These Slides are prepared from
Matt Bishop slides and book "Introduction to Computer Security"
Benefiting from the Slides posted by Ahmad Al-Mulhem

# Cryptography II

## ***Cipher Techniques - Ch 10***

## Key Management - Ch 9

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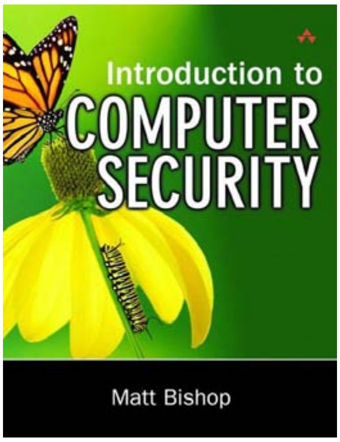





# Chapter 10: Cipher Techniques

- Some Problems
- Types of Ciphers
- Networks
- Examples

# Overview

Problems
- What can go wrong if you naively use ciphers
- Three Attacks, as simple examples !!

Cipher types
- Stream or block ciphers?

Networks
- Link vs end-to-end use

Examples
- Privacy-Enhanced Electronic Mail (PEM)
- Security at the Network Layer (IPsec)



# Network & Cryptography

- Cryptography >>> foundation for secure communication
- Encryption algorithms and protocols are valuable components/tools
- Cryptosystems over a network >>> many problems!
- Cryptography is sensitive to environment:
  - Using cipher requires knowledge of environment, and threats in the environment, in which cipher will be used
  - Is the set of possible messages small?
  - Do the messages exhibit regularities that remain after encipherment?
  - Can an active wiretapper rearrange or change parts of the message?

## 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*



## Attack #1: Precomputation (Example)

- Cathy knows Alice will send Bob one of two messages: enciphered BUY, or enciphered SELL: {BUY, SELL}
- Using public key $e_{Bob}$, Cathy precomputes
  - $c_1$ = { BUY, $e_{Bob}$}
  - $c_2$ = { SELL, $e_{Bob}$ }
- Cathy sees Alice send Bob $c_2$
- Cathy knows Alice sent SELL

## Attack # 2: Misordered Blocks

Alice sends Bob message

– $n_{Bob} = 77$, $e_{Bob} = 17$, $d_{Bob} = 53$
– Message is LIVE (11 08 21 04)
– Enciphered message is 44 57 21 16

Eve intercepts it, rearranges blocks

– Now enciphered message is 16 21 57 44

Bob gets enciphered message, deciphers it

– He sees EVIL



## Notes

Digitally signing each block won't stop this attack

Two approaches:

– Cryptographically hash the *entire* message and sign it

– Place sequence numbers in each block of message, so recipient can tell intended order
  - Then you sign each block

## Attack # 3: Statistical Regularities

If plaintext repeats, ciphertext may too

Example using DES:

- input (in hex):
  3231 3433 3635 3837 3231 3433 3635 3837
- corresponding output (in hex):
  ef7c 4bb2 b4ce 6f3b ef7c 4bb2 b4ce 6f3b

Fix: cascade blocks together (chaining)



## Summary

What These Mean:

Use of:

- strong cryptosystems
- well-chosen (or random) keys

–Is this enough to be secure?? NO….

# Stream & Block Ciphers

$E$ encipherment function

- $E_k(b)$ encipherment of message $b$ with key $k$
- In what follows, $m = b_1 b_2 \ldots$, each $b_i$ of fixed length

Block cipher

- $E_k(m) = E_k(b_1)E_k(b_2) \ldots$

Stream cipher

- $k = k_1 k_2 \ldots$
- $E_k(m) = E_{k1}(b_1)E_{k2}(b_2) \ldots$
- If $k_1 k_2 \ldots$ repeats itself, cipher is *periodic* and the key-length of its period is one cycle of $k_1 k_2 \ldots$



# Examples

DES - Block cipher

- $b_i$ = 64 bits, $k$ = 56 bits
- Each $b_i$ enciphered separately using $k$

Vigenère cipher - Stream cipher

- $b_i$ = 1 character, $k = k_1 k_2 \ldots$ where $k_i$ = 1 character
- Each $b_i$ enciphered using $k_{i \bmod \text{length}(k)}$

One time pad - Stream cipher ------- Good example

- XOR'ing each bit of key with one bit of message
- Not periodic – key period is never supposed to repeat

