Lecture 9
October 10, 2022

Notation

- $X \rightarrow Y : \{ Z \mid\mid W \} k_{X,Y}$
  - 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
- $A \rightarrow T : \{ Z \} k_A \mid\mid \{ W \} k_{A,T}$
  - 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)

Symmetric Key Exchange

- Bootstrap problem: how do Alice, Bob begin?
  - Alice can’t send it to Bob in the clear!
- Assume trusted third party, Cathy
  - Alice and Cathy share secret key k_A
  - Bob and Cathy share secret key k_B
- Use this to exchange shared key k_s

Simple Protocol

Alice $\xrightarrow{\{\text{ request for session key to Bob }\}\, k_A}$ Cathy

Alice $\xleftarrow{\{\, k_s \,\}\, k_A \;||\; \{\, k_s \,\}\, k_B}$ Cathy

Alice $\xrightarrow{\{\, k_s \,\}\, k_B}$ Bob

Problems

- How does Bob know he is talking to Alice?
  - Replay attack: Eve records message from Alice to Bob, later replays it; Bob may think he's talking to Alice, but he isn't
  - Session key reuse: Eve replays message from Alice to Bob, so Bob re-uses session key
- Protocols must provide authentication and defense against replay

Session, Interchange Keys

- Alice wants to send a message *m* to Bob
  - Assume public key encryption
  - Alice generates a random cryptographic key k_s and uses it to encipher *m*
    - To be used for this message *only*
    - Called a *session key*
  - She enciphers k_s with Bob's public key k_B
    - k_B enciphers all session keys Alice uses to communicate with Bob
    - Called an interchange *key*
  - Alice sends $\{ m \} k_s \{ k_s \} k_B$

Benefits

- Limits amount of traffic enciphered with single key
  - Standard practice, to decrease the amount of traffic an attacker can obtain
- Prevents some attacks
  - Example: Alice will send Bob message that is either "BUY" or "SELL". Eve computes possible ciphertexts { "BUY" } k_B and { "SELL" } k_B. Eve intercepts enciphered message, compares, and gets plaintext at once

Kerberos

- Authentication system
  - Based on Needham-Schroeder with Denning-Sacco modification
  - Central server plays role of trusted third party (“Cathy”)
- Ticket
  - Issuer vouches for identity of requester of service
- Authenticator
  - Identifies sender

Idea

- User u authenticates to Kerberos server
  - Obtains ticket $T_{u,TGS}$ for ticket granting service (TGS)
- User u wants to use service s:
  - User sends authenticator A_u, ticket $T_{u,TGS}$ to TGS asking for ticket for service
  - TGS sends ticket $T_{u,s}$ to user
  - User sends A_u, $T_{u,s}$ to server as request to use s
- Details follow

Ticket

- Credential saying issuer has identified ticket requester
- Example ticket issued to user *u* for service *s*

$$T_{u,s} = s \,||\, \{ u \,||\, u\text{'s address} \,||\, \text{valid time} \,||\, k_{u,s} \} k_s$$

where:

- $k_{u,s}$ is session key for user and service
- Valid time is interval for which ticket valid
- *u*'s address may be IP address or something else
  - Note: more fields, but not relevant here

Authenticator

- Credential containing identity of sender of ticket
  - Used to confirm sender is entity to which ticket was issued
- Example: authenticator user *u* generates for service *s*

$$A_{u,s} = \{ u \mid\mid \text{generation time} \mid\mid k_t \}\, k_{u,s}$$

  where:
  - k_t is alternate session key
  - Generation time is when authenticator generated
    - Note: more fields, not relevant here

