Key Management

CS461/ECE422

Fall 2009

Reading

- Handbook of Applied Cryptography http://www.cacr.math.uwaterloo.ca/hac/
  - Section 11.3.2 attack on RSA signature
  - Section 13.8.3 Key Escrow
- Chapter 10 in Computer Security: Art and Science

Key Management Motivation

- Cryptographic security depends on keys
  - Size
  - Generation
  - Retrieval and Storage
- Example
  - House security system no good if key or code is under the mat

Overview

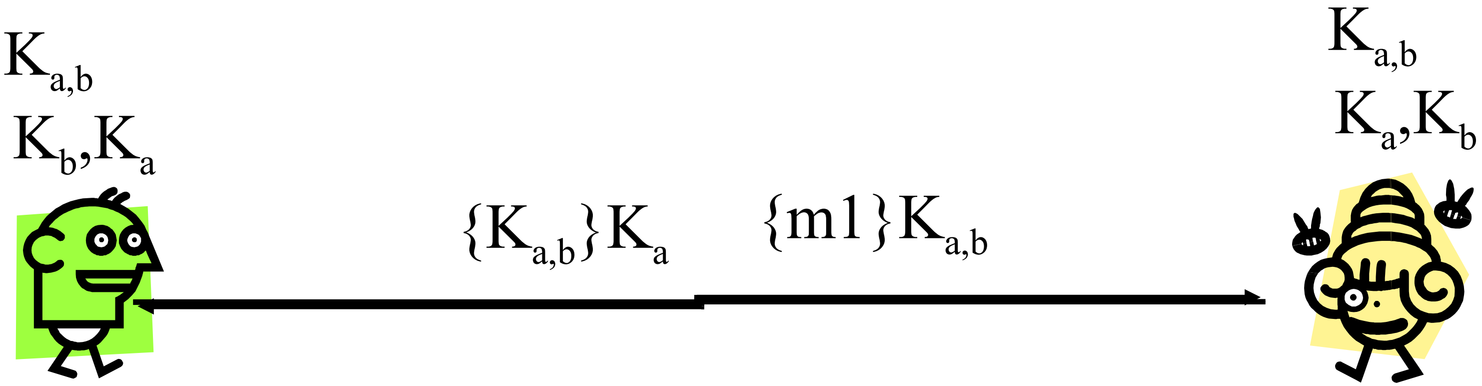
- Key Generation
- Key Exchange and management
  - Classical (symmetric)
  - Public/private
- Digital Signatures
- Key Storage

Notation

- $X \rightarrow Y : \{ Z \| W \} k_{X,Y}$
  - X sends Y the message produced by concatenating Z and W encrypted 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 encrypted using k_A, A's key, and W encrypted using $k_{A,T}$, the key shared by A and T
- r_1, r_2 nonces (nonrepeating random numbers)

Session and Interchange Keys

- Long lived Interchange Keys only exist to boot strap
- Short lived session keys used for bulk encryption



$K_{a,b}$

K_b, K_a

$\{K_{a,b}\}K_a$

$\{m1\}K_{a,b}$

$K_{a,b}$

K_a, K_b

Session and 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 encrypt m
    - To be used for this message *only*
    - Called a *session key*
  - She encrypts k_s with Bob's public key k_B
    - k_B encrypts 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 encrypt 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 encrypted message, compares, and gets plaintext at once

Key Generation

- Goal: generate keys that are difficult to guess
- Problem statement: given a set of *K* potential keys, choose one randomly
  - Equivalent to selecting a random number between 0 and *K*–1 inclusive
- Why is this hard: generating random numbers
  - Actually, numbers are usually *pseudo-random*, that is, generated by an algorithm

What is “Random”?

- *Sequence of cryptographically random numbers*: a sequence of numbers n_1, n_2, … such that for any integer $k > 0$, an observer cannot predict n_k even if all of n_1, …, n_{k-1} are known
  - Best: physical source of randomness
    - Random pulses
    - Electromagnetic phenomena
    - Characteristics of computing environment such as disk latency
    - Ambient background noise

What is “Pseudorandom”?

- *Sequence of cryptographically pseudorandom numbers*: sequence of numbers intended to simulate a sequence of cryptographically random numbers but generated by an algorithm
  - Very difficult to do this well
    - Linear congruential generators [$n_k = (an_{k-1} + b) \bmod n$] broken
    - Polynomial congruential generators [$n_k = (a_j n_{k-1}^j + \ldots + a_1 n_{k-1}$ $a_0) \bmod n$] broken too
    - Here, “broken” means next number in sequence can be determined

Best Pseudorandom Numbers

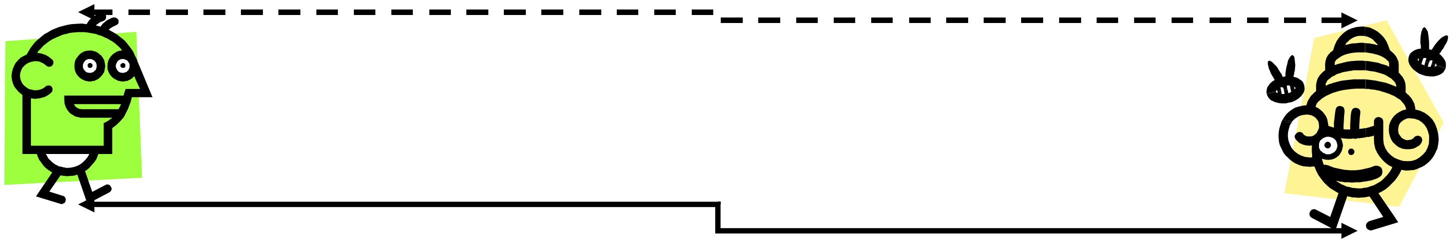
- *Strong mixing function*: function of 2 or more inputs with each bit of output depending on some nonlinear function of all input bits
  - Examples: DES, MD5, SHA-1, avalanche effect
  - Use on UNIX-based systems:

    ```
    (date; ps gaux) | md5
    ```

    where “ps gaux” lists all information about all processes on system

Separate Channel

- Ideally you have separate secure channel for exchanging keys
  - – Direct secret sharing grows at N^2



Telephone, separate data network, ESP, sneaker net

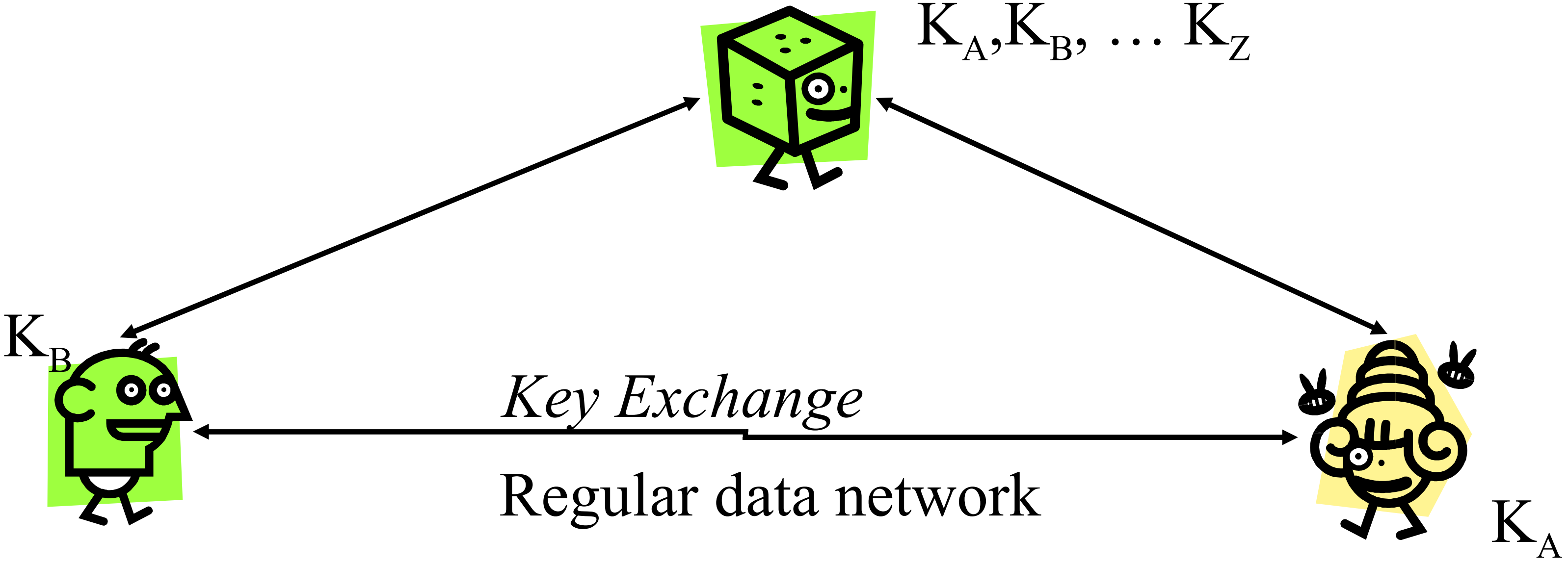
Regular data network

Key Exchange Algorithms

- Goal: Alice, Bob get shared key
  - All cryptosystems, protocols publicly known
    - Only secret data is the keys
  - Anything transmitted is assumed known to attacker
    - Key cannot be sent in clear as attacker can listen in
  - Options
    - Key can be sent encrypted, or derived from exchanged data plus data not known to an eavesdropper (Diffie-Hellman)
    - Alice, Bob may trust third party

Shared Channel: Trusted Third Party

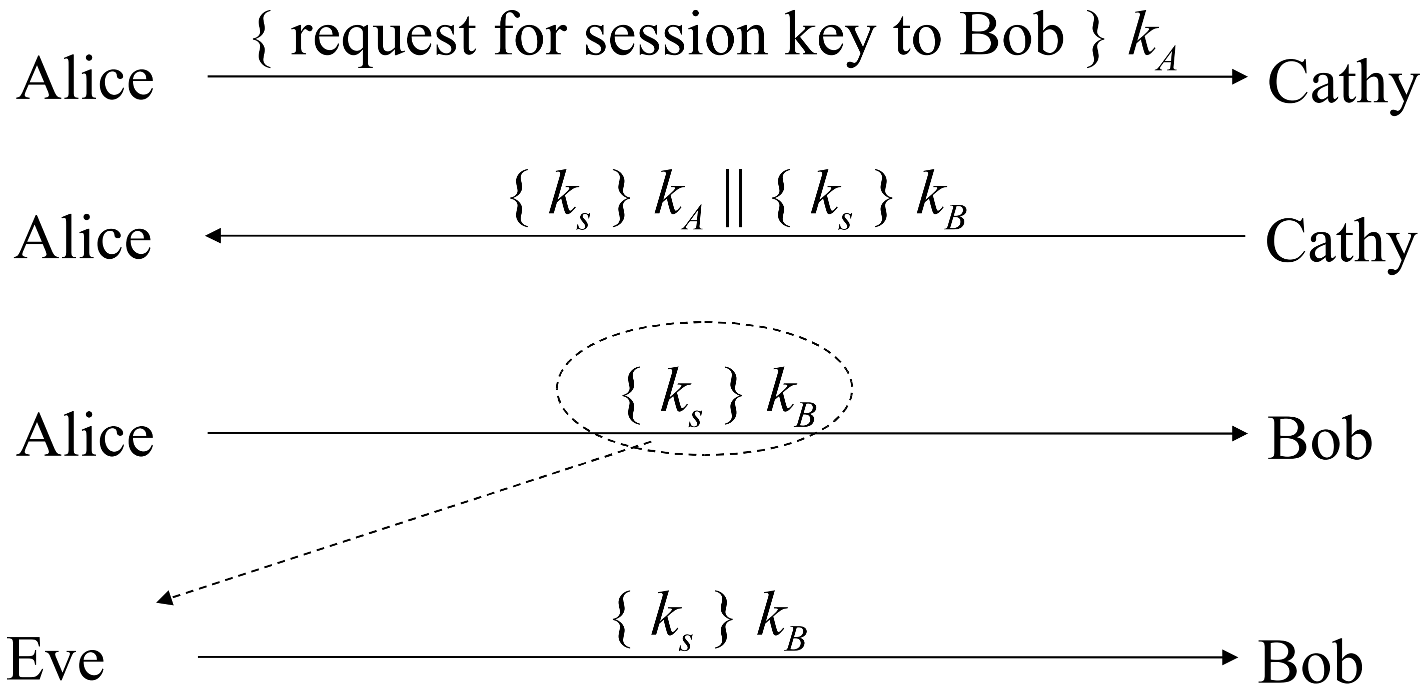
- Generally separate channel is not practical
  - No trustworthy separate channel
  - Want to scale linearly with additional users



