

# CS420: Operating Systems

## Cryptography

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# Cryptography as a Security Tool

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- **Broadest security tool available**

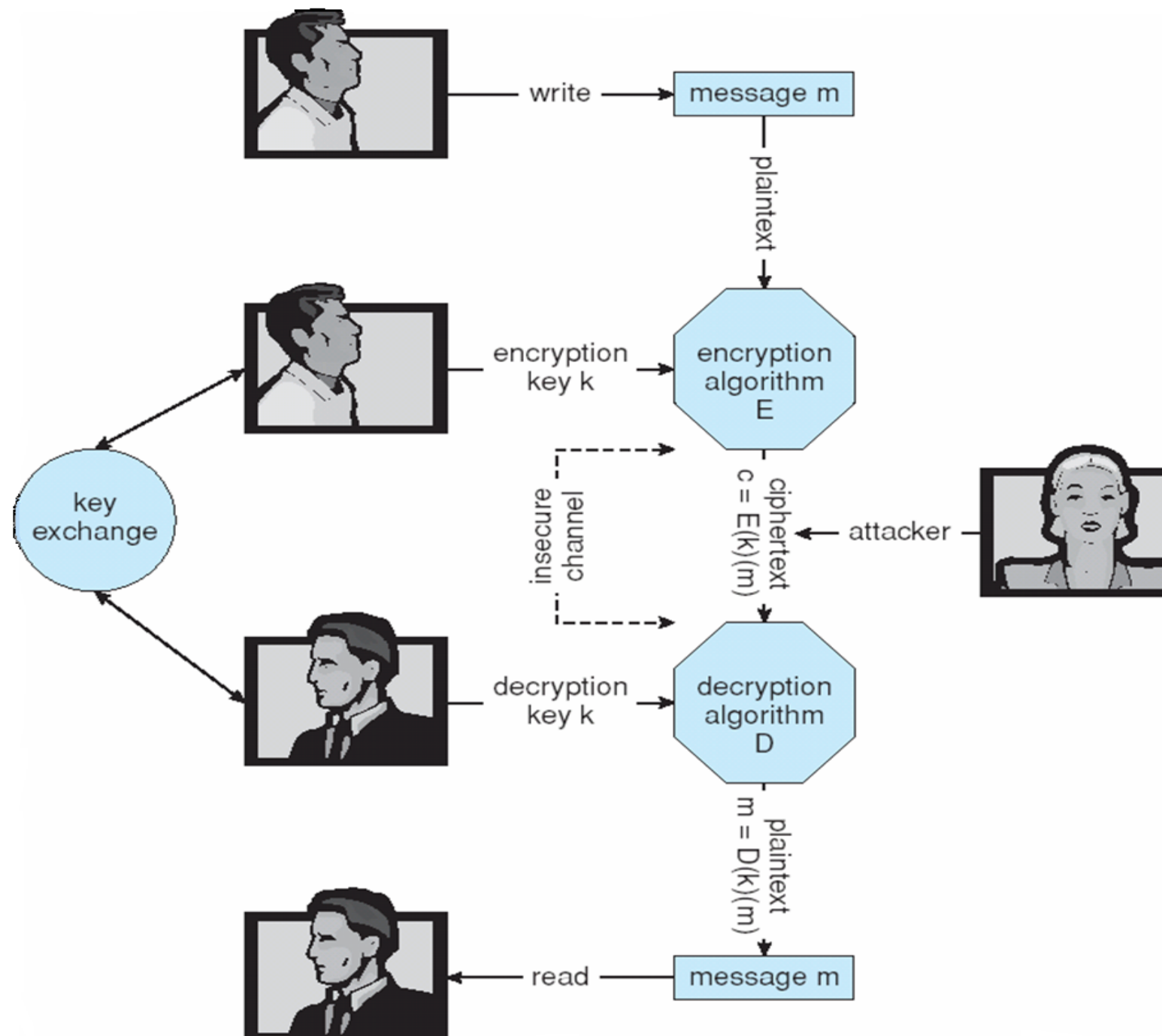
- Internal to a given computer, source and destination of messages can be known and protected
  - OS creates, manages, protects process IDs, communication ports
- Source and destination of messages on network cannot be trusted without cryptography
  - Local network – IP address?
    - Consider unauthorized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

