Security in Computer Networks

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Audio/Video recordings of this lecture are available on-line at:
http://www.cse.wustl.edu/~jain/cse473-16/

Overview

1. Secret Key Encryption
2. Public Key Encryption
3. Hash Functions, Digital Signature, Digital Certificates
4. Secure Email

Not Covered:, SSL, IKE, WEP, IPSec, VPN, Firewalls, Intrusion Detection

Note: This class lecture is based on Chapter 8 of the textbook (Kurose and Ross) and the figures provided by the authors.

Security Requirements

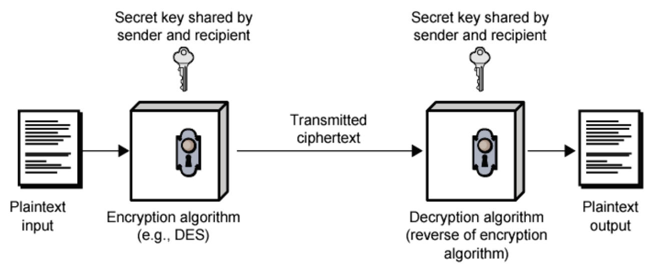
- **Integrity**: Received = sent?
- **Availability**: Legal users should be able to use. Ping continuously ⇒ No useful work gets done.
- **Confidentiality and Privacy**: No snooping or wiretapping
- **Authentication**: You are who you say you are. A student at Dartmouth posing as a professor canceled the exam.
- **Authorization** = Access Control Only authorized users get to the data
- **Non-repudiation**: Neither sender nor receiver can deny the existence of a message

Secret Key Encryption: Overview

1. Concept: Secret Key Encryption
2. Method: Block Encryption
3. Improvement: Cipher Block Chaining (CBC)
4. Standards: DES, 3DES, AES

Secret Key Encryption

- Also known as symmetric key encryption
- Encrypted_Message = Encrypt(Key, Message)
- Message = Decrypt(Key, Encrypted_Message)
- Example: Encrypt = division
- 433 = 48 R 1 (using divisor of 9)



Secret Key: A Simple Example

- **Substitution**: Substituting one thing for another
- **Monoalphabetic**: substitute one letter for another

plaintext: abcdefghijklmnopqrstuvwxyz

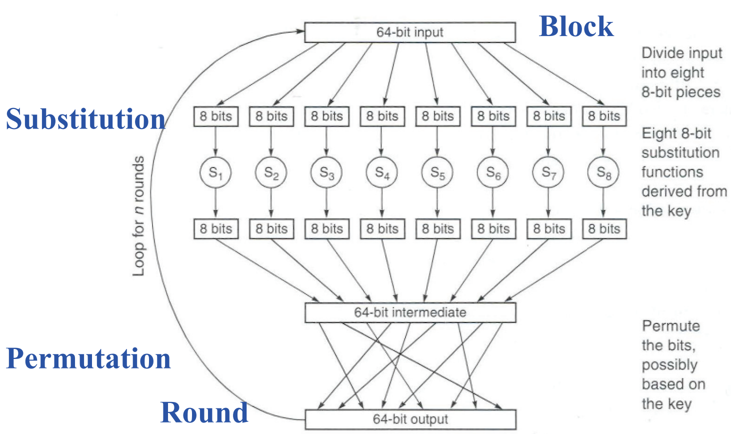
ciphertext: mnbvcxzasdfghjklpoiuytrewq

E.g.: Plaintext: bob. i love you. alice
ciphertext: nkn. s gktc wky. mgsbc

- **Polyalphabetic**: Use multiple substitutions C1, C2, …
Substitution selected depends upon the position
⇒Same letter coded differently in different position