Protocol

user $\longrightarrow$ AS: $user \mid\mid TGS$

AS $\longleftarrow$ *user*: $\{ k_{u,TGS} \} k_u \mid\mid T_{u,TGS}$

user $\longrightarrow$ TGS: $service \mid\mid A_{u,TGS} \mid\mid T_{u,TGS}$

user $\longleftarrow$ TGS: $user \mid\mid \{ k_{u,s} \} k_{u,TGS} \mid\mid T_{u,s}$

user $\longrightarrow$ *service*: $A_{u,s} \mid\mid T_{u,s}$

user $\longleftarrow$ *service*: $\{ t + 1 \} k_{u,s}$

Analysis

- First two steps get user ticket to use TGS
  - User *u* can obtain session key only if *u* knows key shared with AS
- Next four steps show how *u* gets and uses ticket for service *s*
  - Service *s* validates request by checking sender (using $A_{u,s}$) is same as entity ticket issued to
  - Step 6 optional; used when *u* requests confirmation

Problems

- Relies on synchronized clocks
  - If not synchronized and old tickets, authenticators not cached, replay is possible
- Tickets have some fixed fields
  - Dictionary attacks possible
  - Kerberos 4 session keys weak (had much less than 56 bits of randomness); researchers at Purdue found them from tickets in minutes

Public Key Key Exchange

- Here interchange keys known
  - e_A, e_B Alice and Bob’s public keys known to all
  - d_A, d_B Alice and Bob’s private keys known only to owner
- Simple protocol
  - k_s is desired session key

Alice $\xrightarrow{\{\, k_s \,\}\, e_B}$ Bob

Problem and Solution

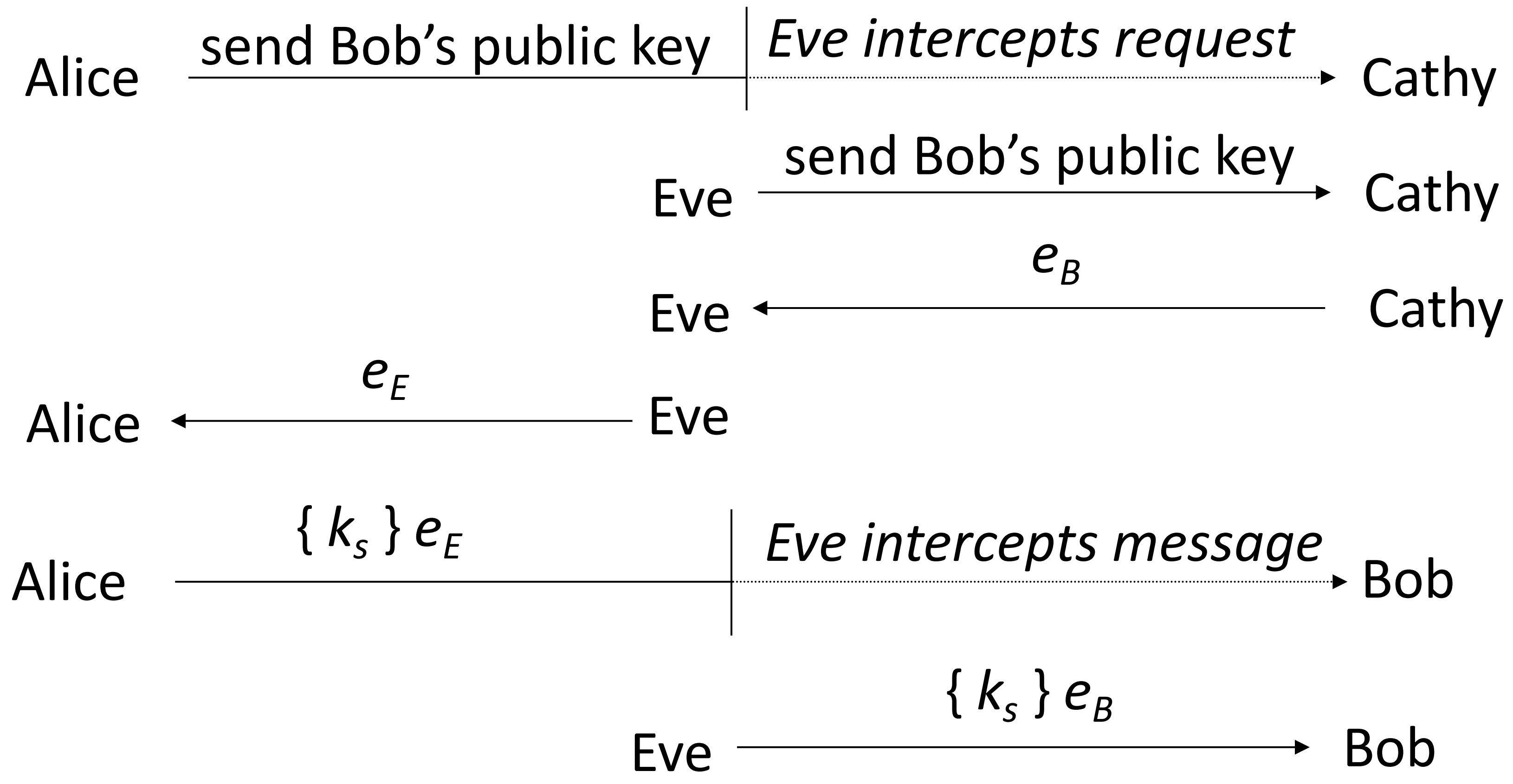
- Vulnerable to forgery or replay
  - Because e_B known to anyone, Bob has no assurance that Alice sent message
- Simple fix uses Alice's private key
  - k_s is desired session key

