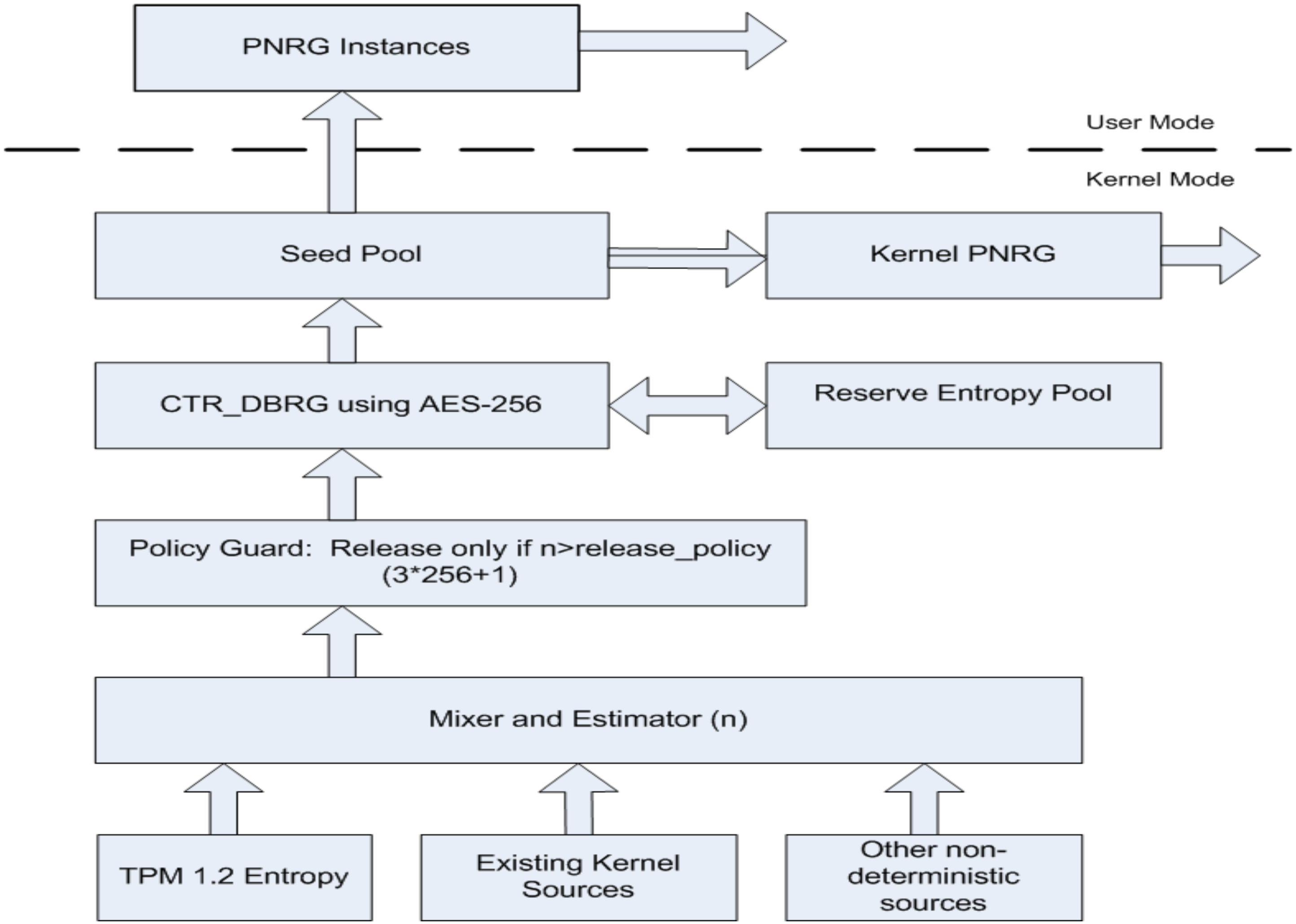
RNG Attacks

- Direct Cryptanalytic attack
- Entropy Input Guessing
- Input-based attack
  - Known input
  - Replayed input
  - Chosen input
- State compromise extension attacks
  - Backtracking attacks (forward immunity)
  - Permanent compromise attacks (backward immunity)
  - Iterative guessing attacks
  - Meet-in-the-middle attacks
- Oversampling

Popular PRNGs

- FIPS 186
  - t, c 160 bits
  - H= t_1 || t_2 || … || t_5
  - Pad c with 0s to get 512 bit giving M
  - Apply SHA-1 step
- ANSI 9.17
  - I= $E_k(D)$. D= timestamp.
  - $x_i = E_k(I \oplus s)$, s= State
  - $s = E_k(x_i \oplus s)$
- Current NIST 800-90
  - HASH-256
  - CTR-AES-256
  - Dual Elliptic Curve

Sample 800-90 RNG System



HASH-256

Initiate

1. seed_material = entropy_input || nonce || personalization_string.
2. seed = Hash_df (seed_material, seedlen).
3. V = seed.
4. C = Hash_df ((0x00 || V), seedlen).
5. reseed_counter = 1.
6. Return V, C, and reseed_counter as initial_working_state.

HASH-256

Generate

1. If reseed_counter > reseed_interval, then return reseed required.
2. If (additional_input != Null), then do

   w = Hash (0x02 || V || additional_input).

   V = (V+w) mod $2^{seedlen}$.

1. (returned_bits) = Hashgen (requested_number_of_bits, V).
2. H = Hash(0x03 || V).
3. V = (V+H+C+reseed_counter) mod $2^{seedlen}$.
4. reseed_counter= reseed_counter+1.
5. Return SUCCESS, returned_bits, and the new values of V, C, and reseed_counter for the new_working_state.

HASH-256

Hash_df

1. temp = the Null string.
2. len =no_of _bits_to_return/outlen
3. counter = 8-bit binary value representing 1.
4. for i = 1 to len do

   temp= temp||Hash(counter||no_of_bits_to_return||input_string).

   counter= counter+1.
5. requested_bits= Leftmost (no_of_bits_to_return) of temp.
6. Return SUCCESS and requested_bits.

HASH-256

Hashgen

1. m =requested_no_of _bits⍰/outlen
2. data = V.
3. W = the Null string.
4. For i = 1 to m

   w_i = Hash (data).

   W = W || w_i.

   data = (data + 1) mod $2^{seedlen}$.
5. returned_bits = Leftmost (requested_no_of_bits) bits of W.
6. Return returned_bits.

CTR-AES-256

Initiate

1. *temp*= len (*personalization_string*).
2. If (*temp*<*seedlen*), then

   personalization_string= *personalization_string* $||0^{seedlen - temp}$.
3. *seed_material* = *entropy_input* $\oplus$ *personalization_string*
4. *Key* = 0^{keylen}.
5. *V* = 0^{outlen}.
6. (*Key*, *V*)= CTR_DRBG_Update(*seed_material*, *Key*, *V*).
7. *reseed_counter*= 1.
8. Return *V*, *Key*, and *reseed_counter* as the *initial_working_state*.

CTR-AES-256

Generate

1. If *reseed_counter* > *reseed_interval*, then return reseed required.
2. If (*additional_input* ≠ *Null*), then

   temp = len (*additional_input*).

   If (*temp*<*seedlen*) then *additional_input*= *additional_input*||$0^{seedlen\ -\ temp}$.

   (*Key*, *V*) = CTR_DRBG_Update (*additional_input*, *Key*, *V*).
3. *temp*= *Null*.
4. While (len (*temp*) < *requested_number_of_bits*)

   V = (*V*+1) mod 2^{outlen}.

   output_block = Block_Encrypt(*Key*, V).

   temp = *temp* || *output_block*.
5. *returned_bits* = Leftmost *requested_number_of_bits* of *temp*.
6. (*Key*, *V*) = CTR_DRBG_Update(*additional_input*, *Key*, *V*).
7. *reseed_counter* = *reseed_counter* + 1.
8. Return SUCCESS and *returned_bits*; also return *Key*, *V*, and *reseed_counter*as the *new_working_state*.

CTR-AES-256

Update

1. *temp = Null.*
2. While(len (*temp*)<*seedlen*)

   $V = (V+1) \bmod 2^{outlen}$.

   output_block = Block_Encrypt(*Key*, *V*).

   temp = *temp* || *ouput_block*.
3. *temp = Leftmost seedlen bits of temp.*
4. *temp* = *temp* $\oplus$ *provided_data.*
5. *Key = Leftmost keylen bits of temp.*
6. *V = Rightmost outlen bits of temp.*
7. *Return the new values of Key and V.*

Preliminaries: Elliptic Curves

- Elliptic curves are the set of points (x,y) with coordinates in a field F that are solutions to an equation:

  $$y^2 = x^3 + ax + b$$

- These points (plus an identity) form a group.
- All of the curves that we will be discussing are over finite fields (characteristic p) and will have prime order q.

The Dual EC PRNG

- φ : prime curve $\rightarrow$ integers
  $\varphi\,(x,y) = x$
- P, Q points on the curve (per SP800-90)

$$
\begin{tikzcd}
 & & \varphi(r_i{*}P) \arrow[dll] & & & \\
s_{i+1} / s_i \arrow[rr] & & r_i \arrow[u] \arrow[r] & \varphi(r_i{*}Q) \arrow[r] & t_i \arrow[r] & \mathrm{LSB}_{\mathrm{bitlen}\text{-}16}(t_i)
\end{tikzcd}
$$

Equations:

$r_i = \varphi(s_i{*}P)$ $\qquad$ $t_i = \varphi(r_i{*}Q)$ $\qquad$ $s_{i+1} = \varphi(r_i{*}P)$

Protocols

Unless otherwise noted, remaining slides courtesy of Mark Stamp, SJSU
See: Information Security: Principles and Practice, Mark Stamp

Protocol

- Human protocols — the rules followed in human interactions
  - Example: Asking a question in class
- Networking protocols — rules followed in networked communication systems
  - Examples: HTTP, FTP, etc.
- Security protocol — the (communication) rules followed in a security application
  - Examples: SSL, IPSec, Kerberos, etc.

Protocols

- Protocol flaws can be very subtle
- Several well-known security protocols have serious flaws
  - Including IPSec, GSM and WEP
- Common to find implementation errors
  - Such as IE implementation of SSL
- Difficult to get protocols right…

Ideal Security Protocol

- Satisfies security requirements
  - Requirements must be precise
- Efficient
  - Minimize computational requirement — in particular, costly public key operations
  - Minimize delays/bandwidth
- Not fragile
  - Must work when attacker tries to break it
  - Works even if environment changes
- Easy to use and implement, flexible, etc.
- Very difficult to satisfy all of these!