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

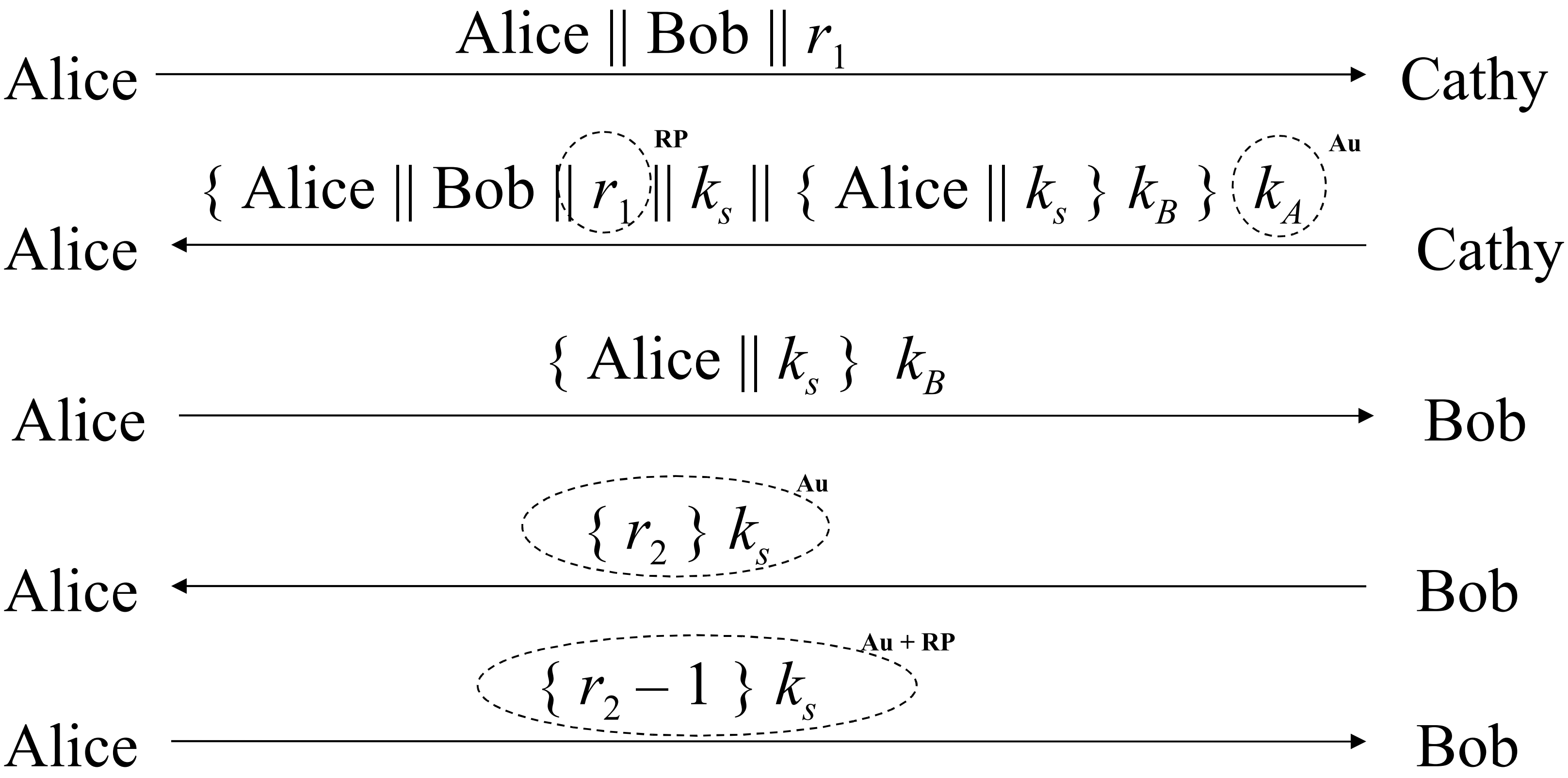
Alice $\xrightarrow{\{\, k_s \,\}\, k_B}$ Bob

