

TDT506: Computer Networks

Instructor: Niklas Carlsson

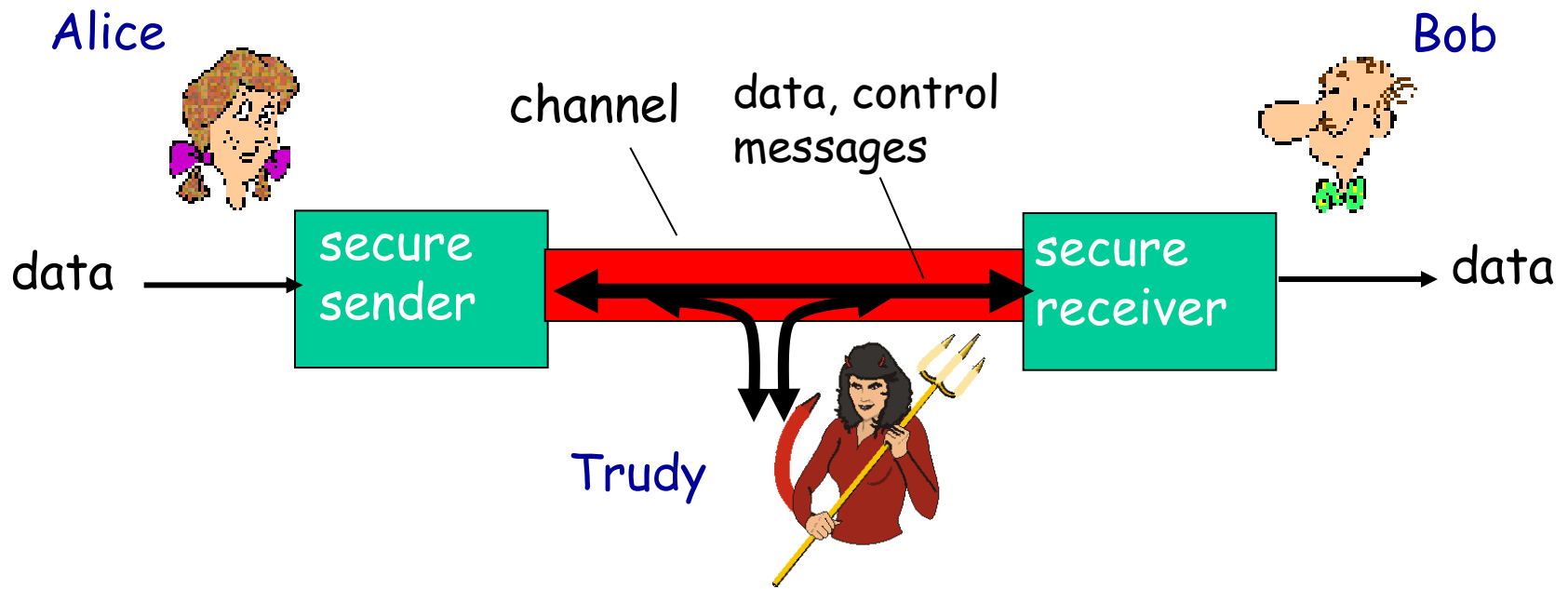
Email: niklas.carlsson@liu.se

Notes derived from "*Computer Networking: A Top Down Approach*", by Jim Kurose and Keith Ross, Addison-Wesley.

The slides are adapted and modified based on slides from the book's companion Web site, as well as modified slides by Anirban Mahanti and Carey Williamson.

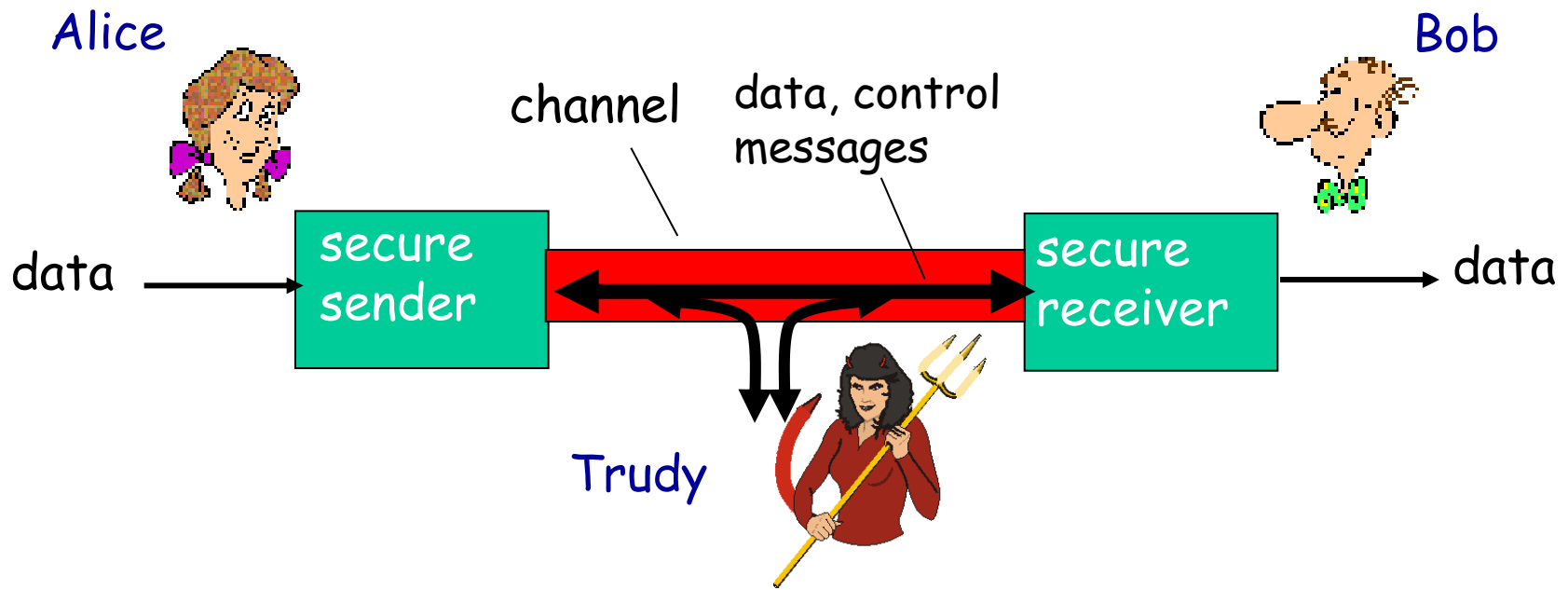
Friends and enemies: Alice, Bob, Trudy

- ❖ well-known in network security world
- ❖ Bob, Alice (lovers!) want to communicate "securely"
- ❖ Trudy (intruder) may intercept, delete, add messages



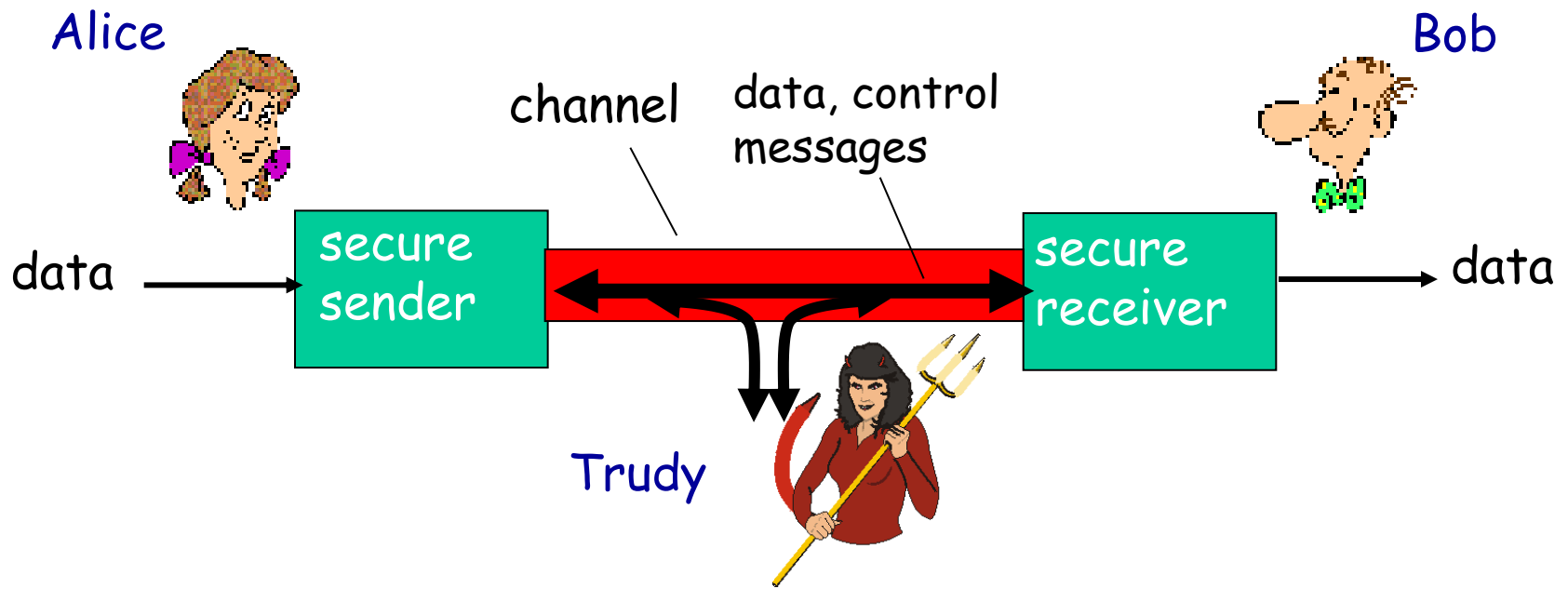
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- 1) **Confidentiality:** only sender, intended receiver should "understand" message contents
- sender encrypts message
 - receiver decrypts message



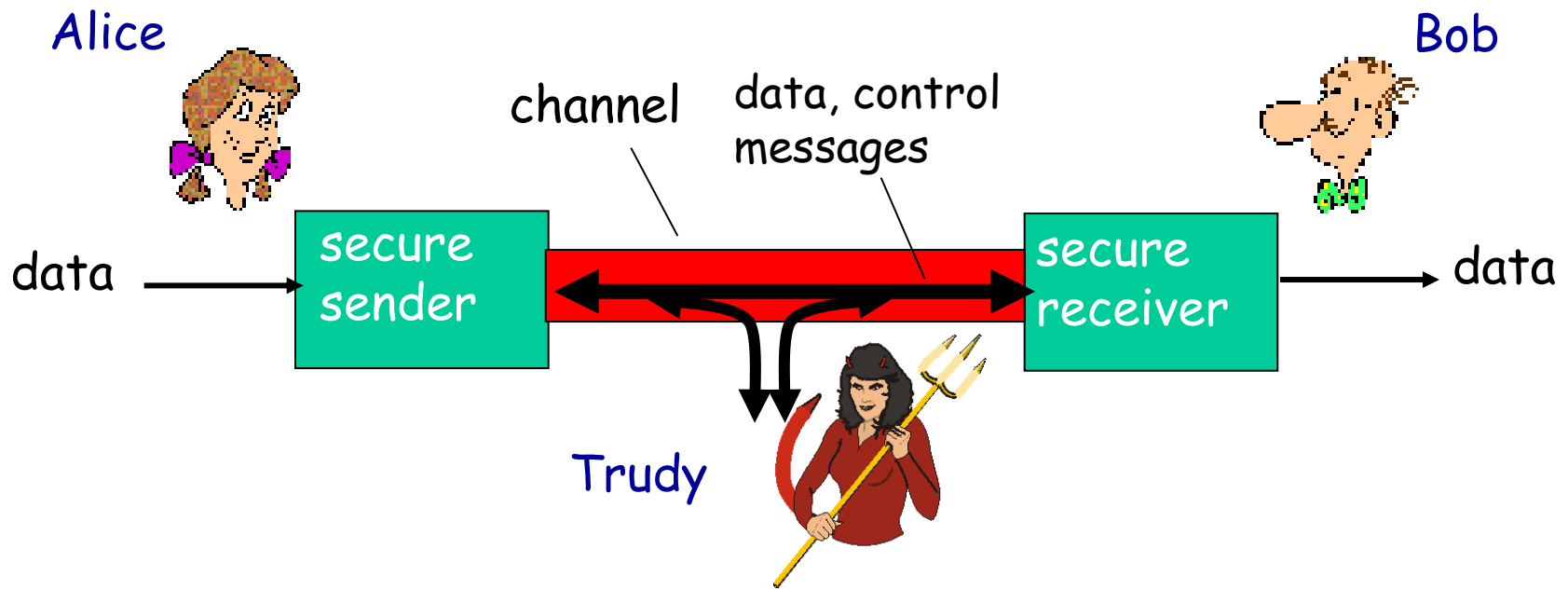
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2) **Authentication:** sender, receiver want to confirm identity of each other