# Cryptography

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- **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

# Secure Communication Over Insecure Medium



# Encryption

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- **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

- **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  $D(k)$**

- Thus, a computer holding  $D(k)$  can decrypt ciphertexts to the plaintexts used to produce them, but a computer not holding  $D(k)$  cannot decrypt ciphertexts
- Since ciphertexts are generally exposed (for example, sent on the network), it is important that it be infeasible to derive  $D(k)$  from the ciphertexts

# Symmetric Encryption

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- **Same key used to encrypt and decrypt**
  - $E(k)$  can be derived from  $D(k)$ , and vice versa
- **DES is most commonly used symmetric block-encryption algorithm (created by US Govt)**
  - Encrypts a block of data at a time
- **Triple-DES considered more secure**
- **Advanced Encryption Standard (AES), twofish up and coming**
- **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 psuedo-random-bit generator
    - Generates an infinite keystream

# Asymmetric Encryption

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- **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 known for finding the prime factors of a number

# Asymmetric Encryption (Cont.)

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- **Formally, it is computationally infeasible to derive  $D(k_d, N)$  from  $E(k_e, N)$ , and so  $E(k_e, N)$  need not be kept secret and can be widely disseminated**
  - $E(k_e, N)$  (or just  $k_e$ ) is the public key
  - $D(k_d, N)$  (or just  $k_d$ ) 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  $E(k_e, N)(m) = m^{k_e} \bmod N$ , where  $k_e$  satisfies  $k_e k_d \bmod (p-1)(q-1) = 1$
  - The decryption algorithm is then  $D(k_d, N)(c) = c^{k_d} \bmod N$

