Authentication and key-exchange protocols

Agenda

- Key exchange basics
- Simple protocols and replay attacks
- Needham Schroeder and refinements
- Public-key exchange protocols
- Man-in-the-middle attacks
- Certificates

Notation

- $X \rightarrow Y : \{ Z \,||\, W \}\, k_{X,Y}$
  - 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)

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

Key Exchange Algorithms

- Goal: Alice, Bob get shared key
  - Key cannot be sent in clear
    - Attacker can listen in
    - Key can be sent enciphered, or derived from exchanged data plus data not known to an eavesdropper
  - Alice, Bob may trust third party
  - All cryptosystems, protocols publicly known
    - Only secret data is the keys, ancillary information known only to Alice and Bob needed to derive keys
    - Anything transmitted is assumed known to attacker

Classical 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

Needham-Schroeder

$$\text{Alice} \xrightarrow{\text{Alice} \,\|\, \text{Bob} \,\|\, r_1} \text{Cathy}$$

$$\text{Alice} \xleftarrow{\{\, \text{Alice} \,\|\, \text{Bob} \,\|\, r_1 \,\|\, k_s \,\|\, \{\, \text{Alice} \,\|\, k_s \,\}\, k_B \,\}\, k_A} \text{Cathy}$$

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

$$\text{Alice} \xleftarrow{\{\, r_2 \,\}\, k_s} \text{Bob}$$

$$\text{Alice} \xrightarrow{\{\, r_2 - 1 \,\}\, k_s} \text{Bob}$$

Argument: Alice talking to Bob

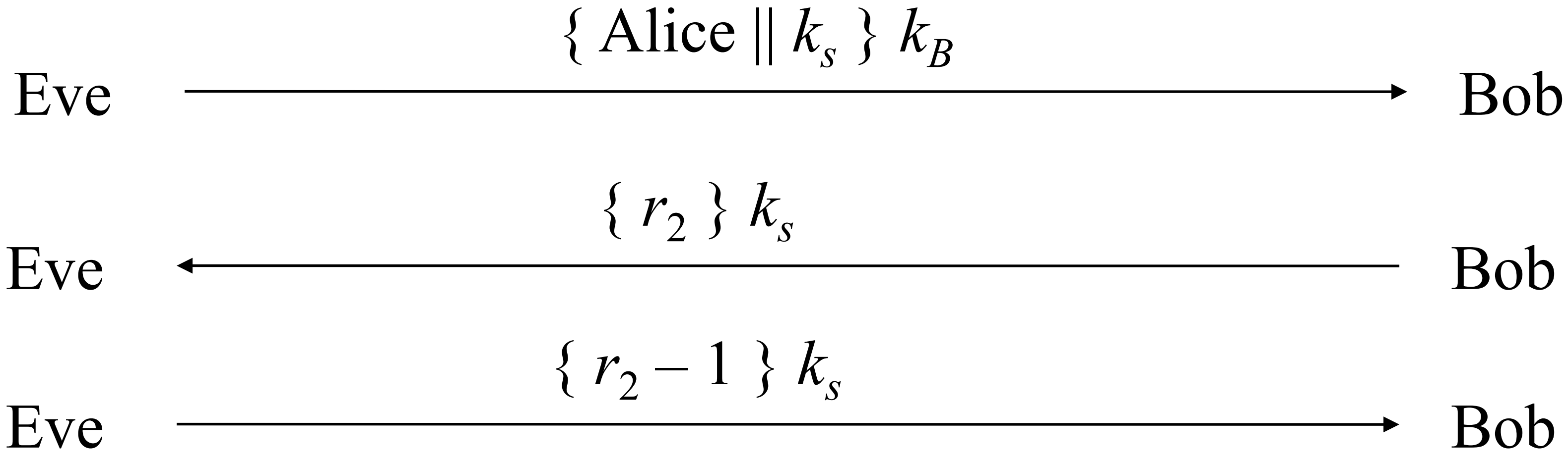
- Second message
  - Enciphered using key only she, Cathy knows
    - So Cathy enciphered it
  - Response to first message
    - As r_1 in it matches r_1 in first message
- Third message
  - Alice knows only Bob can read it
    - As only Bob can derive session key from message
  - Any messages enciphered with that key are from Bob

Argument: Bob talking to Alice

- Third message
  - Enciphered using key only he, Cathy know
    - So Cathy enciphered it
  - Names Alice, session key
    - Cathy provided session key, says Alice is other party
- Fourth message
  - Uses session key to determine if it is replay from Eve
    - If not, Alice will respond correctly in fifth message
    - If so, Eve can't decipher r_2 and so can't respond, or responds incorrectly

