Operating Systems

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S.No.	Course Outcomes	Cognitive Level
1	Explain the fundamentals of operating systems like process, memory, storage, file system, security and protection.	Understand
2	Illustrate various operating System services, interfaces and system calls.	Apply
3	Demonstrate critics of process management and IPC.	Apply
4	Implement page replacement algorithms, memory management techniques and deadlock issues.	Apply
5	Illustrate architecture of file systems and I/O systems for mass storage structures.	Apply
6	Utilize the methods of operating system security and protection.	Apply

UNIT 5: Security and Protection

Protection: Goals, Principles and domain, Access Matrix, Implementation of Access Matrix and Access control, Revocation of Access Rights.

Security: The Security problem, Program threats, System and Network threats, Cryptography as a security tool.

Unit 5 - Security and Protection

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Chapter 1
Protection

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Goals of Protection

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Goals of Protection

- In one protection model, computer consists of a collection of objects, hardware or software
- Each object has a unique name and can be accessed through a well-defined set of operations
- Protection problem - ensure that each object is accessed correctly and only by those processes that are allowed to do so

Principles of Protection

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Principles of Protection

- Guiding principle – **principle of least privilege**
  - Programs, users and systems should be given just enough **privileges** to perform their tasks
  - Limits damage if entity has a bug, gets abused
  - Can be static (during life of system, during life of process)
  - Or dynamic (changed by process as needed) – **domain switching**, **privilege escalation**
  - "Need to know" a similar concept regarding access to data

Principles of Protection (Cont.)

- Must consider "grain" aspect
  - Rough-grained privilege management easier, simpler, but least privilege now done in large chunks
    - For example, traditional Unix processes either have abilities of the associated user, or of root
  - Fine-grained management more complex, more overhead, but more protective
    - File ACL lists, RBAC
- Domain can be user, process, procedure

Domain of Protection

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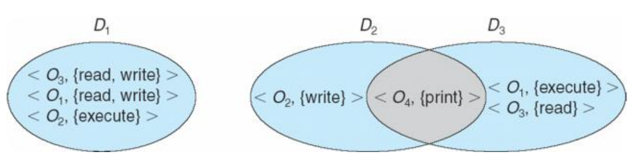
Domain Structure

- Access-right = <*object-name*, *rights-set*>
  where *rights-set* is a subset of all valid operations that can be performed on the object
- Domain = set of access-rights

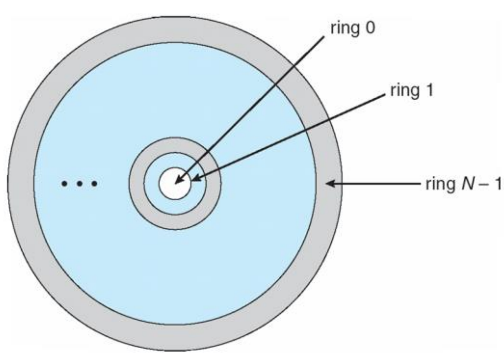


Domain Implementation (UNIX)

- Domain = user-id
- Domain switch accomplished via file system
  - Each file has associated with it a domain bit (setuid bit)
  - When file is executed and setuid = on, then user-id is set to owner of the file being executed
  - When execution completes user-id is reset
- Domain switch accomplished via passwords
  - `su` command temporarily switches to another user's domain when other domain's password provided
- Domain switching via commands
  - `sudo` command prefix executes specified command in another domain (if original domain has privilege or password given)

Domain Implementation (MULTICS)

- Let D_i and D_j be any two domain rings
- If $j < I \Rightarrow D_i \subseteq D_j$



Multics Benefits and Limits

- Ring / hierarchical structure provided more than the basic kernel / user or root / normal user design
- Fairly complex -> more overhead
- But does not allow strict need-to-know
  - Object accessible in D_j but not in D_i, then ***j*** must be < ***i***
  - But then every segment accessible in D_i also accessible in D_j

Access Matrix

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Access Matrix

- View protection as a matrix (access matrix)
- Rows represent domains
- Columns represent objects
- `Access(i, j)` is the set of operations that a process executing in Domain_i can invoke on Object_j

domain \ object	F_1	F_2	F_3	printer
D_1	read		read	
D_2				print
D_3		read	execute	
D_4	read write		read write	

Use of Access Matrix

- If a process in Domain D_i tries to do "op" on object O_j, then "op" must be in the access matrix
- User who creates object can define access column for that object
- Can be expanded to dynamic protection
  - Operations to add, delete access rights
  - Special access rights:
    - *owner of* O_i
    - *copy op from* O_i *to* O_j *(denoted by "*")*
    - *control –* D_i *can modify* D_j *access rights*
    - *transfer – switch from domain* D_i *to* D_j
  - *Copy* and *Owner* applicable to an object
  - *Control* applicable to domain object

Use of Access Matrix (Cont.)

