Chapter 9: Key Management

- Session and Interchange Keys
- Key Exchange
- Cryptographic Key Infrastructure
- Storing and Revoking Keys
- Digital Signatures

Overview

- Key exchange
  - Session vs. interchange keys
  - Classical, public key methods
- Cryptographic key infrastructure
  - Certificates
- Key storage
  - Key revocation
- Digital signatures

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

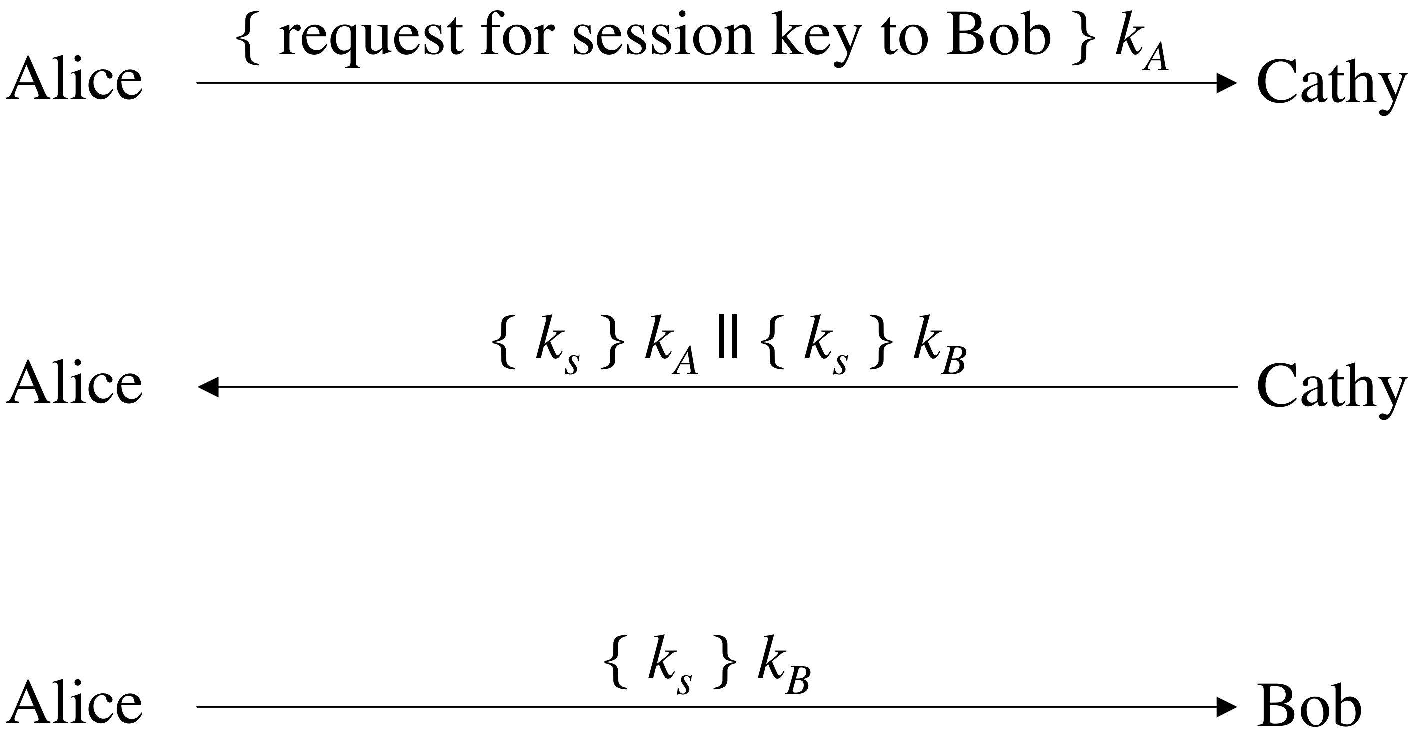
Key Exchange Algorithms

- 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 $\xleftarrow{\{\ k_s\ \}\ k_A \parallel \{\ k_s\ \}\ k_B}$ 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