Block Encryption

- Block Encryption

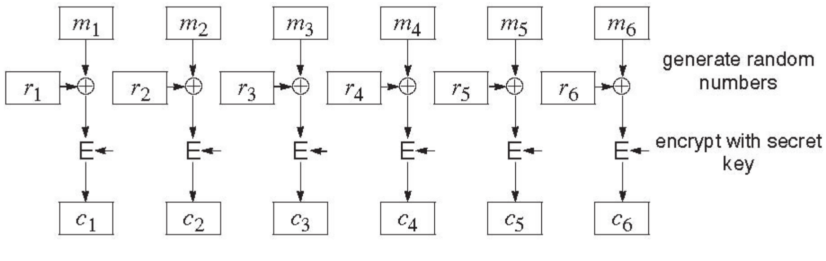


Block Encryption (Cont)

- Short block length ⇒ tabular attack
- 64-bit block
- Transformations:
  - Substitution: replace k-bit input blocks with k-bit output blocks
  - Permutation: move input bits around.
    1 → 13, 2 → 61, etc.
- Round: Substitution round followed by permutation round and so on. Diffusion + Confusion.

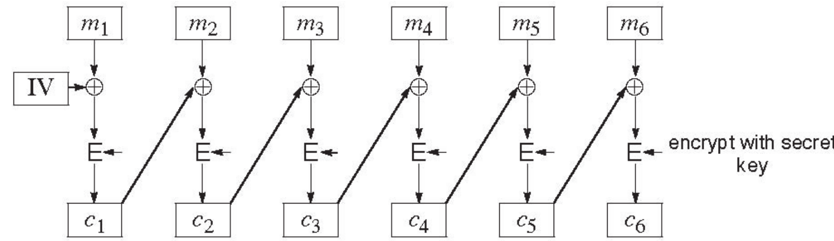
Cipher Block Chaining (CBC)

- Goal: Same message encoded differently
- Add a random number before encoding



CBC (Cont)

- Use C_i as random number for i+1



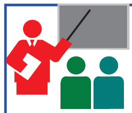
- Need Initial Value (IV)
- no IV ⇒ Same output for same message
  ⇒ one can guess changed blocks
- Example: Continue Holding, Start Bombing

Data Encryption Standard (DES)

- Published by NIST in 1977
- For commercial and *unclassified* government applications
- 8 octet (64 bit) key.
  Each octet with 1 odd parity bit ⇒ 56-bit key
- Efficient hardware implementation
- Used in most financial transactions
- Computing power goes up 1 bit every 2 years
- 56-bit was secure in 1977 but is not secure today
- Now we use DES three times ⇒ Triple DES = 3DES

Advanced Encryption Standard (AES)

- Designed in 1997-2001 by National Institute of Standards and Technology (NIST)
- Federal information processing standard (FIPS 197)
- Symmetric block cipher, Block length 128 bits
- Key lengths 128, 192, and 256 bits



Secret Key Encryption: Review

1. Secret key encryption requires a shared secret key
2. Block encryption, e.g., DES, 3DES, AES break into fixed size blocks and encrypt
3. CBC is one of many modes are used to ensure that the same plain text results in different cipher text.

Ref: Section 8.1, 8.2.1, Review Questions R1, R2, R6, Problems P1-P6

Homework 8A

- Consider 3-bit block cipher in the Table below

Plain	000	001	010	011	100	101	110	111
Cipher	110	111	101	100	011	010	000	001

- Suppose the plaintext is 100100100.

(a) Initially assume that CBC is not used. What is the resulting ciphertext?

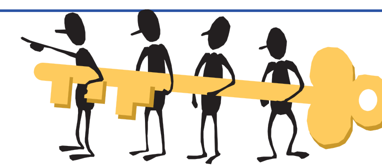
(b) Suppose Trudy sniffs the cipher text. Assuming she knows that a 3-bit block cipher without CBC is being employed (but doesn't know the specific cipher), what can she surmise?

(c) Now suppose that CBC is used with IV-111. What is the resulting ciphertext?