Simple Security Protocols

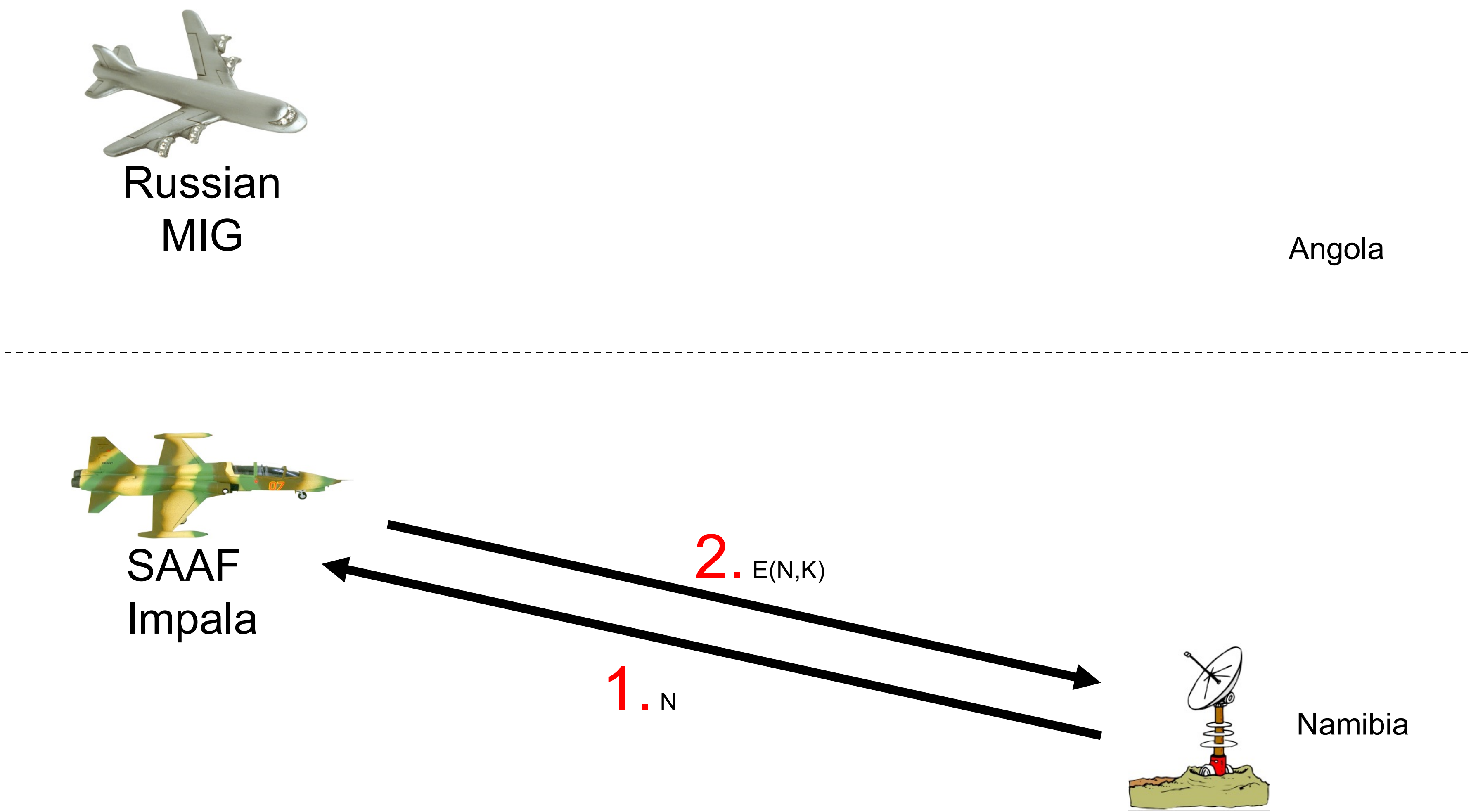
ATM Machine Protocol

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

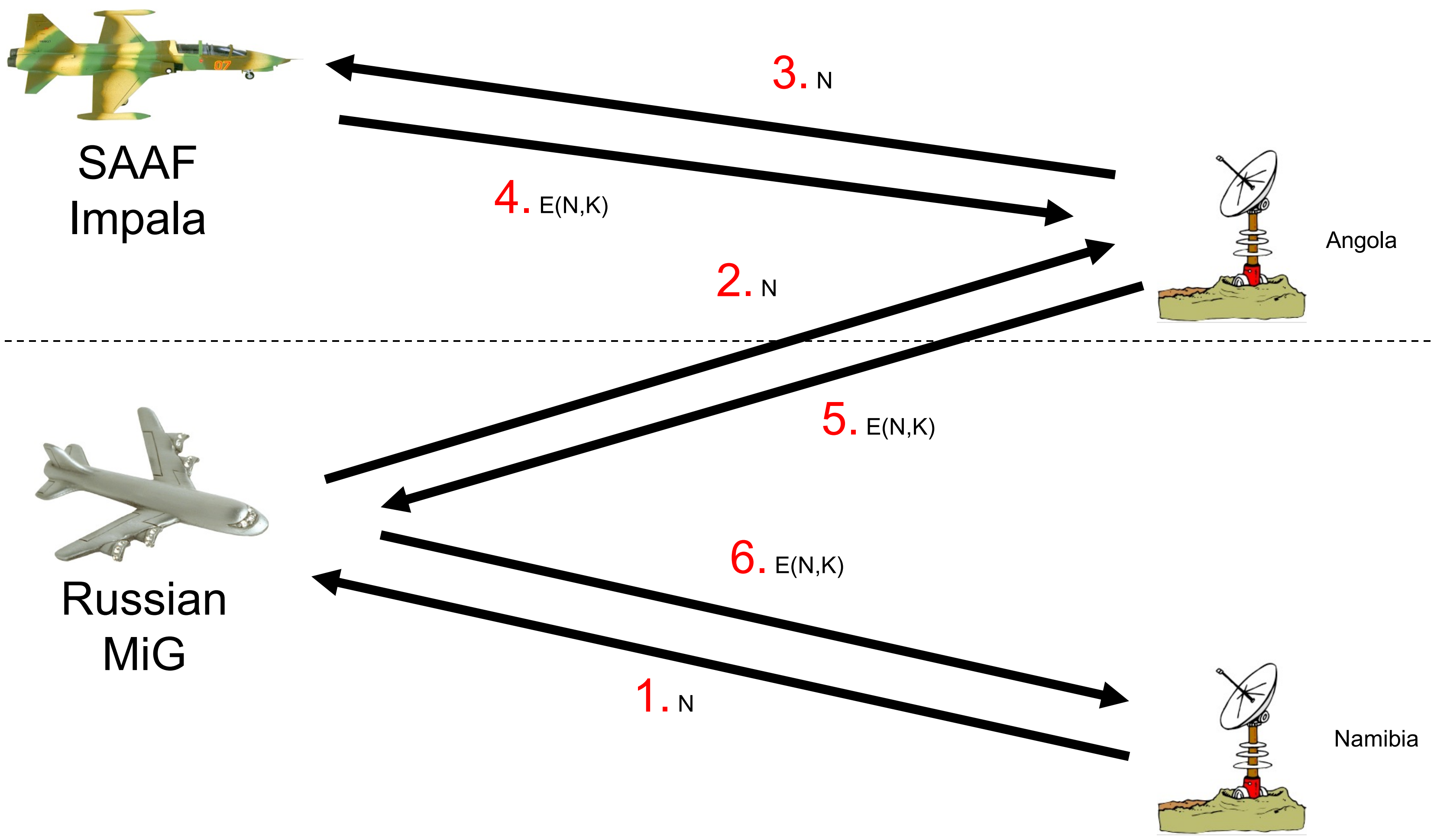
    Yes? Conduct your transaction(s)

    No? Machine eats card

Identify Friend or Foe (IFF)



MIG in the Middle



Authentication Protocols

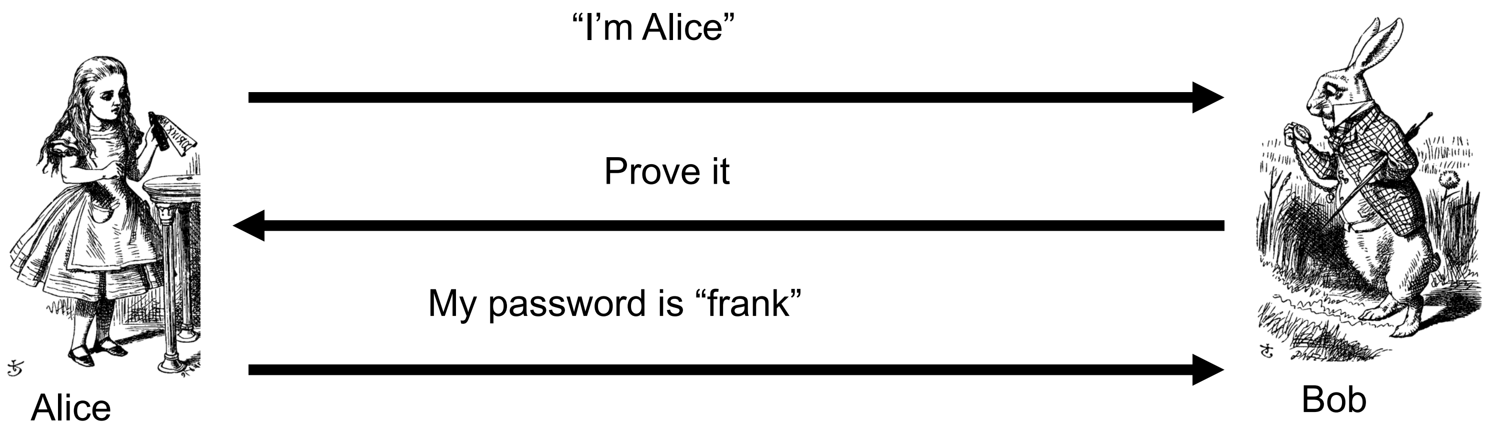
Authentication

- 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)
- 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.

Authentication

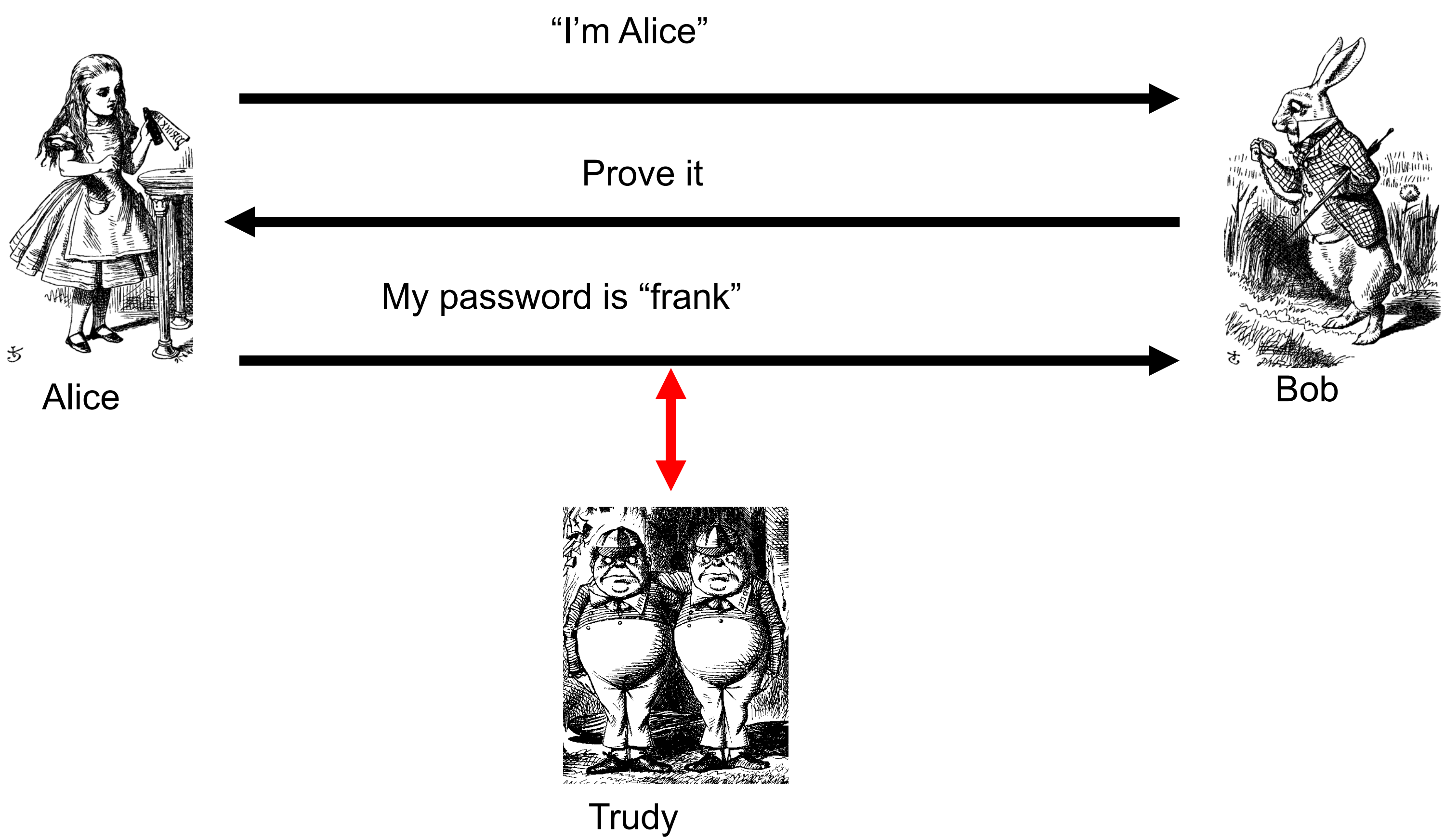
- Authentication on a stand-alone computer is relatively simple
  - "Secure path" is the primary issue
  - Main concern is an attack on authentication software (we discuss software attacks later)
- Authentication over a network is much more complex
  - Attacker can passively observe messages
  - Attacker 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

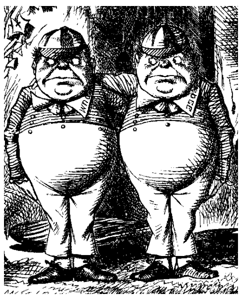


Authentication Attack

“I’m Alice”

Prove it

My password is “frank”



Trudy

Bob

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

Simple Authentication

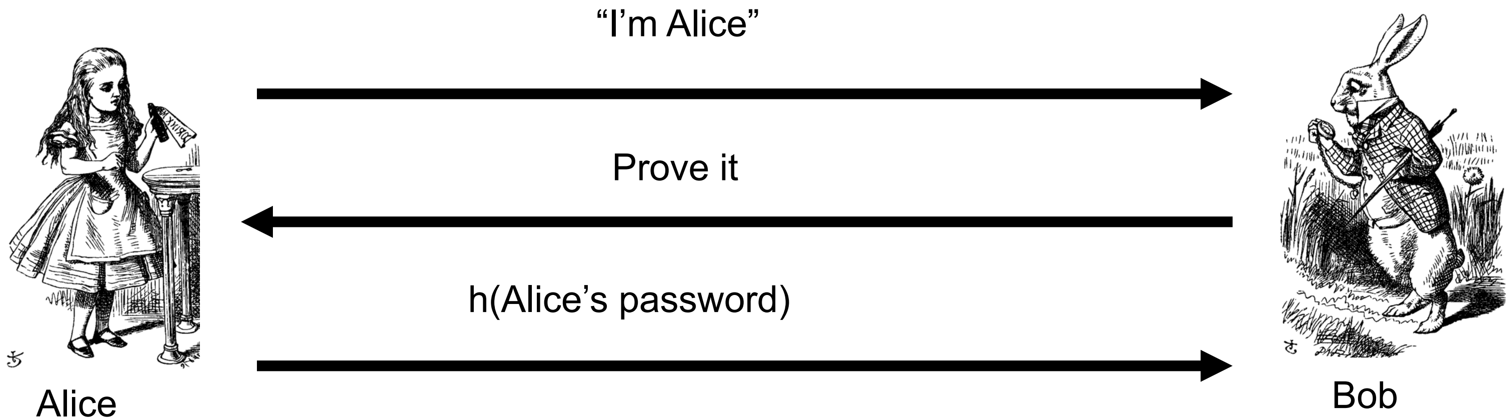
Alice

I’m Alice, My password is “frank”