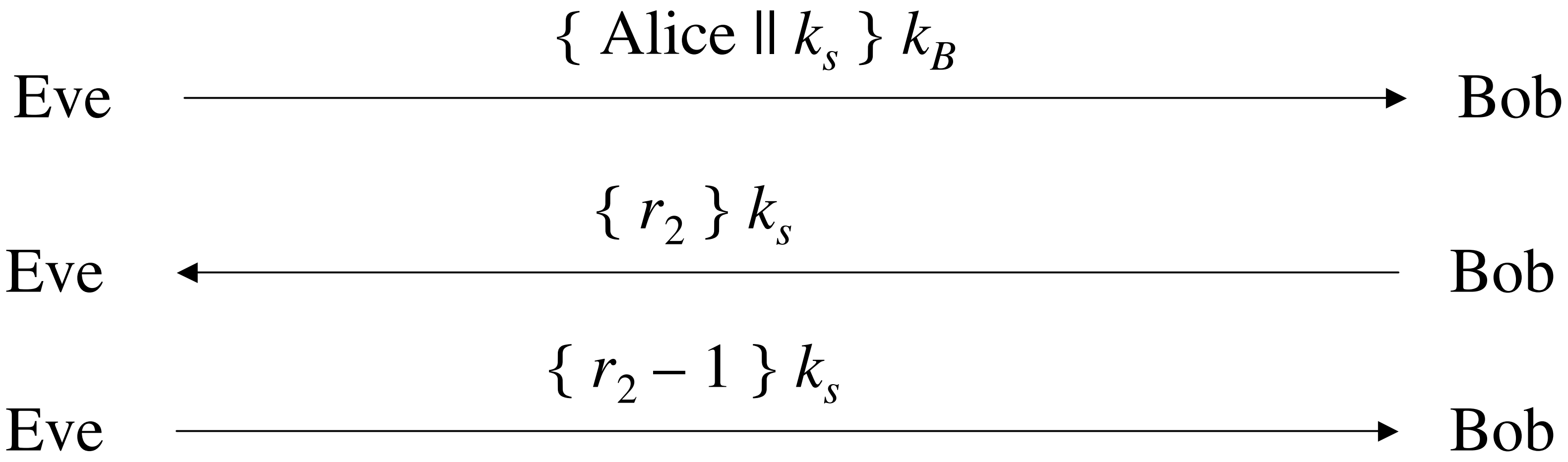
- Second message
  - Enciphered using key only she, Cathy knows
    - So Cathy enciphered it
  - Response to first message
    - As r_1 in it matches r_1 in first message
- Third message
  - Alice knows only Bob can read it
    - As only Bob can derive session key from message
  - Any messages enciphered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