- **Access matrix** design separates mechanism from policy
  - Mechanism
    - Operating system provides access-matrix + rules
    - If ensures that the matrix is only manipulated by authorized agents and that rules are strictly enforced
  - Policy
    - User dictates policy
    - Who can access what object and in what mode
- But doesn't solve the general confinement problem

Access Matrix of Figure A with Domains as Objects

domain \ object	F_1	F_2	F_3	laser printer	D_1	D_2	D_3	D_4
D_1	read		read			switch		
D_2				print			switch	switch
D_3		read	execute					
D_4	read write		read write		switch			

Access Matrix with *Copy* Rights

object / domain	F_1	F_2	F_3
D_1	execute		write*
D_2	execute	read*	execute
D_3	execute		

(a)

object / domain	F_1	F_2	F_3
D_1	execute		write*
D_2	execute	read*	execute
D_3	execute	read	

(b)

Access Matrix With *Owner* Rights

object / domain	F_1	F_2	F_3
D_1	owner execute		write
D_2		read* owner	read* owner write
D_3	execute		

(a)

object / domain	F_1	F_2	F_3
D_1	owner execute		write
D_2		owner read* write*	read* owner write
D_3		write	write

(b)

Modified Access Matrix of Figure B

object / domain	F_1	F_2	F_3	laser printer	D_1	D_2	D_3	D_4
D_1	read		read			switch		
D_2				print			switch	switch control
D_3		read	execute					
D_4	write		write		switch			

Implementation of Access Matrix

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Implementation of Access Matrix

- Generally, a sparse matrix
- Option 1 – Global table
  - Store ordered triples **`<domain, object, rights-set>`** in table
  - A requested operation M on object O_j within domain D_i -> search table for < D_i, O_j, R_k >
    - with M ∈ R_k
  - But table could be large -> won't fit in main memory
  - Difficult to group objects (consider an object that all domains can read)

Implementation of Access Matrix (Cont.)

- Option 2 – Access lists for objects
  - Each column implemented as an access list for one object
  - Resulting per-object list consists of ordered pairs **`<domain, rights-set>`** defining all domains with non-empty set of access rights for the object
  - Easily extended to contain default set -> If M ∈ default set, also allow access

Implementation of Access Matrix (Cont.)

- Each column = Access-control list for one object
  Defines who can perform what operation

  Domain 1 = Read, Write
  Domain 2 = Read
  Domain 3 = Read

- Each Row = Capability List (like a key)
  For each domain, what operations allowed on what objects

  Object F1 – Read
  Object F4 – Read, Write, Execute
  Object F5 – Read, Write, Delete, Copy

Implementation of Access Matrix (Cont.)

- Option 3 – Capability list for domains
  - Instead of object-based, list is domain based
  - **Capability list** for domain is list of objects together with operations allows on them
  - Object represented by its name or address, called a **capability**
  - Execute operation M on object O_j, process requests operation and specifies capability as parameter
    - Possession of capability means access is allowed
  - Capability list associated with domain but never directly accessible by domain
    - Rather, protected object, maintained by OS and accessed indirectly
    - Like a "secure pointer"
    - Idea can be extended up to applications

Implementation of Access Matrix (Cont.)

- Option 4 – Lock-key
  - Compromise between access lists and capability lists
  - Each object has list of unique bit patterns, called **locks**
  - Each domain as list of unique bit patterns called **keys**
  - Process in a domain can only access object if domain has key that matches one of the locks

Comparison of Implementations

- Many trade-offs to consider
  - Global table is simple, but can be large
  - Access lists correspond to needs of users
    - Determining set of access rights for domain non-localized so difficult
    - Every access to an object must be checked
      - Many objects and access rights -> slow
  - Capability lists useful for localizing information for a given process
    - But revocation capabilities can be inefficient
  - Lock-key effective and flexible, keys can be passed freely from domain to domain, easy revocation

Comparison of Implementations (Cont.)

- Most systems use combination of access lists and capabilities
  - First access to an object -> access list searched
    - If allowed, capability created and attached to process
      - Additional accesses need not be checked
    - After last access, capability destroyed
    - Consider file system with ACLs per file

Access Control

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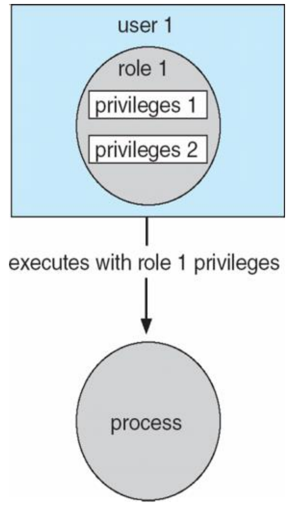
Access Control

- Protection can be applied to non-file resources
- Oracle Solaris 10 provides **role-based access control** (**RBAC**) to implement least privilege
  - ***Privilege*** is right to execute system call or use an option within a system call
  - Can be assigned to processes
  - Users assigned ***roles*** granting access to privileges and programs
    - Enable role via password to gain its privileges
  - Similar to access matrix



Revocation of Access Rights

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Revocation of Access Rights

- Various options to remove the access right of a domain to an object
  - **Immediate vs. delayed**
  - **Selective vs. general**
  - **Partial vs. total**
  - **Temporary vs. permanent**
- Access List – Delete access rights from access list
  - **Simple** – search access list and remove entry
  - **Immediate**, **general** or **selective**, **total** or **partial**, **permanent** or **temporary**

Revocation of Access Rights (Cont.)