Bob

- More efficient…
- But same problem as previous version

Better Authentication

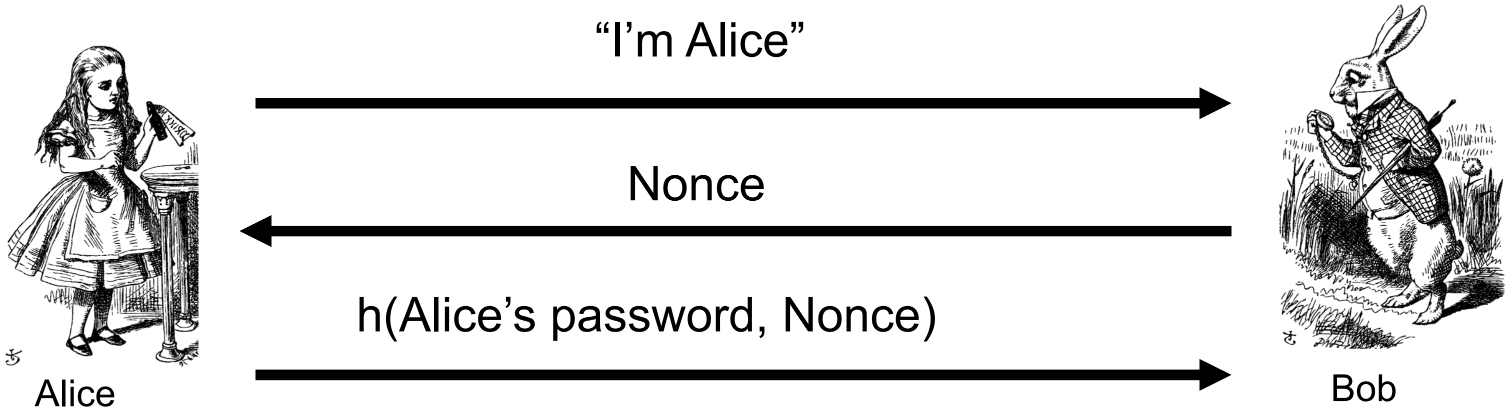


- Better since it hides Alice's password
  - From both Bob and attackers
- But still subject to replay

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**

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

Challenge-Response

“I’m Alice”

Nonce

Something that could only be

from Alice (and Bob can verify)

Alice

Bob

- What can we use to achieve this?
- Hashed passwords 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

Symmetric Key Authentication

- 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

Alice, K_{AB}

“I’m Alice” →

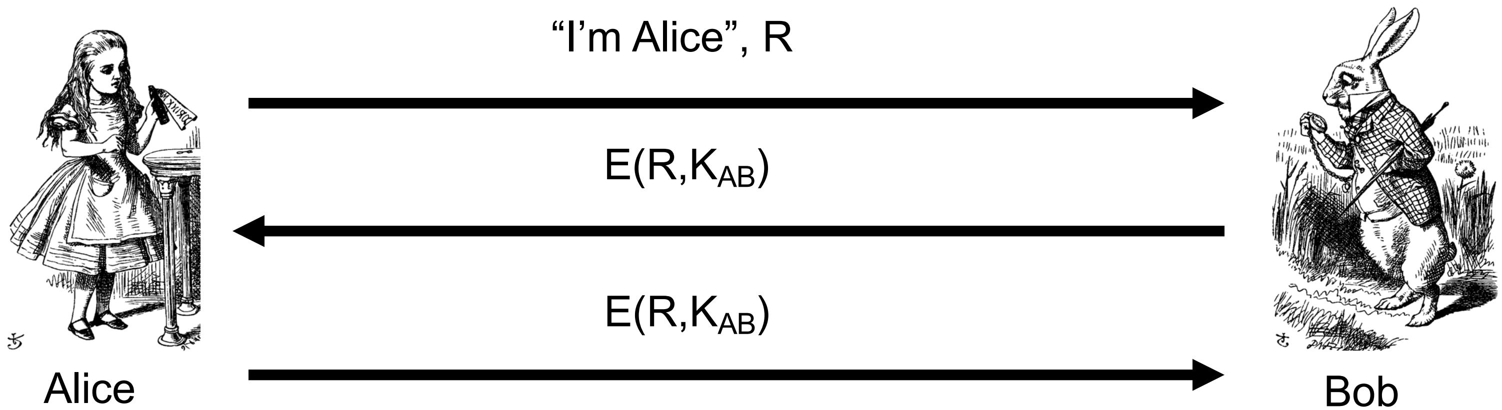
R ←

$E(R, K_{AB})$ →

Bob, K_{AB}

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

Mutual Authentication?

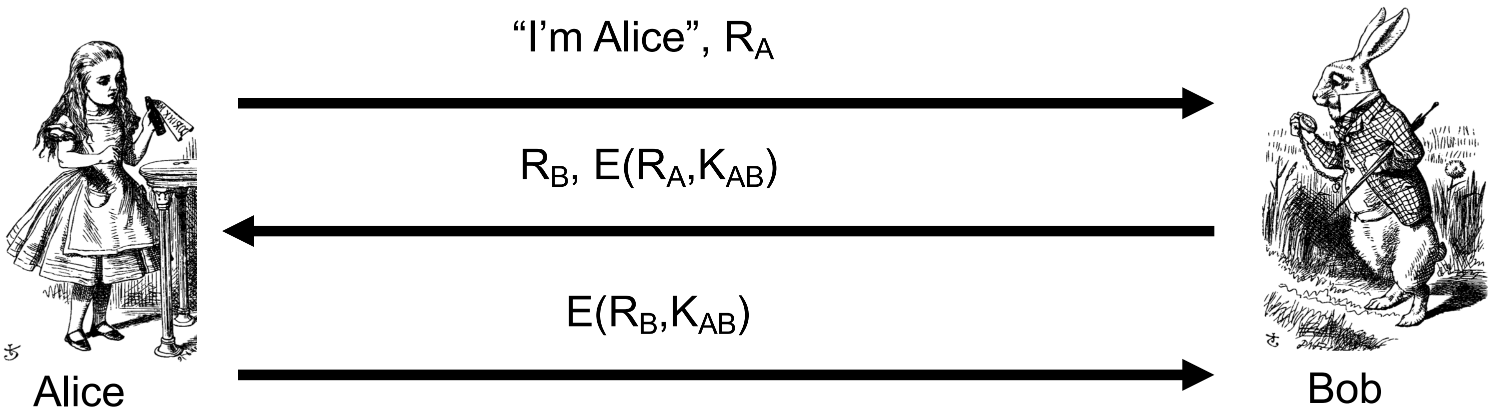


- What's wrong with this picture?
- "Alice" could be Trudy (or anybody else)!

Mutual Authentication

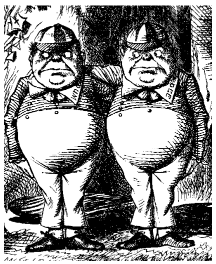
- Since we have a secure one-way authentication protocol…
- The obvious thing to do is to use the protocol twice
  - Once for Bob to authenticate Alice
  - Once for Alice to authenticate Bob
- This has to work…

Mutual Authentication



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

Mutual Authentication Attack



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

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

Symmetric Key Mutual Authentication

Alice

"I'm Alice", R_A

R_B, E("Bob",R_A,K_{AB})

E("Alice",R_B,K_{AB})

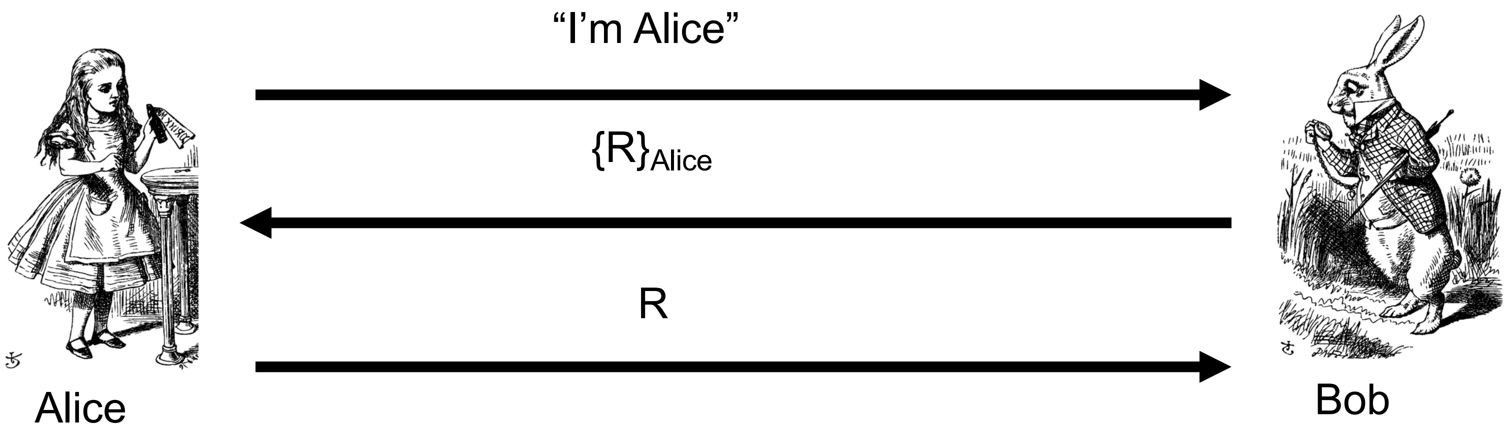
Bob

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

Public Key Notation

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

Public Key Authentication



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

Public Key Authentication

- Is this secure?
- Trudy can get Alice to sign anything!
  - Must have two key pairs

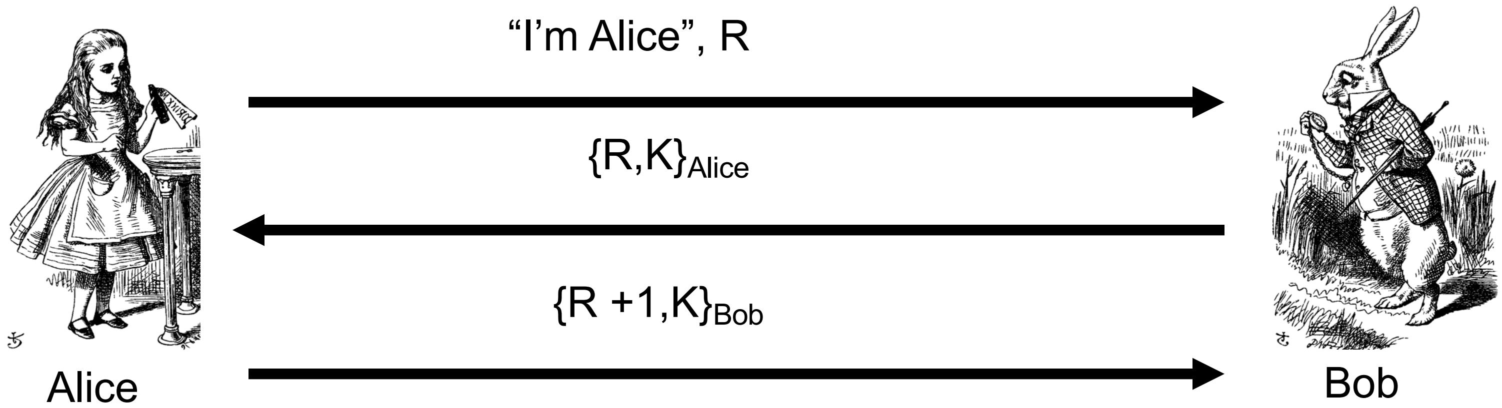
Public Keys

- Never use the same key pair for encryption and signing
- One key pair for encryption/decryption
- A different key pair for signing/verifying signatures

Session Key

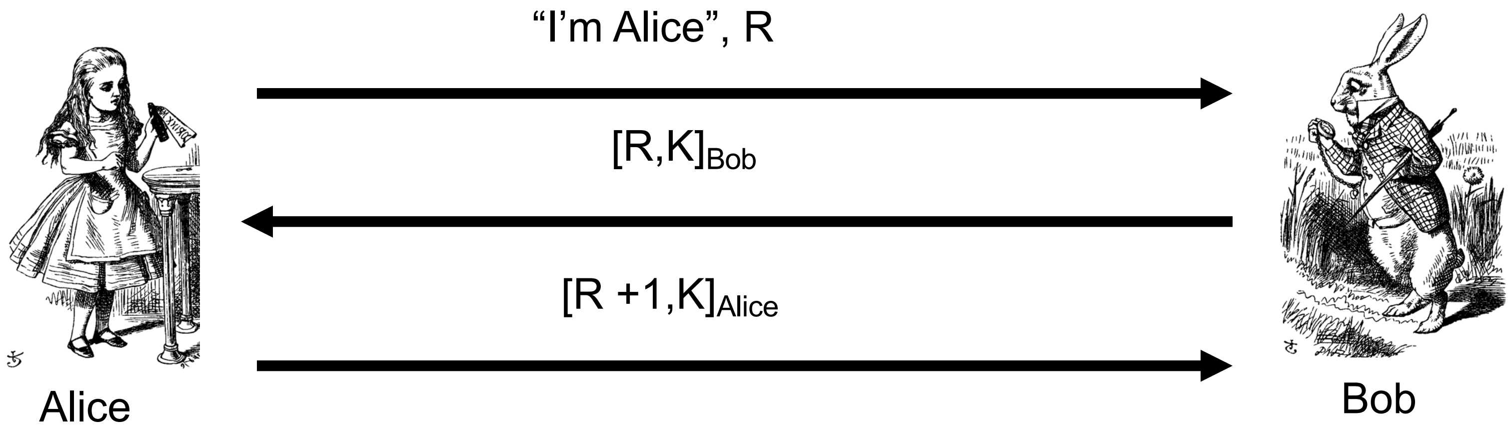
- Usually, a session key is required
  - Symmetric key for a particular session
- Can we authenticate and establish a shared symmetric key?
  - Key can be used for confidentiality
  - Key can be used for integrity
- In some cases, we may also require perfect forward secrecy (PFS)
  - Discussed later…