## Self-Synchronous Stream Cipher
### key drawn from plaintext

Take key from message itself (*autokey*)

Example: Vigenère

- *key* XTHEBOYHASTHEBA
- *plaintext* THEBOYHASTHEBAG
- *ciphertext* QALFPNFHSLALFCT

Problem:

- Statistical regularities in plaintext show in key
- Once you get any part of the message, you can decipher more



## Self-Synchronous Stream Cipher
### key drawn from ciphertext

Take key from ciphertext (*autokey*)

Example: Vigenère

- *key* XQXBCQOVVNGNRTT
- *plaintext* THEBOYHASTHEBAG
- *ciphertext* QXBCQOVVNGNRTTM

Problem:

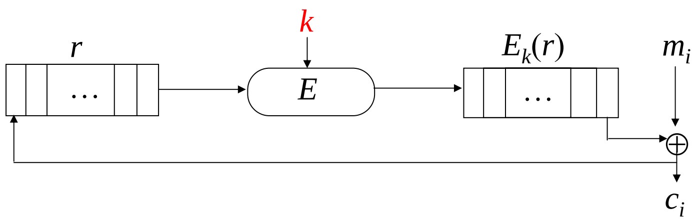
- Attacker gets key along with ciphertext, so deciphering is trivial

# Improving Autokey Stream Cipher

## Cipher feedback mode

Cipher feedback mode: 1 bit of ciphertext fed into $n$ bit register

- Self-healing property: if ciphertext bit received incorrectly, it and next $n$ bits decipher incorrectly; but after that, the ciphertext bits decipher correctly
- Need to know ***k***, $E$ to decipher ciphertext






# Block Ciphers - problem

Encipher, decipher multiple bits at once ----Advantage

- Each block enciphered independently
- Software implementation: block ciphers run faster than software implementation of stream ciphers

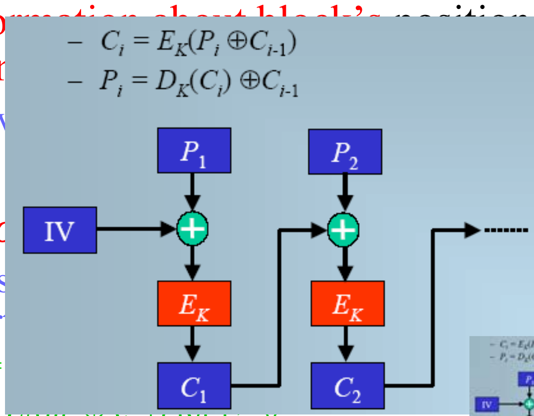
Problem: identical plaintext blocks produce identical ciphertext blocks

- Example: two database records
  - `MEMBER: Basem INCOME $100,000`
  - `MEMBER: Salem INCOME $100,000`
- Encipherment:
  - `ABCQZRME GHRSB CTXUVYSS RMGRPFQN`
  - `ABCQZRME ORPRZ CTXUVYSS RMGRPFQN`

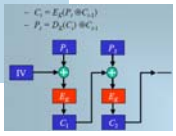
## Solution to Block Cipher Problem

Insert info … into
the plain …
– Disadv … reduced

*Cipher blo…*
– Exclus … previous
cipher …
• $c_0$ = …
• $c_i$ = …




where *IV* is the initialization vector





## Multiple Encryption

Double encipherment: $c = E_{k'}(E_k(m))$
– Effective key length is $2n$, if $k$, $k'$ are length $n$
– Problem: breaking it requires $2^{n+1}$ encryptions, not $2^{2n}$ encryptions

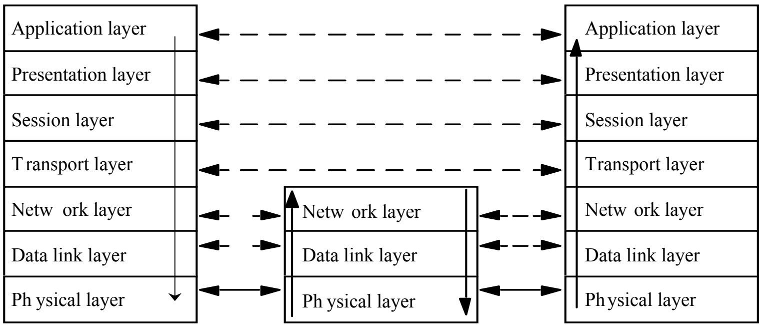
Triple encipherment:
– EDE mode: $c = E_k(D_{k'}(E_k(m))$
• Used in Financial Application: ANSI X9.17 & ISO 8732
– Triple encryption mode: $c = E_k(E_{k'}(E_{k''}(m))$