- Capability List – Scheme required to locate capability in the system before capability can be revoked
  - **Reacquisition** – periodic delete, with require and denial if revoked
  - **Back-pointers** – set of pointers from each object to all capabilities of that object (Multics)
  - **Indirection** – capability points to global table entry which points to object – delete entry from global table, not selective (CAL)
  - **Keys** – unique bits associated with capability, generated when capability created
    - Master key associated with object, key matches master key for access
    - Revocation – create new master key
    - Policy decision of who can create and modify keys – object owner or others?

END of Chapter - 1

Chapter 2
Security

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The Security Problem

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The Security Problem

- We say that System is **secure** if resources used and accessed as intended under all circumstances
  – Unachievable
- **Intruders** (**crackers**) attempt to breach security
- **Threat** is potential security violation
- **Attack** is attempt to breach security
- Attack can be accidental or malicious
- Easier to protect against accidental than malicious misuse

Security Violation Categories

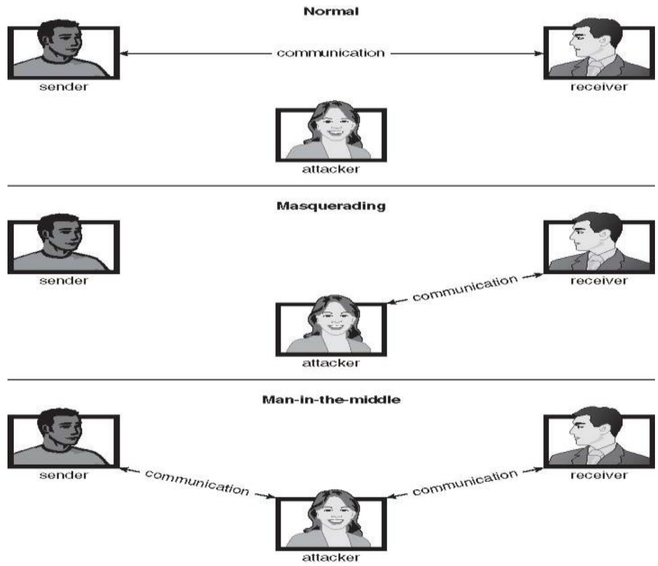
The following list includes several forms of accidental and malicious security violations

- **Breach of confidentiality**
  - Unauthorized reading of data
- **Breach of integrity**
  - Unauthorized modification of data
- **Breach of availability**
  - Unauthorized destruction of data
- **Theft of service**
  - Unauthorized use of resources
- **Denial of service (DOS)**
  - Prevention of legitimate use

Security Violation Methods

- **Masquerading** (breach **authentication**)
  - Pretending to be an authorized user to escalate privileges
- **Replay attack**
  - As is or with **message modification**
- **Man-in-the-middle attack**
  - Intruder sits in data flow, masquerading as sender to receiver and vice versa
- **Session hijacking**
  - Intercept an already-established session to bypass authentication

Standard Security Attacks



Security Measure Levels

- Impossible to have absolute security, but make cost to perpetrator sufficiently high to deter most intruders
- Security measures must occur or consider at four levels to be effective:
  - **Physical**
    - Data centers, servers, connected terminals
  - **Human**
    - Avoid **social engineering**, **phishing**, **dumpster diving**
  - **Operating System**
    - Protection mechanisms, debugging
  - **Network**
    - Intercepted communications, interruption, DOS
- Security is as weak as the weakest link in the chain
- But can too much security be a problem?

Program Threats

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Program Threats

- Many variations, many names
- **Trojan Horse**
  - Code segment that misuses its environment
  - Exploits mechanisms for allowing programs written by users to be executed by other users
  - **Spyware**, **pop-up browser windows**, **covert channels**
  - Up to 80% of spam delivered by spyware-infected systems
- **Trap Door**
  - Specific user identifier or password that circumvents normal security procedures
  - Could be included in a compiler
  - How to detect them?

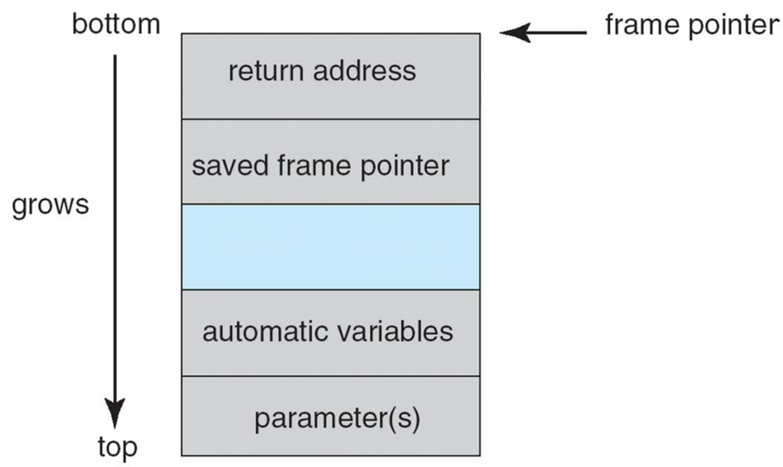
Program Threats (Cont.)