Public Key Encryption

1. Public Key Encryption
2. Modular Arithmetic
3. RSA Public Key Encryption

Public Key Encryption



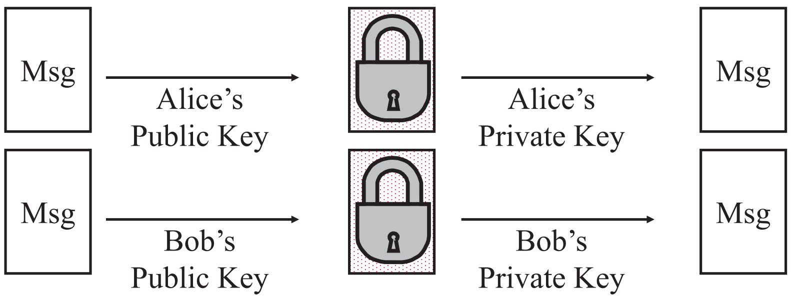
- Invented in 1975 by Diffie and Hellman
- Encrypted_Message = Encrypt(Key1, Message)
- Message = Decrypt(Key2, Encrypted_Message)

$$\text{Text} \xrightarrow{\text{Key1}} \text{Ciphertext}$$

$$\text{Ciphertext} \xrightarrow{\text{Key2}} \text{Text}$$

Public Key (Cont)

- One key is private and the other is public
- Message = Decrypt(Public_Key,
  Encrypt(Private_Key, Message))
- Message = Decrypt(Private_Key,
  Encrypt(Public_Key, Message))



Public Key Encryption Method

- Rivest, Shamir, and Adelson (RSA) method
- Example: Key1 = <3,187>, Key2 = <107,187>
- Encrypted_Message = m^3 mod 187
- Message = Encrypted_Message^{107} mod 187
- Message = 5
- Encrypted Message = 5^3 = 125 mod 187 = 125
- Message = 125^{107} mod 187 = 5
  = $125^{(64+32+8+2+1)}$ mod 187
  = {(125^{64} mod 187)(125^{32} mod 187)...
  (125^2 mod 187)(125 mod 187)} mod 187

Modular Arithmetic

- $xy \bmod m = (x \bmod m)\ (y \bmod m) \bmod m$
- $x^4 \bmod m = (x^2 \bmod m)(x^2 \bmod m) \bmod m$
- $x^{ij} \bmod m = (x^i \bmod m)^j \bmod m$
- 125 mod 187 = 125
- 125^2 mod 187 = 15625 mod 187 = 104
- 125^4 mod 187 = (125^2 mod 187)^2 mod 187
  = 104^2 mod 187 = 10816 mod 187 = 157
- 125^8 mod 187 = 157^2 mod 187 = 152
- 125^{16} mod 187 = 152^2 mod 187 = 103
- 125^{32} mod 187 = 103^2 mod 187 = 137
- 125^{64} mod 187 = 137^2 mod 187 = 69
- $125^{64+32+8+2+1}$ mod 187 = 69×137×152×104×125 mod 187
  = 18679128000 mod 187 = 5

RSA Public Key Encryption

- Ron Rivest, Adi Shamir, and Len Adleman at MIT 1978
- Both plain text M and cipher text C
  are integers between 0 and n-1.
- Key 1 = {e, n},
  Key 2 = {d, n}
- C = M^e mod n
  M = C^d mod n
- How to construct keys:
  - Select two large primes: p, q, p ≠ q
  - n = p×q
  - Calculate z = (p-1)(q-1)
  - Select e, such that gcd(z, e) = 1; 0 < e < z
  - Calculate d such that de mod z = 1

RSA Algorithm: Example

- Select two large primes: p, q, $p \neq q$
  $p = 17, q = 11$
- $n = p \times q = 17 \times 11 = 187$
- Calculate $z = (p-1)(q-1) = 16x10 = 160$
- Select e, such that $\gcd(z, e) = 1$; $0 < e < z$
  say, $e = 7$
- Calculate d such that de mod z = 1
  - $160k+1 = 161, 321, 481, 641$
  - Check which of these is divisible by 7
  - 161 is divisible by 7 giving $d = 161/7 = 23$
- Key 1 = {7, 187}, Key 2 = {23, 187}

Confidentiality and Non-Repudiation

- User 1 to User 2:
- Encrypted_Message
  = Encrypt(Public_Key2,
  Encrypt(Private_Key1, Message))
- Message = Decrypt(Public_Key1,
  Decrypt(Private_Key2, Encrypted_Message)
  ⇒ Authentic and Private

