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Key Management

EECE 412

Kerckhoff's Principle

"The security of a cryptosystem must not depend on keeping secret the crypto-algorithm. The security depends only on keeping secret the key"

Auguste Kerckhoff von Nieuwenhof

Dutch linguist

1883

Outline

- Key exchange
  - Session vs. interchange keys
  - Classical, public key methods
- Cryptographic key infrastructure
  - Certificates
- Quantum key distribution

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?

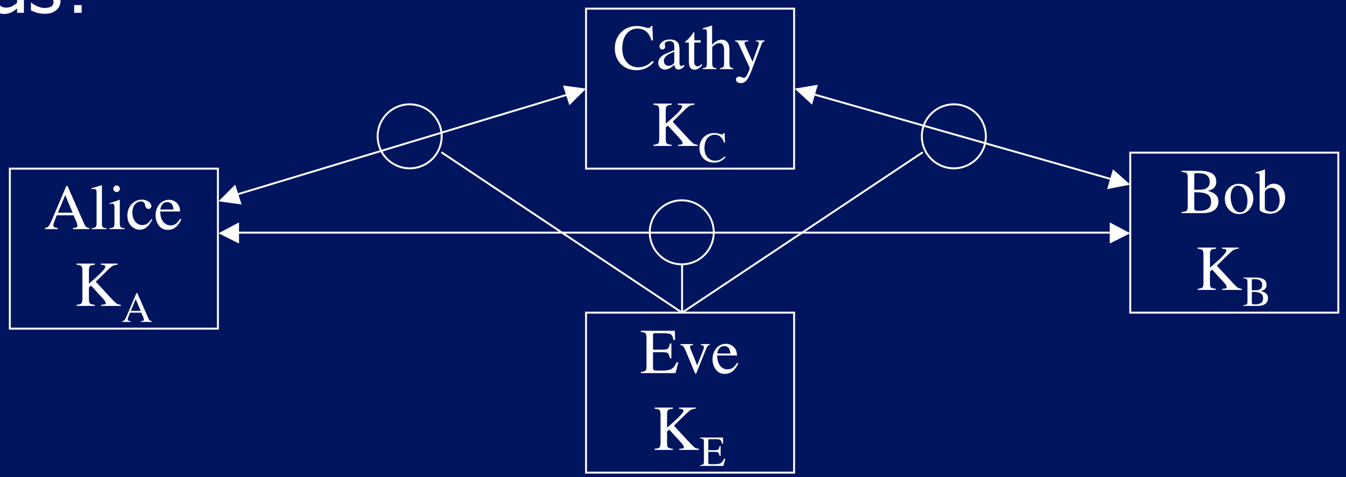
Key Exchange Algorithms

Goal: Alice, Bob get shared key

- Key cannot be sent in clear
- Alice, Bob may trust third party
- All cryptosystems, protocols publicly known

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
- Ideas?



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

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

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

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

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

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

Denning–Sacco Modification

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

Eve → Bob: $\{ \text{Alice} \parallel k_s \} k_B$

Eve ← Bob: $\{ r_2 \} k_s$

Eve → Bob: $\{ r_2 - 1 \} k_s$

Needham-Schroeder with Denning-Sacco Modification

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

Alice → Cathy

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

Alice ← Cathy

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

Alice → Bob

$\{ r_2 \} k_s$

Alice ← Bob

$\{ r_2 - 1 \} k_s$

Alice → Bob

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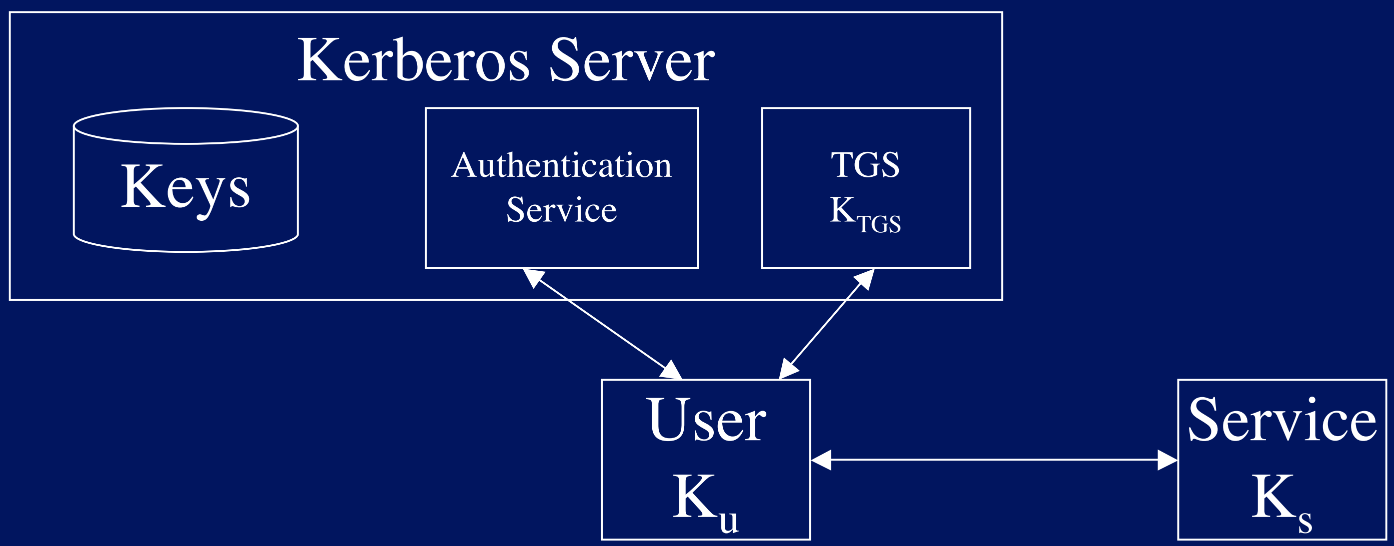
Kerberos