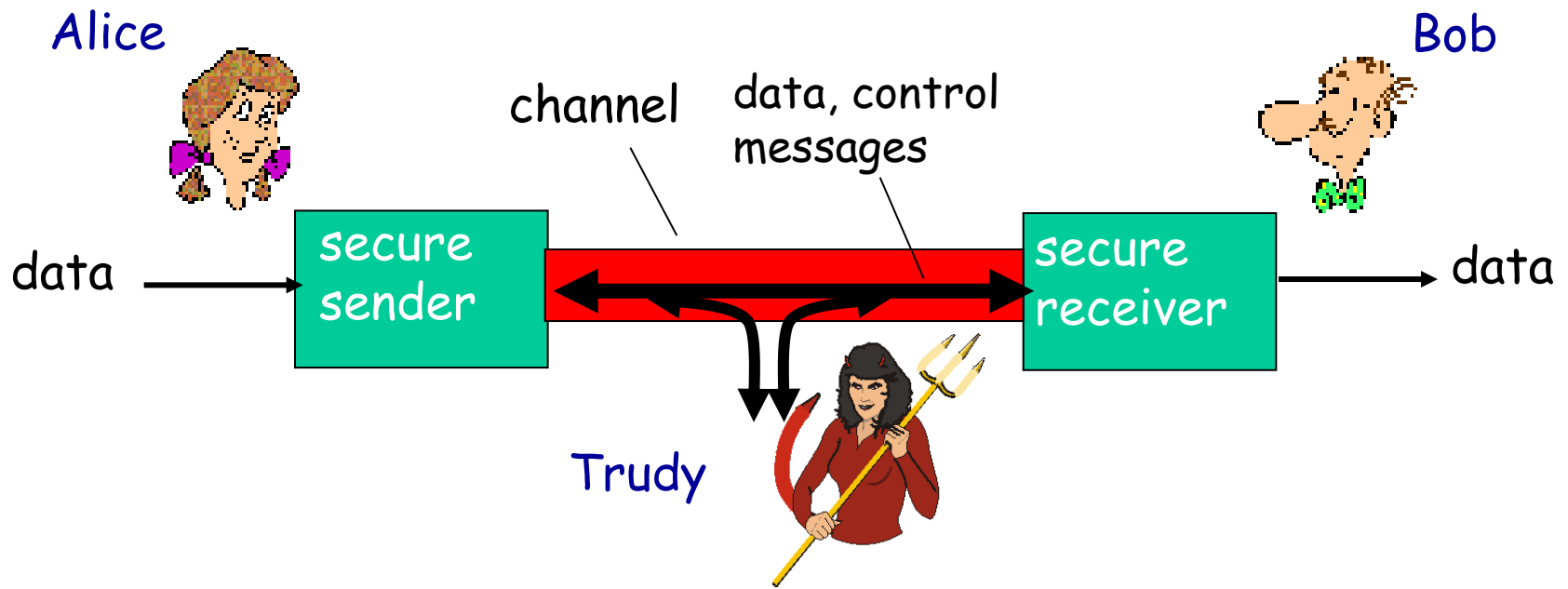
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3) **Message integrity:** sender, receiver want to ensure message not altered (in transit, or afterwards) without detection



Friends and enemies: Alice, Bob, Trudy

4) **Access and availability:** services must be accessible and available to users



Alice



Bob



Who might Bob, Alice be?

- ❖ ... well, *real-life* Bobs and Alices!
- ❖ Web browser/server for electronic transactions (e.g., on-line purchases)
- ❖ on-line banking client/server
- ❖ DNS servers
- ❖ routers exchanging routing table updates
- ❖ ... and many more ...

Trudy



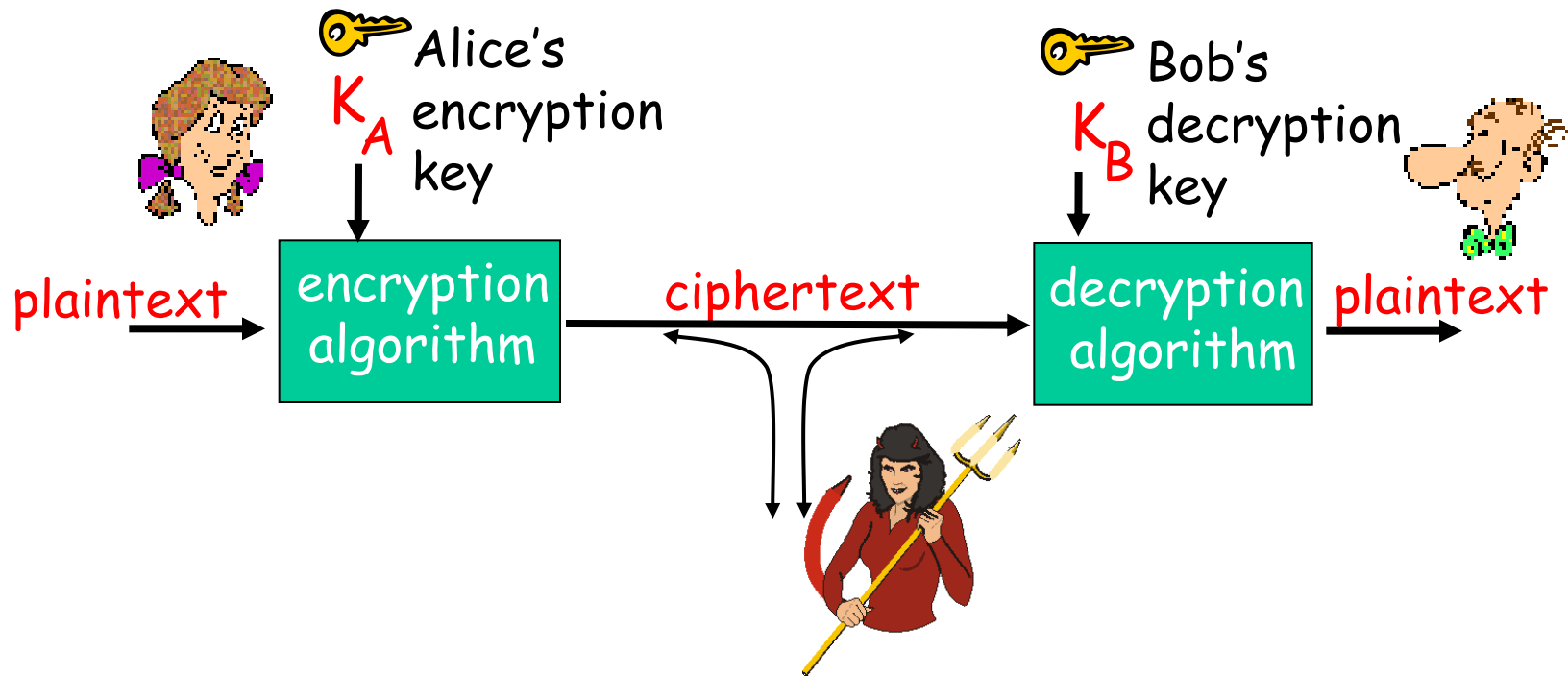
There are bad guys (and girls) out there!

Q: What can a "bad guy" do?

A: A lot! See section 1.6

- *eavesdrop*: intercept messages
- actively *insert* messages into connection
- *impersonation*: can fake (spoof) source address in packet (or any field in packet)
- *hijacking*: "take over" ongoing connection by removing sender or receiver, inserting himself in place
- *denial of service*: prevent service from being used by others (e.g., by overloading resources)

The language of cryptography

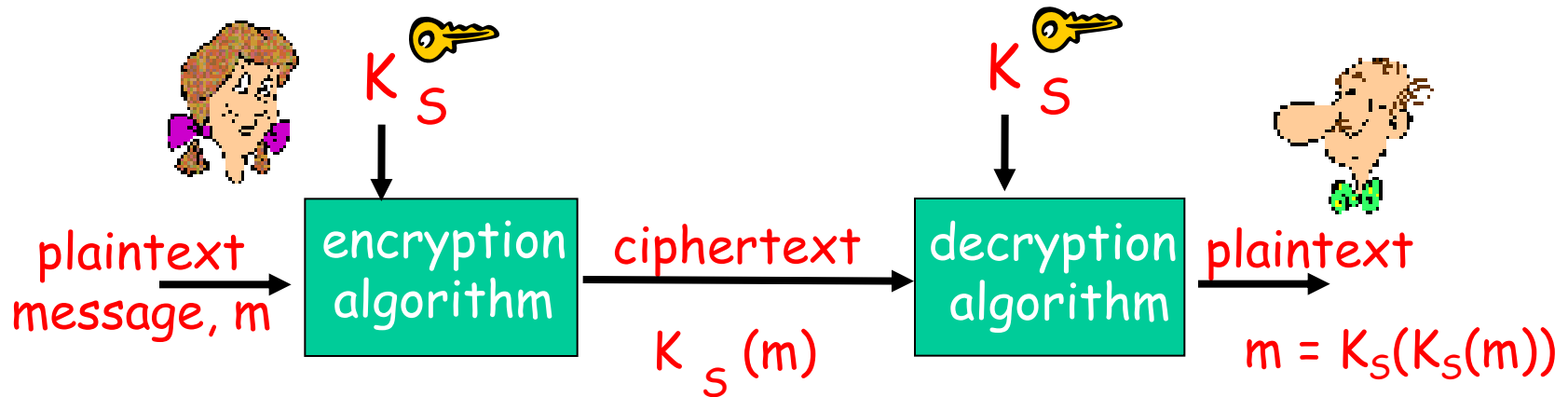


m plaintext message

$K_A(m)$ ciphertext, encrypted with key K_A

$m = K_B(K_A(m))$

Symmetric key cryptography



symmetric key crypto: Bob and Alice share same (symmetric) key: K_S

Q: how do Bob and Alice agree on key value?

Two types of symmetric ciphers

❖ Stream ciphers

- encrypt one bit at time

❖ Block ciphers

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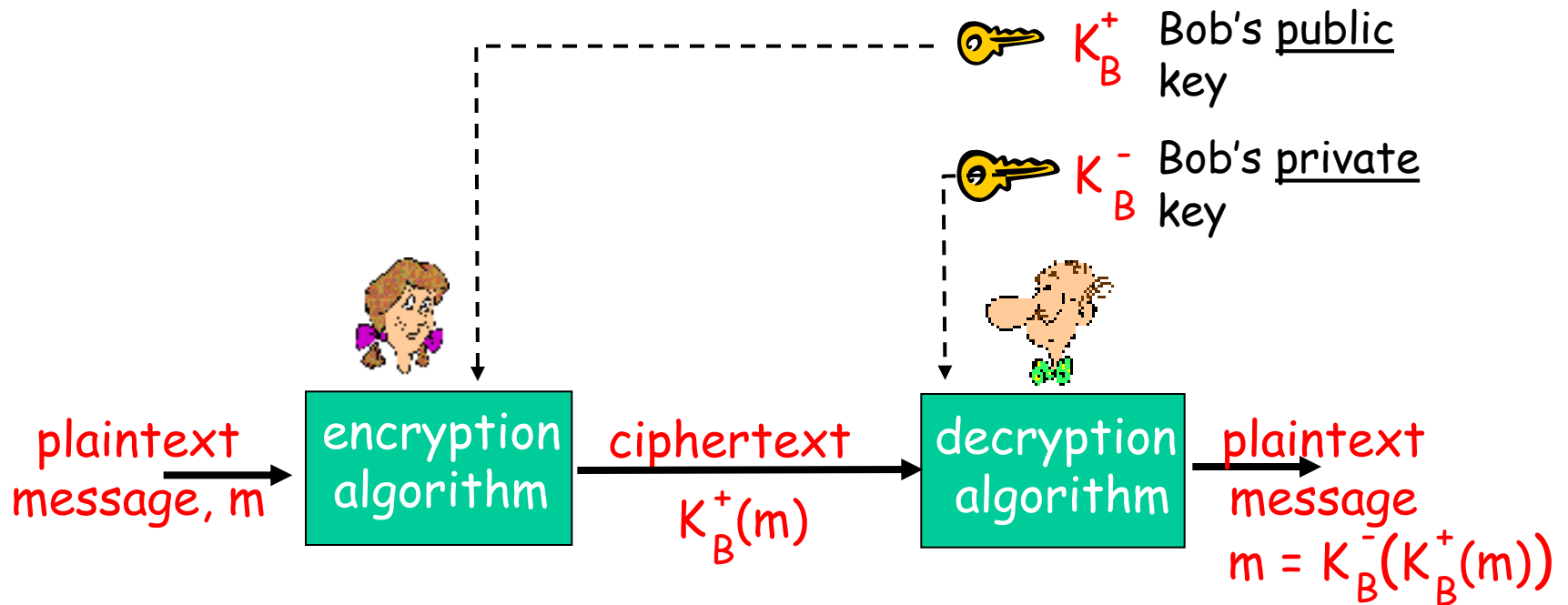
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Public key cryptography



Public key encryption algorithms

Requirements:

① need $K_B^+(\cdot)$ and $K_B^-(\cdot)$ such that

$$K_B^-(K_B^+(m)) = m$$

② given public key K_B^+ , it should be impossible to compute private key K_B^-

RSA: Rivest, Shamir, Adelson algorithm

RSA: another important property

The following property will be *very* useful later:

$$\underbrace{K_B^-(K_B^+(m))}_{\text{use public key first, followed by private key}} = m = \underbrace{K_B^+(K_B^-(m))}_{\text{use private key first, followed by public key}}$$

use public key
first, followed
by private key

use private key
first, followed
by public key

Result is the same!

Why is RSA Secure?

- ❖ suppose you know Bob's public key (n,e) .
How hard is it to determine d ?
- ❖ essentially need to find factors of n
without knowing the two factors p and q .
- ❖ fact: factoring a big number is hard.