Your Public Key | My Private Key | Message

Public Key Encryption: Review

1. Public Key Encryption uses two keys: Public and Private
2. Either key can be used to encrypt. Other key will decrypt.
3. RSA public key method is based on difficulty of factorization

Ref: Section 8.2.2, Review exercises:R3, R7, Problems: P7, P9, P10

Homework 8B

Consider RSA with p=5, q=11

A. what are n and z

B. let e be 3. Why is this an acceptable choice for e?

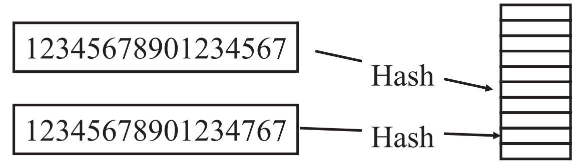
C. Find d such that de=1(mod z) and d<160

D. Encrypt the message m=8 using the key (n,e). Let c be the corresponding cipher text. Show all work including decryption.

Hash, Signatures, Certificates

1. Hash Functions
2. MD5 Hash
3. SHA-1 Algorithm
4. Message Authentication Code (MAC)
5. Digital Signature
6. Digital Certificates
7. End Point Authentication

Hash Functions



Example: CRC can be used as a hash (not recommended for security applications)

Requirements:

1. Applicable to any size message
2. Fixed length output
3. Easy to compute
4. Difficult to Invert ⇒ Can't find x given $H(x)$ ⇒ One-way
5. Difficult to find y, such that $H(x) = H(y)$ ⇒ Can't change msg
6. Difficult to find *any* pair (x, y) such that $H(x) = H(y)$ ⇒ Strong hash

MD5 Hash

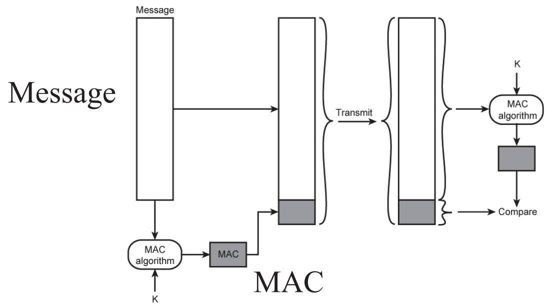
- 128-bit hash using 512 bit blocks using 32-bit operations
- Invented by Ron Rivest in 1991
- Described in RFC 1321
- Commonly used to check the integrity of files (easy to fudge message and the checksum)
- Also used to store passwords

SHA-1 Algorithm

- 160 bit hash using 512 bit blocks and 32 bit operations
- Five passes (4 in MD5 and 3 in MD4)
- Maximum message size is 2^{64} bit

Message Authentication Code (MAC)

- Authentic Message = Contents unchanged + Source Verified
- May also want to ensure that the time of the message is correct
- Encrypt({Message, CRC, Time Stamp}, Source's secret key)
- Message + Encrypt(Hash, Source's secret key)
- Message + Encrypt(Hash, Source's private key)



HMAC Overview

- Keyed Hash ⇒ includes a key along with message
- HMAC is a general design. Can use any hash function ⇒ HMAC-MD5, HMAC-AES
- Uses hash functions without modifications
- Has well understood cryptographic analysis of authentication mechanism strength

Digital Signature

- Message Digest = Hash(Message)
- Signature = Encrypt(Private_Key, Hash)
- Hash(Message) = Decrypt(Public_Key, Signature) ⇒ Authentic
- Also known as Message *authentication* code (MAC)