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

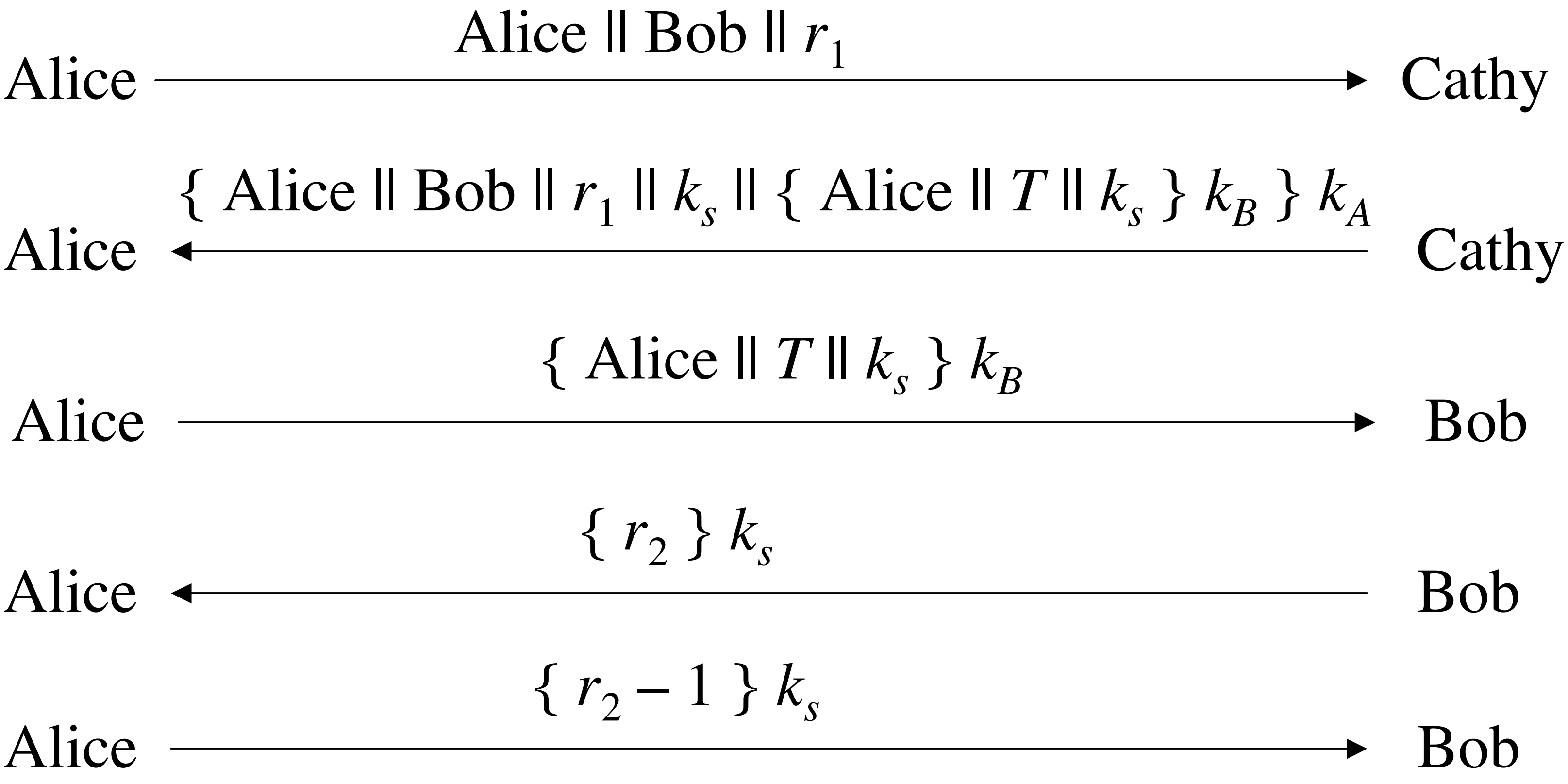
Eve $\xleftarrow{\{ r_2 \}\, k_s}$ Bob

Eve $\xrightarrow{\{ r_2 - 1 \}\, k_s}$ 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
- Weakness: 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

Needham-Schroeder with Denning-Sacco Modification



$$\text{Alice} \xrightarrow{\text{Alice} \parallel \text{Bob} \parallel r_1} \text{Cathy}$$

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

$$\text{Alice} \xrightarrow{\{\ \text{Alice} \parallel T \parallel k_s\ \}\ k_B} \text{Bob}$$

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

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

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

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*

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

where:

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

Protocol

user $\xrightarrow{\mathit{user} \parallel \mathit{TGS}}$ Cathy

Cathy $\xleftarrow{\{ k_{u,TGS} \}\, k_u \parallel T_{u,TGS}}$ *user*

user $\xrightarrow{\mathit{service} \parallel A_{u,TGS} \parallel T_{u,TGS}}$ TGS

user $\xleftarrow{\mathit{user} \parallel \{ k_{u,s} \}\, k_{u,TGS} \parallel T_{u,s}}$ TGS

user $\xrightarrow{A_{u,s} \parallel T_{u,s}}$ *service*

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

Analysis

- First two steps get user ticket to use TGS
  - User *u* can obtain session key only if *u* knows key shared with Cathy
- 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