Eve $\xrightarrow{\{\, k_s \,\}\, k_B}$ 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



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

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

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

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

Alice $\xrightarrow{\overset{\text{Au + RP}}{\{\, r_2 - 1 \,\}\, k_s}}$ Bob

Argument: Alice talking to Bob

- Second message
  - Encrypted using key only she, Cathy knows
    - So Cathy encrypted 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 encrypted with that key are from Bob

Argument: Bob talking to Alice

- Third message
  - Encrypted using key only he, Cathy know
    - So Cathy encrypted 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 decrypt r_2 and so can't respond, or responds incorrectly

Denning-Sacco Modification

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

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

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

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

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

Needham-Schroeder with Denning-Sacco Modification

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

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

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

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

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

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
  - Encrypted part belongs to exchange as r_1 matches r_1 in encrypted part of first message

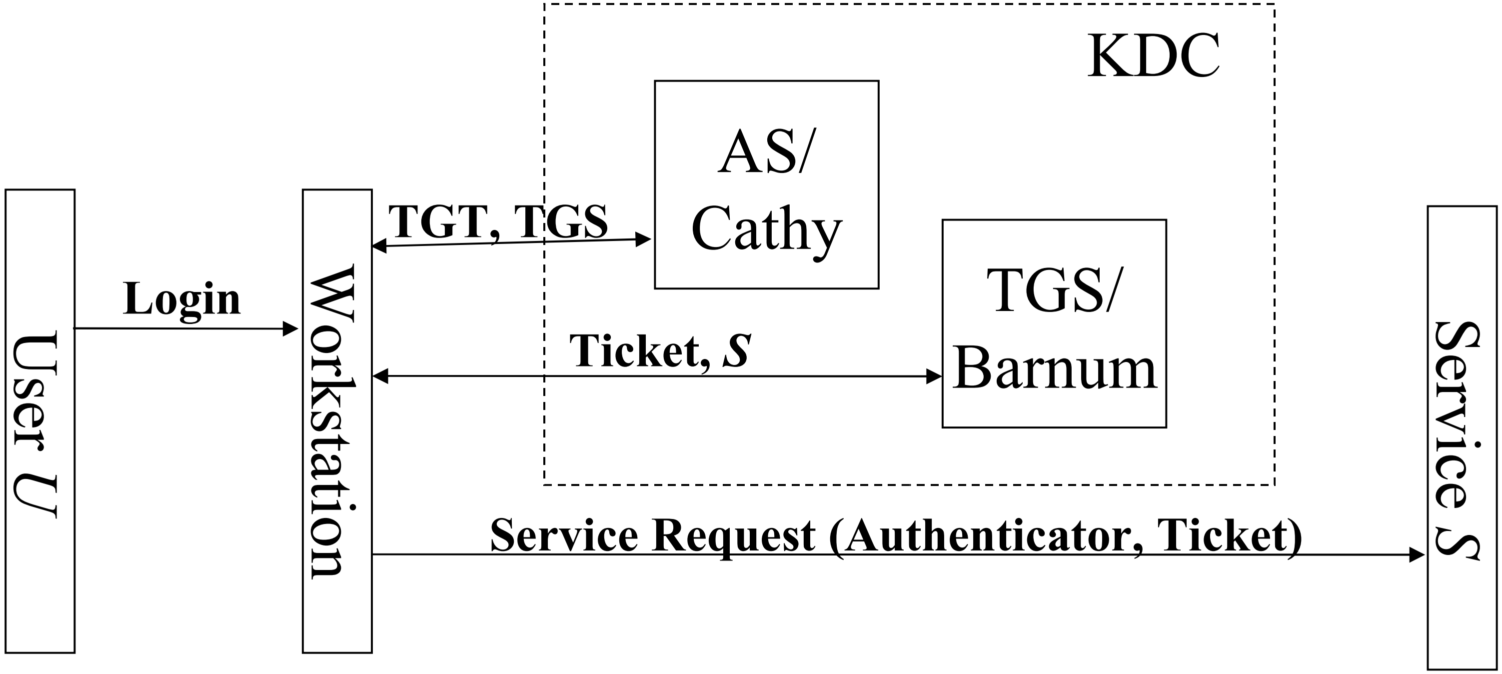
Argument: Bob talking to Alice

- 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
  - Encrypted 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
  - Nonce r_1 matches nothing, so is rejected

Network Authentication with Kerberos



Legend: AS = Authentication Server; TGS = Ticket Granting Server
KDC = Key Distribution Center; TGT = Ticket Granting Ticket;

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
- Two Competing Versions: 4 and 5
  - Version 4 discussed here

Idea

- User u authenticates to Kerberos AS
  - Obtains ticket (TGT) $T_{u,TGS}$ 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 TGS

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

  where:

  - $k_{u,\mathrm{TGS}}$ is session key for user and TGS
  - $k_{\mathrm{AS,TGS}}$ is long-term key shared between AS and TGS
  - Valid time is interval for which ticket valid; e.g., a day
  - *u*'s address may be IP address or something else
    - Note: more fields, but not relevant here

Ticket

- 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
- k_s is long-term key shared between TGS and S
- Valid time is interval for which ticket valid; e.g., hours/days
- *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*

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

where:

- Generation time is when authenticator generated
  - Note: more fields, not relevant here

Protocol

* Initially, user *u* registers with KDC and establishes a password
  - used to derive long-term key k_u

* User U logs into workstation (WS) using password

M1: *user/ws* $\xrightarrow{\text{[AS\_REQ]: } user \parallel TGS}$ AS

M2: *user/ws* $\xleftarrow{\text{[AS\_REP]: } \{ k_{u,TGS} \} k_u \parallel T_{u,TGS}}$ AS