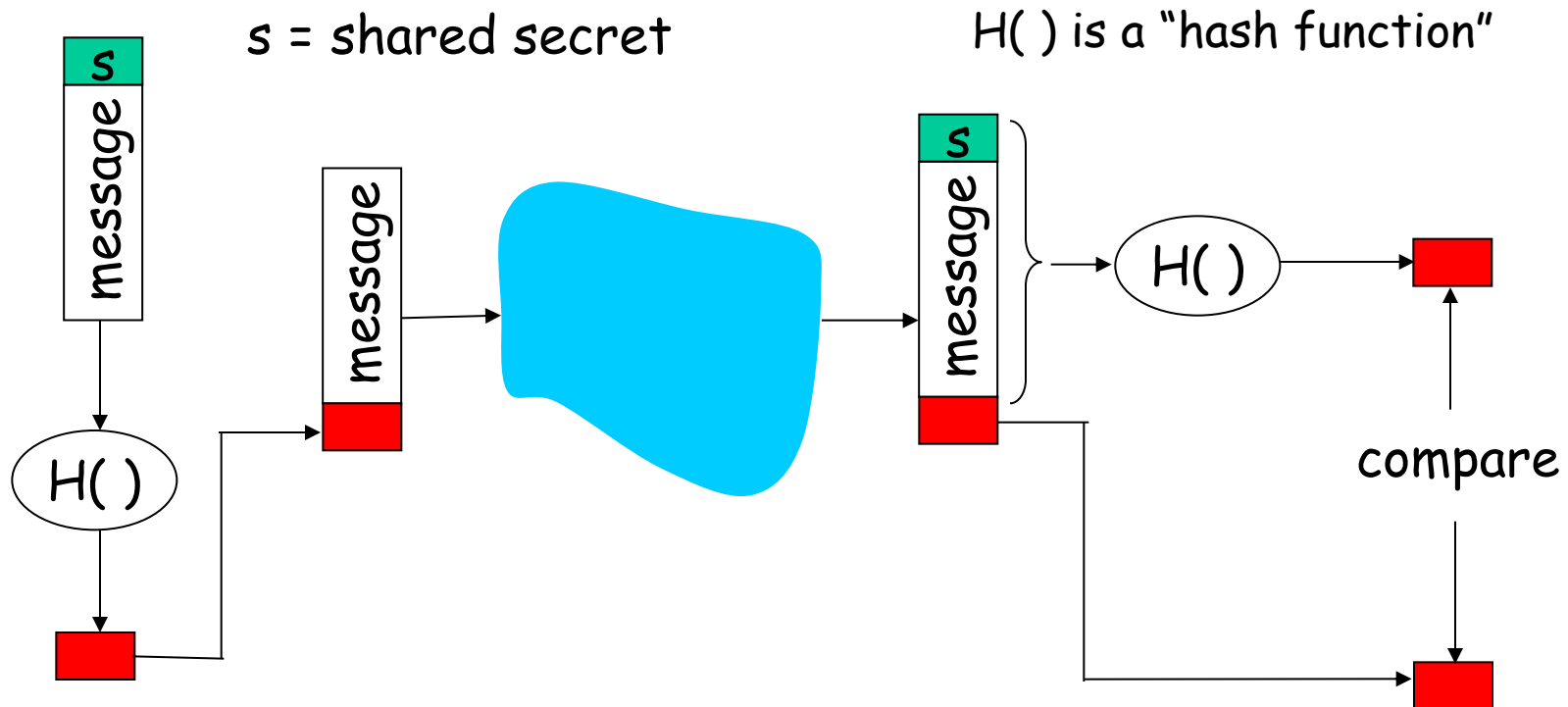
Session keys

- ❖ Exponentiation is computationally intensive
- ❖ Session key, K_S
- ❖ Bob and Alice use RSA to exchange a symmetric key K_S
- ❖ Once both have K_S , they use symmetric key cryptography

Message Integrity

- ❖ allows communicating parties to verify that received messages are authentic.
 - Content of message has not been altered
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Message Authentication Code (MAC)



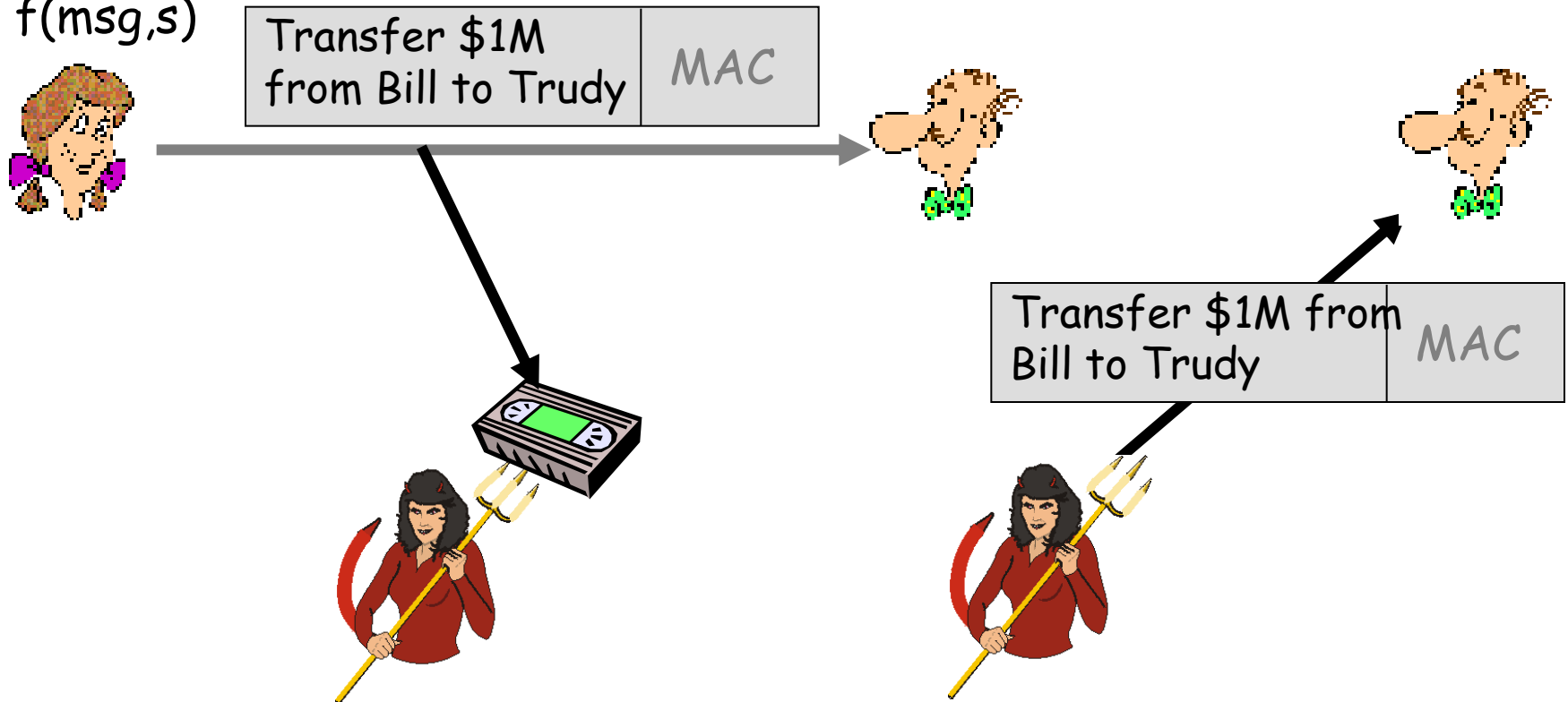
- ❖ *Authenticates sender*
- ❖ *Verifies message integrity*
- ❖ No encryption !

Desirable "hash" $H()$ properties:

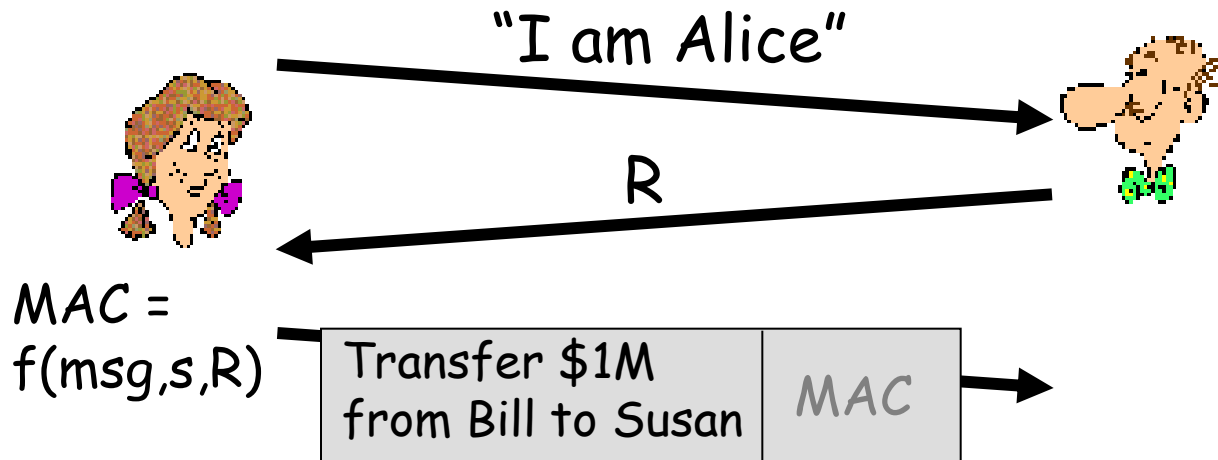
- easy to calculate
- irreversibility: Can't determine m from $H(m)$
- collision resistance: computationally difficult to produce m and m' such that $H(m) = H(m')$
- seemingly random output

Playback attack

$MAC = f(msg, s)$



Defending against playback attack: nonce




Digital Signatures

simple digital signature for message m :

- ❖ Bob signs m by encrypting with his private key K_B^- , creating "signed" message, $K_B^-(m)$

Bob's message, m

Dear Alice
Oh, how I have missed
you. I think of you all the
time! ... (blah blah blah)
Bob

 K_B^- Bob's private
key

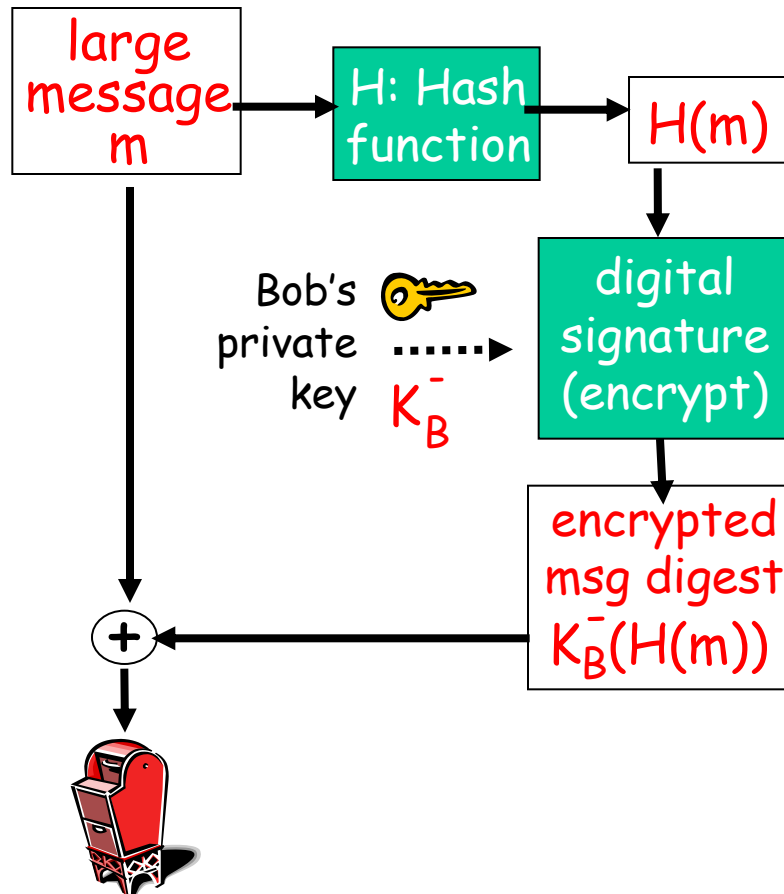
Public key
encryption
algorithm

$K_B^-(m)$

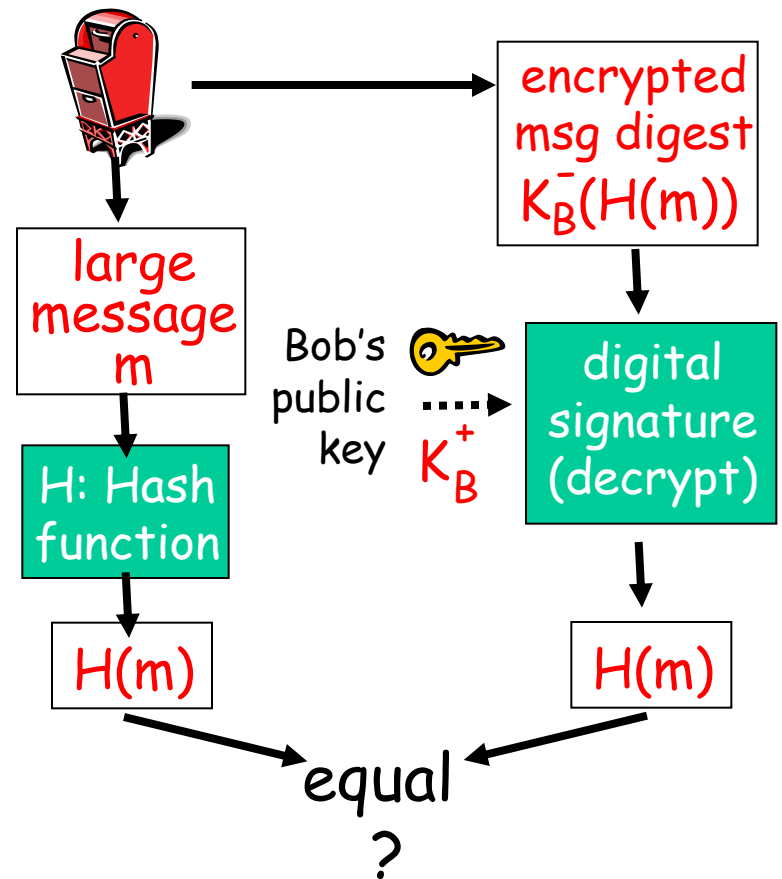
Bob's message,
 m , signed
(encrypted) with
his private key