Private Key

Text $\xrightarrow{\text{Hash}}$ Digest ⟶ Signature

Public Key

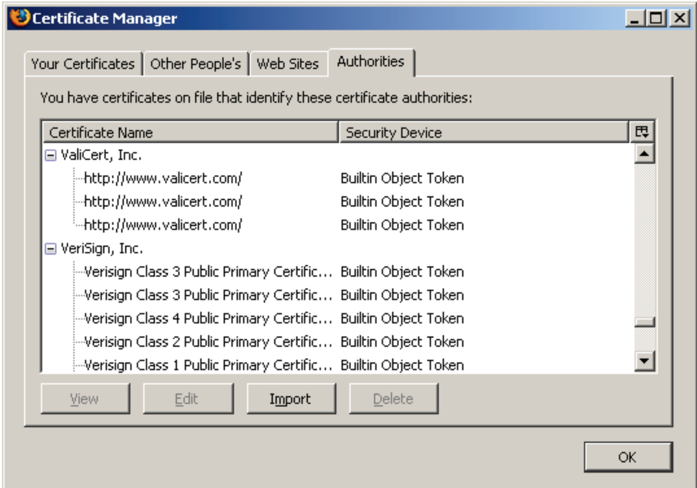
Signature ⟶ Digest $\xleftarrow{\text{Hash}}$ Text

Digital Certificates

- Like driver license or passport
- Digitally signed by Certificate authority (CA) - a trusted organization
- Public keys are distributed with certificates
- CA uses its private key to sign the certificate ⇒ Hierarchy of trusted authorities
- X.509 Certificate includes: Name, organization, effective date, expiration date, public key, issuer's CA name, Issuer's CA signature

User ID Public Key $\xrightarrow{\text{hash}}$ Encrypt CA private key → User ID Public Key

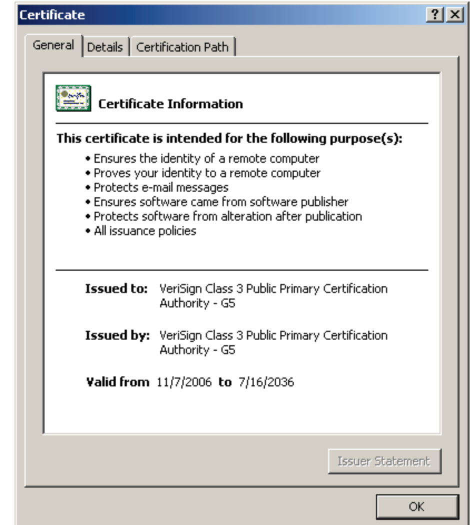
Oligarchy Example



Ref: Windows: http://smallbusiness.chron.com/see-security-certificates-stored-computer-54732.html
MAC: https://superuser.com/questions/992167/where-are-digital-certificates-physically-stored-on-a-mac-os-x-machine

Sample X.509 Certificate

Internet Explorer



X.509 Sample (Cont)

Field	Value
Version	V3
Serial number	18 da d1 9e 26 7d e8 bb 4a 21...
Signature algorithm	sha1RSA
Issuer	VeriSign Class 3 Public Primary ...
Valid from	Tuesday, November 07, 2006 ...
Valid to	Wednesday, July 16, 2036 6:...
Subject	VeriSign Class 3 Public Primary ...
Public key	RSA (2048 Bits)
Version	V3
Serial number	18 da d1 9e 26 7d e8 bb 4a 21...
Signature algorithm	sha1RSA
Issuer	VeriSign Class 3 Public Primary ...
Valid from	Tuesday, November 07, 2006 ...
Valid to	Wednesday, July 16, 2036 6:...
Subject	VeriSign Class 3 Public Primary ...
Public key	RSA (2048 Bits)

End Point Authentication

- Passwords can not be exchanged in clear
- Nonce = random **n**umber used only **once**
- Also done using certificates

User

Server

Hi I am Alice →

← Please encrypt this number 'n' with your password

Here is the encryption 'n' of with my password →

Hashes, Signatures, Certificates

1. Public Key Encryption uses two keys: Public and Private
2. RSA method is based on difficulty of factorization
3. Hashes are one-way functions such that it difficult to find another input with the same hash like MD5, SHA-1
4. Message Authentication Code (MAC) ensures message integrity and source authentication using hash functions Digital Signature consists of encrypting the hash of a message using private key
5. Digital certificates are signed by root certification authorities and contain public keys