Authentication & Session Key



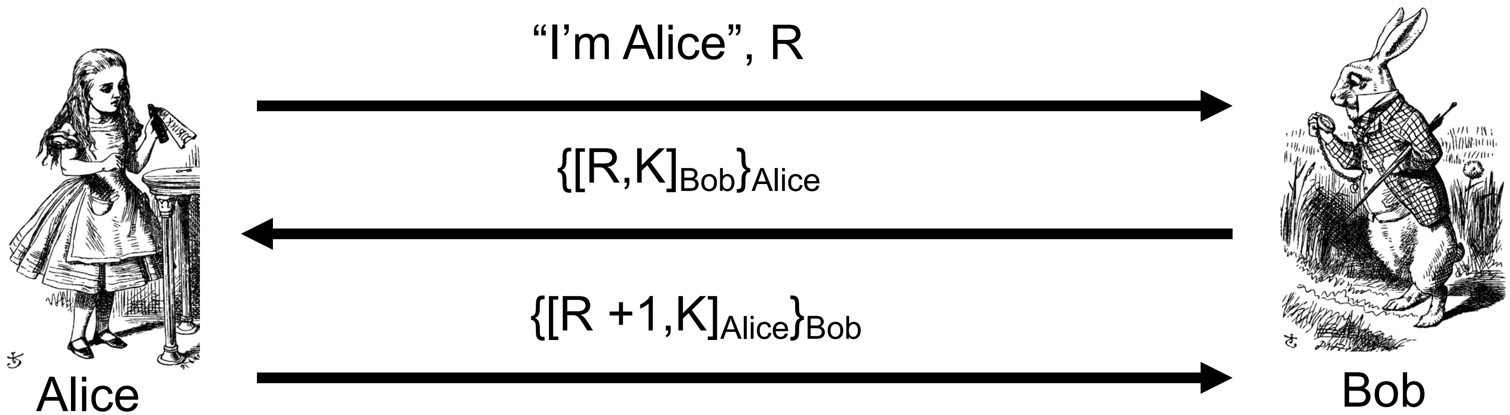
- Is this secure?
- OK for key, but no mutual authentication
- **Note** that K is acting as Bob's nonce

Public Key Authentication and Session Key



- Is this secure?
- Mutual authentication but key is not secret!

Public Key Authentication and Session Key



- 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 $\{R+1,K\}_{Bob}$

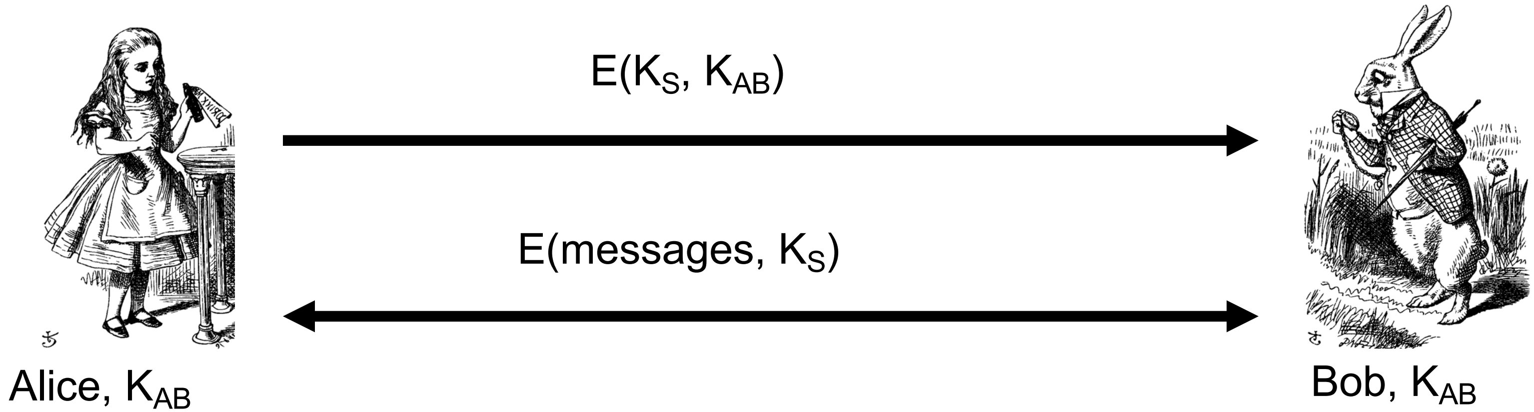
Perfect Forward Secrecy

- 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

- Suppose Alice and Bob share key K_{AB}
- 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 ensure PFS?

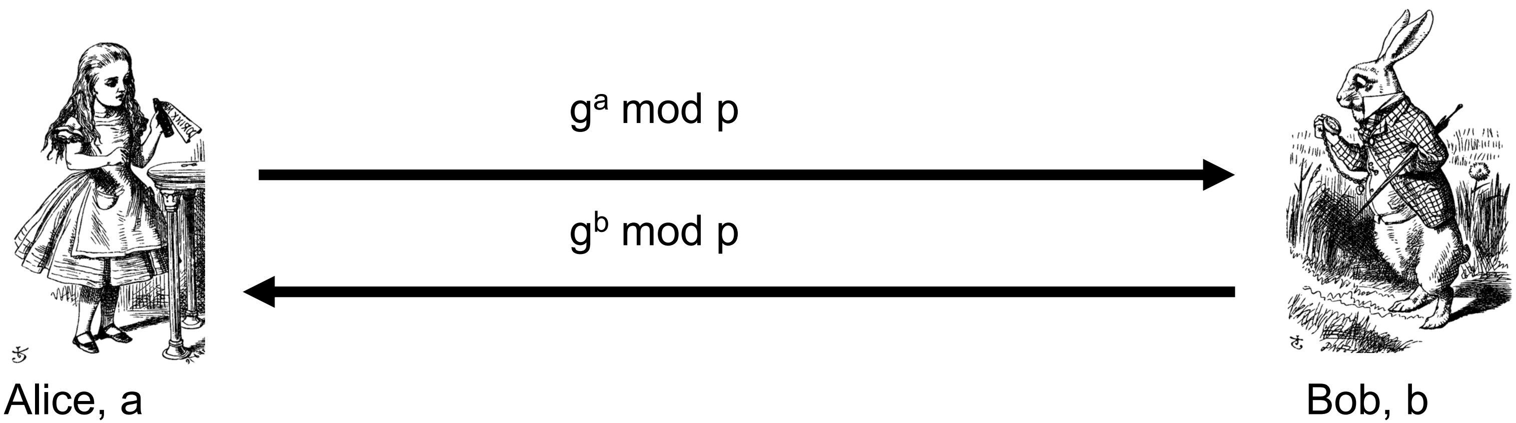
Naïve Session Key Protocol



- 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



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

Perfect Forward Secrecy

Alice, a

$E(g^a \bmod p, K_{AB}) \rightarrow$

$\leftarrow E(g^b \bmod p, K_{AB})$

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, 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

Timestamps

- A timestamp T is the current time
- Timestamps used in many security protocols (Kerberos, for example)
- Timestamps reduce number of messages
  - Like a nonce that both sides know in advance
- But, use of timestamps implies that time is a security-critical parameter
- Clocks never exactly the same, so must allow for **clock skew** — risk of replay
- How much clock skew is enough?

Public Key Authentication with Timestamp T

"I'm Alice", $\{[T,K]_{Alice}\}_{Bob}$

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

Alice

Bob

- Is this secure?
- Seems to be OK

Public Key Authentication with Timestamp T

Alice

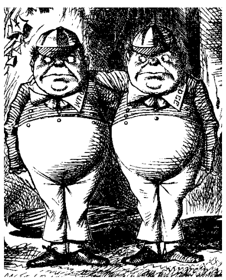
“I’m Alice”, $[\{T,K\}_{Bob}]_{Alice}$ →

← $[\{T+1,K\}_{Alice}]_{Bob}$

Bob

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

Public Key Authentication with Timestamp T



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

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

Trudy

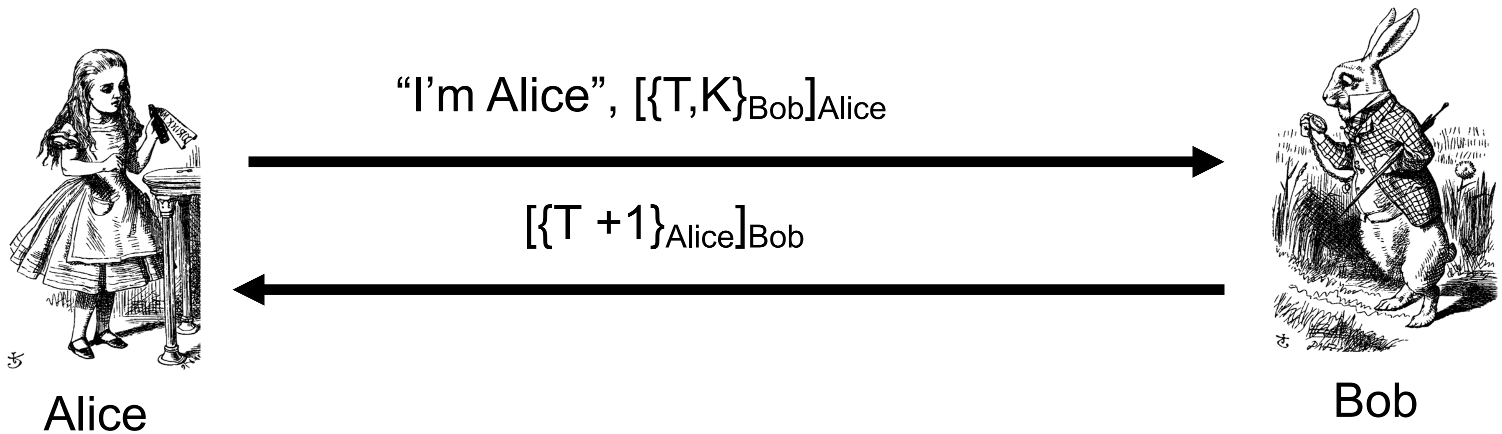
Bob

- 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



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

Kerberos

- In Greek mythology, Kerberos is 3-headed dog that guards entrance to Hades
  - “Wouldn’t it make more sense to guard the exit?”
- In security, Kerberos is an authentication system based on symmetric key crypto
  - Originated at MIT
  - Based on work by Needham and Schroeder
  - Relies on a **trusted third party (TTP)**

Motivation for Kerberos

- Authentication using public keys
  - N users $\Rightarrow$ N key pairs
- Authentication using symmetric keys
  - N users requires about N^2 keys
- Symmetric key case **does not scale!**
- Kerberos based on symmetric keys but only requires N keys for N users
  - But must rely on TTP
  - Advantage is that no PKI is required

Kerberos KDC

- Kerberos **Key Distribution Center** or **KDC**
  - Acts as a TTP
  - TTP must not be compromised!
  - KDC shares symmetric key K_A with Alice, key K_B with Bob, key K_C with Carol, etc.
  - Master key K_{KDC} known only to KDC
  - KDC enables authentication and session keys
  - Keys for confidentiality and integrity
  - In practice, the crypto algorithm used is DES

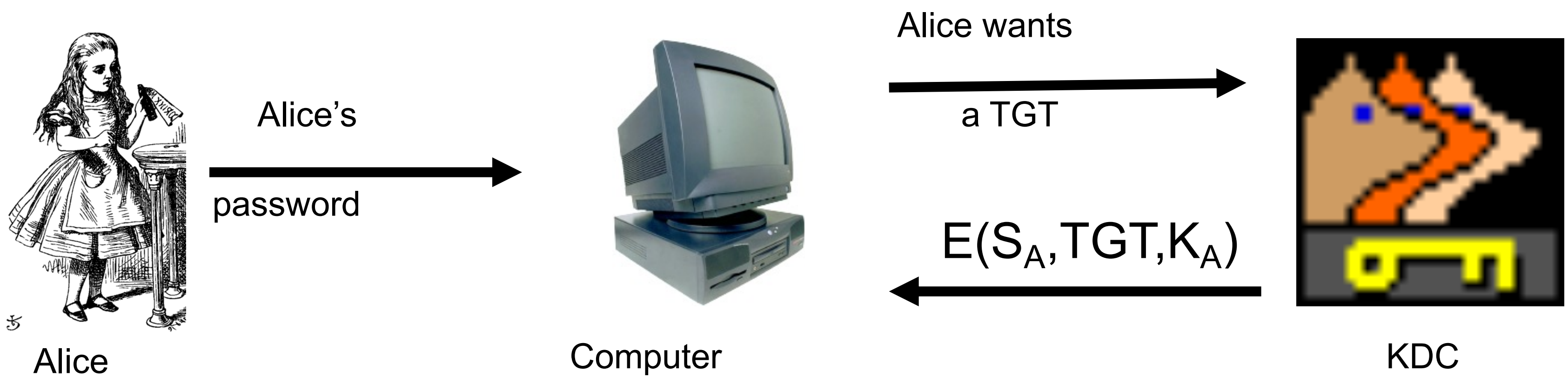
Kerberos Tickets

- KDC issues a **ticket** containing info needed to access a network resource
- KDC also issues **ticket-granting tickets** or **TGTs** that are used to obtain tickets
- Each TGT contains
  - Session key
  - User's ID
  - Expiration time
- Every TGT is encrypted with K_{KDC}
  - TGT can only be read by the KDC