Digital signature = signed message digest

Bob sends digitally signed message:

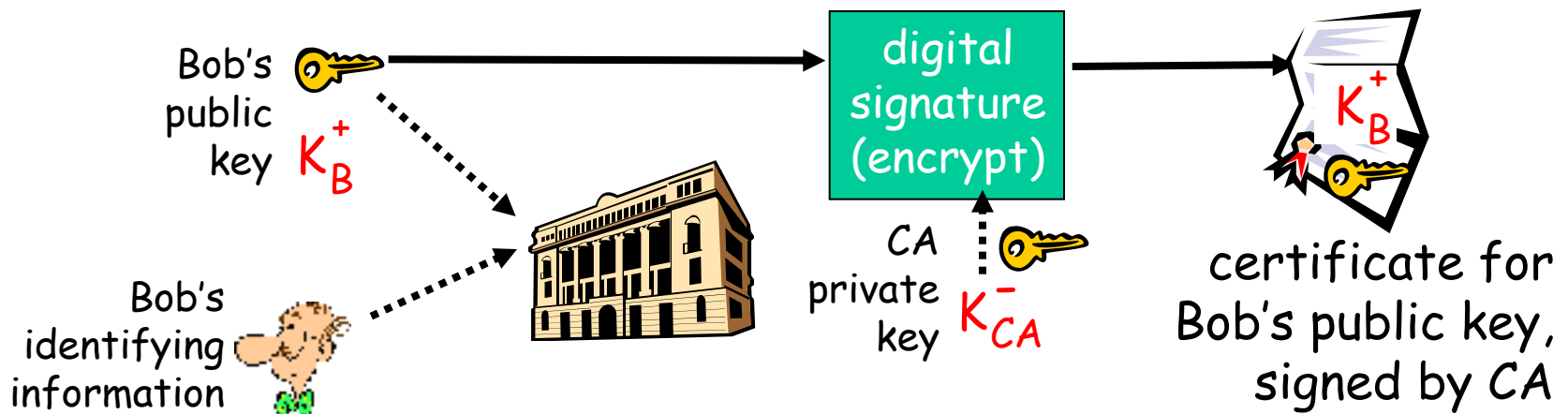


Alice verifies signature and integrity of digitally signed message:



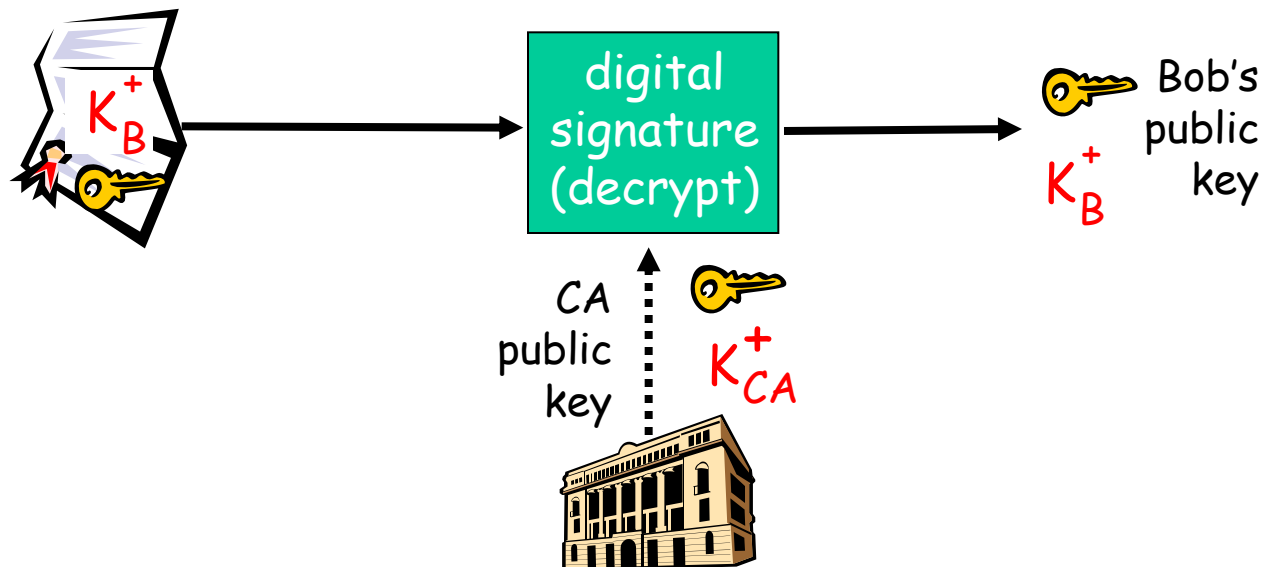
Certification Authorities

- ❖ **Certification authority (CA):** binds public key to particular entity, E.
- ❖ E (person, router) registers its public key with CA.
 - E provides "proof of identity" to CA.
 - CA creates certificate binding E to its public key.
 - certificate containing E's public key digitally signed by CA
 - CA says "this is E's public key"



Certification Authorities

- ❖ when Alice wants Bob's public key:
 - gets Bob's certificate (Bob or elsewhere).
 - apply CA's public key to Bob's certificate, get Bob's public key



Chapter 8 roadmap

8.1 What is network security?

8.2 Principles of cryptography

8.3 Message integrity

8.4 Securing e-mail

8.5 Securing TCP connections: SSL

8.6 Network layer security: IPsec

8.7 Securing wireless LANs

8.8 Operational security: firewalls and IDS

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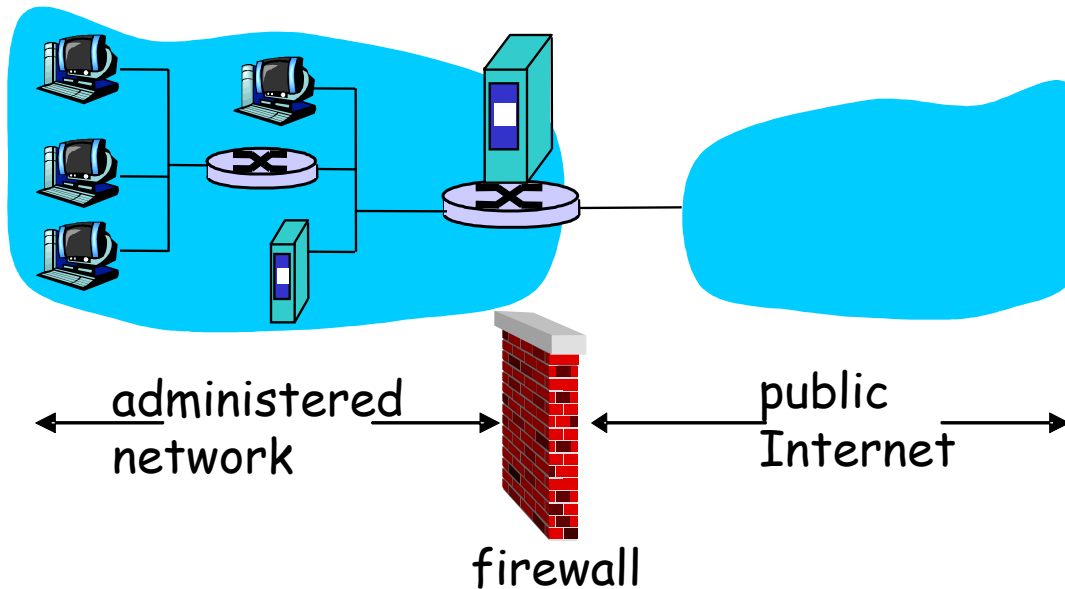
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Firewalls

firewall

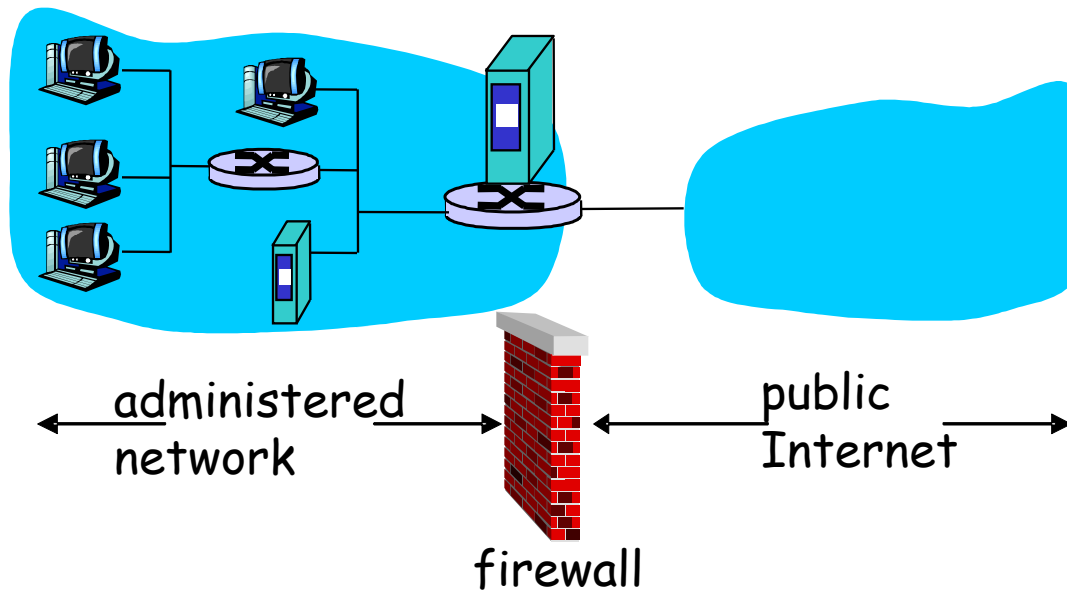
isolates organization's internal net from larger Internet, allowing some packets to pass, blocking others



Firewalls: Why?

1) prevent denial of service attacks:

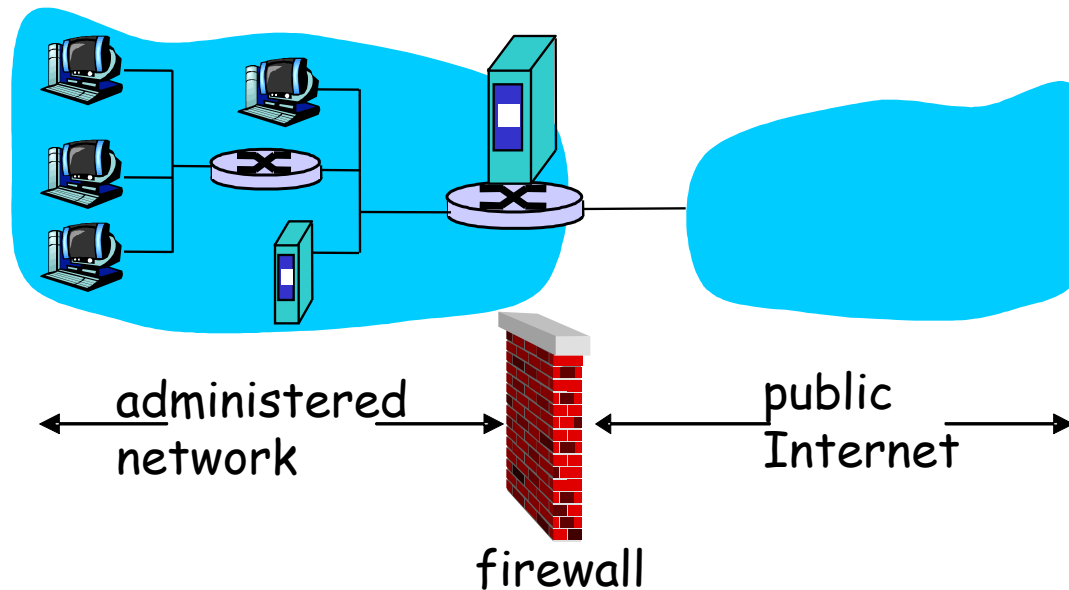
- ❖ SYN flooding: attacker establishes many bogus TCP connections, no resources left for "real" connections



Firewalls: Why?

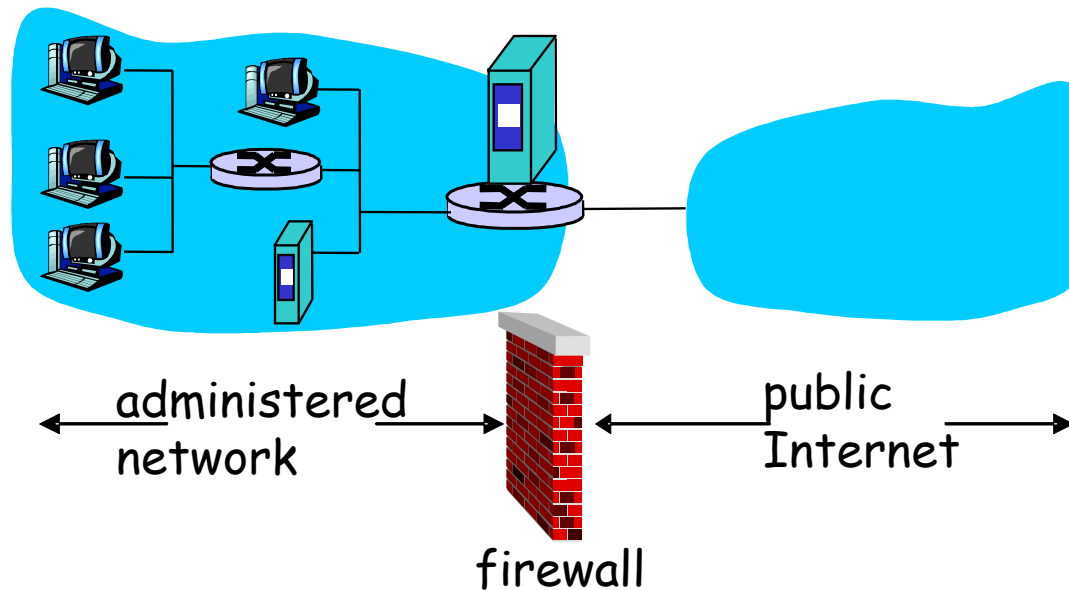
2) prevent illegal modification/access of internal data.