# Networks & Cryptography

ISO/OSI model

Conceptually, each host has peer at each layer

- Peers communicate with peers at same layer

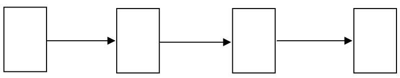





# Link & End-to-End (E2E) Protocols
## Encryption

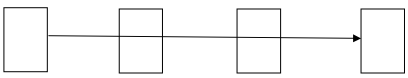
Link encryption

- Each host enciphers message so host at "next hop" can read it
- Message can be read at intermediate (in-between) hosts



End-to-end (E2E) encryption

- Host enciphers message so host at other end of communication can read it
- Message cannot be read at intermediate (in-between) hosts



# Examples & Crypto Considerations

## PPP Encryption Control Protocol - Link protocol

- Host gets message, deciphers it
  - Figures out where to forward it – which neighbor to send it to
  - Re-Enciphers it in appropriate key with that neighbor and forwards it
    - Secure among attackers monitoring the network
    - Vulnerable among attackers within the intermediate hosts
    - Each host shares key with neighbor

## TELNET protocol - End-to-end (E2E) protocol

- Application layer protocol – virtual terminal on a remote host
- Messages between client, server enciphered
  - Encipherment, decipherment occur only at the end hosts
    - » message encipherd throughout its journey
  - Secure among attackers monitoring the network & within the hosts
  - Each host shares key with destination
  - But, Attackers can read the routing information used to forward the message



# Encryption Protocols & Traffic Analysis

## Link encryption

- Shares crypto key with neighbors
- Can protect headers of packets
- Me
  eve
  enc
  for
- Att
  -
  -
- Pos
  destination
  - Note: may be able to deduce this from traffic flows

## End-to-end encryption

-each host & destination share crypto key

- No deciphering is in the

et headers

ediate nodes

route packet

monitoring

mediate hosts

tination

**Traffic Analysis:**

Crypto-analyst can sometimes gain information from the sender and recipient information and from the routing information; without benefiting from the content of the message

# Example Protocols

Privacy-Enhanced Electronic Mail (PEM)

– Applications layer protocol

Internet Protocol (IP) Security (IPSec)

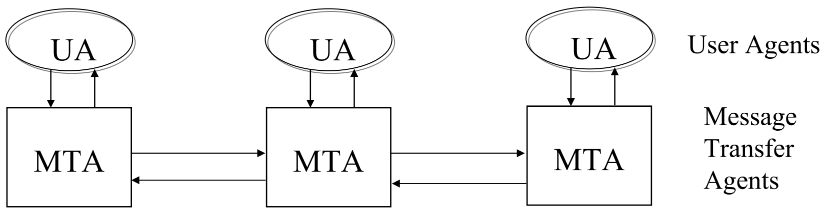
– Network layer protocol

- Successor of the NLSP (Network Layer Security Protocol) that was standardized by ISO



# Message Handling System

***need for Privacy-Enhanced Electronic Mail (PEM)***

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Assumptions:

Interchange Key – Available

- Asymmetric Crypto System:
  Authentic Public keys are with all parties
- Symmetric Crypto System:
  Authentic Secret keys are with all parties

rabilities:
essage at any MTA
essage at network
message fooling
e letters and inject it
Sender can deny having sent a letter

## Goals of
## Privacy-Enhanced Electronic Mail (PEM)

Confidentiality
- Only sender and recipient(s) can read message

Origin authentication
- Identify the sender precisely

Data integrity
- Any changes in message are easy to detect

Non-repudiation of origin
- Whenever possible …



## PEM Design Principles

Do not change related existing protocols
- Cannot alter SMTP

Do not change existing software
- Need compatibility with existing software

Make use of PEM optional & independent
- Available if desired, but email still works without them
- Some recipients may use it, others not

Enable communication without pre-arrangement
- Out-of-bands authentication, key exchange problematic

# PEM Basic Design: Key Types

**will be revisited at the Key-Management Chapter 9**

Two key types

- *Interchange keys* tied to sender, recipients and is static (for some set of messages)
  - Like a public/private key pair
  - Must be available *before* messages sent
- *Data exchange keys* generated for each message
  - Like a session key, session being the message