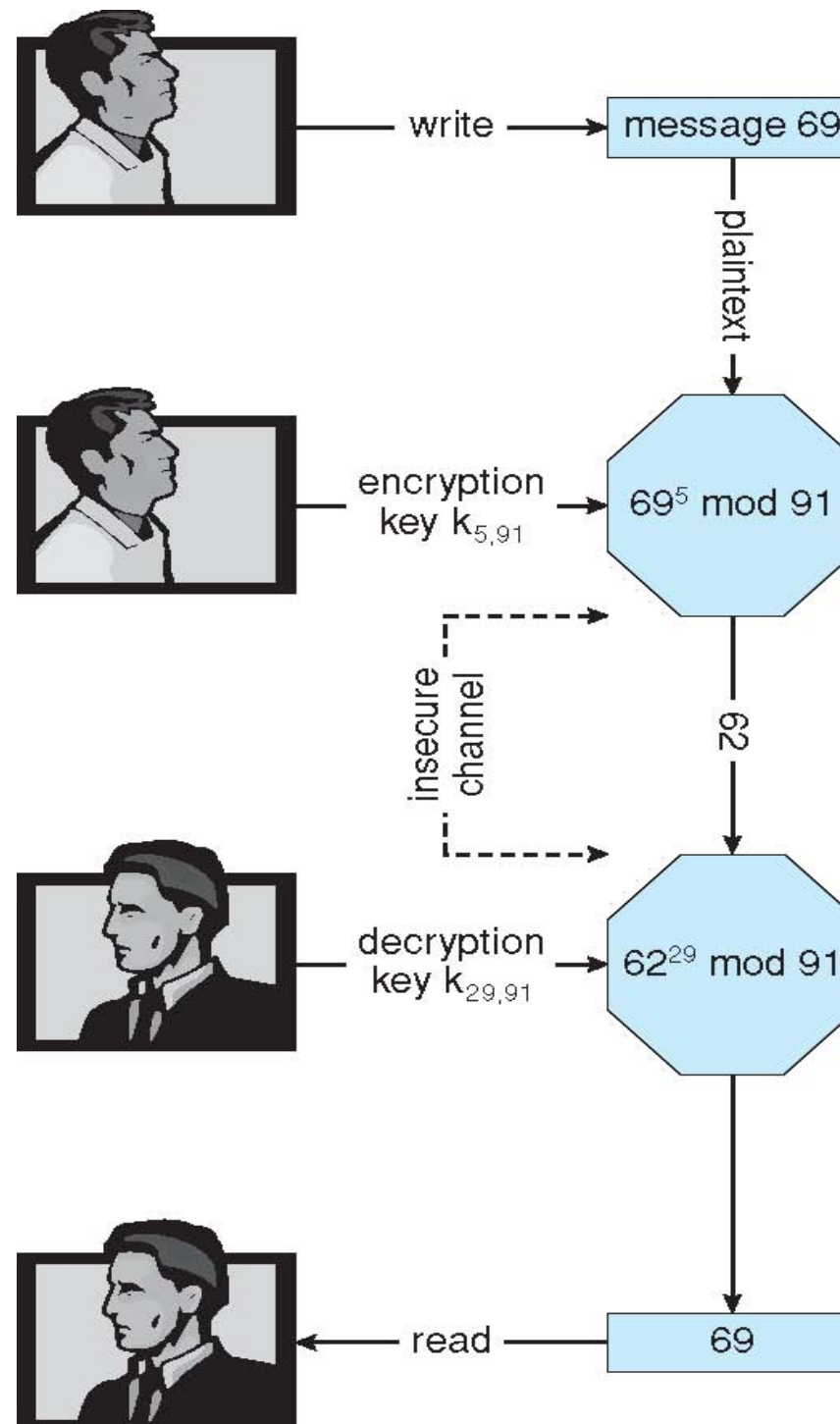


# Asymmetric Encryption Example

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- 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 now 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 ciphertext 62
- Ciphertext 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/Decryption with RSA Asymmetric Cryptography



# Cryptography (Cont.)

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

# Authentication

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- **Constraining set of potential senders of a message**

- Complementary and sometimes redundant 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  $V : K \rightarrow (M \times A \rightarrow \{\text{true}, \text{false}\})$ . 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.)

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- For a message  $m$ , a computer can generate an authenticator  $a \in A$  such that  $V(k)(m, a) = \text{true}$  only if it possesses  $S(k)$
- Thus, computer holding  $S(k)$  can generate authenticators on messages so that any other computer possessing  $V(k)$  can verify them
- Computer not holding  $S(k)$  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  $S(k)$  from the authenticators

# Authentication – Hash Functions

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- **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**

# Authentication - MAC

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- **Symmetric encryption used in message-authentication code (MAC) authentication algorithm**
- **Simple example:**
  - MAC defines  $S(k)(m) = f(k, H(m))$ 
    - Where  $f$  is a function that is one-way on its first argument
      - $k$  cannot be derived from  $f(k, H(m))$
    - Because of the collision resistance in the hash function, reasonably assured no other message could create the same MAC
    - A suitable verification algorithm is  $V(k)(m, a) \equiv (f(k, m) = a)$
    - 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

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- **Based on asymmetric keys and digital signature algorithm**
- **Authenticators produced are digital signatures**
- **In a digital-signature algorithm, computationally infeasible to derive  $S(k_s)$  from  $V(k_v)$** 
  - $V$  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  $S(k_s)(m) = H(m)^{k_s} \bmod N$
  - 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  $V(k_v)(m, a) \equiv (a^{k_v} \bmod N = H(m))$ 
    - Where  $k_v$  satisfies  $k_v k_s \bmod (p-1)(q-1) = 1$