- ❖ e.g., attacker replaces CIA's homepage with something else



Firewalls: Why?

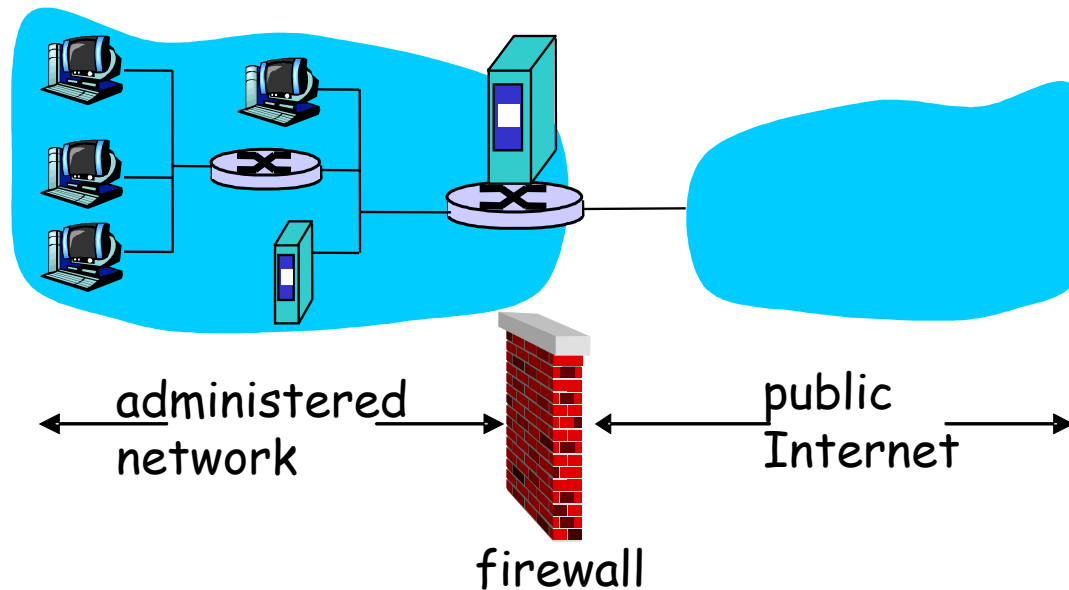
3) allow only authorized access to inside network
(set of authenticated users/hosts)



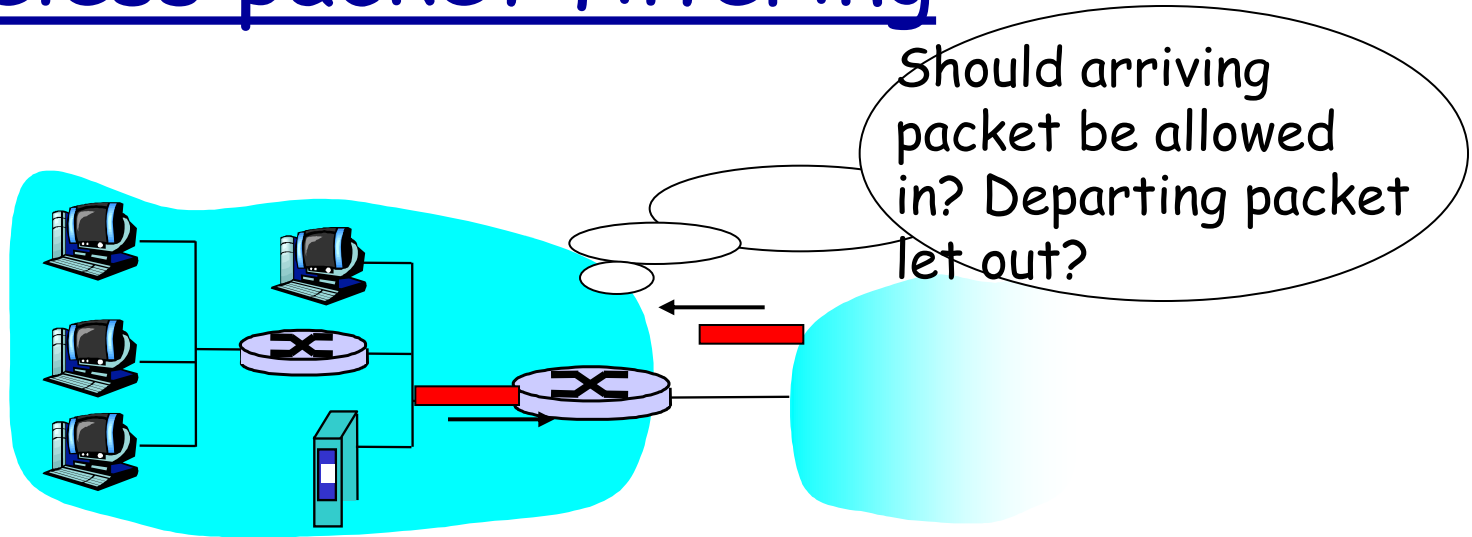
Firewalls: Types

three types of firewalls:

- ❖ stateless packet filters
- ❖ stateful packet filters
- ❖ application gateways



Stateless packet filtering



- ❖ internal network connected to Internet via **router firewall**
- ❖ router **filters packet-by-packet**, decision to forward/drop packet based on:
 - source IP address, destination IP address
 - TCP/UDP source and destination port numbers
 - ICMP message type
 - TCP SYN and ACK bits

Stateful packet filtering

- ❖ stateless packet filter: heavy handed tool
 - admits packets that "make no sense," e.g., dest port = 80, ACK bit set, even though no TCP connection established:

action	source address	dest address	protocol	source port	dest port	flag bit
allow	outside of 222.22/16	222.22/16	TCP	80	> 1023	ACK

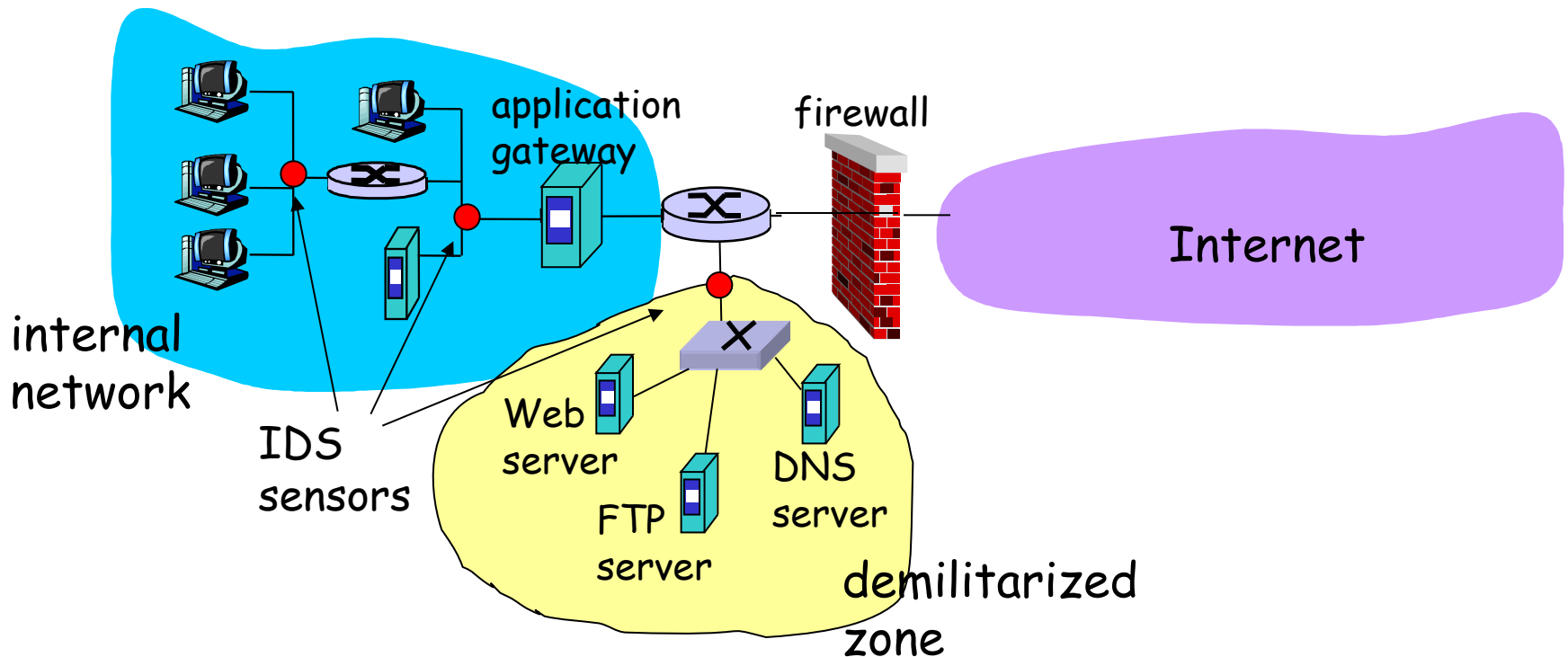
- ❖ *stateful packet filter*: track status of every TCP connection
 - track connection setup (SYN), teardown (FIN): can determine whether incoming, outgoing packets "makes sense"
 - timeout inactive connections at firewall: no longer admit packets

Intrusion detection systems

- ❖ packet filtering:
 - operates on TCP/IP headers only
 - no correlation check among sessions
- ❖ *IDS: intrusion detection system*
 - *deep packet inspection*: look at packet contents (e.g., check character strings in packet against database of known virus, attack strings)
 - *examine correlation* among multiple packets
 - port scanning
 - network mapping
 - DoS attack

Intrusion detection systems

- ❖ multiple IDSs: different types of checking at different locations



Network Security (summary)

basic techniques.....

- cryptography (symmetric and public)
- message integrity
- end-point authentication

.... used in many different security scenarios

- secure email
- secure transport (SSL)
- IP sec
- 802.11

operational security: firewalls and IDS

More slides ...

What is network security?

Confidentiality: only sender, intended receiver should “understand” message contents