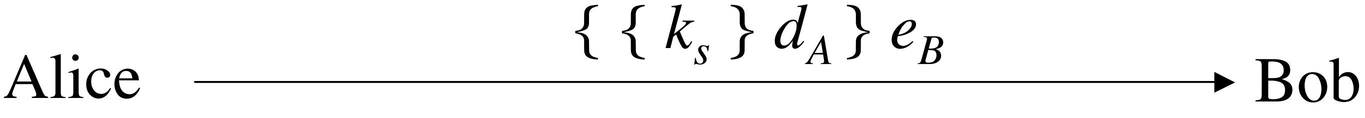
Public Key Key Exchange

- 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

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

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

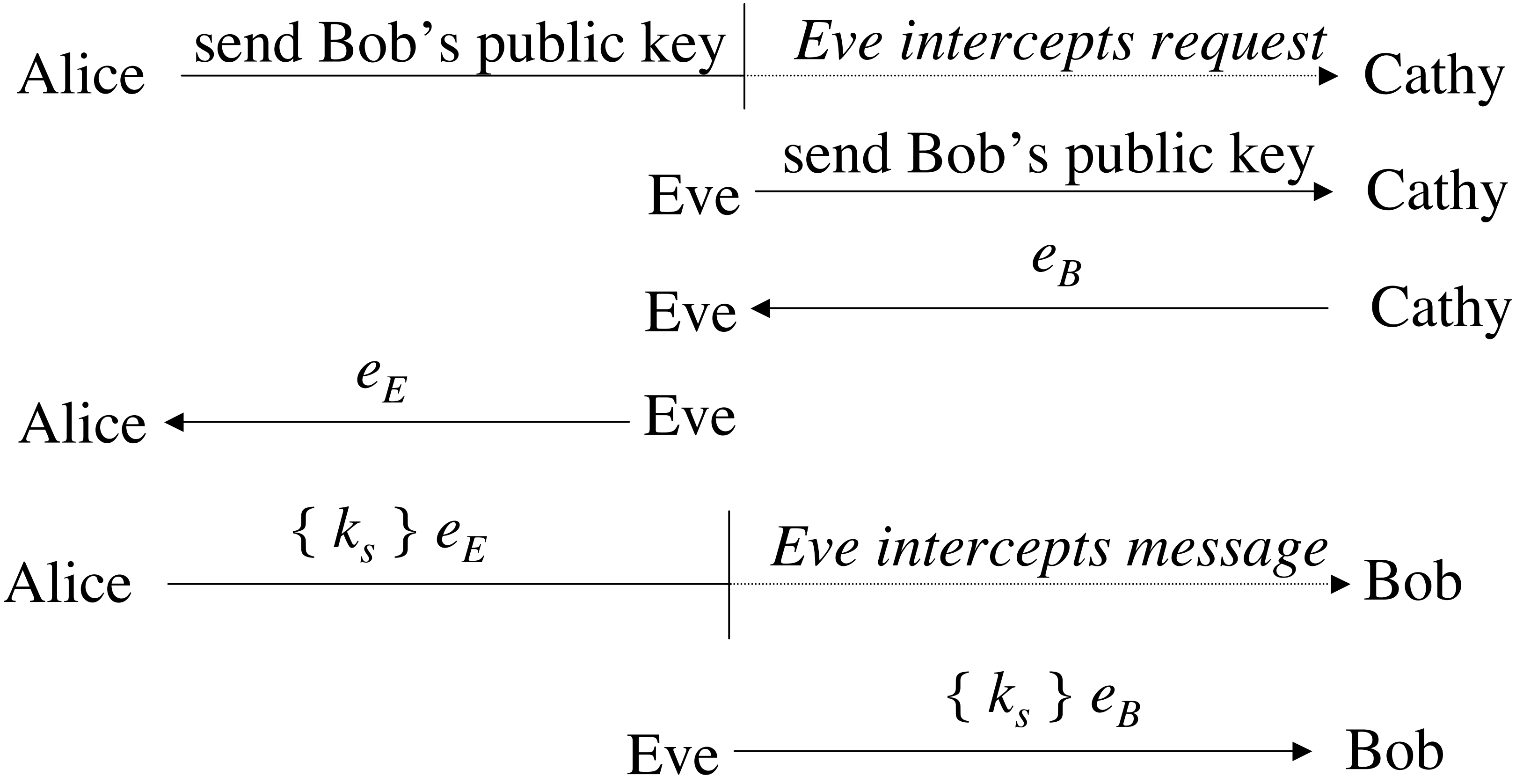


$$\text{Alice} \xrightarrow{\{\,\{\,k_s\,\}\,d_A\,\}\,e_B} \text{Bob}$$

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)

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

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
  - Two approaches: Merkle's tree, 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

X.509 Chains

- Some certificate components in X.509v3:
  - Version
  - Serial number
  - Signature algorithm identifier: hash algorithm
  - Issuer's name; uniquely identifies issuer
  - Interval of validity
  - Subject's name; uniquely identifies subject
  - Subject's public key
  - Signature: enciphered hash

X.509 Certificate Validation

- Obtain issuer's public key
  - The one for the particular signature algorithm
- Decipher signature
  - Gives hash of certificate
- Recompute hash from certificate and compare
  - If they differ, there's a problem
- Check interval of validity
  - This confirms that certificate is current