* WS decrypts session key $k_{u,TGS}$ using supplied password

Protocol

M3: *user/ws* $\xrightarrow{\text{[TGS\_REQ]: } service \parallel A_{u,TGS} \parallel T_{u,TGS}}$ TGS

* TGS decrypts ticket using long-term key $k_{AS,TGS}$

M4: *user/ws* $\xleftarrow{\text{[TGS\_REP]: } user \parallel \{ k_{u,s} \} k_{u,TGS} \parallel T_{u,s}}$ TGS

M5: *user/ws* $\xrightarrow{\text{[AP\_REQ]: } A_{u,s} \parallel T_{u,s}}$ *service*

* Service decrypts ticket using long-term key $k_{TGS,s}$

M6: *user/ws* $\xleftarrow{\text{[AP\_REP]: } \{ t + 1 \} k_{u,s}}$ *service*

Summary of Messages

- First two messages get user ticket to use TGS
  - User *u* can obtain session key only if *u* knows key shared with AS
- Next four messages 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
  - Typical clock skew allowed is 5 minutes
  - 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

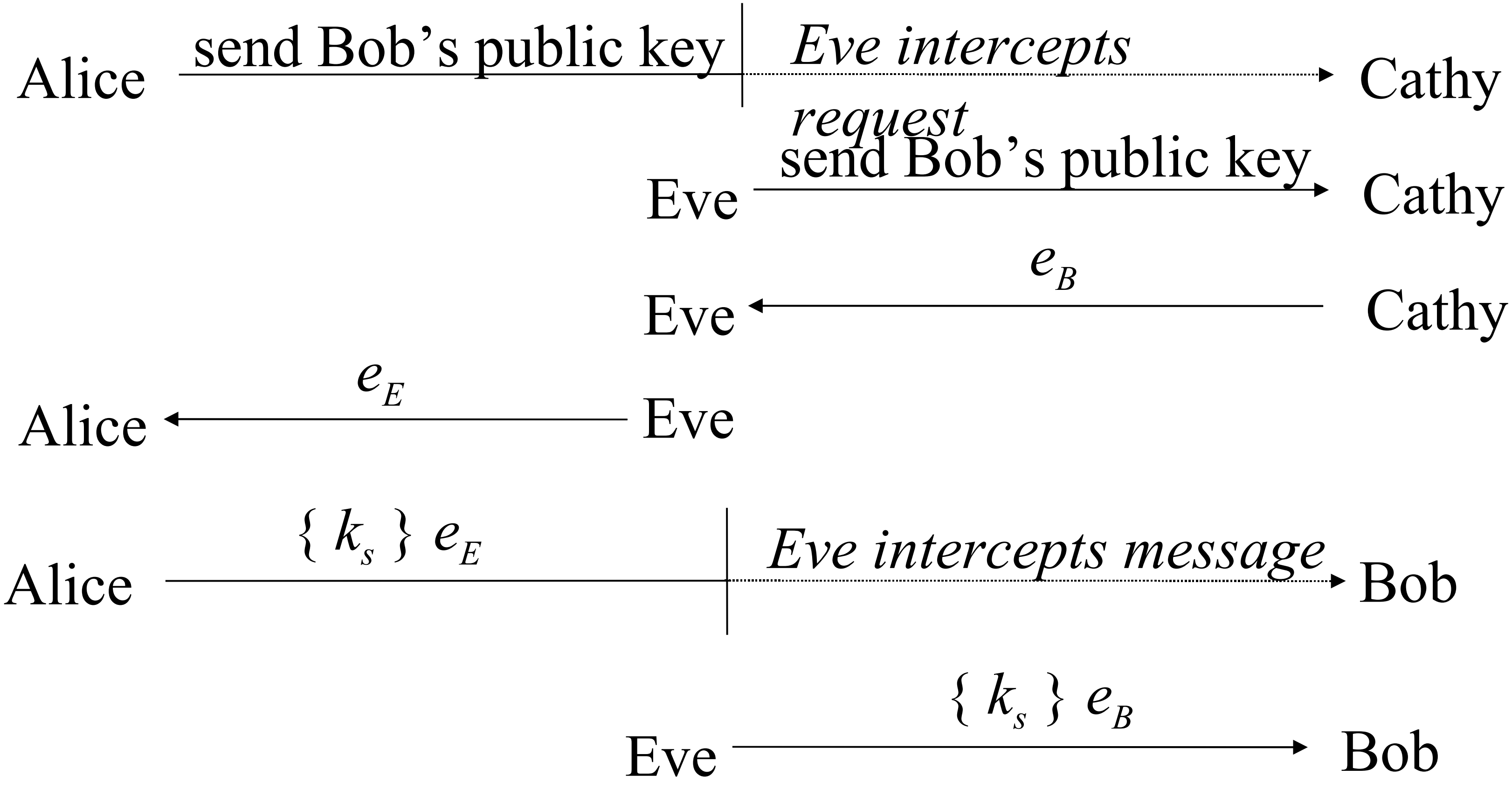
- Vulnerable to forgery or replay
  - Because e_B known to anyone, Bob has no assurance that Alice sent message
- Simple fix uses Alice's private key
  - k_s is desired session key

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

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)
  - Compute hash (message digest) of token

Hash encrypted by trusted authority (here, Cathy) using private key: called a “signature”