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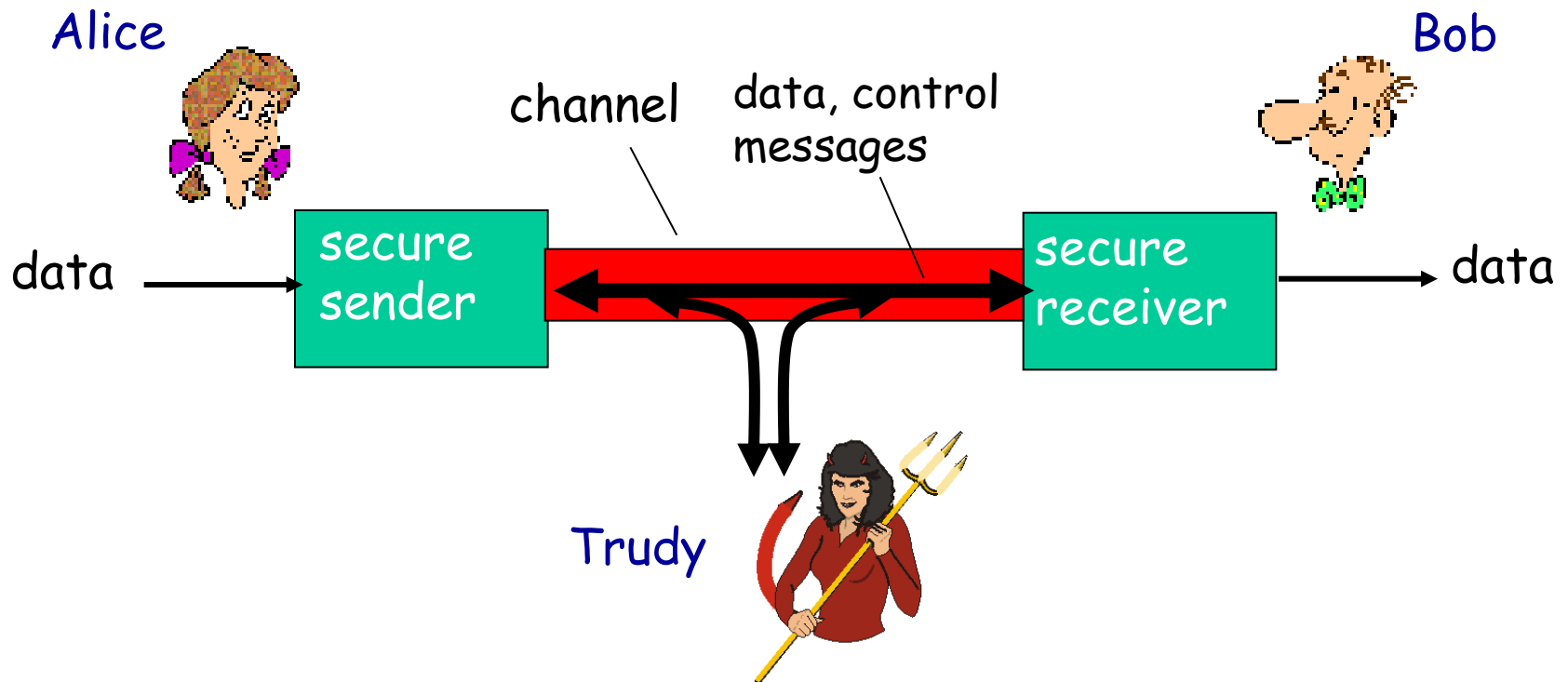
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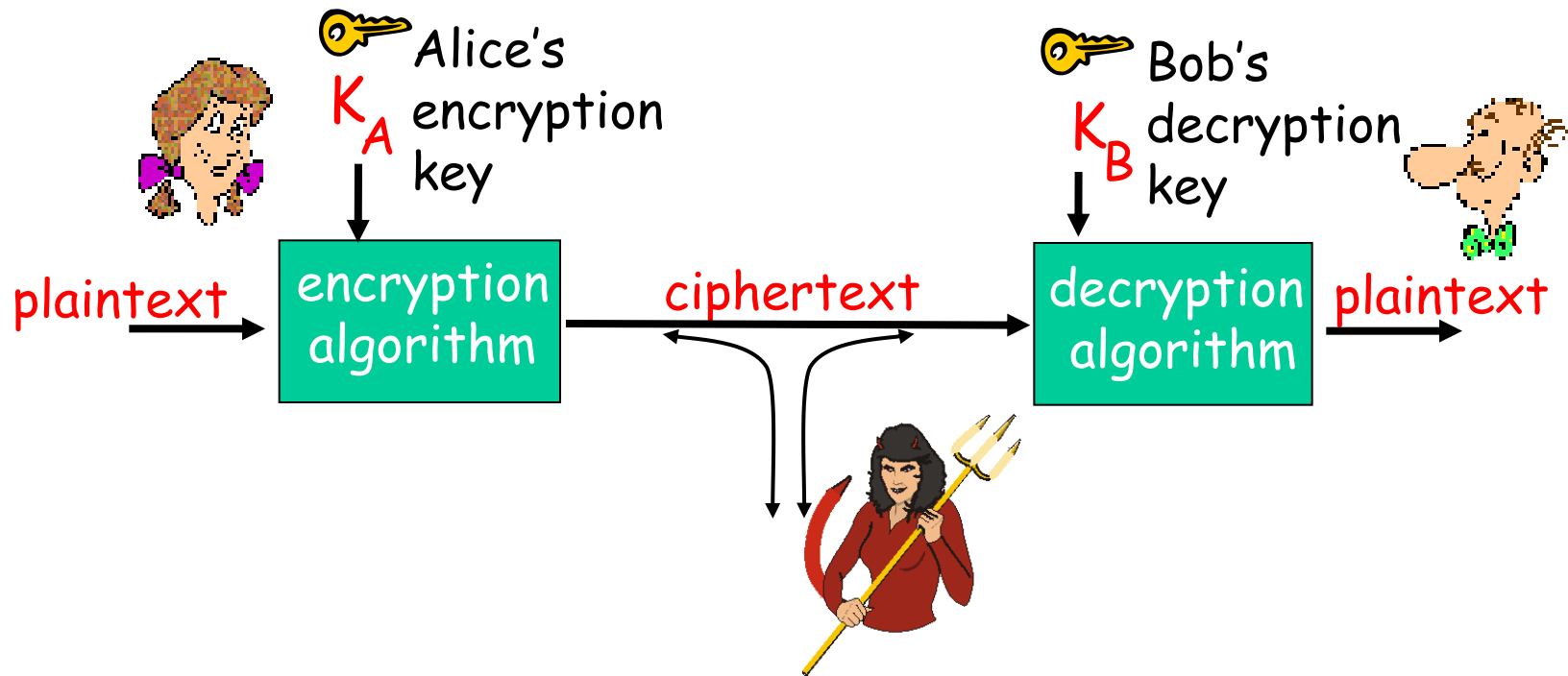
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The language of cryptography



m plaintext message

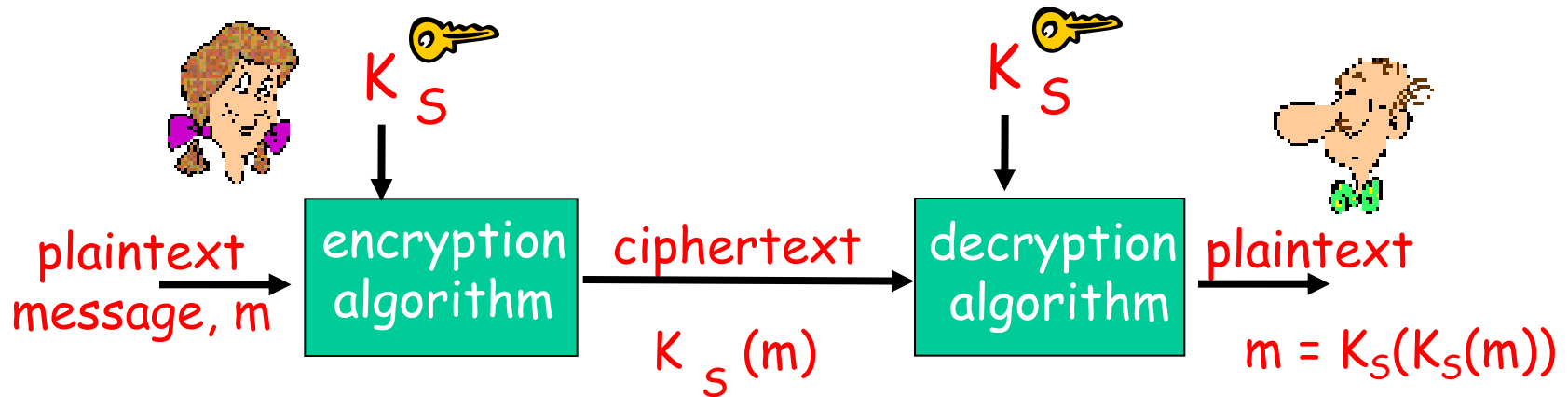
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Types of Cryptography

- ❖ Crypto often uses keys:
 - Algorithm is known to everyone
 - Only "keys" are secret
- ❖ Public key cryptography
 - Involves the use of two keys
- ❖ Symmetric key cryptography
 - Involves the use one key
- ❖ Hash functions
 - Involves the use of no keys
 - Nothing secret: How can this be useful?

Symmetric key cryptography



symmetric key crypto: Bob and Alice share same (symmetric) key: K_S

Q: how do Bob and Alice agree on key value?

Two types of symmetric ciphers

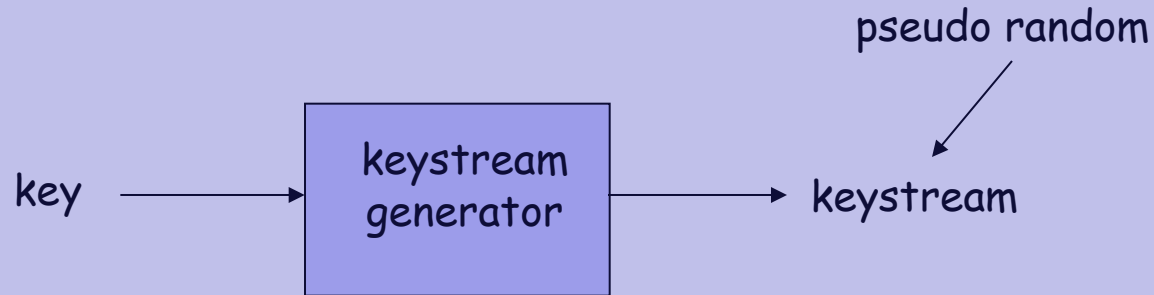
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Stream Ciphers



❖ Combine each bit of keystream with bit of plaintext to get bit of ciphertext

- $m(i)$ = i th bit of message
- $ks(i)$ = i th bit of keystream
- $c(i)$ = i th bit of ciphertext

- $c(i) = ks(i) \oplus m(i)$ (\oplus = exclusive or)
- $m(i) = ks(i) \oplus c(i)$

Block ciphers

- ❖ Message to be encrypted is processed in blocks of k bits (e.g., 64-bit blocks).
- ❖ 1-to-1 mapping is used to map k -bit block of plaintext to k -bit block of ciphertext

Example with $k=3$:

<u>input</u>	<u>output</u>
000	110
001	111
010	101
011	100

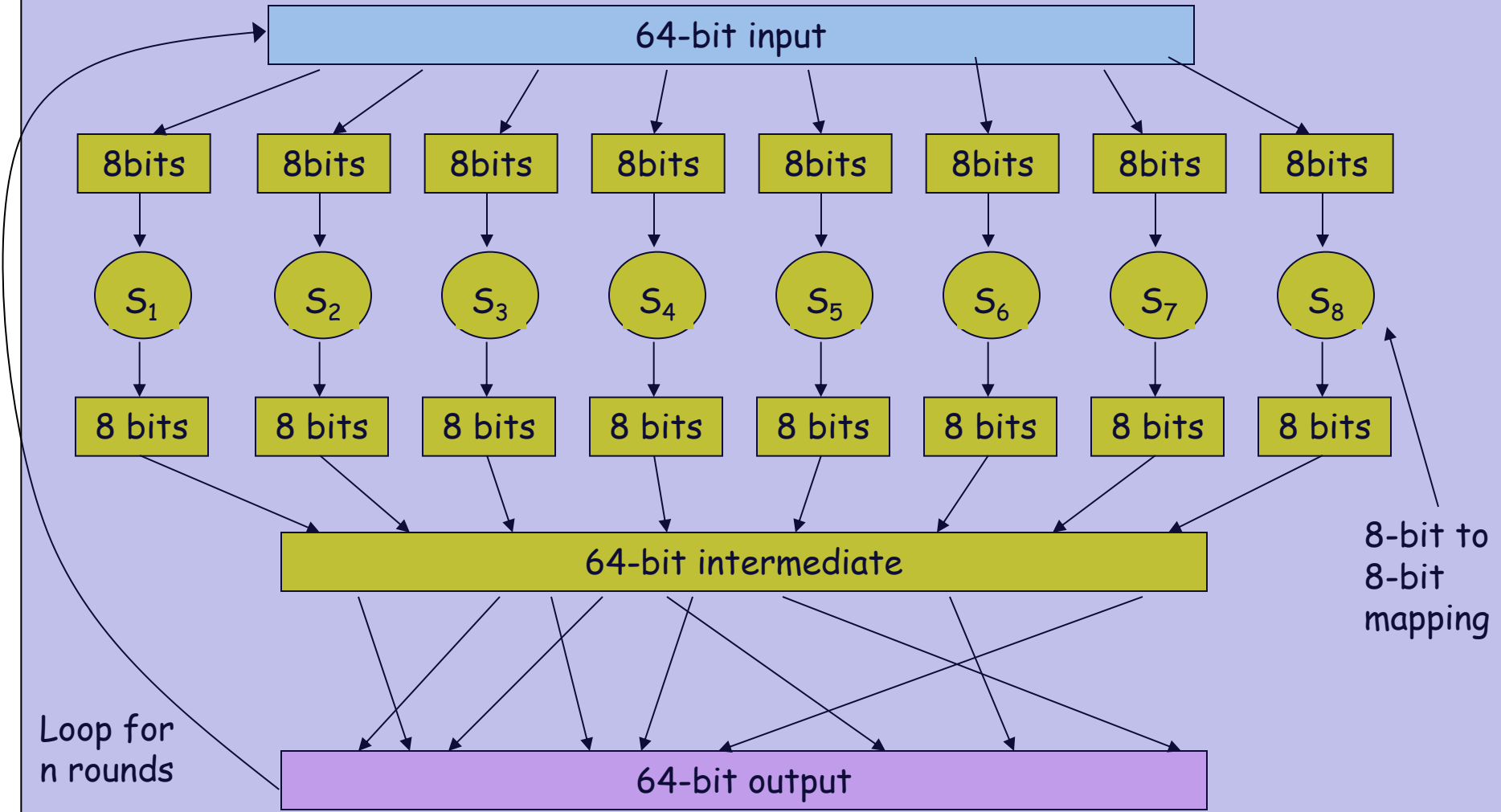
<u>input</u>	<u>output</u>
100	011
101	010
110	000
111	001

What is the ciphertext for 010110001111 ?

Block ciphers

- ❖ In general, $2^k!$ mappings; huge for $k=64$
- ❖ Problem:
 - Table approach requires table with 2^{64} entries, each entry with 64 bits
- ❖ Table too big: instead use function that simulates a randomly permuted table

Prototype function



Public Key Cryptography

symmetric key crypto

- ❖ requires sender, receiver know shared secret key
- ❖ Q: how to agree on key in first place (particularly if never "met")?