**Key Types**

Interchange Keys : associated with user

- long-term
- compromising is catastrophic

Session Keys : associated with communication

- short-term
- compromising does not affect long-term security



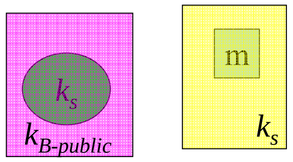
# PEM Basic Design: Sending

PEM Confidentiality

- $m$ message
- $k_s$ data exchange key - DEK
  - Session Key (Short term – used once)
- $k_{B\text{-}public}$ Bob's interchange key

$\{ m \} k_s \,||\, \{ k_s \} k_{B\text{-}public}$

Alice ⟶ Bob

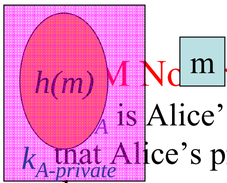


# PEM Basic Design: Integrity

PEM Integrity & authentication:

- *m* message
- *h*(*m*) hash of message *m* —*h(m)*=Message Integrity Check (MIC)
- $k_{A\text{-}private}$ Alice's interchange key

$$\text{Alice} \xrightarrow{\; m \,||\, \{\, h(m) \,\}\, k_{A\text{-}private} \;} \text{Bob}$$




PEM Non-repudiation:

- If $k_A$ is Alice's private key, this establishes that Alice's private key was used to sign the message

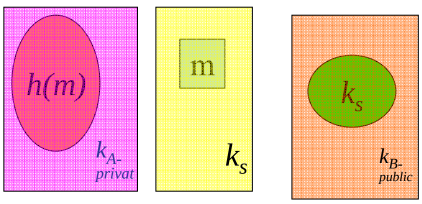


# PEM Basic Design: Everything

Confidentiality, integrity, authentication:

- Notations as in previous slides
- If $k_{A\text{-}private}$ is private key, get non-repudiation too

$$\text{Alice} \xrightarrow{\; \{\, m \,\}\, k_s \,||\, \{\, h(m) \,\}\, k_{A\text{-}private} \,||\, \{\, k_s \,\}\, k_{B\text{-}public} \;} \text{Bob}$$



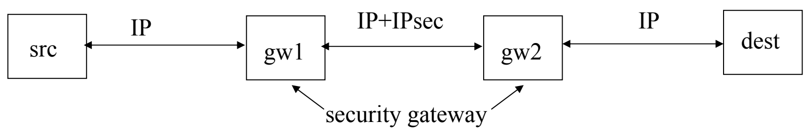
# Internet Protocol Security (IPSec)

IP is the primary protocol in the Internet Network Layer having the task of *delivering* datagrams (packets) from the source host to the destination host solely based on its address.

IPSec: Network layer security

- Provides confidentiality, integrity, authentication of endpoints, replay detection

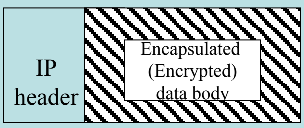
IPsec: used to protect data flows between a pair of hosts (e.g. computer users or servers), between a pair of security gateways (e.g. routers or firewalls), or *between security gateway and host*.






# IPsec Modes: Transport Mode / Tunnel Mode

## Transport Mode



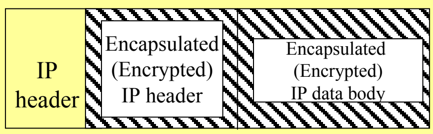

Encapsulate IP packet *data area* only

Use IP to send IPsec-wrapped data packet

Note: IP header not protected

Used when both end-points supports IPsec

## Tunnel Mode




Encapsulate *IP packet* (header and data)

Use IP to send IPsec-wrapped packet

Note: IP header protected

The unencrypted IP header is used to deliver the encrypted packets to a system where can be decrypted and forwarded

Used when any or both end-points do not support IPsec but at least two intermediate hosts do

# Two Protocols of IPsec
## for Message Security

Authentication Header (AH)
- Message integrity
- Origin authentication
- Anti-replay

Encapsulating Security Payload (ESP)
- Confidentiality ----extra: added to AH
- Beside all others provided by AH
  - Message integrity
  - Origin authentication
  - Anti-replay

Both are based on Cryptography supplied by the Internet Key Exchange (IKE)



# IPsec Architecture

Security Policy Database (SPD)
- Says how to handle messages based on *IP & transport layer headers* to do one of the following:
  1. discard them
  2. add security services
  3. forward message unchanged
- SPD associated with network interface
- SPD determines appropriate entry from packet attributes:
  - Including source
  - Including destination
  - Including transport protocol

## Without detailing the IPsec!! – left for a HW

# Which to Use: PEM, IPsec

What do the security services apply to?