- **Logic Bomb**
  - Program that initiates a security incident under certain circumstances
- **Stack** and **Buffer Overflow**
  - Exploits a bug in a program (overflow either the stack or memory buffers)
  - Failure to check bounds on inputs, arguments
  - Write past arguments on the stack into the return address on stack
  - When routine returns from call, returns to hacked address
    - Pointed to code loaded onto stack that executes malicious code
  - Unauthorized user or privilege escalation

C Program with Buffer-overflow Condition

```
#include <stdio.h>
#define BUFFERSIZE 256
int main(int argc, char *argv[])
{
  char buffer[BUFFERSIZE];
  if (argc < 2)
     return -1;
  else {
     strcpy(buffer,argv[1]);
     return 0;
  }
}
```

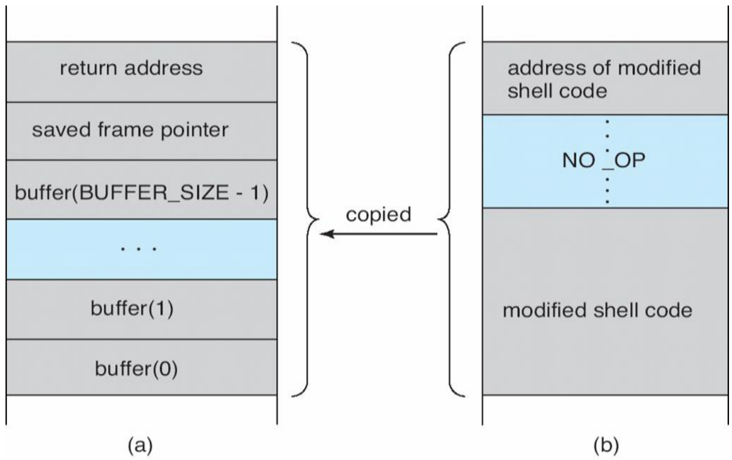
Layout of Typical Stack Frame



Modified Shell Code

```
#include <stdio.h>
int main(int argc, char *argv[])
{
  execvp(‘‘\bin\sh’’,‘‘\bin \sh’’, NULL);
  return 0;
}
```

Hypothetical Stack Frame



Before attack After attack

Great Programming Required?

- For the first step of determining the bug, and second step of writing exploit code, yes
- Script kiddies can run pre-written exploit code to attack a given system
- Attack code can get a shell with the processes' owner's permissions
  - Or open a network port, delete files, download a program, etc
- Depending on bug, attack can be executed across a network using allowed connections, bypassing firewalls
- Buffer overflow can be disabled by disabling stack execution or adding bit to page table to indicate "non-executable" state
  - Available in SPARC and x86
  - But still have security exploits

Program Threats (Cont.)

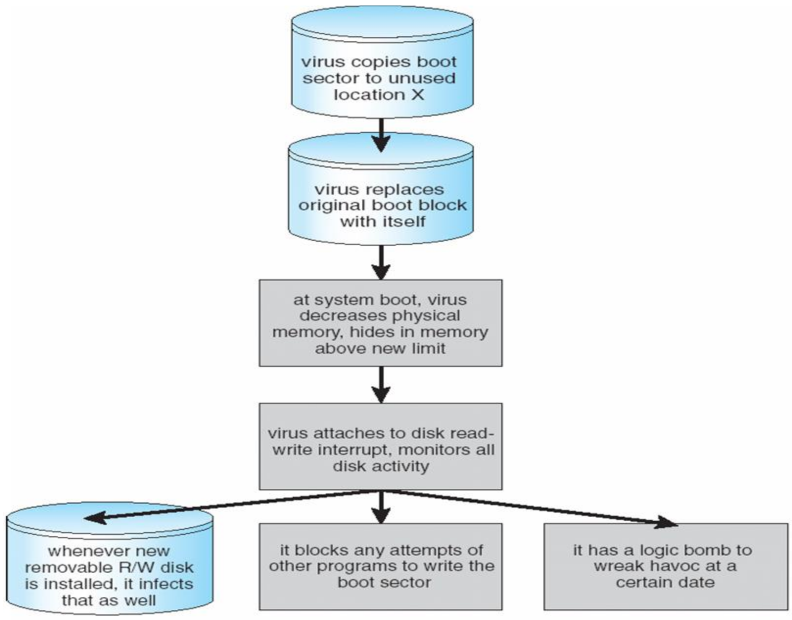
- **Viruses**
  - **Code fragment embedded in legitimate program**
  - Self-replicating, designed to infect other computers
  - Very specific to CPU architecture, operating system, applications
  - Usually borne via email or as a macro
  - Visual Basic Macro to reformat hard drive

```
Sub AutoOpen()
Dim oFS
  Set oFS = CreateObject(''Scripting.FileSystemObject'')
  vs = Shell(''c:command.com /k format c:'',vbHide)
End Sub
```

Program Threats (Cont.)