Public Key Cryptography

symmetric key crypto

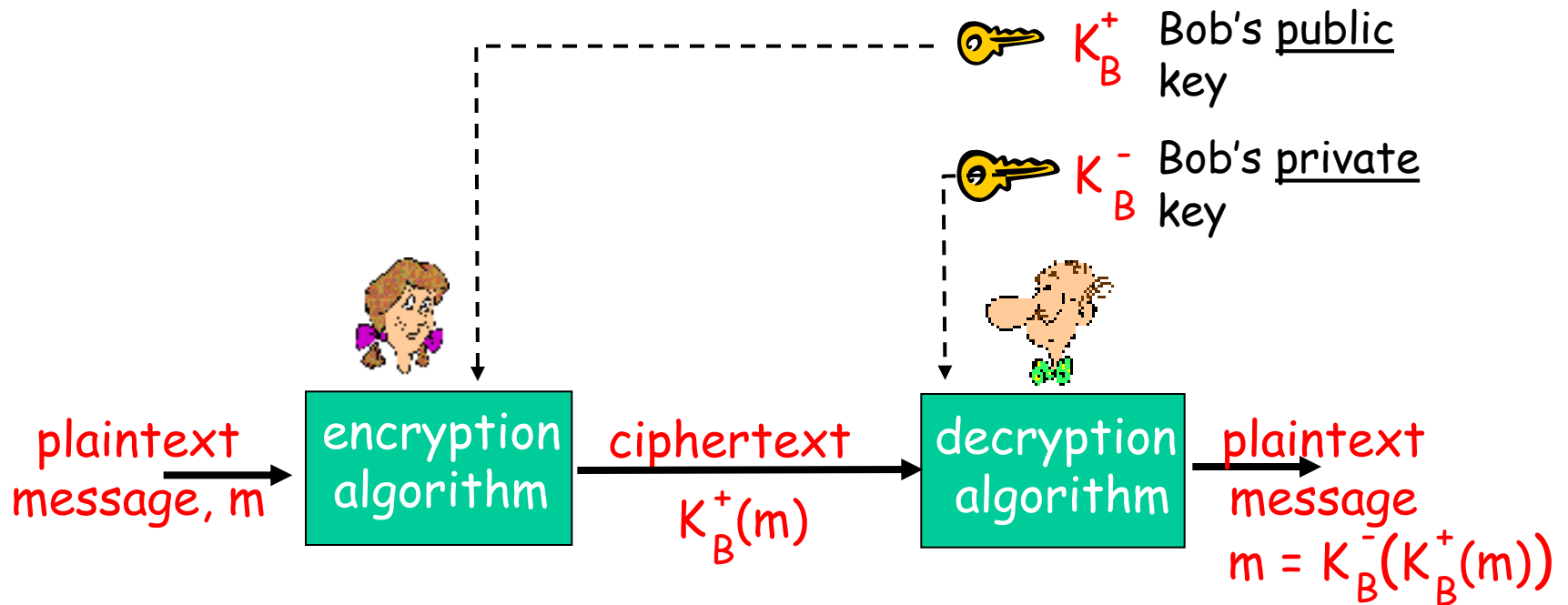
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public key cryptography

- ❖ radically different approach [Diffie-Hellman76, RSA78]
- ❖ sender, receiver do *not* share secret key
- ❖ *public* encryption key known to *all*
- ❖ *private* decryption key known only to receiver



Public key cryptography



Public key encryption algorithms

Requirements:

① need $K_B^+(\cdot)$ and $K_B^-(\cdot)$ such that

$$K_B^-(K_B^+(m)) = m$$

② given public key K_B^+ , it should be impossible to compute private key K_B^-

RSA: Rivest, Shamir, Adelson algorithm

RSA: getting ready

- ❖ A message is a bit pattern.
- ❖ A bit pattern can be uniquely represented by an integer number.
- ❖ Thus encrypting a message is equivalent to encrypting a number.

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Example

- ❖ $m = 10010001$. This message is uniquely represented by the decimal number 145.
- ❖ To encrypt m , we encrypt the corresponding number, which gives a new number (the ciphertext).

RSA: Creating public/private key pair

1. Choose two large prime numbers p, q .
(e.g., 1024 bits each)
2. Compute $n = pq$, $z = (p-1)(q-1)$
3. Choose e (with $e < n$) that has no common factors with z . (e, z are "relatively prime").
4. Choose d such that $ed-1$ is exactly divisible by z .
(in other words: $ed \bmod z = 1$).
5. Public key is (n, e) . Private key is (n, d) .

$\underbrace{\hspace{1.5cm}}_{K_B^+}$

$\underbrace{\hspace{1.5cm}}_{K_B^-}$

RSA: Encryption, decryption

0. Given (n,e) and (n,d) as computed above

1. To encrypt message m ($<n$), compute

$$c = m^e \bmod n$$

2. To decrypt received bit pattern, c , compute

$$m = c^d \bmod n$$

Magic
happens!

$$m = \underbrace{(m^e \bmod n)}_c^d \bmod n$$

RSA example:

Bob chooses $p=5$, $q=7$. Then $n=35$, $z=24$.

$e=5$ (so e , z relatively prime).

$d=29$ (so $ed-1$ exactly divisible by z).

Encrypting 8-bit messages.

encrypt:	<u>bit pattern</u>	<u>m</u>	<u>m^e</u>	<u>$c = m^e \bmod n$</u>
	00001000	12	24832	17

decrypt:	<u>c</u>	<u>c^d</u>	<u>$m = c^d \bmod n$</u>
	17	481968572106750915091411825223071697	12

RSA: another important property

The following property will be *very* useful later:

$$\underbrace{K_B^-(K_B^+(m))}_{\text{use public key first, followed by private key}} = m = \underbrace{K_B^+(K_B^-(m))}_{\text{use private key first, followed by public key}}$$

use public key
first, followed
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use private key
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Result is the same!

Why $K_B^-(K_B^+(m)) = m = K_B^+(K_B^-(m))$?

Follows directly from modular arithmetic:

$$\begin{aligned}(m^e \bmod n)^d \bmod n &= m^{ed} \bmod n \\ &= m^{de} \bmod n \\ &= (m^d \bmod n)^e \bmod n\end{aligned}$$

Why is RSA Secure?

- ❖ suppose you know Bob's public key (n,e) .
How hard is it to determine d ?
- ❖ essentially need to find factors of n
without knowing the two factors p and q .
- ❖ fact: factoring a big number is hard.

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Generating RSA keys

- ❖ have to find big primes p and q
- ❖ approach: make good guess then apply testing rules (see Kaufman)

Session keys

- ❖ Exponentiation is computationally intensive
- ❖ Session key, K_S
- ❖ Bob and Alice use RSA to exchange a symmetric key K_S
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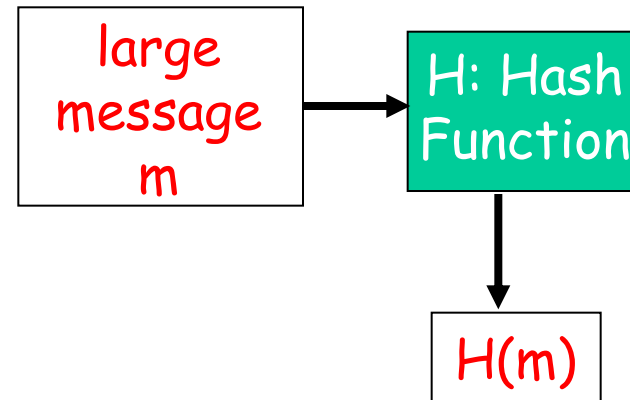
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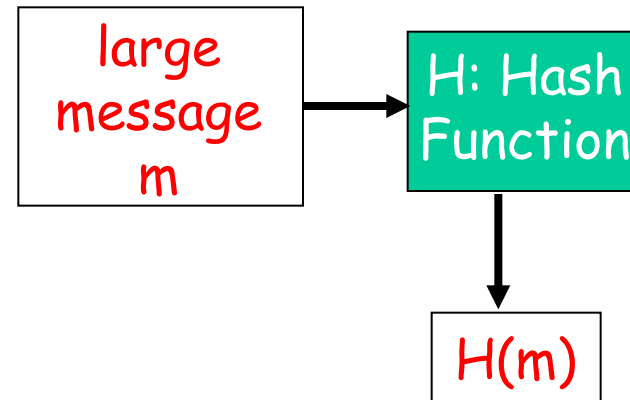
Message Digests

- ❖ “hash function” $H()$
 - Input: arbitrary length message
 - Output: fixed-length string: “message signature”
- ❖ Note that $H()$ is a many-to-1 function



Message Digests

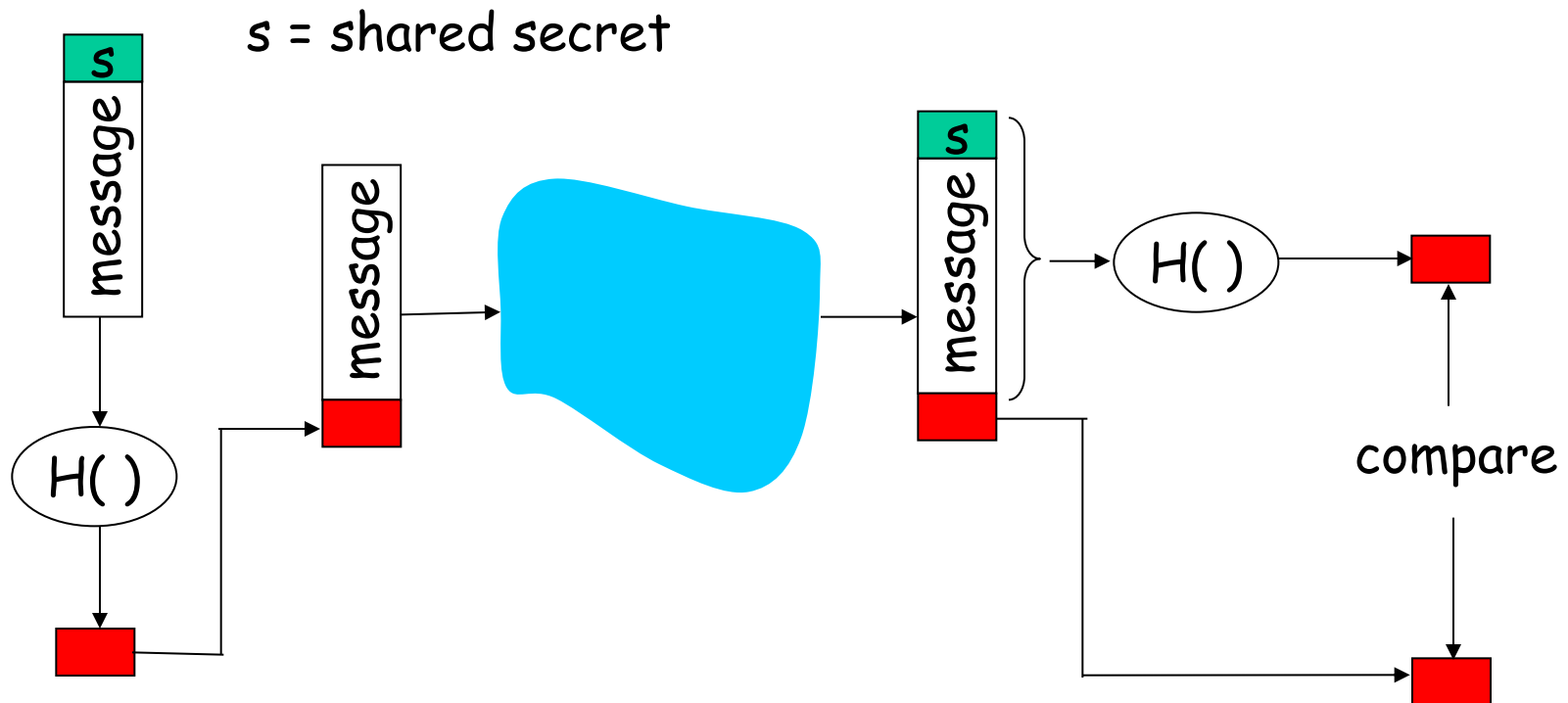
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Desirable properties:

- easy to calculate
- irreversibility: Can't determine m from $H(m)$
- collision resistance: computationally difficult to produce m and m' such that $H(m) = H(m')$
- seemingly random output

Message Authentication Code (MAC)



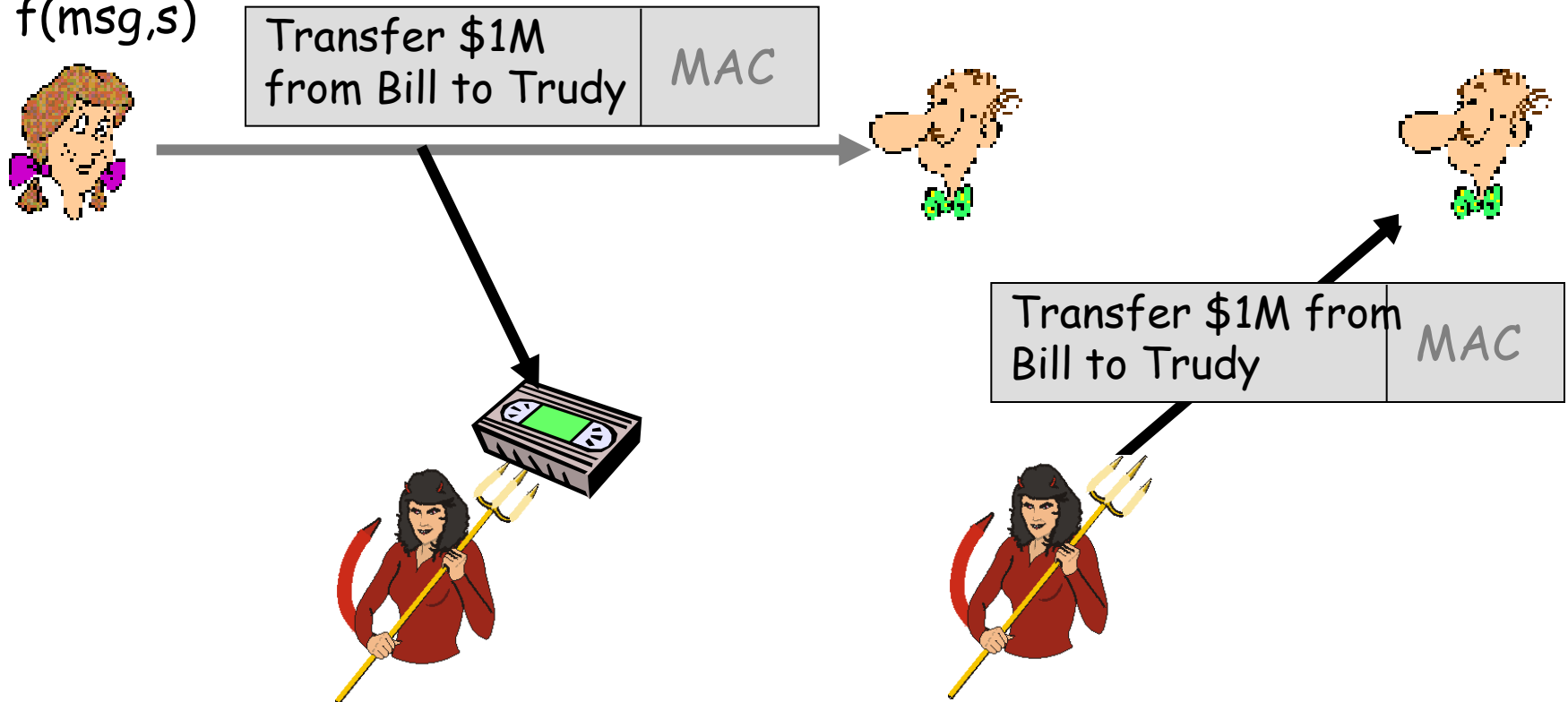
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- ❖ *Verifies message integrity*
- ❖ No encryption !