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>>

PGP Chains

- OpenPGP certificates structured into packets
  - One public key packet
  - Zero or more signature packets
- Public key packet:
  - Version (3 or 4; 3 compatible with all versions of PGP, 4 not compatible with older versions of PGP)
  - Creation time
  - Validity period (not present in version 3)
  - Public key algorithm, associated parameters
  - Public key

OpenPGP Signature Packet

- Version 3 signature packet
  - Version (3)
  - Signature type (level of trust)
  - Creation time (when next fields hashed)
  - Signer's key identifier (identifies key to encipher hash)
  - Public key algorithm (used to encipher hash)
  - Hash algorithm
  - Part of signed hash (used for quick check)
  - Signature (enciphered hash)
- Version 4 packet more complex

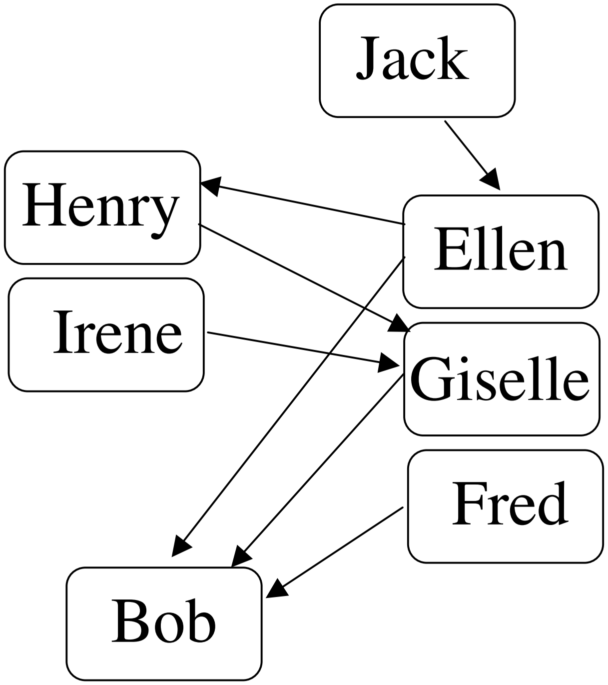
Signing

- Single certificate may have multiple signatures
- Notion of “trust” embedded in each signature
  - Range from “untrusted” to “ultimate trust”
  - Signer defines meaning of trust level (no standards!)
- All version 4 keys signed by subject
  - Called “self-signing”

Validating Certificates

- Alice needs to validate Bob's OpenPGP cert
  - Does not know Fred, Giselle, or Ellen
- Alice gets Giselle's cert
  - Knows Henry slightly, but his signature is at "casual" level of trust
- Alice gets Ellen's cert
  - Knows Jack, so uses his cert to validate Ellen's, then hers to validate Bob's

Arrows show signatures
Self signatures not shown



Storing Keys

- Multi-user or networked systems: attackers may defeat access control mechanisms
  - Encipher file containing key
    - Attacker can monitor keystrokes to decipher files
    - Key will be resident in memory that attacker may be able to read
  - Use physical devices like “smart card”
    - Key never enters system
    - Card can be stolen, so have 2 devices combine bits to make single key

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

Digital Signature

- Construct that authenticated origin, contents of message in a manner provable to a disinterested third party ("judge")
- Sender cannot deny having sent message (service is "nonrepudiation")
  - Limited to *technical* proofs
    - Inability to deny one's cryptographic key was used to sign
  - One could claim the cryptographic key was stolen or compromised
    - Legal proofs, *etc*., probably required; not dealt with here