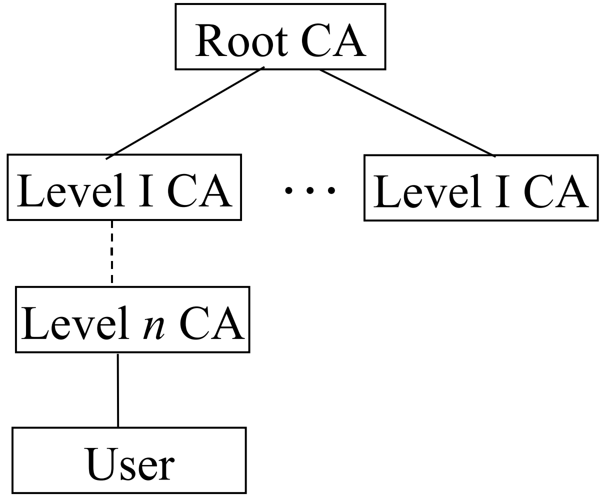
$$C_A = e_A \parallel \text{Alice} \parallel T \parallel \{\mathrm{h}(e_A \parallel \text{Alice} \parallel T)\}\, d_C$$

Use

- Bob gets Alice's certificate
  - If he knows Cathy's public key, he can validate the certificate
    - Decrypt encrypted hash using Cathy's public key
    - Re-compute hash from certificate and compare
    - Check validity
    - Is the principal Alice?
  - Now Bob has Alice's public key
- Problem: Bob needs Cathy's public key to validate certificate
  - That is, secure distribution of public keys
  - Solution: Public Key Infrastructure (PKI) using trust anchors called Certificate Authorities (CAs) that issue certificates

PKI Trust Models

- **A Single Global CA**
  - Unmanageable, inflexible
  - There is no universally trusted organization
- **Hierarchical CAs (Tree)**



  - Offloads burden on multiple CAs
  - Need to verify a chain of certificates
  - Still depends on a single trusted root CA

PKI Trust Models

- Hierarchical CAs with cross-certification
  - Multiple root CAs that are cross-certified
  - Cross-certification at lower levels for efficiency
- Web Model
  - Browsers come pre-configured with multiple trust anchor certificates
  - New certificates can be added
- Distributed (e.g., PGP)
  - No CA; instead, users certify each other to build a "web of trust"

X.509 Certificates

- 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: encrypted hash

Validation and Cross-Certifying

- 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
- 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 encrypt hash)
  - Public key algorithm (used to encrypt hash)
  - Hash algorithm
  - Part of signed hash (used for quick check)
  - Signature (encrypted hash)
- Version 4 packet more complex

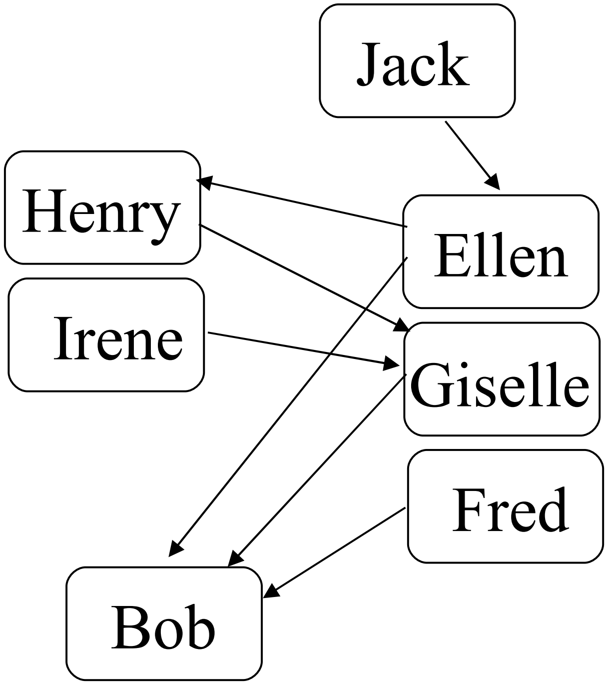
Signing

- 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



Key Revocation

- Certificates invalidated *before* expiration
  - Usually due to compromised key
  - May be due to change in circumstance (*e.g.,* someone leaving company)
- Problems
  - Verify that 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

Simple Approach

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

This is a digital signature

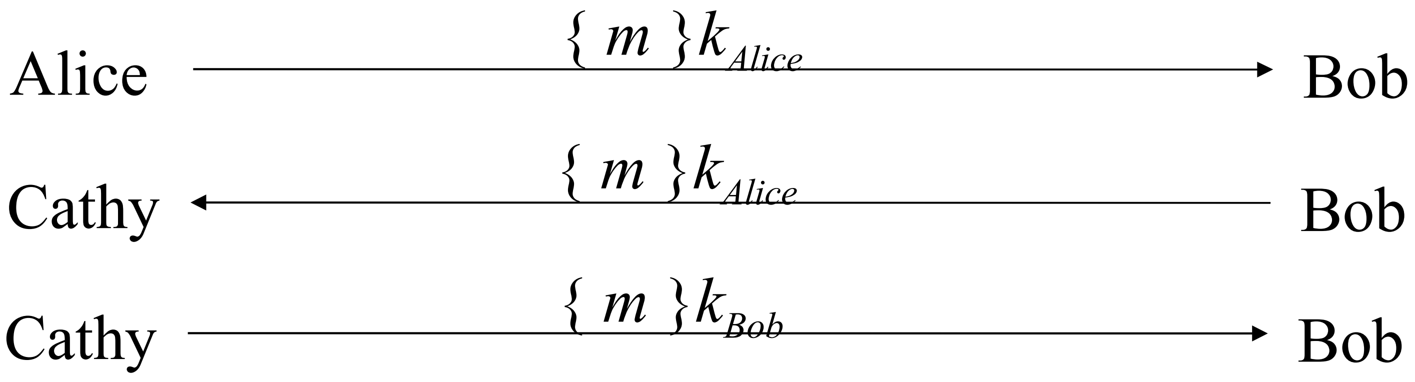
WRONG

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 encrypt 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 encrypt
    - Changing public keys causes forgery