What is 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*



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

$$user \xrightarrow{user \parallel TGS} AS$$

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

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

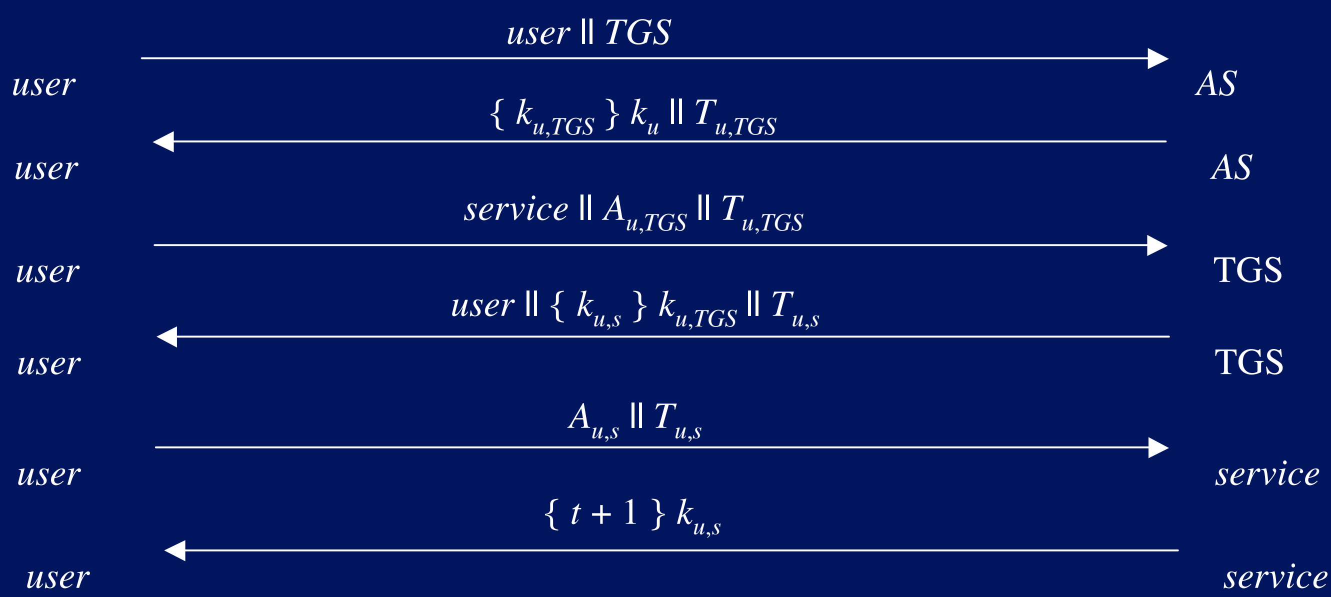
$$user \xleftarrow{user \parallel \{ k_{u,s} \} k_{u,TGS} \parallel T_{u,s}} \mathrm{TGS}$$

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

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

Analysis

- First two steps
  - get user ticket to use TGS
  - User *u* can obtain session key only if *u* knows key shared with AS
- Next four steps
  - *u* gets and uses ticket for service *s*
  - Service *s* validates request by checking sender (using $A_{u,s}$)
  - 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 Exchange

What is 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

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

Why Alice Can't Get Bob's Public Key

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

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Cryptographic Key Infrastructure

What's 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

Certificates

- Token (message) containing
  - Corresponding public key
  - Identity of principal (here, Alice)
  - 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

- Cathy issues Alice's certificate
    - Creates certificate
    - Generates hash of certificate
    - Enciphers hash with her private key
- Bob gets Alice's certificate
  - Validates
    - Obtains issuer's public key
    - Deciphers enciphered hash
    - Recomputes hash from certificate and compare
- Problem?
  - Bob needs Cathy's public key to validate certificate
  - Two approaches: Merkle's trees, signature chains

Certificate Signature Chains

- Purpose: getting issuer's public key
- Solutions:
  - tree-like hierarchies
  - Webs of trust (PGP)

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

PGP Certification

- 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!)