- **Virus dropper** inserts virus onto the system
- Many categories of viruses, literally many thousands of viruses
  - File / parasitic
  - Boot / memory
  - Macro
  - Source code
  - Polymorphic to avoid having a **virus signature**
  - Encrypted
  - Stealth
  - Tunneling
  - Multipartite
  - Armored

A Boot-sector Computer Virus



The Threat Continues

- Attacks still common, still occurring
- Attacks moved over time from science experiments to tools of organized crime
  - Targeting specific companies
  - Creating botnets to use as tool for spam and DDOS delivery
  - **Keystroke logger** to grab passwords, credit card numbers
- Why is Windows the target for most attacks?
  - Most common
  - Everyone is an administrator
    - Licensing required?
  - **Monoculture** considered harmful

System and Network threats

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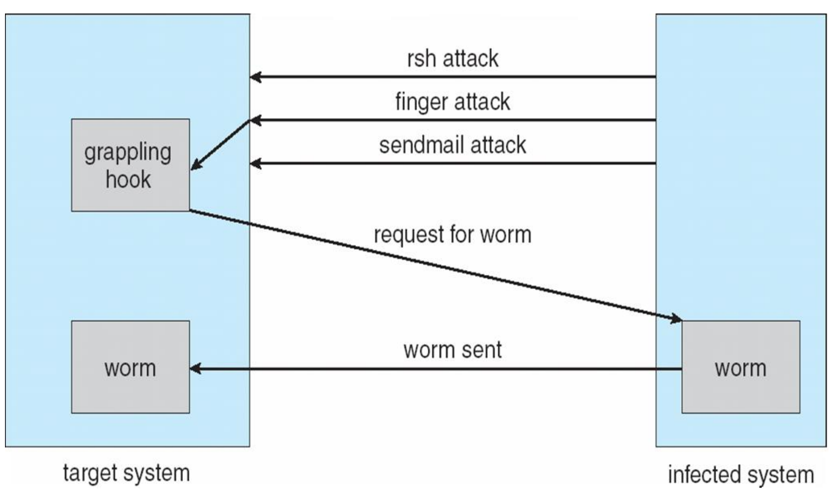
System and Network Threats

- Some systems "open" rather than **secure by default**
  - Reduce **attack surface**
  - But harder to use, more knowledge needed to administer
- Network threats harder to detect, prevent
  - Protection systems weaker
  - More difficult to have a shared secret on which to base access
  - No physical limits once system attached to internet
    - Or on network with system attached to internet
  - Even determining location of connecting system difficult
    - IP address is only knowledge

System and Network Threats (Cont.)

- **Worms** – use **spawn** mechanism; standalone program
- Internet worm
  - Exploited UNIX networking features (remote access) and bugs in *finger* and *sendmail* programs
  - Exploited trust-relationship mechanism used by *rsh* to access friendly systems without use of password
  - **Grappling hook** program uploaded main worm program
    - 99 lines of C code
  - Hooked system then uploaded main code, tried to attack connected systems
  - Also tried to break into other users accounts on local system via password guessing
  - If target system already infected, abort, except for every 7th time

The Morris Internet Worm



System and Network Threats (Cont.)

- **Port scanning**
  - Automated attempt to connect to a range of ports on one or a range of IP addresses
  - Detection of answering service protocol
  - Detection of OS and version running on system
  - `nmap` scans all ports in a given IP range for a response
  - `nessus` has a database of protocols and bugs (and exploits) to apply against a system
  - Frequently launched from **zombie systems**
    - To decrease trace-ability

System and Network Threats (Cont.)

- **Denial of Service**
  - Overload the targeted computer preventing it from doing any useful work
  - **Distributed denial-of-service** (**DDOS**) come from multiple sites at once
  - Consider the start of the IP-connection handshake (SYN)
    - How many started-connections can the OS handle?
  - Consider traffic to a web site
    - How can you tell the difference between being a target and being really popular?
  - Accidental – CS students writing bad `fork()` code
  - Purposeful – extortion, punishment

Cryptography as a Security Tool

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Cryptography as a Security Tool

- Broadest security tool available
  - Internal to a given computer, source and destination of messages can be known and protected
    - OS creates, manages, protects process IDs, communication ports
  - Source and destination of messages on network cannot be trusted without cryptography
    - Local network – IP address?
      - Consider unauthorized host added
    - WAN / Internet – how to establish authenticity
      - Not via IP address

Cryptography

- Means to constrain potential senders (*sources*) and / or receivers (*destinations*) of *messages*
  - Based on secrets (**keys**)
  - Enables
    - Confirmation of source
    - Receipt only by certain destination
    - Trust relationship between sender and receiver