Ref: Section 8.3-8.4, Review questions R9-18

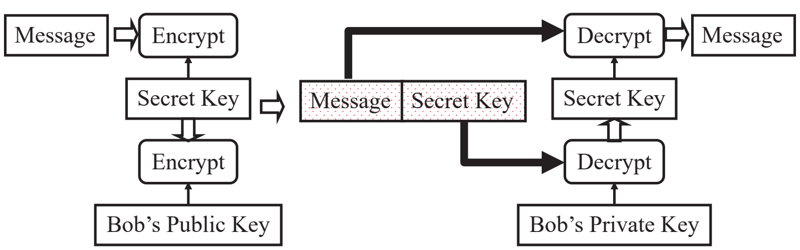
Secure Email

Overview

1. Secure E-Mail
2. Signed Secure E-Mail
3. Pretty Good Privacy (PGP)

Secure E-Mail

- Alice wants to send confidential e-mail, m, to Bob.

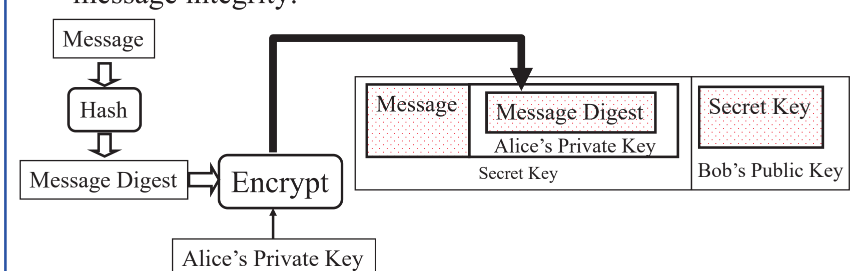


- Alice:
- Generates random *secret* key, K_S.
- Encrypts message with K_S (for efficiency)
- Also encrypts K_S with Bob's public key.
- Sends both $K_S(m)$ and $K_B(K_S)$ to Bob.

- Bob uses his private key to recover K_s

Signed Secure E-Mail

- Alice wants to provide secrecy, sender authentication, message integrity.



- Alice uses three keys: her private key, Bob's public key, newly created secret key
- Bob uses his private key to recover the secret key
- Bob uses Alice's private key to verify that the message came from Alice and was not changed.

Pretty Good Privacy (PGP)

- Used RSA and IDEA (RSA patent in US until 2000)
- V2.6.2 became legal for use within US and can be downloaded from MIT
- A patent-free version using public algorithm has also been developed
- Code published as an OCRable book
- Initially used web of trust- certificates issued by people
- Certificates can be registered on public sites, e.g., MIT
- hushmail.com is an example of PGP mail service
- OpenPGP standard [RFC 4880]

Ref: http://en.wikipedia.org/wiki/Pretty_Good_Privacy

Lab 8

You will receive a "signed" email from the TA. Reply to this email with a "encrypted and signed" email to TA.

Hints:

1. To sign your email with a private key you need your digital certificate. To send an encrypted email you need TA's public key.
2. TA's public key is attached with his email.
3. The steps to obtain a free certificate and use it for email depend upon your email software.
4. Instructions for Outlook and Gmail are as included next.

Lab 8 Hints (Cont)

Getting your Certificate:

- Use **Internet Explorer** to request and collect a free email certificate from:

http://www.comodo.com/home/email-security/free-email-certificate.php

- After you have collected the certificate, in Internet Explorer go to Tools → Internet Options → Contents → Certificates → Personal
- Select your certificate and export it to a file.
  Select "Yes – Export the private key" click next
  Select "Include all certificates in the certification path"
  Select "Enable strong protection"
  Do not select "Delete the private key if the export is successful"
  Save it with a password of your choice.
- Import this certificate in Outlook as follows:
  Tools → Options → Security → Import/Export
- Browse to your certificate file and add it.