Denning-Sacco Modification

- Assumption: all keys are secret
- Question: suppose Eve can obtain session key. How does that affect protocol?
  - In what follows, Eve knows k_s



$\{ \text{Alice} \| k_s \} k_B$

Eve → Bob

$\{ r_2 \} k_s$

Eve ← Bob

$\{ r_2 - 1 \} k_s$

Eve → Bob

Solution

- In protocol above, Eve impersonates Alice
- Problem: replay in third step
  - First in previous slide
- Solution: use time stamp *T* to detect replay
- Proposed by Denning and Sacco

Needham-Schroeder with Denning-Sacco Modification

$$\text{Alice} \xrightarrow{\text{Alice} \,||\, \text{Bob} \,||\, r_1} \text{Cathy}$$

$$\text{Alice} \xleftarrow{\{\, \text{Alice} \,||\, \text{Bob} \,||\, r_1 \,||\, k_s \,||\, \{\, \text{Alice} \,||\, T \,||\, k_s \,\}\, k_B \,\}\, k_A} \text{Cathy}$$

$$\text{Alice} \xrightarrow{\{\, \text{Alice} \,||\, T \,||\, k_s \,\}\, k_B} \text{Bob}$$

$$\text{Alice} \xleftarrow{\{\, r_2 \,\}\, k_s} \text{Bob}$$

$$\text{Alice} \xrightarrow{\{\, r_2 - 1 \,\}\, k_s} \text{Bob}$$

Problem with timestamps?

- If clocks not synchronized, may either reject valid messages or accept replays
  - Parties with either slow or fast clocks vulnerable to replay
  - Resetting clock does *not* eliminate vulnerability

- We'll see timestamps used in Kerberos as well.

Otway-Rees Protocol

- Corrects problem
  - That is, Eve replaying the third message in the protocol
- Does not use timestamps
  - Not vulnerable to the problems that Denning-Sacco modification has
- Uses integer *n* to associate all messages with particular exchange

The Protocol

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

$$\text{Cathy} \xleftarrow[\{\, r_2 \,\|\, n \,\|\, \text{Alice} \,\|\, \text{Bob} \,\}\, k_B]{n \,\|\, \text{Alice} \,\|\, \text{Bob} \,\|\, \{\, r_1 \,\|\, n \,\|\, \text{Alice} \,\|\, \text{Bob} \,\}\, k_A \,\|} \text{Bob}$$

$$\text{Cathy} \xrightarrow{n \,\|\, \{\, r_1 \,\|\, k_s \,\}\, k_A \,\|\, \{\, r_2 \,\|\, k_s \,\}\, k_B} \text{Bob}$$

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

Argument: Alice talking to Bob

- Fourth message
  - If *n* matches first message, Alice knows it is part of this protocol exchange
  - Cathy generated k_s because only she, Alice know k_A
  - Enciphered part belongs to exchange as r_1 matches r_1 in encrypted part of first message

Argument: Bob talking to Alice

- Third message
  - If n matches second message, Bob knows it is part of this protocol exchange
  - Cathy generated k_s because only she, Bob know k_B
  - Enciphered part belongs to exchange as r_2 matches r_2 in encrypted part of second message

Replay Attack

- Eve acquires old k_s, message in third step
  - $n \,||\, \{\, r_1 \,||\, k_s \,\}\, k_A \,||\, \{\, r_2 \,||\, k_s \,\}\, k_B$
- Eve forwards appropriate part to Alice
  - Alice has no ongoing key exchange with Bob: n matches nothing, so is rejected
  - Alice has ongoing key exchange with Bob: n does not match, so is again rejected
    - If replay is for the current key exchange, *and* Eve sent the relevant part *before* Bob did, Eve could simply listen to traffic; no replay involved