Kerberized Login

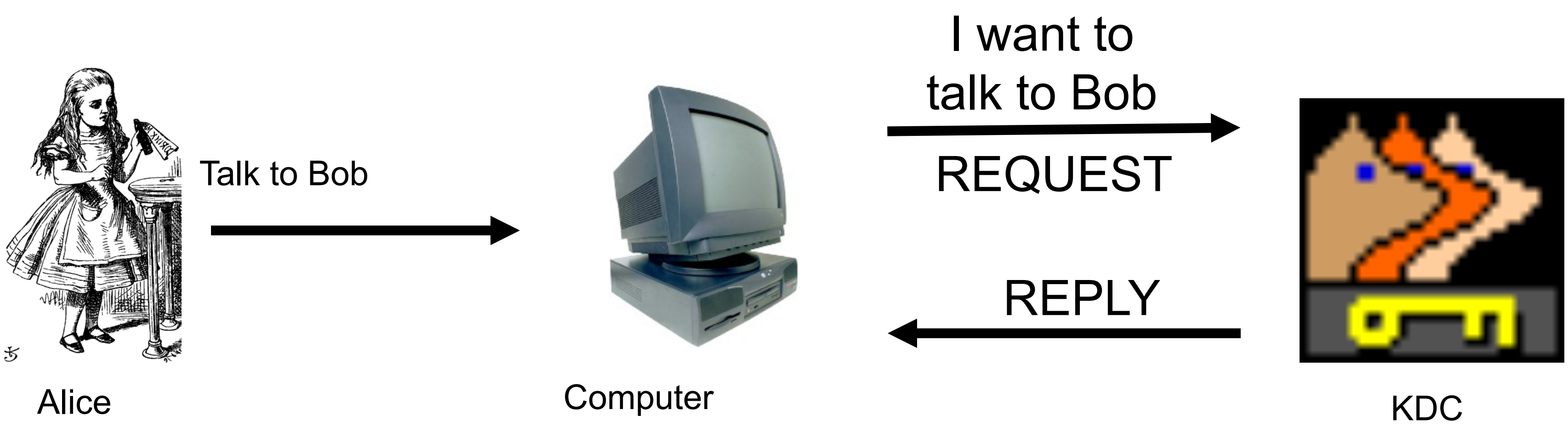
- Alice enters her password
- Alice's workstation
  - Derives K_A from Alice's password
  - Uses K_A to get TGT for Alice from the KDC
- Alice can then use her TGT (credentials) to securely access network resources
- **Plus:** Security is transparent to Alice
- **Minus:** KDC must be secure — it's trusted!

Kerberized Login



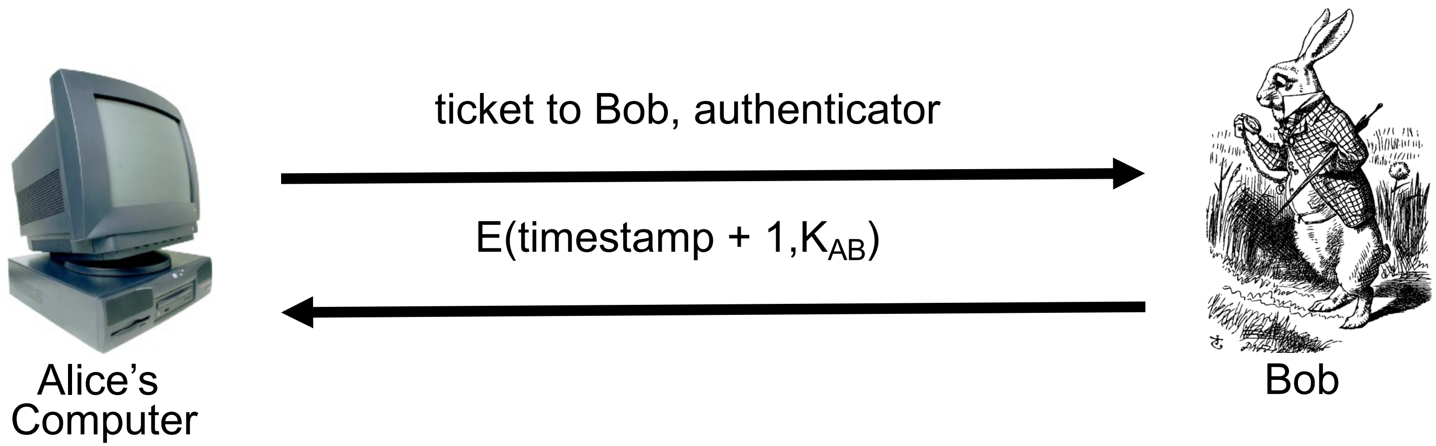
- Key K_A derived from Alice's password
- KDC creates session key S_A
- Workstation decrypts S_A, TGT, forgets K_A
- TGT = E("Alice", S_A, K_{KDC})

Alice Requests Ticket to Bob



- REQUEST = (TGT, authenticator) where
  authenticator = E(timestamp,S_A)
- REPLY = E("Bob", K_{AB}, ticket to Bob, S_A)
- ticket to Bob = E("Alice", K_{AB}, K_B)
- KDC gets S_A from TGT to verify timestamp

Alice Uses Ticket to Bob



- ticket to Bob = E("Alice",K_{AB}, K_B)
- authenticator = E(timestamp, K_{AB})
- Bob decrypts "ticket to Bob" to get K_{AB} which he then uses to verify timestamp

Kerberos

- Session key S_A used for authentication
- Can also be used for confidentiality/integrity
- Timestamps used for mutual authentication
- Recall that timestamps reduce number of messages
  - Acts like a nonce that is known to both sides
  - Note: **time** is a security-critical parameter!

Kerberos Questions

- When Alice logs in, KDC sends $E(S_A,TGT,K_A)$ where $TGT = E(\text{"Alice"},S_A,K_{KDC})$

  Q: Why is TGT encrypted with K_A?

  A: Extra work and no added security!
- In Alice's Kerberized login to Bob, why can Alice remain anonymous?
- Why is "ticket to Bob" sent to Alice?
- Where is replay prevention in Kerberos?

Kerberos Alternatives

- Could have Alice's workstation remember password and use that for authentication
  - Then no KDC required
  - But hard to protect password on workstation
  - Scaling problem
- Could have KDC remember session key instead of putting it in a TGT
  - Then no need for TGTs
  - But **stateless** KDC is big feature of Kerberos

Kerberos Keys

- In Kerberos, K_A = h(Alice's password)
- Could instead generate random K_A and
  - Compute K_h = h(Alice's password)
  - And workstation stores $E(K_A, K_h)$
- Then K_A need not change (on workstation or KDC) when Alice changes her password
- But $E(K_A, K_h)$ subject to password guessing
- This alternative approach is often used in applications (but not in Kerberos)

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
  - Even though he 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"

Fiat-Shamir Protocol

- Finding square roots modulo N is difficult (like 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

$x = r^2 \bmod N$ →

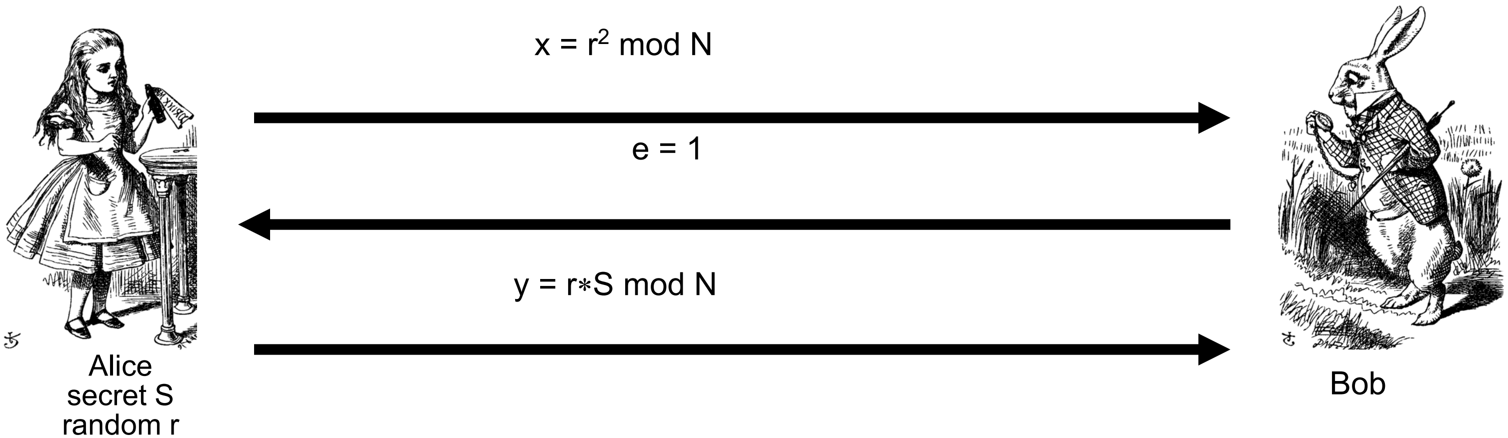
← $e \in \{0,1\}$

$y = r * S^e \bmod N$ →

Bob

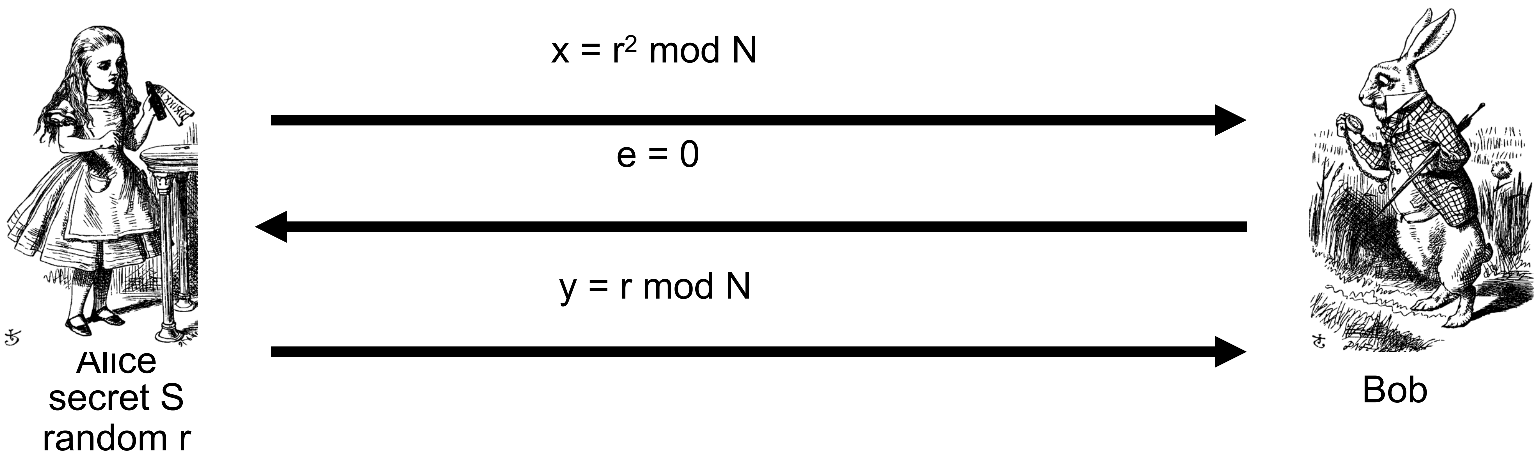
- **Public:** Modulus N and $v = S^2 \bmod N$
- Alice selects random r
- Bob chooses $e \in \{0,1\}$
- Bob verifies that $y^2 = r^2 * S^{2e} = r^2 * (S^2)^e = x * v^e \bmod N$

Fiat-Shamir: e = 1



- **Public:** Modulus N and $v = S^2 \bmod N$
- Alice selects random r
- Suppose Bob chooses e =1
- Bob must verify that $y^2 = x * v \bmod N$
- Alice must know S in this case

Fiat-Shamir: e = 0



- **Public:** Modulus N and $v = S^2 \bmod N$
- Alice selects random r
- Suppose Bob chooses e = 0
- Bob must verify that $y^2 = x \bmod N$
- Alice does **not** need 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 $y = r*S^e \bmod N$
- Bob checks that $y^2 = x*v^e \bmod N$
- Does this prove response is from Alice?

Does Fiat-Shamir Work?

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

Fiat-Shamir Facts

- Trudy can fool Bob with prob 1/2, but…
- …after n iterations, the probability that Trudy can fool Bob is only $1/2^n$
- Bob's $e \in \{0,1\}$ must be unpredictable
- Alice must use new r each iteration or else
  - If e = 0, Alice sends r in message 3
  - If e = 1, Alice sends $r*S$ in message 3
  - Anyone can find S given **both** r and $r*S$

Fiat-Shamir Zero Knowledge?