Lab 8 Hints (Cont)

- If you use Firefox, use the following procedure to request and collect a free email certificate from:

http://www.comodo.com/home/email-security/free-email-certificate.php

- After you have collected the certificate, in Firefox go to Tools → Options → Advanced → Encryption → View Certificates → Your Certificates
- Select your certificate and backup to a file.
  Save it with a password of your choice.
- Import this certificate in Outlook as follows:
  Tools → Options → Security → Import/Export
- Browse to your certificate file and add it.
  Note: You have to use the same browser to collect the certificate from Comodo that you used to request the certificate.

Lab 8 Hints (Cont)

Importing Other's Certificates in Outlook:

- In Outlook, open the signed message received from TA. In the message window, right click on the name in the "From field" and select "save as outlook contact"
- This will open a new contact window. In that window, click on the "certificates" tab.
- You will see the certificate listed there.
- Save this contact in your contacts list.
- When you reply or send email to this contact, you can enable the security options for encryption and signatures by:
  View → Options → Security Options
  Select Encrypt Message or Add Digital Signature or both
  Select Security Settings: <Automatic>

Lab 8 Hints (Cont)

Gmail Instructions:

- The certificate will show up as an attachment name smime.p7s
- Download and save this attachment on your computer.
- Transfer this file to the computer where you have an outlook email.
- Manually create a new contact entry in outlook with proper name and email address.
- Open this contact entry. Go to certificate panel and import. Select all files *.* and select the file smime.p7s
- Save and close the entry.
- To send an email with your Gmail address in the from field, you will need to create a new email account in Outlook with the corresponding Gmail address in the from field. Outlook allows email security. Gmail does not.

Lab 8 Hints (Cont)

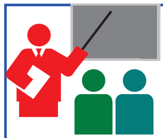
Sending Encrypted and Signed Messages w Outlook:

- You can reply to the TA's email with a signed encrypted message. Content of the reply is not important.
- Before sending the message, on the message window,
  Select View → Options → Security Settings
  Select encryption and signature
  Now send the message.

Lab 8 Hints (Cont)

Thunderbird:

- To import your certificate into Thunderbird:
  Tools -> Options -> Advanced -> Certificates -> View Certificates -> Your Certificates -> Import
- Then navigate to where you saved the certificate and select it. Enter the password you encrypted the certificate with.
- Now go to Tools->Account Settings->Security
- Under "Digital Signing", click select to choose the certificate you just imported.
- Click "Yes" to automatically use the same certificate for encryption/decryption.
- Thunderbird keeps track of other people's certificates automatically. "Add to address book" step is not necessary for Thunderbird.
- To send a message: After opening a new message, go to Options-> Encrypt this Message and Options->Digitally Sign this message, as desired.



Secure Email: Review

1. Email provide confidentiality using a secret key
2. Public key and Certificates are used to:
   1. Sign the message
   2. To send the secret key

Ref: Section 8.5, Review question R19

Summary

1. Network security requires confidentiality, integrity, availability, authentication, and non-repudiation
2. Encryption can use one secret key or two keys (public and private)
3. Public key is very compute intensive and is generally used to send secret key
4. Digital certificate system is used to certify the public key
5. Secure email uses confidentiality using a secret key, uses certificates and public keys to sign the email and to send the secret key

Ref: Sections 8.1 through 8.5

Acronyms

- 3DES Triple DES
- AES Advanced Encryption Standard
- CA Certificate authority
- CBC Cipher Block Chaining (CBC)
- CRC Cyclic Redundancy Check
- DES Data Encryption Standard (DES)
- FIPS Federal Information Processing standard
- HMAC
- ID Identifier
- IDEA
- IKE Internet Key Exchange
- IPSec Secure IP
- IV Initialization Vector
- MAC Message Authentication Code
- MD4 Message Digest 4
- MD5 Message Digest 5

Acronyms (Cont)

- NIST National Institute of Science and Technology
- OCR Optical Character Recognition
- OpenPGP Open PGP
- PGP Pretty Good Privacy
- RFC Request for Comment
- RSA Rivest, Shamir, Adleman
- SHA Secure Hash
- SSL Secure Socket Layer
- TA Teaching Assistant
- US United States
- VPN Virtual Private Network
- WEP Wired Eqivalent Privacy
- XOR Exclusive OR

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