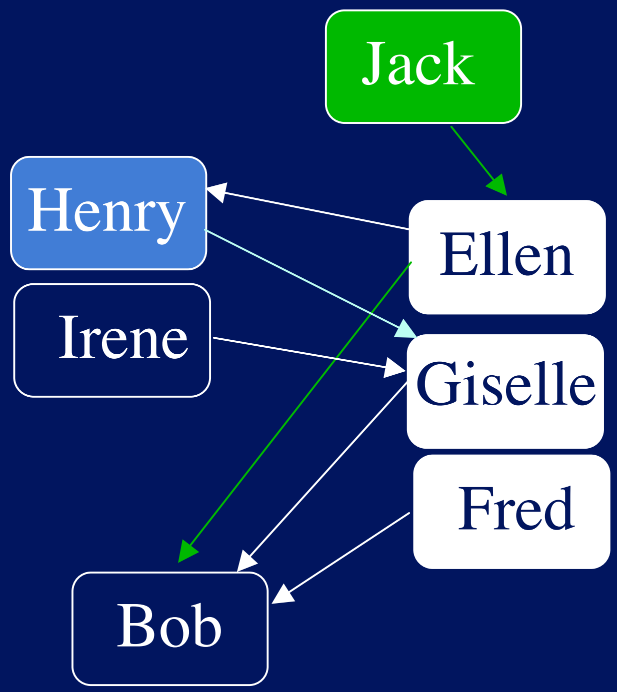
Validating Certificates

Alice needs to validate Bob's OpenPGP cert

- Does not know Fred, Giselle, or Ellen

1. Alice gets Giselle's cert
   - Knows Henry slightly, but his signature is at "casual" level of trust
2. 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



Key Revocation

- Why revoke a key?
  - 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

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

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Quantum Key Distribution (QKD)

Slides from this section are adopted from
Ravi Kumar Balachandran's slides on QKD available at
http://cse.unl.edu/~ashok/CSCE990Seminar/slides/ravib.ppt

Why QKD?

- The security of all current encryption algorithms depend on solving some computationally difficult problems
  - RSA – factoring large prime numbers
  - Symmetric ciphers -- brute force search of the key.
- Quantum computers (in the future) can speed up this process making such ciphers trivial to break
- Quantum theory also forms the basis for QKD

Polarization of light

- Every photon from a light source vibrates in all directions – unpolarized light
- When light is passed through a polarizer, the out coming light is said to be polarized with respect to the polarizer

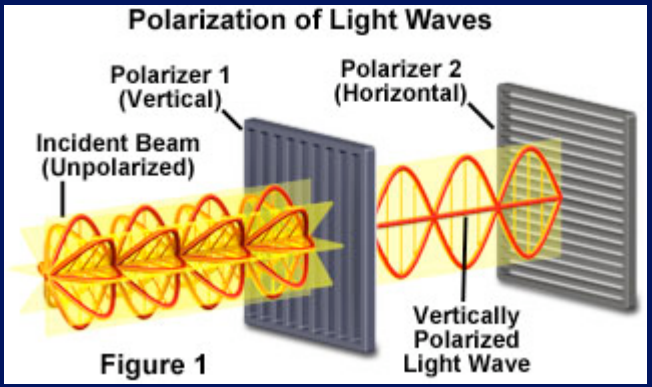

Figure 1

QKD Scheme

Alice's Sending Bases	×	+	+	×	×	+	×	+
Alice's Values	↘	↔	↔	↗	↘	↔	↗	↕
Bob's Receiving Bases	+	×	+	×	+	+	×	×
Bob's Values	↔	↗	↔	↗	↔	↔	↗	↘
Alice Confirms			✓	✓		✓	✓	
Key			1	0		1	0	

Implementation of QKD

- First prototype in 1989, two computers separated by a distance of 32 cm by Bennet
- Los Alamos – 1996 – 14 Km with fiber in the field
- British Telecom – 1998 – 30 Km
- Successful tests have been done over distances of 1.6 Km with no waveguide
- March 2002 – 67 Km using optical fiber working at 1550nm
- October 2003 -- world's first quantum cryptographic network: 6 QKD nodes in Cambridge, MA; 22 Km
- High-grade key material at rate 5Kb/s