- If applicable to one application *and* application layer mechanisms available, use that
  - PEM for electronic mail
- If more generic services needed, look to lower layers
  - IPsec for network layer, either end-to-end or link mechanisms, for connectionless channels as well as connections
- If endpoint is host, IPsec sufficient; if endpoint is user, application layer mechanism such as PEM needed



# 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

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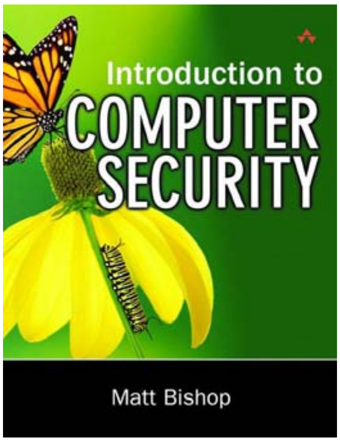
# Cryptography II

Cipher Techniques - Ch 10

***Key Management - Ch 9***

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# Chapter 9: Key Management

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

# Overview

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

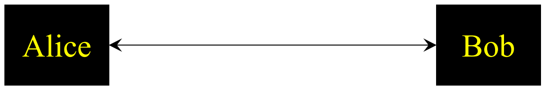


# Classical Key Exchange

- 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 $k_s$

# Key Distribution Problem

Algorithm like DES, Rijndael requires a shared a key!
Bootstrap problem: how do Alice and Bob begin?
Alice can't send the key to Bob in the clear!




**Key Types**

Interchange Keys : associated with user
- long-term
- compromising is catastrophic

Session Keys : associated with communication
- short-term
- compromising does not affect long-term security



# 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



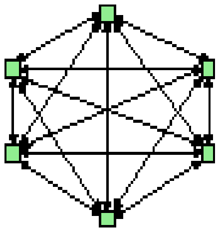
# Key Distribution Problem

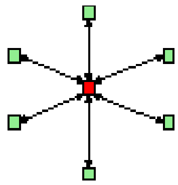
**Possible Solutions:**

1. Physical Distribution:
   - use a trusted courier (secure channel)
   - used widely until 1970s
2. Distribution Protocol:
   - assume a trusted 3rd party
3. Public Key Cryptography:
   - most widely used technique

# Key Distribution Problem

For n users, [n(n−1)]/2 keys!
10000 students, 50 million keys!
How do you manage them?
What if compromised?!

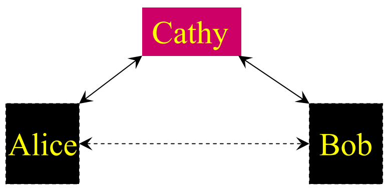




For n users, n keys
For 10000 students, 10000 keys
Session keys generated as needed
Needs protocol and trusted server



# Key Exchange Protocols




Assumptions

– Alice & Bob cannot arrange the session key in the clear
– Alice & Bob trust a 3rd part Cathy
– Alice & Bob already have interchange keys with Cathy
– Cryptosystem and protocol are public; keys are secret
– Attacker is the network!

# Notation

$X \rightarrow Y : \{M\}\ k$

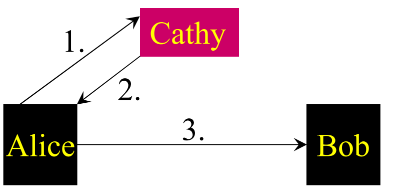
– $X$ sends to $Y$ message M enciphered by key $k$

$A \rightarrow B : r_1 || \{ M || N_a\}\ k_{ab} || \{ T_a \}\ k_{bs}$

– communicating parties: A, B, S
– message: M
– concatenation: ||
– nonce numbers (numbers used once; random): $r_1$, $N_a$, $N_b$, . . .
– timestamps: $T_a$, $T_b$, . . .
– shared keys: $K_{ab}$, $K_{bs}$