# Authentication (Cont.)

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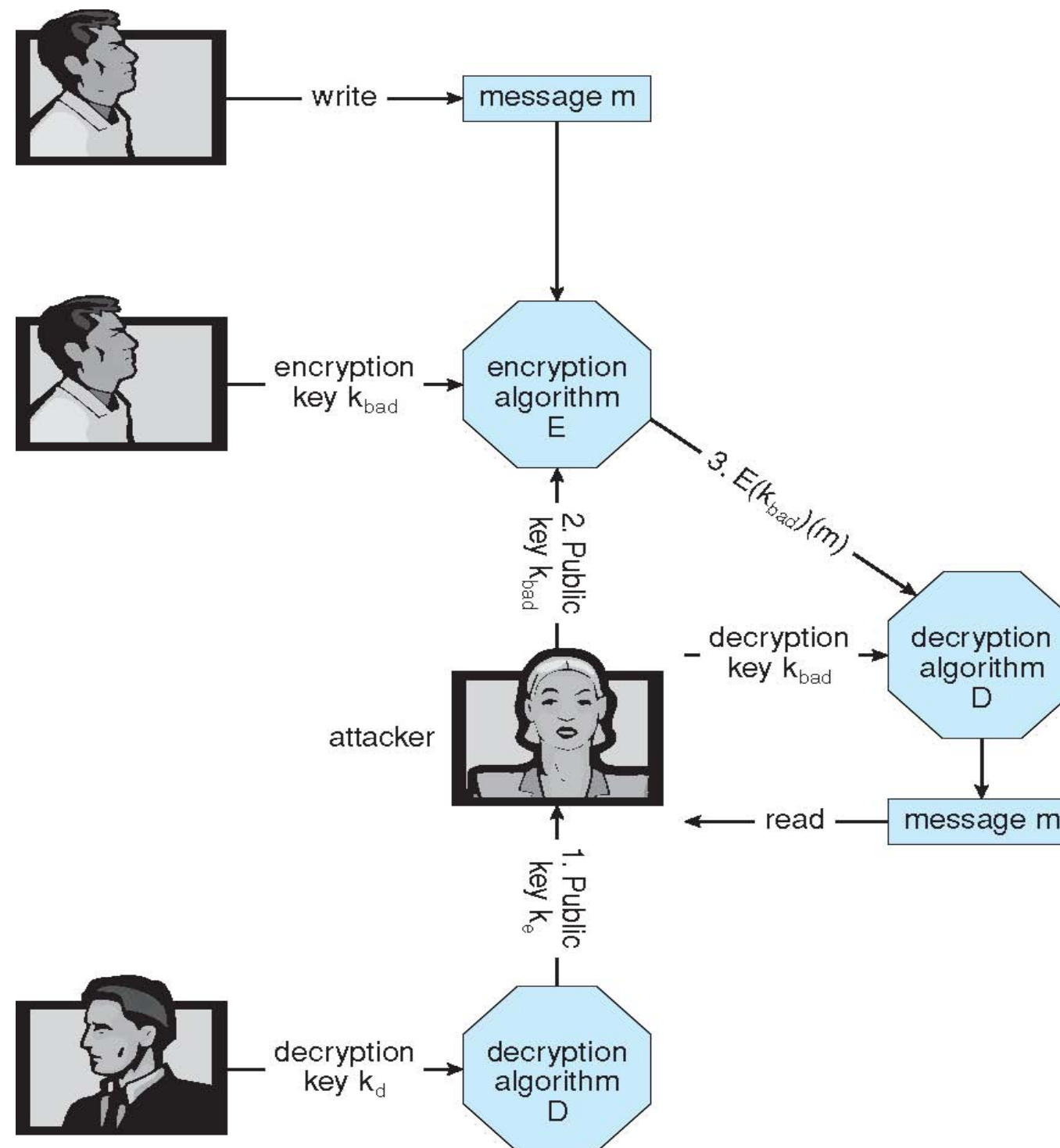
- **Why authentication is a subset of encryption?**
  - Fewer computations (except for RSA digital signatures)
  - Authenticator usually shorter than message
  - Sometimes want authentication but not confidentiality
    - Signed patches et al
  - Can be basis for non-repudiation

# Key Distribution

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- **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

# Man-in-the-middle Attack On Asymmetric Cryptography



# Digital Certificates

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- **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