- Zero knowledge means that Bob learns **nothing** about the secret S
  - **Public:** $v = S^2 \bmod N$
  - Bob sees $r^2 \bmod N$ in message 1
  - Bob sees $r*S \bmod N$ in message 3 (if $e = 1$)
  - If Bob can find r from $r^2 \bmod N$, he gets S
  - But that requires modular square root
  - If Bob can find modular square roots, he can get S from **public** v
- The protocol does not "help" Bob to find S

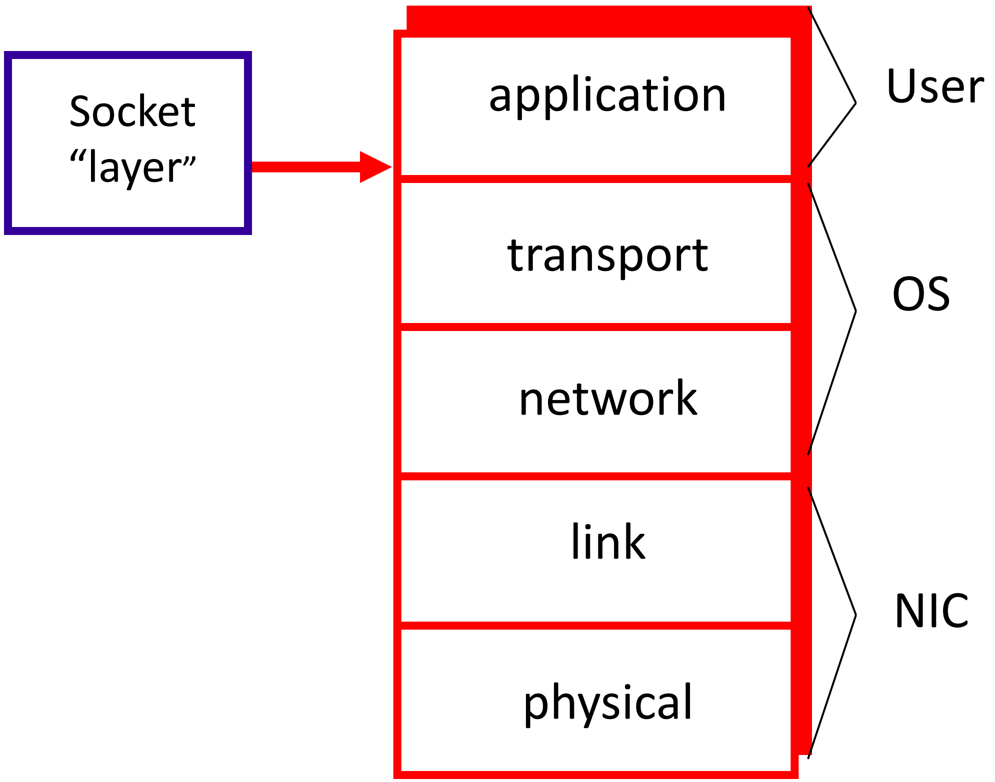
ZKP in the Real World

- Public key certificates identify users
  - No anonymity if certificates transmitted
- ZKP offers a way to authenticate without revealing identities
- ZKP supported in Microsoft's Next Generation Secure Computing Base (NGSCB)
  - ZKP used to authenticate software "without revealing machine identifying data"

Secure Socket Layer

Socket layer

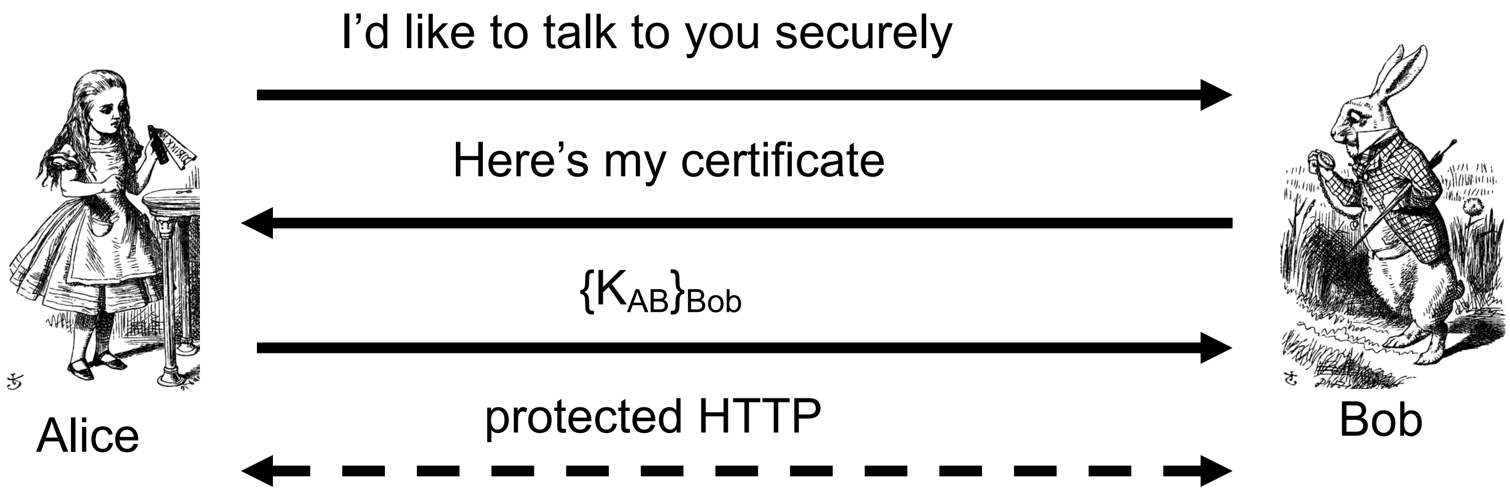
- "Socket layer" lives between application and transport layers
- SSL usually lies between HTTP and TCP



What is SSL?

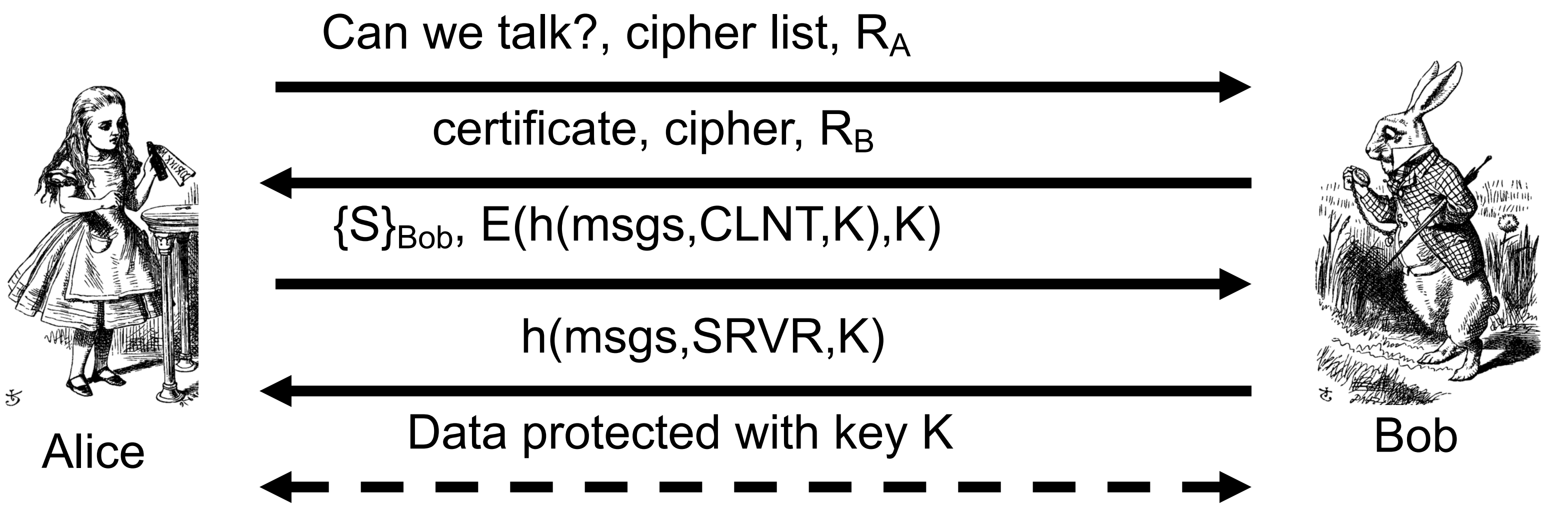
- SSL is the protocol used for most secure transactions over the Internet
- For example, if you want to buy a book at amazon.com…
  – You want to be sure you are dealing with Amazon (**authentication**)
  – Your credit card information must be protected in transit (**confidentiality** and/or **integrity**)
  – As long as you have money, Amazon doesn't care who you are (authentication need not be mutual)

Simple SSL-like Protocol



- Is Alice sure she's talking to Bob?
- Is Bob sure he's talking to Alice?

Simplified SSL Protocol



- S is **pre-master secret**
- $K = h(S, R_A, R_B)$
- msgs = all previous messages
- CLNT and SRVR are constants

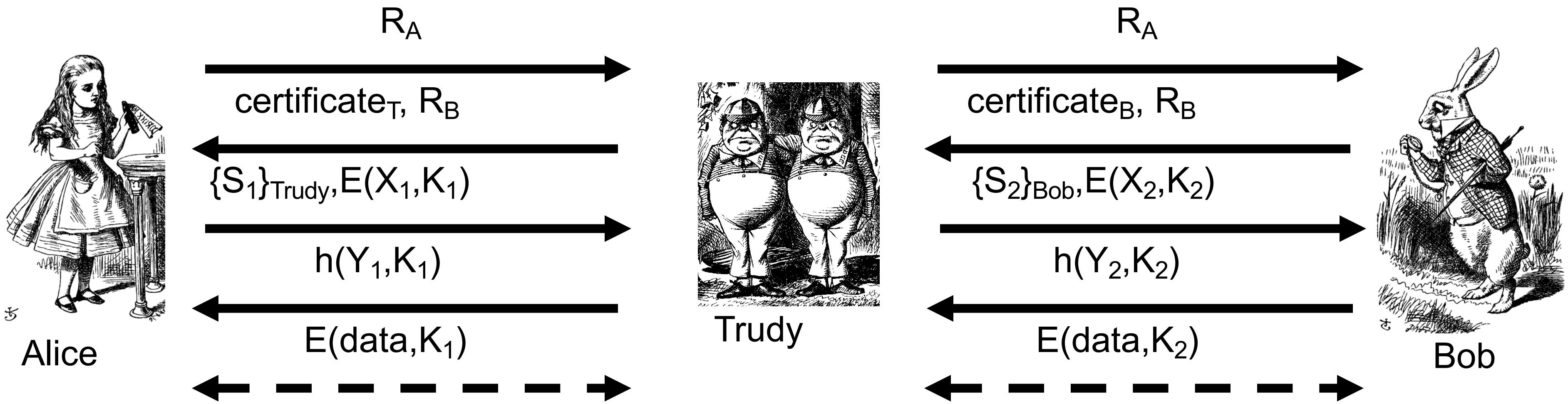
SSL Keys

- 6 “keys” derived from K = hash(S,R_A,R_B)
  - 2 encryption keys: send and receive
  - 2 integrity keys: send and receive
  - 2 IVs: send and receive
  - Why different keys in each direction?
- **Q:** Why is h(msgs,CLNT,K) encrypted (and integrity protected)?
- **A:** It adds no security…

SSL Authentication

- Alice authenticates Bob, not vice-versa
  - How does client authenticate server?
  - Why does server not authenticate client?
- Mutual authentication is possible: Bob sends **certificate request** in message 2
  - This requires client to have certificate
  - If server wants to authenticate client, server could instead require (encrypted) password

SSL MiM Attack

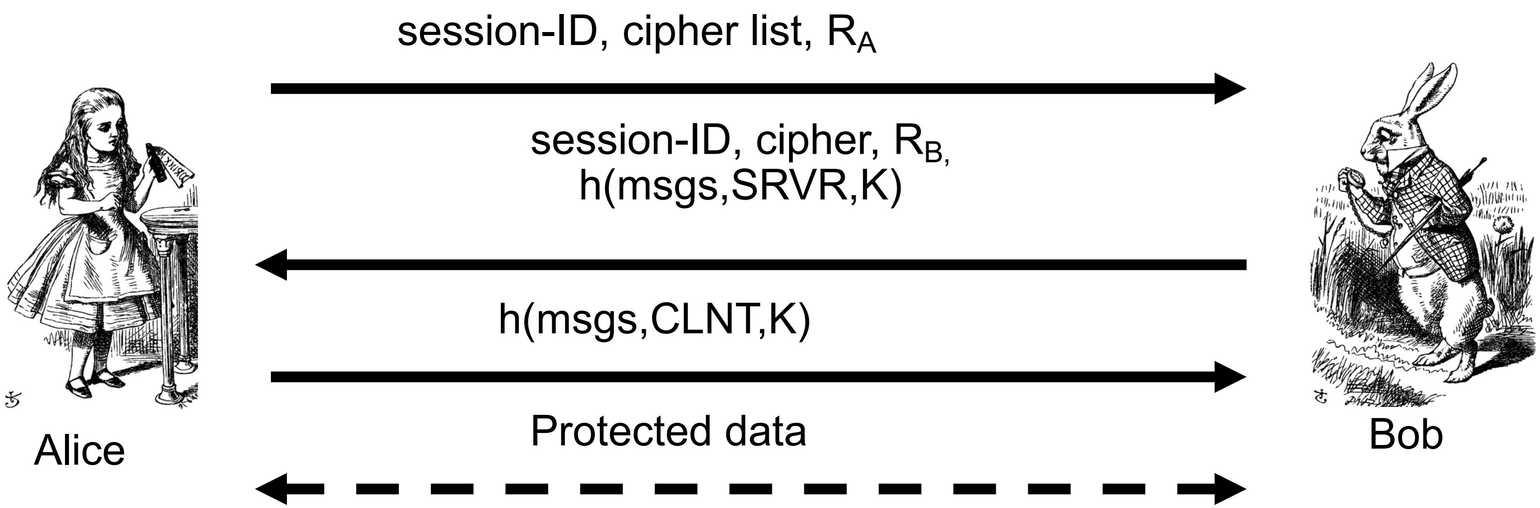


- **Q:** What prevents this MiM attack?
- **A:** Bob's certificate must be signed by a certificate authority (such as Verisign)
- What does Web browser do if sig. not valid?
- What does user do if signature is not valid?