# Simple Protocol




## Steps

1. A→C: $\{B\}K_{ac}$
2. C→A: $\{K_{ab}\}K_{ac} || \{K_{ab}\}K_{bc}$
3. A→B: $\{K_{ab}\}K_{bc}$

## Problems

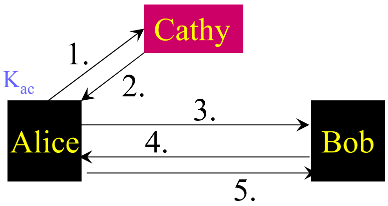
- How does Bob know he is talking to Alice?
- Replay attack (3, msg)
  - Eve records message from Alice to Bob, later replays it; Bob may think he's talking to Alice, but he isn't
  - Session key reuse: Eve replays message from Alice to Bob, so Bob re-uses session key
- msg = "deposit $199 in my account"

Protocols must provide authentication and defense against replay

# Needham-Schroeder Protocol

Steps :

1. $A \rightarrow C : \{A \parallel B \parallel N_a\}$
2. $C \rightarrow A : \{A \parallel B \parallel N_a \parallel K_{ab} \parallel \{ A \parallel K_{ab} \}K_{bc}\}K_{ac}$
3. $A \rightarrow B : \{A \parallel K_{ab}\}K_{bc}$
4. $B \rightarrow A : \{N_b\}K_{ab}$
5. $A \rightarrow B : \{N_b - 1\}K_{ab}$




Argument: Alice talking to Bob

Second message:

- Enciphered using key only she and Cathy knows (So Cathy enciphered it)
- Response to first message ($N_a$ in it matches $N_a$ in first message)

Third message:

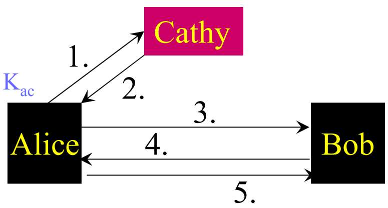
- Alice knows only Bob can read it (only Bob can derive session key from message)
- Any messages enciphered with that key are from Bob



# Needham-Schroeder Protocol

Steps :

1. $A \rightarrow C : \{A \parallel B \parallel N_a\}$
2. $C \rightarrow A : \{A \parallel B \parallel N_a \parallel K_{ab} \parallel \{ A \parallel K_{ab} \}K_{bc}\}K_{ac}$
3. $A \rightarrow B : \{A \parallel K_{ab}\}K_{bc}$
4. $B \rightarrow A : \{N_b\}K_{ab}$
5. $A \rightarrow B : \{N_b - 1\}K_{ab}$




Argument: Bob talking to Alice

Third message:

- Enciphered using key only he and Cathy knows (So Cathy enciphered it)
- Cathy provided session key and says Alice is other party

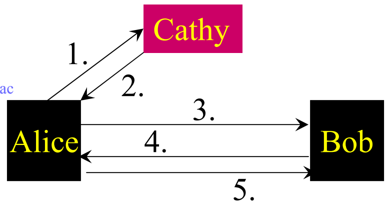
Fourth & Fifth message:

- Uses session key to determine if it is replay from Eve
- If not, Alice will respond correctly in fifth message
- If so, Eve cant decipher $N_b$ and so cant respond, or responds incorrectly

# Needham-Schroeder Protocol

Steps :

1. $A \rightarrow C : \{A \parallel B \parallel N_a\}$
2. $C \rightarrow A : \{A \parallel B \parallel N_a \parallel K_{ab} \parallel \{A \parallel K_{ab}\}K_{bc}\}K_{ac}$
3. $A \rightarrow B : \{A \parallel K_{ab}\}K_{bc}$
4. $B \rightarrow A : \{N_b\}K_{ab}$
5. $A \rightarrow B : \{N_b - 1\}K_{ab}$




Discussion

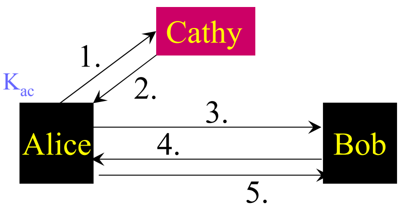
- Prevent eavesdropping, replay, modification, masquerading
- Fails if the session key ($K_{ab}$) is compromised!
  - Eve can replay the last 3 messages
  - Eve can pretend to be Alice
- Variations:
  - use timestamps (Denning and Sacco 81)
  - use an identification-number (Otway-Rees 87)



# Needham-Schroeder Protocol + Timestamps

Steps :