Alice $\xrightarrow{\{ \{ k_s \} d_A \} e_B}$ Bob

Notes

- Can include message enciphered with k_s
- Assumes Bob has Alice’s public key, and *vice versa*
  - If not, each must get it from public server
  - If keys not bound to identity of owner, attacker Eve can launch a *man-in-the-middle* attack (next slide; Cathy is public server providing public keys)
    - Solution to this (binding identity to keys) discussed later as public key infrastructure (PKI)

Man-in-the-Middle Attack



Diffie-Hellman

- Compute a common, shared key
  - Called a *symmetric key exchange protocol*
- Based on discrete logarithm problem
  - Given integers n, g and prime number p, compute k such that $n = g^k \bmod p$
  - Solutions known for small p
  - Solutions computationally infeasible as p grows large

Algorithm

- Constants: prime p, integer $g \neq 0, 1, p{-}1$
  - Known to all participants
- Alice chooses private key k_{Alice}, computes public key $K_{\text{Alice}} = g^{k_{\text{Alice}}} \bmod p$
- Bob chooses private key k_{Bob}, computes public key $K_{\text{Bob}} = g^{k_{\text{Bob}}} \bmod p$
- To communicate with Bob, Anne computes $K_{\text{Alice,Bob}} = K_{\text{Bob}}{}^{k_{\text{Alice}}} \bmod p$
- To communicate with Anne, Bob computes $K_{\text{Bob,Alice}} = K_{\text{Alice}}{}^{k_{\text{Bob}}} \bmod p$
- It can be shown $K_{\text{Alice,Bob}} = K_{\text{Bob,Alice}}$

Example

- Assume p = 121001 and g = 6981
- Alice chooses k_{Alice} = 526784
  - Then $K_{\text{Alice}} = 6981^{26874} \bmod 121001 = 22258$
- Bob chooses k_{Bob} = 5596
  - Then $K_{\text{Bob}} = 6981^{5596} \bmod 121001 = 112706$
- Shared key:
  - $K_{\text{Bob}}{}^{k_{\text{Alice}}} \bmod p = 112706^{26874} \bmod 121001 = 78618$
  - $K_{\text{Alice}}{}^{k_{Bob}} \bmod p = 22258^{5596} \bmod 121001 = 78618$

Problems

- Using cipher requires knowledge of environment, and threats in the environment, in which cipher will be used
  - Is the set of possible messages small?
  - Can an active wiretapper rearrange or change parts of the message?
  - Do the messages exhibit regularities that remain after encipherment?
  - Can the components of the message be misinterpreted?