Attack #1

- m_1 x m_2 mod $n_b = m$
- Get Bob to sign m_1 and m_2
- m_1^d mod n_b x m_2^d mod n_b =
- $(m_1^d$ x $m_2^d)$ mod n_b =
- $(m_1$ x $m_2)^d$ mod $n_b = m^d$ mod n_b

Attack #1 example

- 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 $05 \times 17 \bmod 77 = 08$; corresponding signature is $03 \times 19 \bmod 77 = 57$; 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 m but wants it to appear that she signed contract M
  - Alice encrypts, then signs:

    $(m^{eB} \bmod n_B)^{dA} \bmod n_A$
- Bob now changes his public key
  - Computes r such that $M^r \bmod n_B = m$
  - Replace public key e'_B with re_B and computes a new matching private key d'_B
- Bob claims contract was M. Judge computes:
  - $(c^{eA} \bmod n_A)^{d'B} \bmod n_B = M$

Attack #2 Example

- Bob, Alice agree to sign contract 06
- Alice encrypts, 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

El Gamal Digital Signature

- Relies on discrete log problem
- Choose p prime, g, $d < p$; compute $y = g^d \bmod p$
- Public key: (y, g, p); private key: d
- To sign contract m:
  - Choose k relatively prime to p–1, and not yet used
  - Compute $a = g^k \bmod p$
  - Find b such that $m = (da + kb) \bmod p{-}1$
  - Signature is (a, b)
- To validate, check that
  - $y^a a^b \bmod p = g^m \bmod p$

Example

- Alice chooses $p = 29$, $g = 3$, $d = 6$

  $y = 3^6 \bmod 29 = 4$
- Alice wants to send Bob signed contract 23
  - Chooses $k = 5$ (relatively prime to 28)
  - This gives $a = g^k \bmod p = 3^5 \bmod 29 = 11$
  - Then solving $23 = (6 \times 11 + 5b) \bmod 28$ gives $b = 25$
  - Alice sends message 23 and signature (11, 25)
- Bob verifies signature: $g^m \bmod p = 3^{23} \bmod 29 = 8$ and $y^a a^b \bmod p = 4^{11} 11^{25} \bmod 29 = 8$
  - They match, so Alice signed

Attack

- Eve learns k, corresponding message m, and signature (a, b)
  - Extended Euclidean Algorithm gives d, the private key
- Example from above: Eve learned Alice signed last message with $k = 5$

$$m = (da + kb) \bmod p-1 = (11d + 5\times25) \bmod 28$$

so Alice's private key is $d = 6$

Storing Keys

- Multi-user or networked systems: attackers may defeat access control mechanisms
  - Encrypt file containing key
    - Attacker can monitor keystrokes to decrypt 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 Escrow

- *Key escrow system* allows authorized third party to recover key
  - Useful when keys belong to roles, such as system operator, rather than individuals
  - Business: recovery of backup keys
  - Law enforcement: recovery of keys that authorized parties require access to
- Goal: provide this without weakening cryptosystem
- Very controversial

Desirable Properties

- Escrow system should not depend on encryption algorithm
- Privacy protection mechanisms must work from end to end and be part of user interface
- Requirements must map to key exchange protocol
- System supporting key escrow must require all parties to authenticate themselves
- If message to be observable for limited time, key escrow system must ensure keys valid for that period of time only

Beth, Knobloch, Otten, Simmons, Wichmann 94

Components

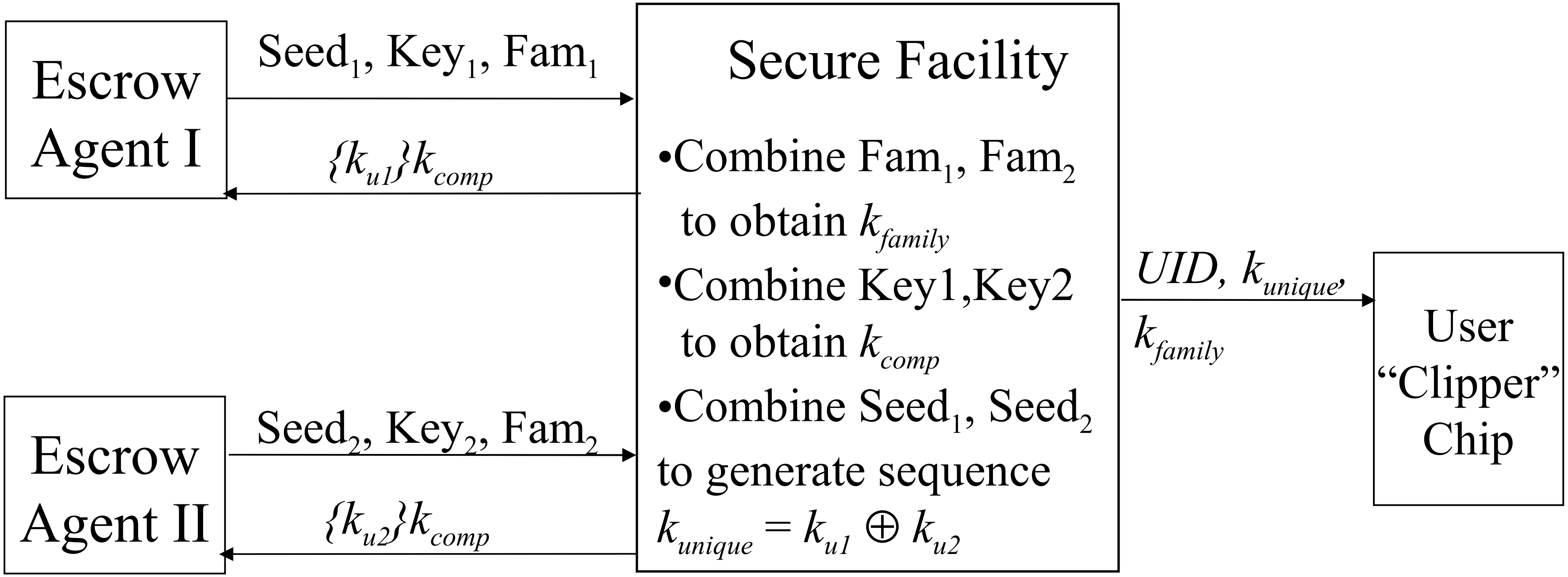
- User security component
  - Does the encryption, decryption
  - Supports the key escrow component
- Key escrow component
  - Manages storage, use of data recovery keys
- Data recovery component
  - Does key recovery