1. $A \rightarrow C : \{A \parallel B \parallel N_a\}$
2. $C \rightarrow A : \{A \parallel B \parallel N_a \parallel K_{ab} \parallel \{A \parallel T \parallel K_{ab}\}K_{bc}\}K_{ac}$
3. $A \rightarrow B : \{A \parallel T \parallel K_{ab}\}K_{bc}$
4. $B \rightarrow A : \{N_b\}K_{ab}$
5. $A \rightarrow B : \{N_b - 1\}K_{ab}$




Discussion

- Adding timestamps prevent replaying old session keys
- Needs clock synchronization!
  - may either reject valid messages or accept replays
- Forms the basis for Kerberos protocol (Ticket - issuer proofs identity)
  - Used by MS Window OS

## Key Exchange through Public Key Crypto

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 (Version 1)

- Alice and Bob exchange session key $k_{ab}$

Alice —— $\{ k_{ab} \} e_B$ ——→ 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

Simple protocol (Version 2)

- Alice and Bob exchange session key $k_{ab}$

Alice —— $\{ \{ k_{ab} \} d_A \} e_B$ ——→ Bob

## Man In the Middle Attack (Spoofing)

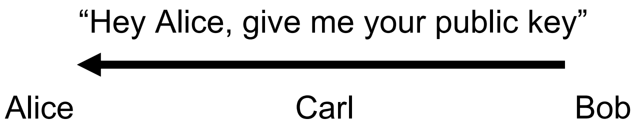
Cautions

Assumes Bob has Alice's public key, and *vice versa*

- If not, each must get it from public server
- If keys <u>*not*</u> *bound to identity of owner*, attacker Eve can launch a *man-in-the-middle* attack
  - Solution to this (binding identity to keys) discussed later as public key infrastructure (PKI)

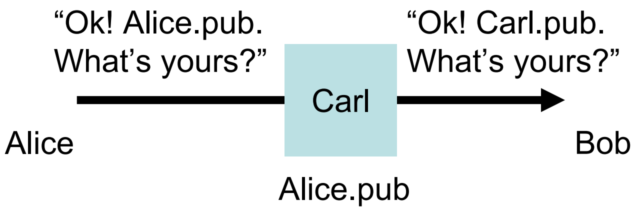


## Man In the Middle Attack (Spoofing)




SSL-Like Example

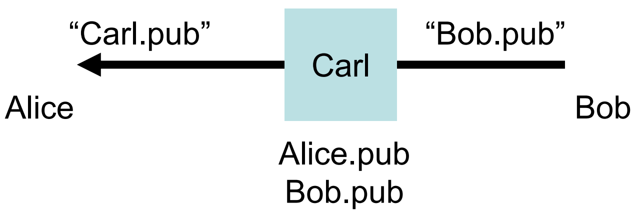
# Man In the Middle Attack (Spoofing)




**Carl takes Alice.pub and replaces is it by Carl.pub**
**Bob receives Carl.pub as if it is Alice.pub**

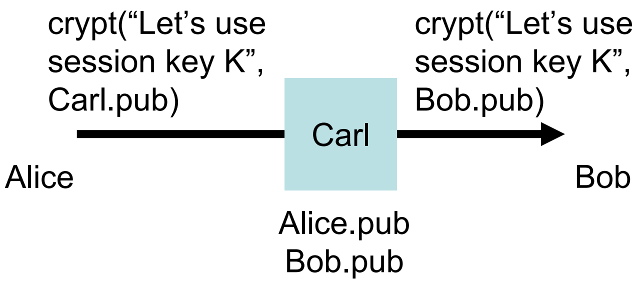


# Man In the Middle Attack (Spoofing)



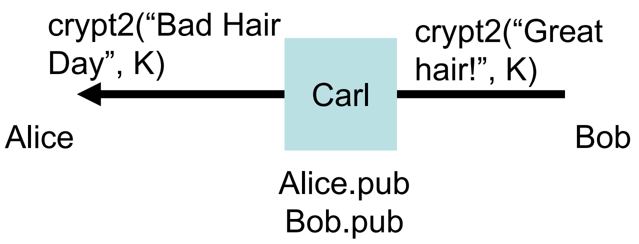

**Carl then, sends to Alice Carl.pub**
**Alice receives Carl.pub as if it is Bob.pub**

# Man In the Middle Attack (Spoofing)






# Man In the Middle Attack (Spoofing)



# Cryptographic Key Infrastructure

Goal: bind identity (Alice) to public 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