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

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

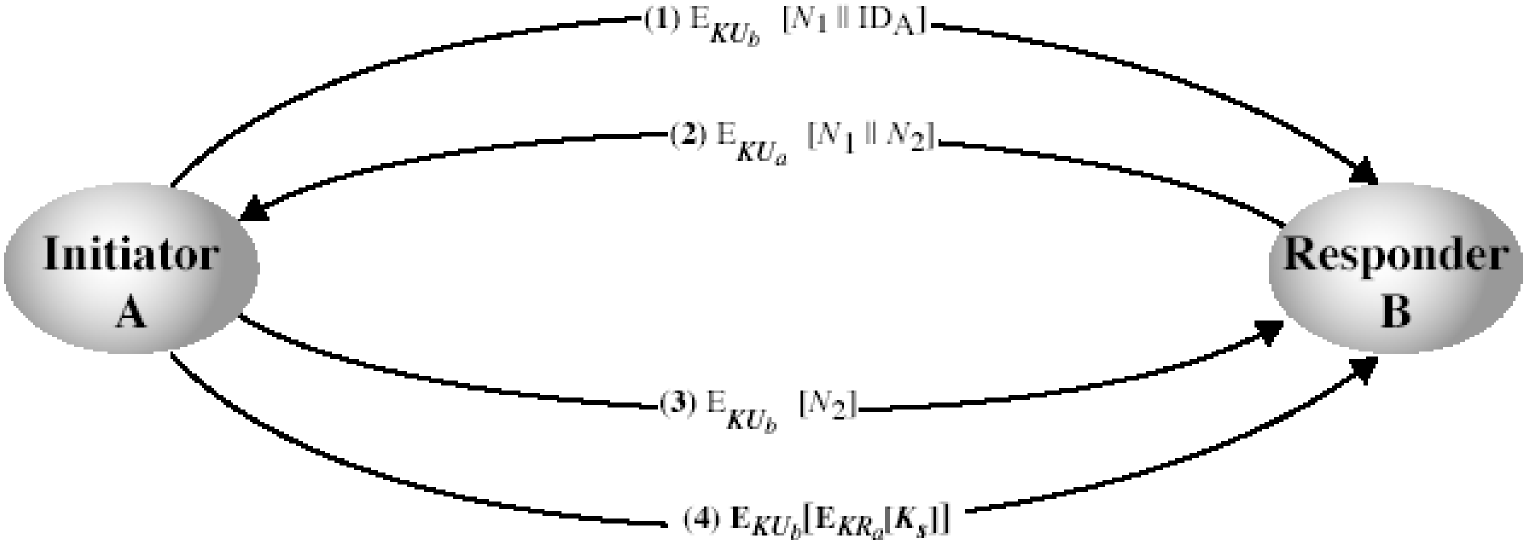
Problem and Solution

- 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

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

Public-Key Distribution of Secret Keys

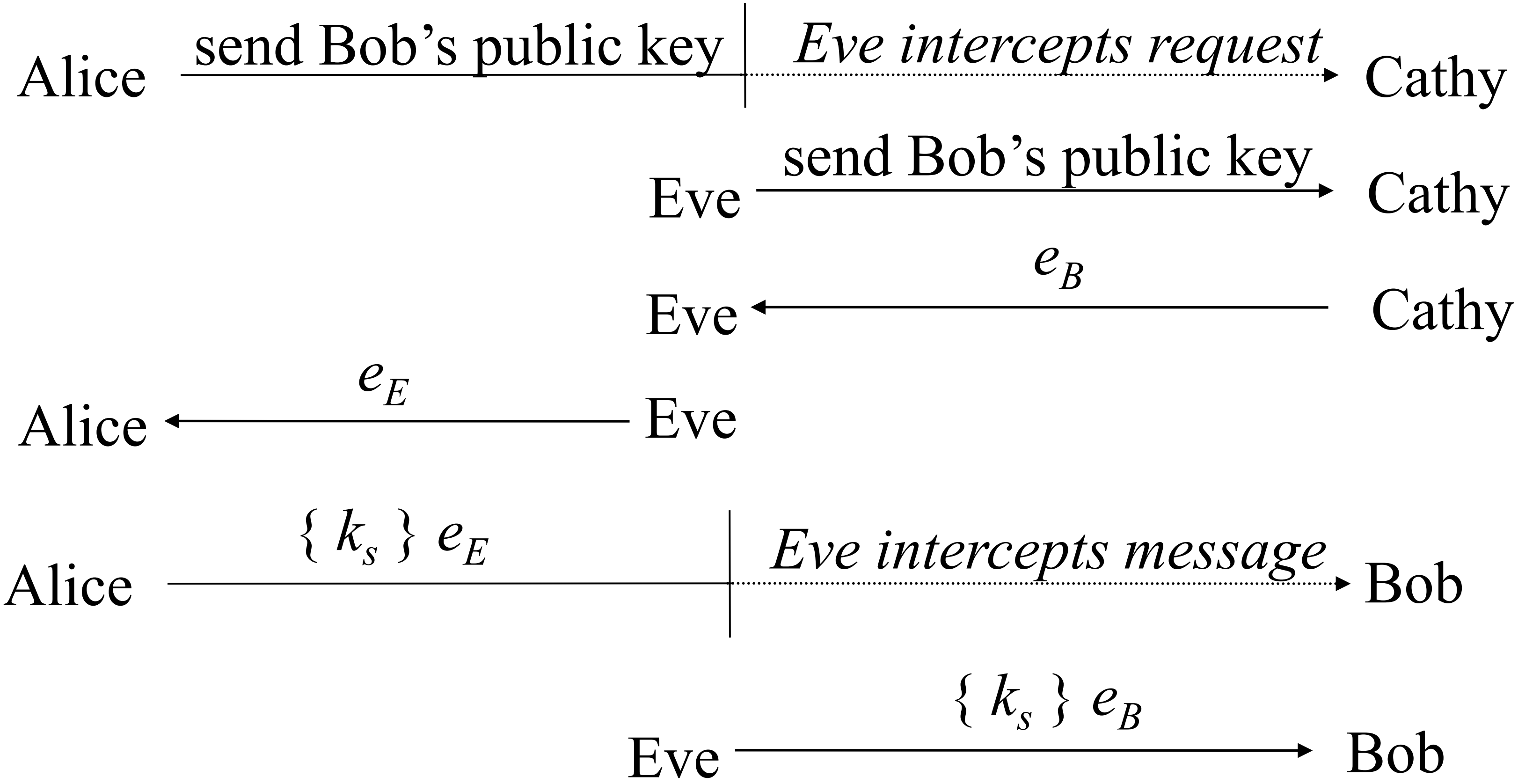
- if have securely exchanged public-keys:



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



Alice — send Bob’s public key — | *Eve intercepts request* → Cathy

Eve — send Bob’s public key → Cathy

Eve ← e_B — Cathy

Alice ← e_E — Eve

Alice — $\{ k_s \}\, e_E$ — | *Eve intercepts message* → Bob

Eve — $\{ k_s \}\, e_B$ → Bob

Cryptographic Key Infrastructure

- Goal: bind identity to key
- Classical: not possible as all keys are shared
  - Use protocols to agree on a shared key (see earlier)
- Public key: bind identity to public key
  - Crucial as people will use key to communicate with principal whose identity is bound to key
  - Erroneous binding means no secrecy between principals
  - Assume principal identified by an acceptable name

Certificates

- Create token (message) containing
  - Identity of principal (here, Alice)
  - Corresponding public key
  - Timestamp (when issued)
  - Other information (perhaps identity of signer)

signed by trusted authority (here, Cathy)

$$C_A = \{ e_A \,||\, \text{Alice} \,||\, T \} \, d_C$$

Use

- Bob gets Alice’s certificate
  - If he knows Cathy’s public key, he can decipher the certificate
    - When was certificate issued?
    - Is the principal Alice?
  - Now Bob has Alice’s public key
- Problem: Bob needs Cathy’s public key to validate certificate
  - Problem pushed “up” a level
  - Solution: Signature chains

Certificate Signature Chains

- Create certificate
  - Generate hash of certificate
  - Encipher hash with issuer's private key
- Validate
  - Obtain issuer's public key
  - Decipher enciphered hash
  - Recompute hash from certificate and compare
- Problem: getting issuer's public key
- Popular implementation/standard: X509

Issuers

- *Certification Authority (CA)*: entity that issues certificates
  - Multiple issuers pose validation problem
  - Alice’s CA is Cathy; Bob’s CA is Don; how can Alice validate Bob’s certificate?
  - Have Cathy and Don cross-certify
    - Each issues certificate for the other

Validation and Cross-Certifying

- Certificates:
  - Cathy<<Alice>>
  - Dan<<Bob>
  - Cathy<<Dan>>
  - Dan<<Cathy>>
- Alice validates Bob’s certificate
  - Alice obtains Cathy<<Dan>>
  - Alice uses (known) public key of Cathy to validate Cathy<<Dan>>
  - Alice uses Cathy<<Dan>> to validate Dan<<Bob>>

Key Revocation

- Certificates invalidated *before* expiration
  - Usually due to compromised key
  - May be due to change in circumstance (*e.g.,* someone leaving company)
- Problems
  - Entity revoking certificate authorized to do so
  - Revocation information circulates to everyone fast enough
    - Network delays, infrastructure problems may delay information

CRLs

- *Certificate revocation list* lists certificates that are revoked
- X.509: only certificate issuer can revoke certificate
  - Added to CRL
- PGP: signers can revoke signatures; owners can revoke certificates, or allow others to do so
  - Revocation message placed in PGP packet and signed
  - Flag marks it as revocation message