Encryption

- Constrains the set of possible receivers of a message
- **Encryption** algorithm consists of
  - Set K of keys
  - Set M of Messages
  - Set C of ciphertexts (encrypted messages)
  - A function $E : K \rightarrow (M \rightarrow C)$. That is, for each $k \in K$, E_k is a function for generating ciphertexts from messages
    - Both E and E_k for any k should be efficiently computable functions
  - A function $D : K \rightarrow (C \rightarrow M)$. That is, for each $k \in K$, D_k is a function for generating messages from ciphertexts
    - Both D and D_k for any k should be efficiently computable functions

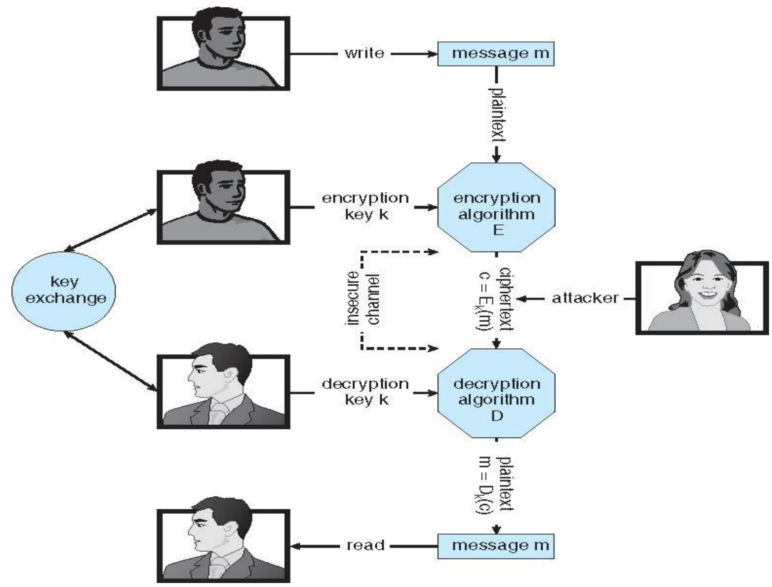
Encryption (Cont.)

- An encryption algorithm must provide this essential property: Given a ciphertext $c \in C$, a computer can compute m such that $E_k(m) = c$ only if it possesses *k*
  - Thus, a computer holding *k* can decrypt ciphertexts to the plaintexts used to produce them, but a computer not holding *k* cannot decrypt ciphertexts
  - Since ciphertexts are generally exposed (for example, sent on the network), it is important that it be infeasible to derive *k* from the ciphertexts

Symmetric Encryption

- Same key used to encrypt and decrypt
  - Therefore *k* must be kept secret
- DES was most commonly used symmetric block-encryption algorithm (created by US Govt)
  - Encrypts a block of data at a time
  - Keys too short so now considered insecure
- Triple-DES considered more secure
  - Algorithm used 3 times using 2 or 3 keys
  - For example $c = E_{k3}(D_{k2}(E_{k1}(m)))$
- 2001 NIST adopted new block cipher - Advanced Encryption Standard (**AES**)
  - Keys of 128, 192, or 256 bits, works on 128 bit blocks
- RC4 is most common symmetric stream cipher, but known to have vulnerabilities
  - Encrypts/decrypts a stream of bytes (i.e., wireless transmission)
  - Key is a input to pseudo-random-bit generator
    - Generates an infinite **keystream**

Secure Communication over Insecure Medium



Asymmetric Encryption

- **Public-key encryption** based on each user having two keys:
  - **public key** – published key used to encrypt data
  - **private key** – key known only to individual user used to decrypt data
- Must be an encryption scheme that can be made public without making it easy to figure out the decryption scheme
  - Most common is **RSA** block cipher
  - Efficient algorithm for testing whether or not a number is prime
  - No efficient algorithm is know for finding the prime factors of a number

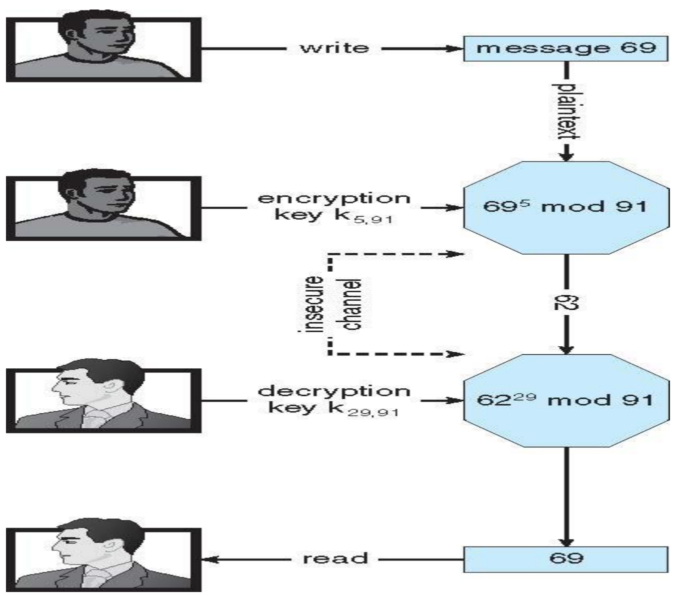
Asymmetric Encryption (Cont.)