# Digital Certificates

Goal: Binding identity (Alice) to public key

Create token (message) containing

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

Sign it with public key of trusted authority (here, Cathy)

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

# 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

Issued by a Certification Authority (CA), containing:

- version (1, 2, or 3)
- serial number (unique within CA) identifying certificate
- signature algorithm identifier
- issuer X.500 name (CA)
- period of validity (from - to dates)
- subject X.500 name (name of owner)
- subject public-key info (algorithm, parameters, key)
- issuer unique identifier (v2+)
- subject unique identifier (v2+)
- extension fields (v3)
- signature (of hash of all fields in certificate)

Notation CA<<A>> denotes certificate for A signed by CA



# 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

# Using Digital Certificates

- The (Certificate Authority) CA owns a public key and a private key
- The CA's public key is put in a self-signed certificate that is distributed through many channels (e.g embedded in browser)
- The CA use its private key to sign certificates containing identity and corresponding public key of requesters after verifying their identities
- Certificates are made available in public databases or exchanged online



# 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

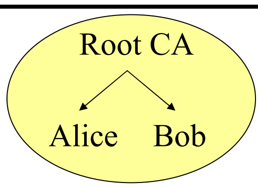
# Communicating with Certificates

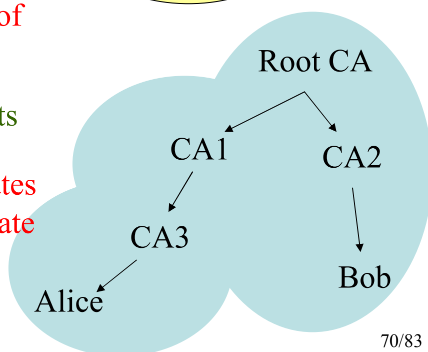
- Both Alice and Bob have the CA self-signed certificate
  - obtained through off-line means
- When Alice wants to send a message to Bob
  - She retrieves Bob's certificate from a public database
  - She verifies the CAs signature on Bobs certificate
  - She extracts Bob's public key
  - She uses the Bob's public key and her own secret key to encrypt the message
- Self-signed (root) certificates



# Certificate Hierarchy

- If both users share a common CA then they are assumed to know its public key
- Otherwise CA's must form a hierarchy
- Use certificates linking members of hierarchy to validate other CA's (cross-certify)
- Each CA has certificates for clients (forward) and parent (backward)
- Each client *trusts* parents certificates
- Enable verification of any certificate from one CA by users of all other CAs in hierarchy



# 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>>



# Certificate Hierarchy

A establishes a certificate path to B:

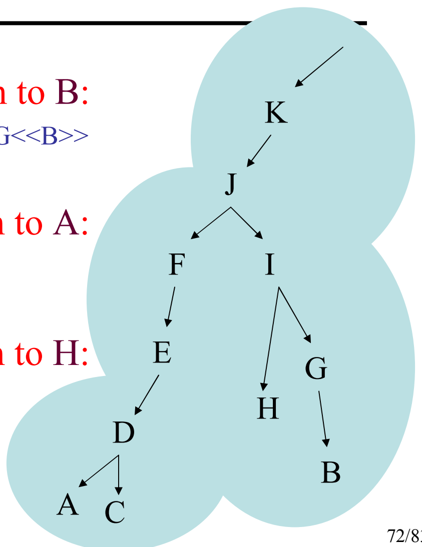
D<<E>>E<<F>>F<<J>>J<<I>>I<<G>>G<<B>>

C establishes a certificate path to A:

D<<A>>

B establishes a certificate path to H:

G<<I>>I<<H>>



# Pretty Good Privacy (PGP)

Created by Philip Zimmermann in 1991 e-mail communications

Use a bottom-up approach; instead of a top-down PKI

- Each user acts as a CA

A certificate is composed of:

- One public key packet
- Zero or more signature packets

Forms a "web of trust" among users



# 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
- *CRL - Certificate revocation list*
  - lists certificates that are revoked (no longer valid)



## Digital Signature - Again

- 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 → $\{ m \}k_{Alice}$ → Bob

Cathy ← $\{ m \}k_{Alice}$ ← Bob

Cathy → $\{ m \}k_{Bob}$ → Bob

# Public Key Digital Signatures

Alice's keys are $d_{Alice}$, $e_{Alice}$

Alice sends Bob

$$m \parallel \{ m \} d_{Alice}$$

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 $05 \times 17 \bmod 77 = 08$; 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 & Payback

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