# Implementation of Cryptography

- **Can be done at various levels of ISO Reference Model**
  - SSL at the Transport layer
  - Network layer is typically IPSec
    - IKE for key exchange
    - Basis of 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	
<b>7. Application Layer</b>	
NNTP · SIP · SSI · DNS · FTP · Gopher · HTTP · NFS · NTP · SMPP · SMTP · SNMP · Telnet · Netconf · (more)	
<b>6. Presentation Layer</b>	
MIME · XDR · TLS · SSL	
<b>5. Session Layer</b>	
Named Pipes · NetBIOS · SAP · L2TP · PPTP · SPDY	
<b>4. Transport Layer</b>	
TCP · UDP · SCTP · DCCP · SPX	
<b>3. Network Layer</b>	
IP (IPv4, IPv6) · ICMP · IPsec · IGMP · IPX · AppleTalk	
<b>2. Data Link Layer</b>	
ATM · SDLC · HDLC · ARP · CSLIP · SLIP · GFP · PLIP · IEEE 802.3 · Frame Relay · ITU-T G.hn DLL · PPP · X.25 · Network Switch · DHCP	
<b>1. Physical Layer</b>	
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

[http://en.wikipedia.org/wiki/OSI\\_model](http://en.wikipedia.org/wiki/OSI_model)

# Encryption Example - SSL

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- **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**

# User Authentication

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- **Crucial to identify user correctly, as protection systems depend on user ID**
- **User identity most often established through passwords, can be considered a special case of either keys or capabilities**
- **Passwords must be kept secret**
  - Frequent change of passwords
  - History to avoid repeats
  - Use of “non-guessable” passwords
  - Log all invalid access attempts (but not the passwords themselves)
  - Unauthorized transfer
- **Passwords may also either be encrypted or allowed to be used only once**
  - Does encrypting passwords solve the exposure problem?
    - Might solve sniffing
    - Consider shoulder surfing
    - Consider Trojan horse keystroke logger
    - How are passwords stored at authenticating site?

# Passwords

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- **Encrypt to avoid having to keep secret**

- But keep secret anyway (i.e. Unix uses superuser-only readable file /etc/shadow)
- Use algorithm easy to compute but difficult to invert
- Only encrypted password stored, never decrypted
- Add “salt” to avoid the same password being encrypted to the same value

- **One-time passwords**

- Use a function based on a seed to compute a password, both user and computer
- Hardware device / calculator / key fob to generate the password
  - Changes very frequently

- **Biometrics**

- Some physical attribute (fingerprint, hand scan)

- **Multi-factor authentication**

- Need two or more factors for authentication
  - i.e. USB “dongle”, biometric measure, and password