- Formally, it is computationally infeasible to derive $k_{d,N}$ from $k_{e,N}$, and so k_e need not be kept secret and can be widely disseminated
  - k_e is the **public key**
  - k_d is the **private key**
  - N is the product of two large, randomly chosen prime numbers p and q (for example, p and q are 512 bits each)
  - Encryption algorithm is $E_{ke,N}(m) = m^{k_e} \bmod N$, where k_e satisfies $k_e k_d \bmod (p-1)(q-1) = 1$
  - The decryption algorithm is then $D_{kd,N}(c) = c^{k_d} \bmod N$

Asymmetric Encryption Example

- For example. make $p = 7$and $q = 13$
- We then calculate $N = 7*13 = 91$ and $(p-1)(q-1) = 72$
- We next select k_e relatively prime to 72 and< 72, yielding 5
- Finally, we calculate k_d such that $k_e k_d \bmod 72 = 1$, yielding 29
- We how have our keys
  - Public key, $k_{e,N} = 5, 91$
  - Private key, $k_{d,N} = 29, 91$
- Encrypting the message 69 with the public key results in the cyphertext 62
- Cyphertext can be decoded with the private key
  - Public key can be distributed in cleartext to anyone who wants to communicate with holder of public key

Encryption using RSA Asymmetric Cryptography



Cryptography (Cont.)

- Note symmetric cryptography based on transformations, asymmetric based on mathematical functions
  - Asymmetric much more compute intensive
  - Typically not used for bulk data encryption

Authentication

- Constraining set of potential senders of a message
  - Complementary to encryption
  - Also can prove message unmodified
- Algorithm components
  - A set *K* of keys
  - A set *M* of messages
  - A set *A* of authenticators
  - A function $S : K \rightarrow (M \rightarrow A)$
    - That is, for each $k \in K$, S_k is a function for generating authenticators from messages
    - Both *S* and S_k for any *k* should be efficiently computable functions
  - A function $V : K \rightarrow (M \times A \rightarrow \{\text{true, false}\})$. That is, for each $k \in K$, V_k is a function for verifying authenticators on messages
    - Both *V* and V_k for any *k* should be efficiently computable functions

Authentication (Cont.)

- For a message *m*, a computer can generate an authenticator $a \in A$ such that $V_k(m, a)$ = `true` only if it possesses *k*
- Thus, computer holding *k* can generate authenticators on messages so that any other computer possessing *k* can verify them
- Computer not holding *k* cannot generate authenticators on messages that can be verified using V_k
- Since authenticators are generally exposed (for example, they are sent on the network with the messages themselves), it must not be feasible to derive *k* from the authenticators
- Practically, if $V_k(m,a)$ = **`true`** then we know *m* has not been modified and that send of message has *k*
  - If we share *k* with only one entity, know where the message originated

Authentication – Hash Functions

- Basis of authentication
- Creates small, fixed-size block of data **message digest** (**hash value)** from *m*
- Hash Function *H* must be collision resistant on *m*
  - Must be infeasible to find an $m' \neq m$ such that $H(m) = H(m')$
- If $H(m) = H(m')$, then $m = m'$
  - The message has not been modified
- Common message-digest functions include **MD5**, which produces a 128-bit hash, and **SHA-1**, which outputs a 160-bit hash
- Not useful as authenticators
  - For example *H(m)* can be sent with a message
    - But if *H* is known someone could modify *m* to *m'* and recompute *H(m')* and modification not detected
    - So must authenticate *H(m)*

Authentication - MAC

- Symmetric encryption used in **message-authentication code** (**MAC**) authentication algorithm
- Cryptographic checksum generated from message using secret key
  - Can securely authenticate short values
- If used to authenticate *H(m)* for an *H* that is collision resistant, then obtain a way to securely authenticate long message by hashing them first
- Note that *k* is needed to compute both S_k and V_k, so anyone able to compute one can compute the other

Authentication – Digital Signature

- Based on asymmetric keys and digital signature algorithm
- Authenticators produced are **digital signatures**
- Very useful – ***anyone*** can verify authenticity of a message
- In a digital-signature algorithm, computationally infeasible to derive k_s from k_v
  - V is a one-way function
  - Thus, k_v is the public key and k_s is the private key
- Consider the RSA digital-signature algorithm
  - Similar to the RSA encryption algorithm, but the key use is reversed
  - Digital signature of message $S_{ks}(m) = H(m)^{k_s} \bmod N$
  - The key k_s again is a pair (d, N), where N is the product of two large, randomly chosen prime numbers p and q
  - Verification algorithm is $V_{kv}(m, a) \quad (a^{k_v} \bmod N \stackrel{?}{=} H(m))$
    - Where k_v satisfies $k_v k_s \bmod (p - 1)(q - 1) = 1$

Authentication (Cont.)