SSL Sessions vs Connections

- SSL **session** is established as shown on previous slides
- SSL designed for use with HTTP 1.0
- HTTP 1.0 usually opens multiple simultaneous (parallel) **connections**
- SSL session establishment is costly
  - Due to public key operations
- SSL has an efficient protocol for opening new connections given an existing session

SSL Connection



- Assuming SSL **session** exists
- So S is already known to Alice and Bob
- Both sides must remember session-ID
- Again, $K = h(S,R_A,R_B)$
- No public key operations! (relies on known S)

SSL vs IPSec

- IPSec — discussed in next section
  - Lives at the network layer (part of the OS)
  - Has encryption, integrity, authentication, etc.
  - Is overly complex (including serious flaws)
- SSL (and IEEE standard known as TLS)
  - Lives at socket layer (part of user space)
  - Has encryption, integrity, authentication, etc.
  - Has a simpler specification

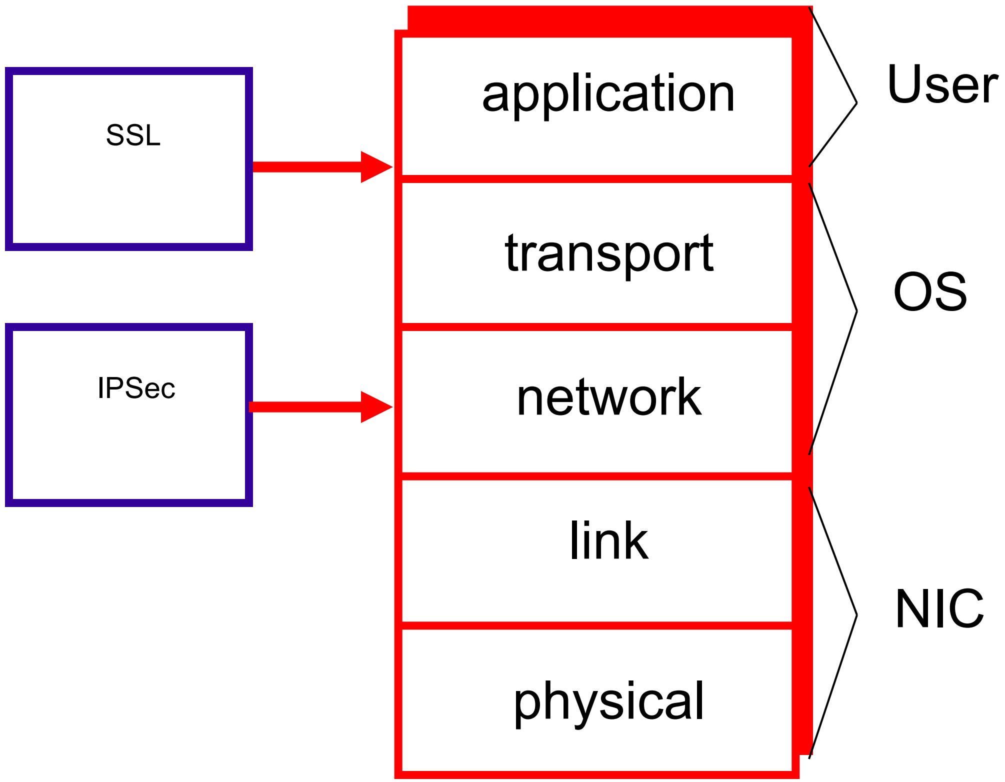
SSL vs IPSec

- IPSec implementation
  - Requires changes to OS, but no changes to applications
- SSL implementation
  - Requires changes to applications, but no changes to OS
- SSL built into Web application early on (Netscape)
- IPSec used in VPN applications (secure tunnel)
- Reluctance to retrofit applications for SSL
- Reluctance to use IPSec due to complexity and interoperability issues
- Result? **Internet less secure than it should be!**

IPSec

IPSec and SSL

- IPSec lives at the network layer
- IPSec is transparent to applications



IPSec and Complexity

- IPSec is a complex protocol
- Over-engineered
  - Lots of generally useless extra features
- Flawed
  - Some serious security flaws
- Interoperability is serious challenge
  - Defeats the purpose of having a standard!
- Complex
- Did I mention, it's complex?

IKE and ESP/AH

- Two parts to IPSec
- **IKE:** Internet Key Exchange
  - Mutual authentication
  - Establish shared symmetric key
  - Two “phases” — like SSL session/connection
- **ESP/AH**
  - ESP: Encapsulating Security Payload — for encryption and/or integrity of IP packets
  - AH: Authentication Header — integrity only

IKE

IKE

- IKE has 2 phases
  - Phase 1 — IKE security association (SA)
  - Phase 2 — AH/ESP security association
- Phase 1 is comparable to SSL session
- Phase 2 is comparable to SSL connection
- Not an obvious need for two phases in IKE
- If multiple Phase 2's do not occur, then it is **more** expensive to have two phases!

IKE Phase 1

- Four different "key" options
  - Public key encryption (original version)
  - Public key encryption (improved version)
  - Public key signature
  - Symmetric key
- For each of these, two different "modes"
  - Main mode
  - Aggressive mode
- **There are 8 versions of IKE Phase 1!**
- Evidence that IPSec is over-engineered?

IKE Phase 1

- We'll discuss 6 of 8 phase 1 variants
  - Public key signatures (main and aggressive modes)
  - Symmetric key (main and aggressive modes)
  - Public key encryption (main and aggressive)
- Why public key encryption and public key signatures?
  - Always know your own private key
  - **May not** (initially) know other side's public key

IKE Phase 1

- Uses ephemeral Diffie-Hellman to establish session key
  - Achieves perfect forward secrecy (PFS)
- Let a be Alice's Diffie-Hellman exponent
- Let b be Bob's Diffie-Hellman exponent
- Let g be generator and p prime
- Recall p and g are public

IKE Phase 1: Digital Signature (Main Mode)

Alice

Bob

Alice → Bob: IC, CP

Bob → Alice: IC,RC, CS

Alice → Bob: IC,RC, g^a mod p, R_A

Bob → Alice: IC,RC, g^b mod p, R_B

Alice → Bob: IC,RC, E("Alice", proof_A, K)

Bob → Alice: IC,RC, E("Bob", proof_B, K)

- CP = crypto proposed, CS = crypto selected
- IC = initiator "cookie", RC = responder "cookie"
- K = h(IC,RC,g^{ab} mod p,R_A,R_B)
- SKEYID = h(R_A, R_B, g^{ab} mod p)
- proof_A = [h(SKEYID,g^a,g^b,IC,RC,CP,"Alice")]$_{\text{Alice}}$

IKE Phase 1: Public Key Signature (Aggressive Mode)

Alice

IC, “Alice”, g^a mod p, R_A, CP

IC,RC, “Bob”, R_B,
g^b mod p, CS, $proof_B$

IC,RC, $proof_A$

Bob

- Main difference from main mode
  - Not trying to protect identities
  - Cannot negotiate g or p

Main vs Aggressive Modes

- Main mode **MUST** be implemented
- Aggressive mode **SHOULD** be implemented
  - In other words, if aggressive mode is not implemented, “you should feel guilty about it”
- Might create interoperability issues
- For public key signature authentication
  - Passive attacker knows identities of Alice and Bob in aggressive mode
  - Active attacker can determine Alice’s and Bob’s identity in main mode

IKE Phase 1: Symmetric Key (Main Mode)

Alice

$\xrightarrow{\text{IC, CP}}$

$\xleftarrow{\text{IC,RC, CS}}$

$\xrightarrow{\text{IC,RC, } g^a \text{ mod p, } R_A}$

$\xleftarrow{\text{IC,RC, } g^b \text{ mod p, } R_B}$

$\xrightarrow{\text{IC,RC, E(“Alice”, proof}_A\text{, K)}}$

$\xleftarrow{\text{IC,RC, E(“Bob”, proof}_B\text{, K)}}$

Bob

- Same as signature mode except
  - K_{AB} = symmetric key shared in advance
  - $K = h(IC,RC,g^{ab} \bmod p,R_A,R_B,K_{AB})$
  - SKEYID = $h(K, g^{ab} \bmod p)$
  - $\text{proof}_A = h(\text{SKEYID},g^a,g^b,IC,RC,CP,\text{“Alice”})$

Problems with Symmetric Key (Main Mode)

- Catch-22
  - Alice sends her ID in message 5
  - Alice's ID encrypted with K
  - To find K Bob must know K_{AB}
  - To get K_{AB} Bob must know he's talking to Alice!
- Result: **Alice's ID must be IP address!**
- Useless mode for the "road warrior"
- Why go to all of the trouble of trying to hide identities in 6 message protocol?

IKE Phase 1: SymmetricKey (Aggressive Mode)

Alice

IC, “Alice”, g^a mod p, R_A, CP $\rightarrow$

$\leftarrow$ IC,RC, “Bob”, R_B, g^b mod p, CS, $proof_B$

IC,RC, $proof_A$ $\rightarrow$

Bob

- Same format as digital signature aggressive mode
- Not trying to hide identities…
- As a result, does **not** have problems of main mode
- But does not (pretend to) hide identities

IKE Phase 1: Public Key Encryption (Main Mode)

Alice

IC, CP $\rightarrow$

IC,RC, CS $\leftarrow$

IC,RC, g^a mod p, $\{R_A\}_{Bob}$, $\{$"Alice"$\}_{Bob}$ $\rightarrow$

IC,RC, g^b mod p, $\{R_B\}_{Alice}$, $\{$"Bob"$\}_{Alice}$ $\leftarrow$

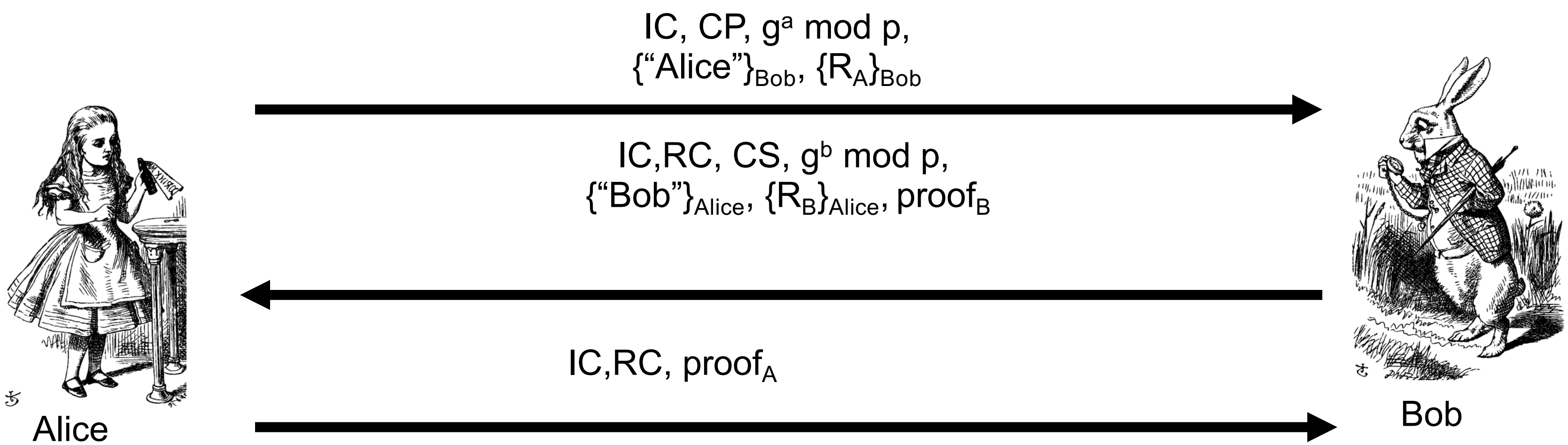
IC,RC, E(proof$_A$, K) $\rightarrow$

IC,RC, E(proof$_B$, K) $\leftarrow$

Bob

- CP = crypto proposed, CS = crypto selected
- IC = initiator "cookie", RC = responder "cookie"
- K = h(IC,RC,g^{ab} mod p,R_A,R_B)
- SKEYID = h(R_A, R_B, g^{ab} mod p)
- proof$_A$ = h(SKEYID,g^a,g^b,IC,RC,CP,"Alice")

IKE Phase 1: Public Key Encryption (Aggressive Mode)

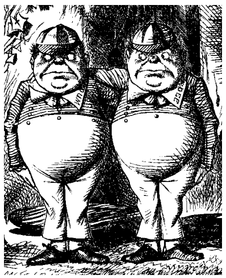


- K, proof$_A$, proof$_B$ computed as in main mode
- Note that identities are hidden
  - The only aggressive mode to hide identities
  - Then why have main mode?

Public Key Encryption Issue?

- Public key encryption, aggressive mode
- Suppose Trudy generates
  - Exponents a and b
  - Nonces R_A and R_B
- Trudy can compute "valid" keys and proofs: $g^{ab} \bmod p$, K, SKEYID, $proof_A$ and $proof_B$
- Also true of main mode

Public Key Encryption Issue?

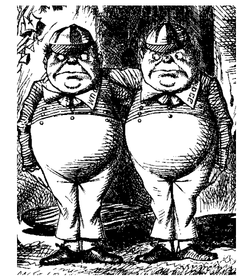


Trudy
as Alice

IC, CP, $g^a \bmod p$,
{"Alice"}$_{Bob}$, $\{R_A\}_{Bob}$

IC,RC, CS, $g^b \bmod p$,
{"Bob"}$_{Alice}$, $\{R_B\}_{Alice}$, $proof_B$

IC,RC, $proof_A$



Trudy
as Bob

- Trudy can create exchange that appears to be between Alice and Bob
- Appears valid to any observer, including Alice and Bob!

Plausible Deniability

- Trudy can create “conversation” that appears to be between Alice and Bob
- Appears valid, even to Alice and Bob!
- A security failure?
- In this mode of IPSec, it is a feature
  - **Plausible deniability:** Alice and Bob can deny that any conversation took place!
- In some cases it might be a security failure
  - If Alice makes a purchase from Bob, she could later repudiate it (unless she had signed)

IKE Phase 1 Cookies

- Cookies (or “anti-clogging tokens”) supposed to make denial of service more difficult
- No relation to Web cookies
- To reduce DoS, Bob wants to remain stateless as long as possible
- But Bob must remember CP from message 1 (required for proof of identity in message 6)
- Bob must keep state from 1st message on!
- These cookies offer little DoS protection!