Example: EES, Clipper Chip

- Escrow Encryption Standard
  - Set of interlocking components
  - Designed to balance need for law enforcement access to enciphered traffic with citizens' right to privacy
- Clipper chip given to users prepares per-message escrow information
  - Each chip numbered uniquely by UID
  - Special facility programs chip
- Key Escrow Decrypt Processor (KEDP)
  - Available to agencies authorized to read messages
- Details in Handbook of Applied Cryptography
  - http://www.cacr.math.uwaterloo.ca/hac/about/chap13.p

NIST 94

Initialization of User Security Component



Escrow Agent I

Seed_1, Key_1, Fam_1

$\{k_{u1}\}k_{comp}$

Escrow Agent II

Seed_2, Key_2, Fam_2

$\{k_{u2}\}k_{comp}$

Secure Facility

- Combine Fam_1, Fam_2 to obtain k_{family}
- Combine Key1,Key2 to obtain k_{comp}
- Combine Seed_1, Seed_2 to generate sequence $k_{unique} = k_{u1} \oplus k_{u2}$

UID, k_{unique}, k_{family}

User "Clipper" Chip

User Security Component

- Unique device key k_{unique}
- Non-unique family key k_{family}
- Cipher is Skipjack
  - Classical cipher: 80 bit key, 64 bit input, output blocks
- Generates Law Enforcement Access Field (LEAF) of 128 bits:
  - $\{ \mathrm{UID} \,||\, \{ k_{session} \}\, k_{unique} \,||\, hash \}\, k_{family}$
  - *hash*: 16 bit authenticator from session key and initialization vector

Obtaining Access

- Alice obtains legal authorization to read message
- She runs message LEAF through KEDP
    - LEAF is $\{ \text{UID} \parallel \{ k_{session} \} k_{unique} \parallel hash \} k_{family}$
- KEDP uses (known) k_{family} to validate LEAF, obtain sending device's UID
- Authorization, LEAF taken to escrow agencies

Agencies' Role

- Each validates authorization
- Each supplies $\{ k_{ui} \} k_{comp}$, corresponding key number
- KEDP takes these and LEAF: $\{ \text{UID} \,\|\, \{ k_{session} \} k_{unique} \,\|\, hash \} k_{family}$
  - Key numbers produce k_{comp}
  - k_{comp} produces k_{u1} and k_{u2}
  - k_{u1} and k_{u2} produce k_{unique}
  - k_{unique} and LEAF produce $k_{session}$

Problems

- *hash* too short
  - LEAF 128 bits, so given a hash:
    - 2^{112} LEAFs show this as a valid hash
    - 1 has actual session key, UID
    - Takes about 42 minutes to generate a LEAF with a valid hash but meaningless session key and UID
      - Turns out deployed devices would prevent this attack
  - Scheme does not meet temporal requirement
    - *As* k_{unique} fixed for each unit, once message is read, any future messages can be read

Yaksha Security System

- Key escrow system meeting all 5 criteria
- Based on RSA, central server
  - Central server (Yaksha server) generates session key
- Each user has 2 private keys
  - Alice's modulus n_A, public key e_A
  - First private key d_{AA} known only to Alice
  - Second private key d_{AY} known only to Yaksha central server
  - $d_{AA}\, d_{AY} = d_A \bmod \Phi(n_{A)}$

Ganesan 96

Alice and Bob

- Alice wants to send message to Bob
  - Alice asks Yaksha server for session key
  - Yaksha server generates $k_{session}$
  - Yaksha server sends Alice the key as:

$$C_A = (k_{session})^{d_{AY} e_A} \bmod n_A$$

  - Alice computes

$$(C_A)^{d_{AA}} \bmod n_A = k_{session}$$

Analysis

- Authority can read only one message per escrowed key
  - Meets requirement 5 (temporal one), because “time” interpreted as “session”
- Independent of message enciphering key
  - Meets requirement 1
  - Interchange algorithm, keys fixed
- Others met by supporting infrastructure

Alternate Approaches

- Tie to time
  - Session key not given as escrow key, but related key is
  - To derive session key, must solve instance of discrete log problem
- Tie to probability
  - Oblivious transfer: message received with specified probability
  - Idea: *translucent cryptography* allows fraction *f* of messages to be read by third party
  - Not key escrow, but similar in spirit

Key Points

- Key management critical to effective use of cryptosystems
  - Different levels of keys (session *vs*. interchange)
- Exchange algorithms can be vulnerable to attacks
  - Replay
  - Identity integrity
- Digital signatures provide integrity of origin and content

  Much easier with public key cryptosystems than with classical cryptosystems
- Keys need infrastructure to identify holders, allow revoking and possible escrow