- Why authentication if a subset of encryption?
  - Fewer computations (except for RSA digital signatures)
  - Authenticator usually shorter than message
  - Sometimes want authentication but not confidentiality
    - Signed patches et al
  - Can be basis for **non-repudiation**

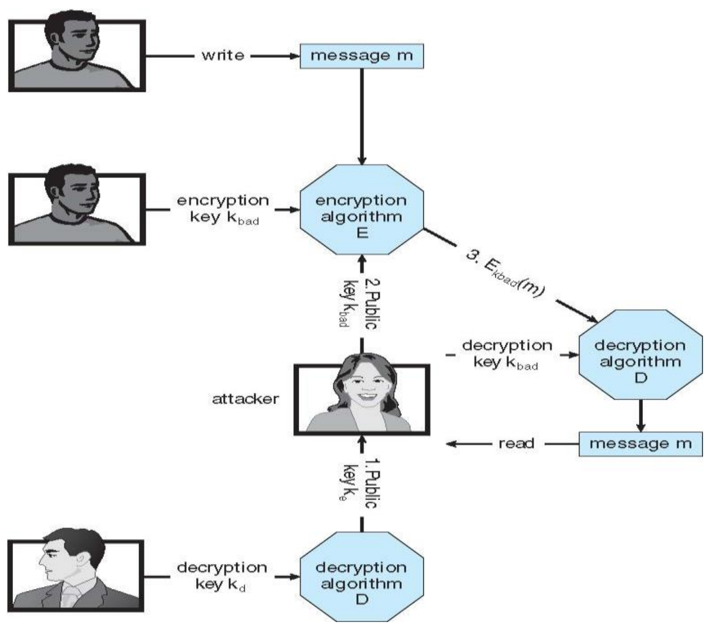
Key Distribution

- Delivery of symmetric key is huge challenge
  - Sometimes done **out-of-band**
- Asymmetric keys can proliferate – stored on **key ring**
  - Even asymmetric key distribution needs care – man-in-the-middle attack

Digital Certificates

- Proof of who or what owns a public key
- Public key digitally signed a trusted party
- Trusted party receives proof of identification from entity and certifies that public key belongs to entity
- **Certificate authority** are trusted party – their public keys included with web browser distributions
  - They vouch for other authorities via digitally signing their keys, and so on

Man-in-the-middle Attack on Asymmetric Cryptography



Implementation of Cryptography

- Can be done at various **layers** of ISO Reference Model
  - SSL at the Transport layer
  - Network layer is typically **IPSec**
    - **IKE** for key exchange
    - Basis of **Virtual Private Networks (VPNs)**
- Why not just at lowest level?
  - Sometimes need more knowledge than available at low levels
    - i.e. User authentication
    - i.e. e-mail delivery

OSI model
7. Application Layer
NNTP · SIP · SSI · DNS · FTP · Gopher · HTTP · NFS · NTP · SMPP · SMTP · SNMP · Telnet · Netconf · (more)
6. Presentation Layer
MIME · XDR · TLS · SSL
5. Session Layer
Named Pipes · NetBIOS · SAP · L2TP · PPTP · SPDY
4. Transport Layer
TCP · UDP · SCTP · DCCP · SPX
3. Network Layer
IP (IPv4, IPv6) · ICMP · IPsec · IGMP · IPX · AppleTalk
2. Data Link Layer
ATM · SDLC · HDLC · ARP · CSLIP · SLIP · GFP · PLIP · IEEE 802.3 · Frame Relay · ITU-T G.hn DLL · PPP · X.25 · Network Switch · DHCP
1. Physical Layer
EIA/TIA-232 · EIA/TIA-449 · ITU-T V-Series · I.430 · I.431 · POTS · PDH · SONET/SDH · PON · OTN · DSL · IEEE 802.3 · IEEE 802.11 · IEEE 802.15 · IEEE 802.16 · IEEE 1394 · ITU-T G.hn PHY · USB · Bluetooth · Hubs
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OSI Model

	Data unit	Layer	Function
Host layers	Data	7. Application	Network process to application
		6. Presentation	Data representation, encryption and decryption, convert machine dependent data to machine independent data
		5. Session	Interhost communication
	Segments	4. Transport	End-to-end connections and reliability, flow control
Media layers	Packet/Datagram	3. Network	Path determination and logical addressing
	Frame	2. Data Link	Physical addressing
	Bit	1. Physical	Media, signal and binary transmission

Source: http://en.wikipedia.org/wiki/OSI_model

Encryption Example - SSL

- Insertion of cryptography at one layer of the ISO network model (the transport layer)
- SSL – Secure Socket Layer (also called TLS)
- Cryptographic protocol that limits two computers to only exchange messages with each other
  - Very complicated, with many variations
- Used between web servers and browsers for secure communication (credit card numbers)
- The server is verified with a **certificate** assuring client is talking to correct server
- Asymmetric cryptography used to establish a secure **session key** (symmetric encryption) for bulk of communication during session
- Communication between each computer then uses symmetric key cryptography
- More details in textbook

END of Chapter - 2

END of Unit-5