# Implementing Security Defenses

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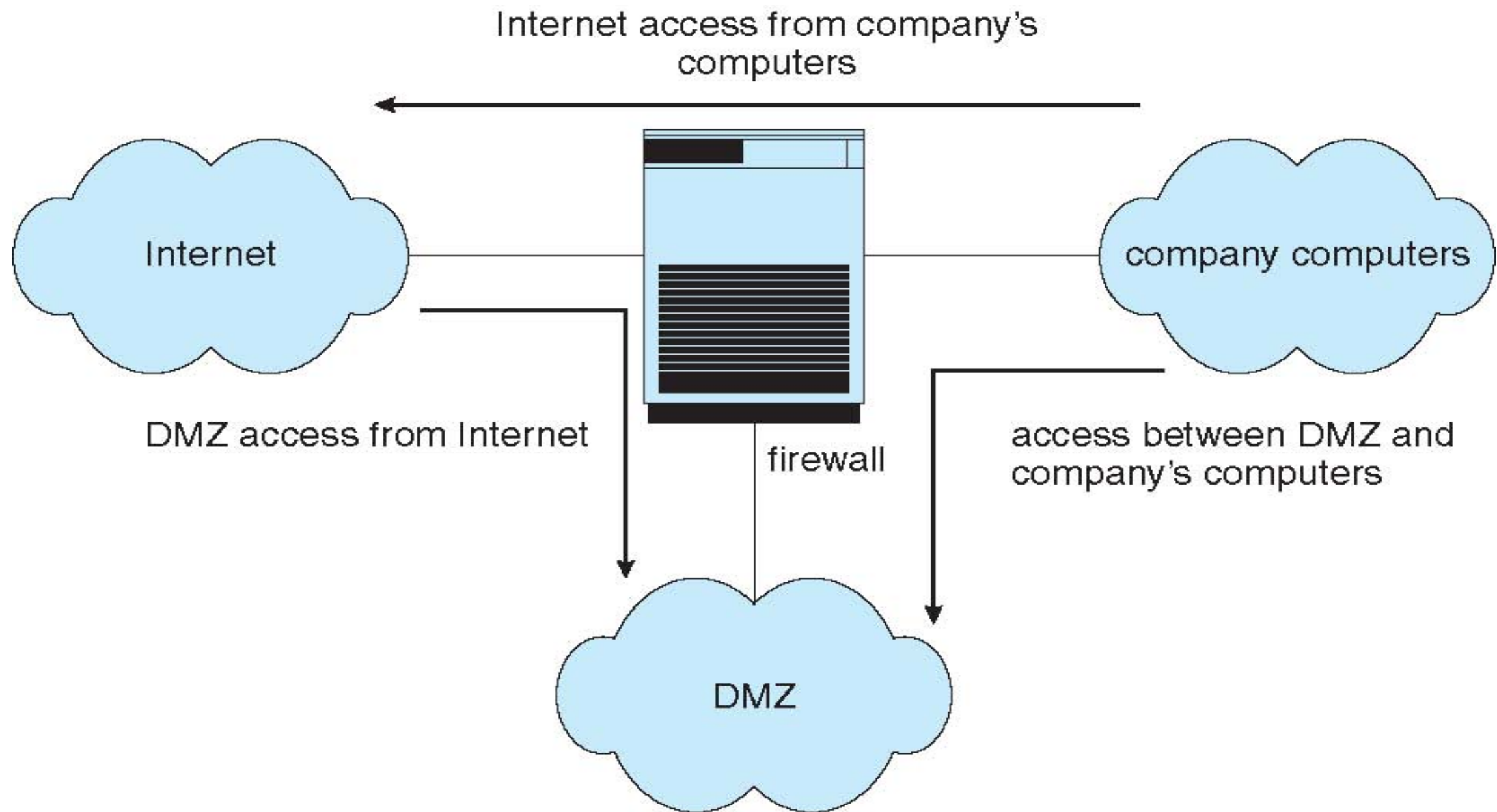
- **Defense in depth is most common security theory – multiple layers of security**
- **Security policy describes what is being secured**
- **Vulnerability assessment compares real state of system / network compared to security policy**
- **Intrusion detection endeavors to detect attempted or successful intrusions**
  - Signature-based detection spots known bad patterns
  - Anomaly detection spots differences from normal behavior
    - **Can detect zero-day attacks**
  - False-positives and false-negatives a problem
- **Virus protection**
- **Auditing, accounting, and logging of all or specific system or network activities**

# Firewalling to Protect Systems and Networks

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- **A network firewall is placed between trusted and untrusted hosts**
  - The firewall limits network access between these two security domains
- **Can be tunneled or spoofed**
  - Tunneling allows disallowed protocol to travel within allowed protocol (i.e., telnet inside of HTTP)
  - Firewall rules typically based on host name or IP address which can be spoofed
- **Personal firewall is software layer on given host**
  - Can monitor / limit traffic to and from the host
- **Application proxy firewall understands application protocol and can control them (i.e., SMTP)**
- **System-call firewall monitors all important system calls and apply rules to them (i.e., this program can execute that system call)**

# Network Security Through Domain Separation Via Firewall



# Computer Security Classifications

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- **U.S. Department of Defense outlines four divisions of computer security: A, B, C, and D**
- **D – Minimal security**
- **C – Provides discretionary protection through auditing**
  - Divided into C1 and C2
    - C1 identifies cooperating users with the same level of protection
    - C2 allows user-level access control
- **B – All the properties of C, however each object may have unique sensitivity labels**
  - Divided into B1, B2, and B3
- **A – Uses formal design and verification techniques to ensure security**

# Example: Windows

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- **Security is based on user accounts**
  - Each user has unique security ID
  - Login to ID creates security access token
    - Includes security ID for user, for user's groups, and special privileges
    - Every process gets copy of token
    - System checks token to determine if access allowed or denied
- **Uses a subject model to ensure access security**
  - A subject tracks and manages permissions for each program that a user runs
- **Each object in Windows has a security attribute defined by a security descriptor**
  - For example, a file has a security descriptor that indicates the access permissions for all users