Common Error

- Classical: Alice, Bob share key k
  - Alice sends m || { m } k to Bob

This is a digital signature

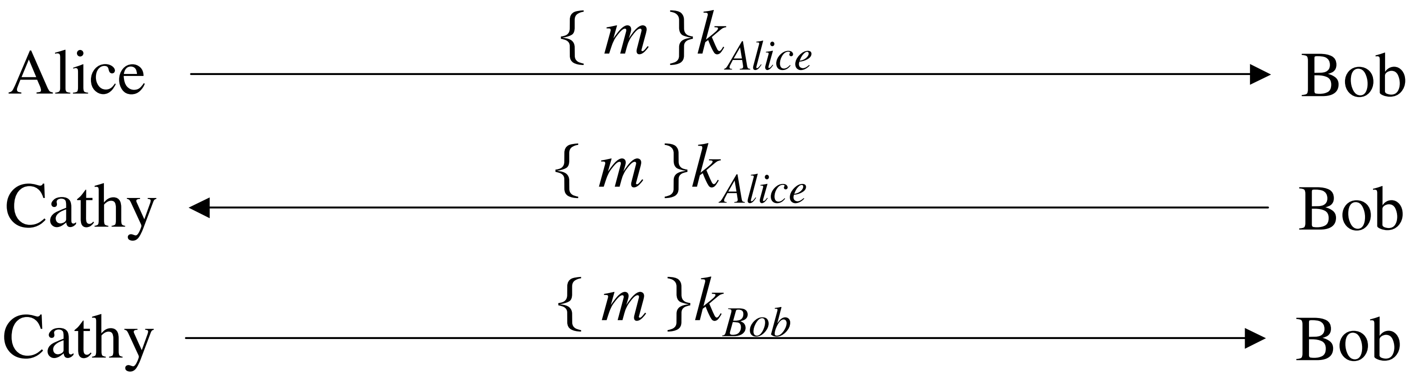
WRONG

This is not a digital signature

- Why? Third party cannot determine whether Alice or Bob generated message

Classical Digital Signatures

- Require trusted third party
  - Alice, Bob each share keys with trusted party Cathy
- To resolve dispute, judge gets $\{ m \} k_{Alice}$, $\{ m \} k_{Bob}$, and has Cathy decipher them; if messages matched, contract was signed



Alice $\xrightarrow{\{ m \} k_{Alice}}$ Bob

Cathy $\xleftarrow{\{ m \} k_{Alice}}$ Bob

Cathy $\xrightarrow{\{ m \} k_{Bob}}$ Bob

Public Key Digital Signatures

- Alice's keys are d_{Alice}, e_{Alice}
- Alice sends Bob

$$m \,||\, \{ m \}\, d_{Alice}$$

- In case of dispute, judge computes

$$\{ \{ m \}\, d_{Alice} \}\, e_{Alice}$$

- and if it is *m*, Alice signed message
  - She's the only one who knows d_{Alice}!

RSA Digital Signatures

- Use private key to encipher message
  - Protocol for use is *critical*
- Key points:
  - Never sign random documents, and when signing, always sign hash and never document
    - Mathematical properties can be turned against signer
  - Sign message first, then encipher
    - Changing public keys causes forgery

Attack #1

- Example: Alice, Bob communicating
  - $n_A = 95$, $e_A = 59$, $d_A = 11$
  - $n_B = 77$, $e_B = 53$, $d_B = 17$
- 26 contracts, numbered 00 to 25
  - Alice has Bob sign 05 and 17:
    - $c = m^{d_B} \bmod n_B = 05^{17} \bmod 77 = 3$
    - $c = m^{d_B} \bmod n_B = 17^{17} \bmod 77 = 19$
  - Alice computes 05×17 mod 77 = 08; corresponding signature is 03×19 mod 77 = 57; claims Bob signed 08
  - Judge computes $c^{e_B} \bmod n_B = 57^{53} \bmod 77 = 08$
    - Signature validated; Bob is toast

Attack #2: Bob's Revenge

- Bob, Alice agree to sign contract 06
- Alice enciphers, then signs:

  $(m^{e_B} \bmod 77)^{d_A} \bmod n_A = (06^{53} \bmod 77)^{11} \bmod 95 = 63$
- Bob now changes his public key
  - Computes r such that $13^r \bmod 77 = 6$; say, $r = 59$
  - Computes $re_B \bmod \phi(n_B) = 59 \times 53 \bmod 60 = 7$
  - Replace public key e_B with 7, private key $d_B = 43$
- Bob claims contract was 13. Judge computes:
  - $(63^{59} \bmod 95)^{43} \bmod 77 = 13$
  - Verified; now Alice is toast

Key Points

- Key management critical to effective use of cryptosystems
  - Different levels of keys (session *vs*. interchange)
- Keys need infrastructure to identify holders, allow revoking
  - Key escrowing complicates infrastructure
- Digital signatures provide integrity of origin and content

  Much easier with public key cryptosystems than with classical cryptosystems