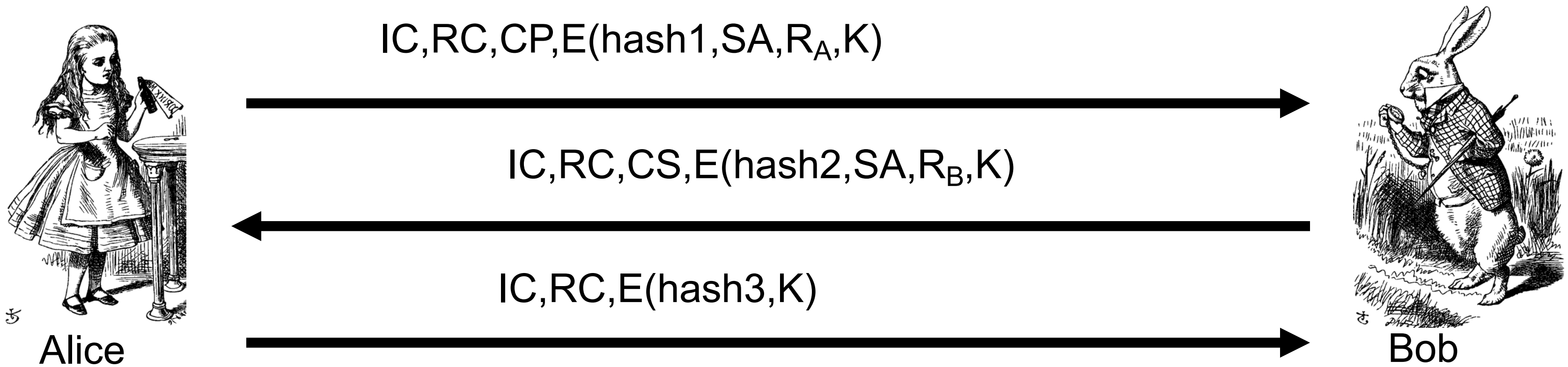
IKE Phase 1 Summary

- Result of IKE phase 1 is
  - Mutual authentication
  - Shared symmetric key
  - IKE **Security Association** **(SA)**
- But phase 1 is expensive (in public key and/or main mode cases)
- Developers of IKE thought it would be used for lots of things — not just IPSec
- Partly explains over-engineering…

IKE Phase 2

- Phase 1 establishes IKE SA
- Phase 2 establishes IPSec SA
- Comparison to SSL
  - SSL session is comparable to IKE Phase 1
  - SSL connections are like IKE Phase 2
- IKE **could** be used for lots of things
- But in practice, it's **not!**

IKE Phase 2



- Key K, IC, RC and SA known from Phase 1
- Proposal CP includes ESP and/or AH
- Hashes 1,2,3 depend on SKEYID, SA, R_A and R_B
- Keys derived from KEYMAT = h(SKEYID,R_A,R_B,junk)
- Recall SKEYID depends on phase 1 key method
- Optional PFS (ephemeral Diffie-Hellman exchange)

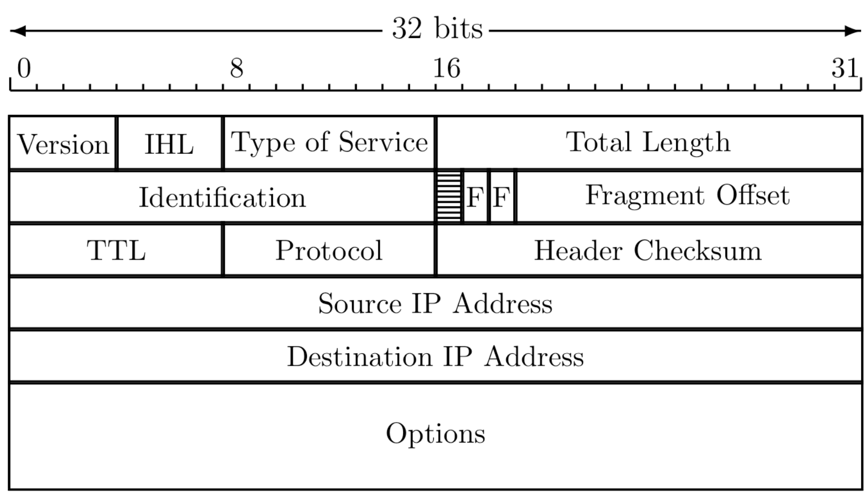
IPSec

- After IKE Phase 1, we have an IKE SA
- After IKE Phase 2, we have an IPSec SA
- Both sides have a shared symmetric key
- Now what?
  - We want to protect IP datagrams
- But what is an IP datagram?
  - From the perspective of IPSec…

IP Review

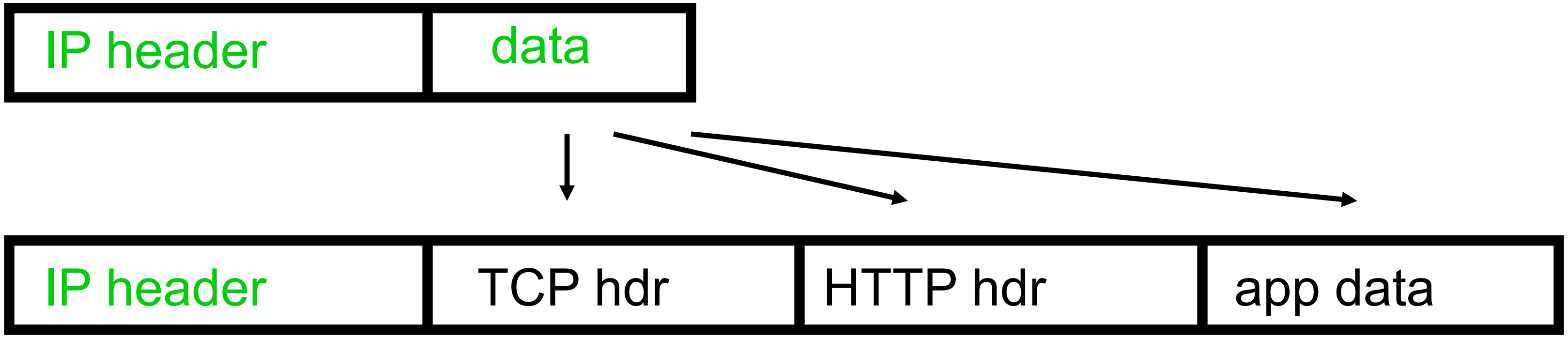
- IP datagram is of the form

- Where IP header is



IP and TCP

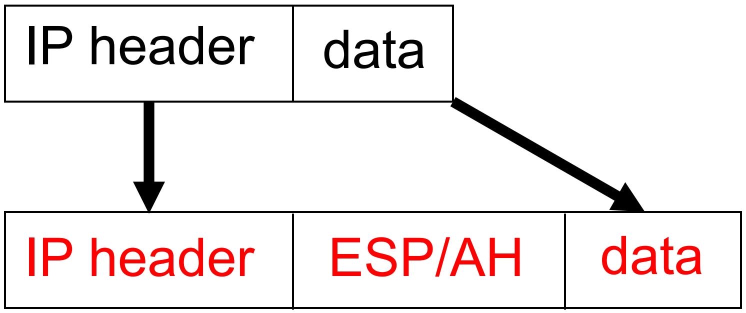
- Consider HTTP traffic (over TCP)
- IP encapsulates TCP
- TCP encapsulates HTTP



- IP data includes TCP header, etc.

IPSec Transport Mode

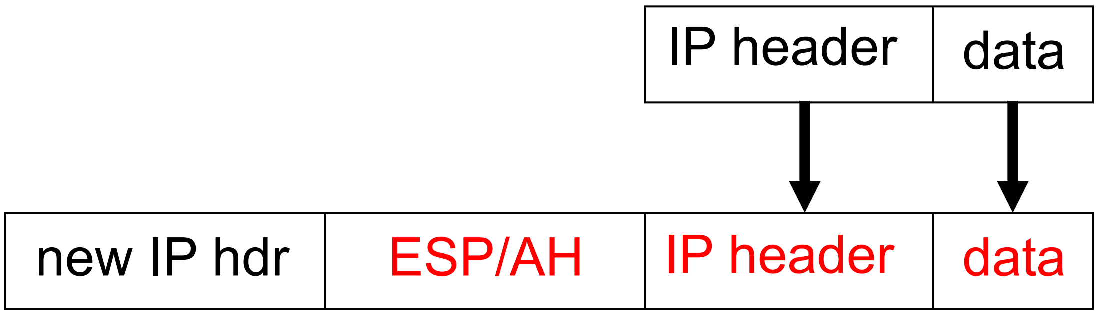
- IPSec **Transport Mode**



- Transport mode designed for host-to-host
- Transport mode is efficient
  - Adds minimal amount of extra header
- The original header remains
  - Passive attacker can see who is talking

IPSec Tunnel Mode

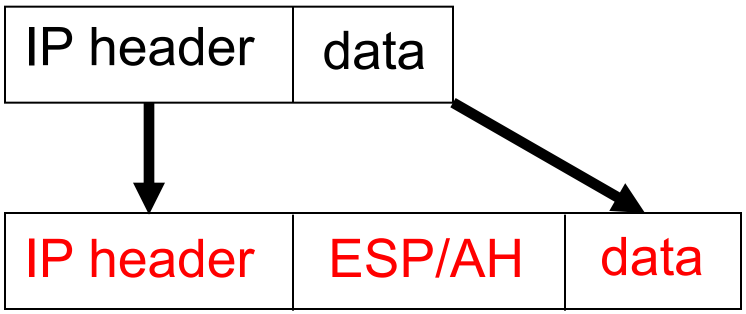
- IPSec Tunnel Mode



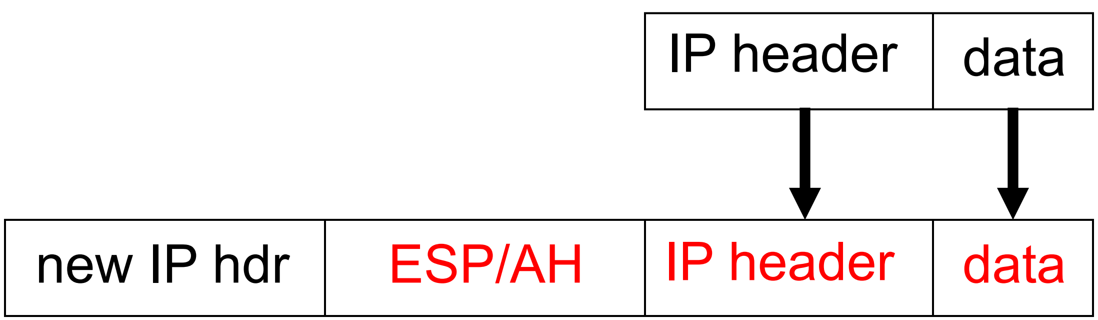
- Tunnel mode for firewall to firewall traffic
- Original IP packet encapsulated in IPSec
- Original IP header not visible to attacker
  - New header from firewall to firewall
  - Attacker does not know which hosts are talking

Comparison of IPSec Modes

- Transport Mode



- Tunnel Mode



- Transport Mode
  - Host-to-host
- Tunnel Mode
  - Firewall-to-firewall
- Transport mode not necessary
- Transport mode is more efficient

IPSec Security

- What kind of protection?
  - Confidentiality?
  - Integrity?
  - Both?
- What to protect?
  - Data?
  - Header?
  - Both?
- ESP/AH do some combinations of these

AH vs ESP

- AH
  - Authentication Header
  - **Integrity only** (no confidentiality)
  - Integrity-protect everything beyond IP header and some fields of header (why not all fields?)
- ESP
  - Encapsulating Security Payload
  - **Integrity and confidentiality**
  - Protects everything beyond IP header
  - Integrity only by using NULL encryption

ESP’s NULL Encryption

- According to RFC 2410
  - NULL encryption “is a block cipher the origins of which appear to be lost in antiquity”
  - “Despite rumors”, there is no evidence that NSA “suppressed publication of this algorithm”
  - Evidence suggests it was developed in Roman times as exportable version of Caesar’s cipher
  - Can make use of keys of varying length
  - No IV is required
  - Null(P,K) = P for any P and any key K
- Security people have a strange sense of humor!

Why Does AH Exist? (1)

- Cannot encrypt IP header
  - Routers must look at the IP header
  - IP addresses, TTL, etc.
  - IP header exists to route packets!
- AH protects **immutable fields** in IP header
  - Cannot integrity protect all header fields
  - TTL, for example, must change
- ESP does not protect IP header at all

Why Does AH Exist? (2)

- ESP encrypts everything beyond the IP header (if non-null encryption)
- If ESP encrypted, firewall cannot look at TCP header (e.g., port numbers)
- Why not use ESP with null encryption?
  - Firewall sees ESP header, but does not know whether null encryption is used
  - End systems know, but **not** firewalls
- Aside 1: Do firewalls reduce security?
- Aside 2: Is IPSec compatible with NAT?

Why Does AH Exist? (3)

- The real reason why AH exists
  - At one IETF meeting “someone from Microsoft gave an impassioned speech about how AH was useless…”
  - “…everyone in the room looked around and said `Hmm. He’s right, and we hate AH also, but if it annoys Microsoft let’s leave it in since we hate Microsoft more than we hate AH.”

Best Authentication Protocol?

- What is best depends on many factors…
- The sensitivity of the application
- The delay that is tolerable
- The cost (computation) that is tolerable
- What crypto is supported
  - Public key, symmetric key, hash functions
- Is mutual authentication required?
- Is a session key required?
- Is PFS a concern?
- Is anonymity a concern?, etc.

End