Attack #1: Precomputation

- Set of possible messages *M* small
- Public key cipher *f* used
- Idea: precompute set of possible ciphertexts *f*(*M*), build table (*m*, *f*(*m*))
- When ciphertext *f*(*m*) appears, use table to find *m*
- Also called *forward searches*

Example

- Cathy knows Alice will send Bob one of two messages: enciphered BUY, or enciphered SELL
- Using public key e_{Bob}, Cathy precomputes

  $$m_1 = \{ \text{BUY} \} e_{Bob},\ m_2 = \{ \text{SELL} \} e_{Bob}$$

- Cathy sees Alice send Bob m_2
- Cathy knows Alice sent SELL

May Not Be Obvious

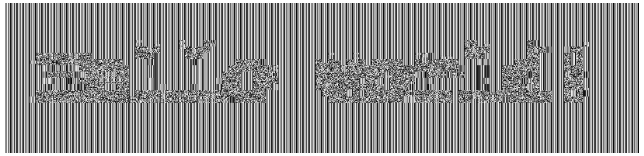
- Digitized sound
  - Seems like far too many possible plaintexts, as initial calculations suggest 2^{32} such plaintexts
  - Analysis of redundancy in human speech reduced this to about 100,000 ($\approx 2^{17}$), small enough for precomputation attacks

Misordered Blocks

- Alice sends Bob message
  - n_{Bob} = 262631, e_{Bob} = 45539, d_{Bob} = 235457
- Message is TOMNOTANN (191412 131419 001313)
- Enciphered message is 193459 029062 081227
- Eve intercepts it, rearranges blocks
  - Now enciphered message is 081227 029062 193459
- Bob gets enciphered message, deciphers it
  - He sees ANNNOTTOM, opposite of what Alice sent

Statistical Regularities

- If plaintext repeats, ciphertext may too
- Example using AES-128:
  - Input image: `Hello world!`
  - corresponding output image:



  - Note you can still make out the words
- Fix: cascade blocks together (chaining); more details later

Type Flaw Attacks

- Assume components of messages in protocol have particular meaning
- Example: Otway-Rees:

$n \,||\, \text{Alice} \,||\, \text{Bob} \,||\, \{ r_1 \,||\, n \,||\, \text{Alice} \,||\, \text{Bob} \}\, k_A$

Alice → Bob

$n \,||\, \text{Alice} \,||\, \text{Bob} \,||\, \{ r_1 \,||\, n \,||\, \text{Alice} \,||\, \text{Bob} \}\, k_A \,||\, \{ r_2 \,||\, n \,||\, \text{Alice} \,||\, \text{Bob} \}\, k_B$

Cathy ← Bob

$n \,||\, \{ r_1 \,||\, k_s \}\, k_A \,||\, \{ r_2 \,||\, k_s \}\, k_B$

Cathy → Bob

$n \,||\, \{ r_1 \,||\, k_s \}\, k_A$

Alice ← Bob

The Attack

- Ichabod intercepts message from Bob to Cathy in step 2
- Ichabod *replays* this message, sending it to Bob
  - Slight modification: he deletes the cleartext names
- Bob *expects* $n \,||\, \{ r_1 \,||\, k_s \} k_A \,||\, \{ r_2 \,||\, k_s \} k_B$
- Bob *gets* $n \,||\, \{ r_1 \,||\, n \,||\, \text{Alice} \,||\, \text{Bob} \} k_A \,||\, \{ r_2 \,||\, n \,||\, \text{Alice} \,||\, \text{Bob} \} k_B$
- So Bob sees $n \,||\, \text{Alice} \,||\, \text{Bob}$ as the session key — and Ichabod knows this
- When Alice gets her part, she makes the same assumption
- Now Ichabod can read their encrypted traffic

Solution

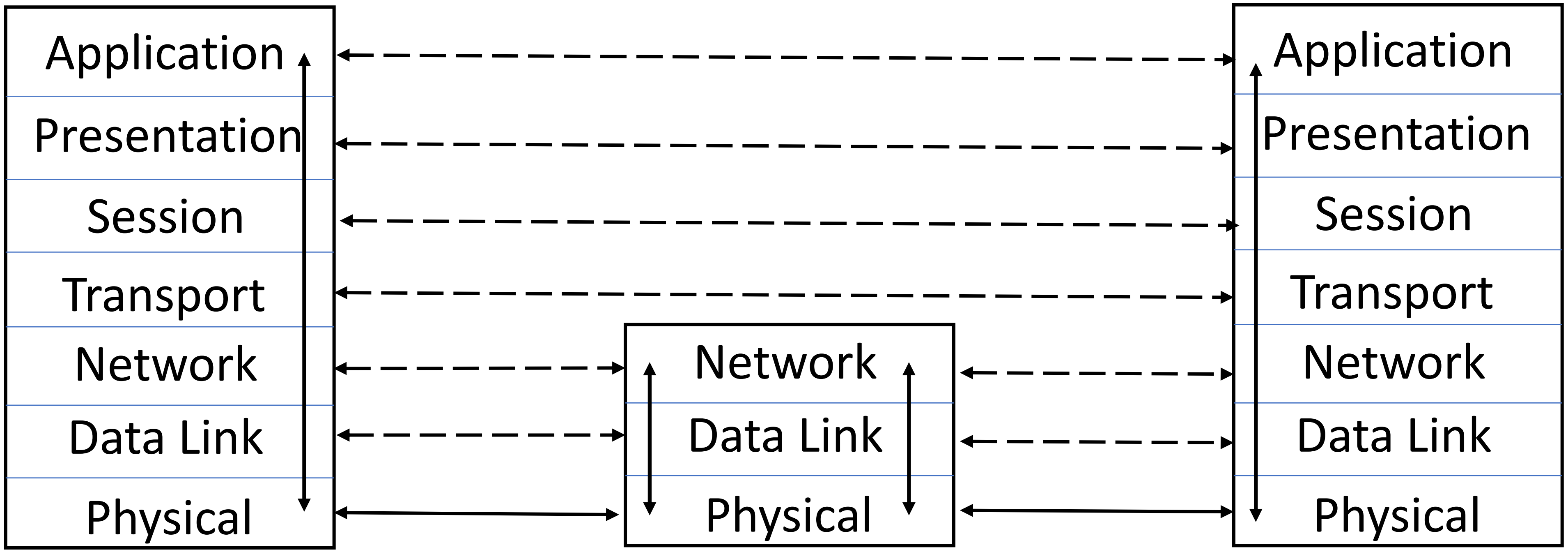
- Tag components of cryptographic messages with information about what the component is
  - But the tags themselves may be confused with data …

What These Mean

- Use of strong cryptosystems, well-chosen (or random) keys not enough to be secure
- Other factors:
  - Protocols directing use of cryptosystems
  - Ancillary information added by protocols
  - Implementation (not discussed here)
  - Maintenance and operation (not discussed here)

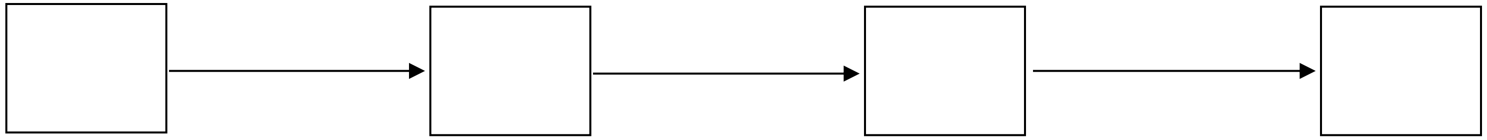
Networks and Cryptography

- ISO/OSI model
- Conceptually, each host communicates with peer at each layer



Link and End-to-End Protocols

Link Protocol



End-to-End (or E2E) Protocol