End-point authentication

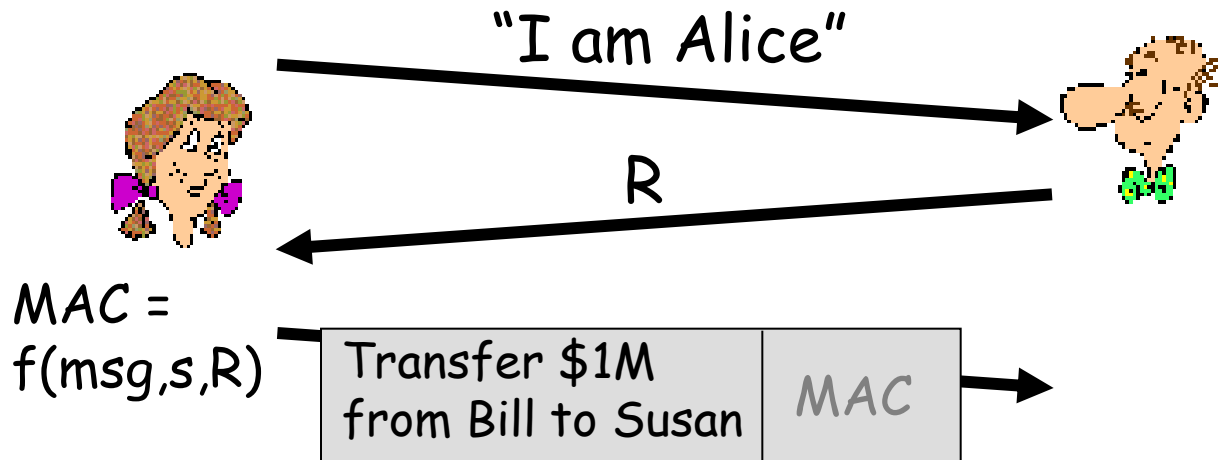
- ❖ want to be sure of the originator of the message - *end-point authentication*
- ❖ assuming Alice and Bob have a shared secret, will MAC provide end-point authentication?
 - we do know that Alice created message.
 - ... but did she send it?

Playback attack

$MAC = f(msg, s)$



Defending against playback attack: nonce




Digital Signatures

simple digital signature for message m :

- ❖ Bob signs m by encrypting with his private key K_B^- , creating "signed" message, $K_B^-(m)$

Bob's message, m

Dear Alice
Oh, how I have missed
you. I think of you all the
time! ... (blah blah blah)
Bob

 K_B^- Bob's private
key

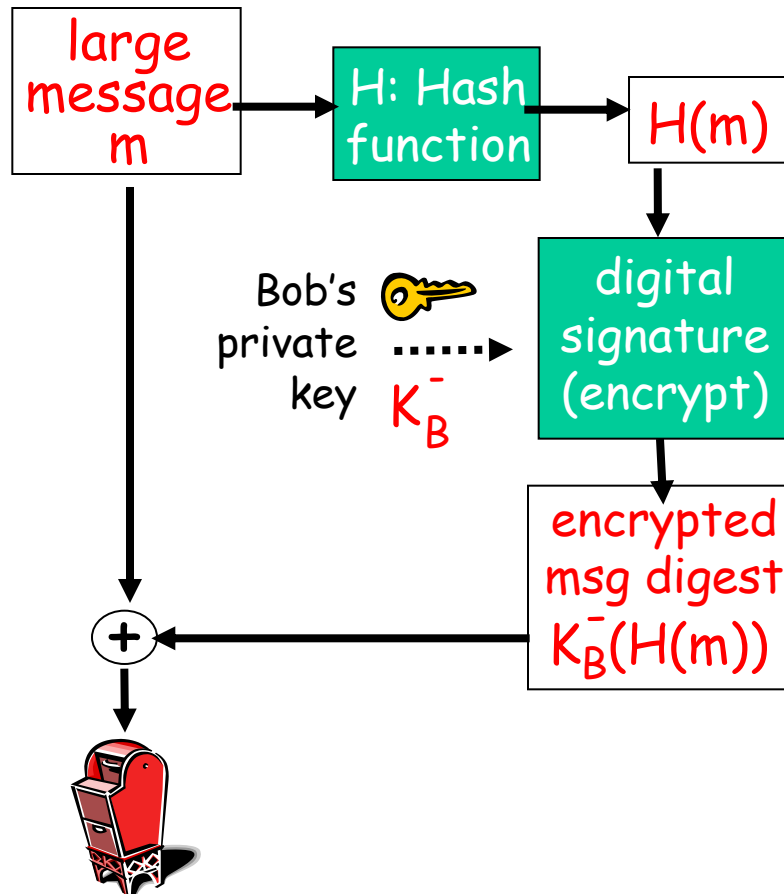
Public key
encryption
algorithm

$K_B^-(m)$

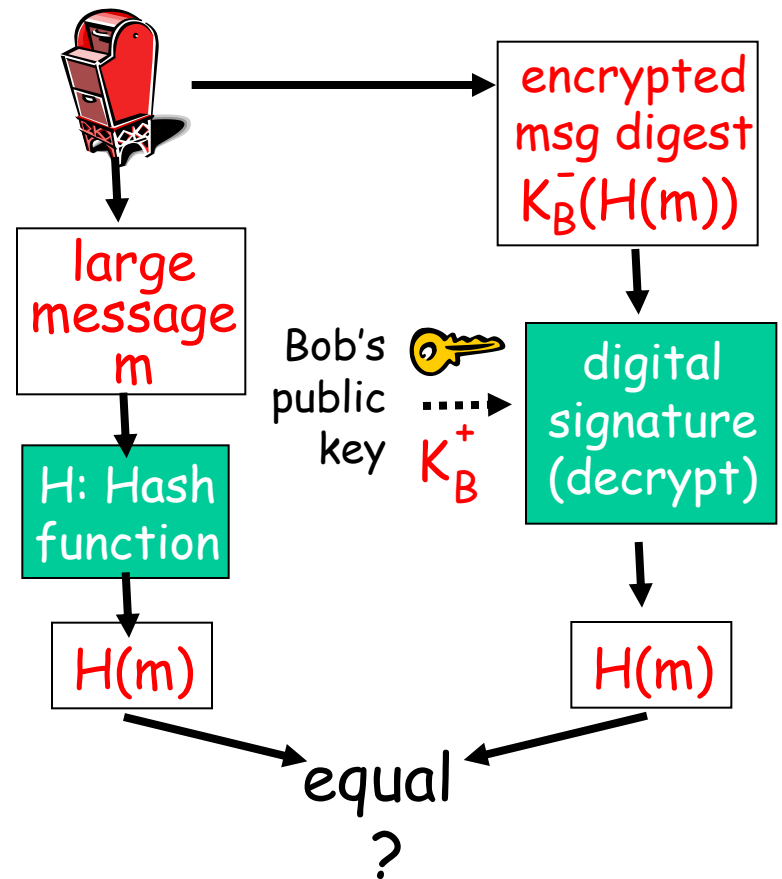
Bob's message,
 m , signed
(encrypted) with
his private key

Digital signature = signed message digest

Bob sends digitally signed message:

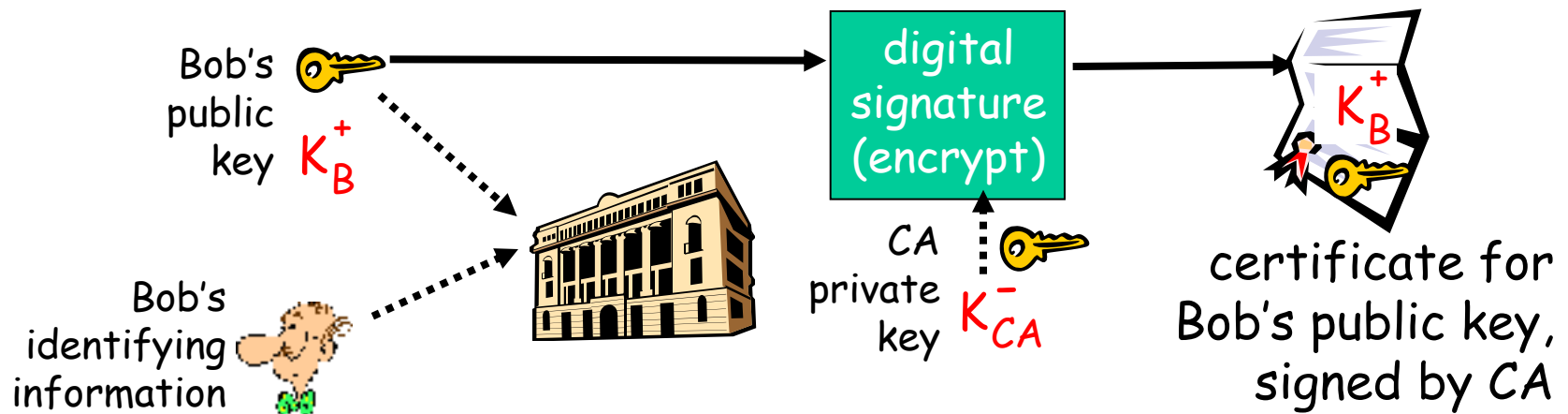


Alice verifies signature and integrity of digitally signed message:



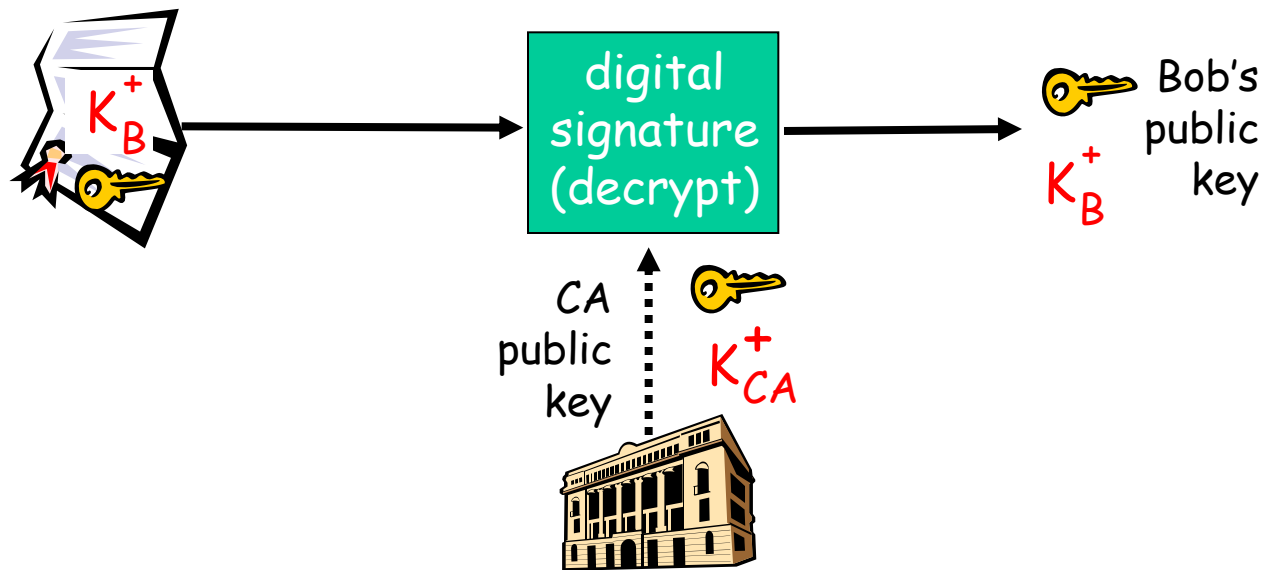
Certification Authorities

- ❖ **Certification authority (CA):** binds public key to particular entity, E.
- ❖ E (person, router) registers its public key with CA.
 - E provides "proof of identity" to CA.
 - CA creates certificate binding E to its public key.
 - certificate containing E's public key digitally signed by CA
 - CA says "this is E's public key"



Certification Authorities

- ❖ when Alice wants Bob's public key:
 - gets Bob's certificate (Bob or elsewhere).
 - apply CA's public key to Bob's certificate, get Bob's public key



Chapter 8 roadmap

8.1 What is network security?

8.2 Principles of cryptography

8.3 Message integrity

8.4 Securing e-mail

8.5 Securing TCP connections: SSL

8.6 Network layer security: IPsec

8.7 Securing wireless LANs

8.8 Operational security: firewalls and IDS

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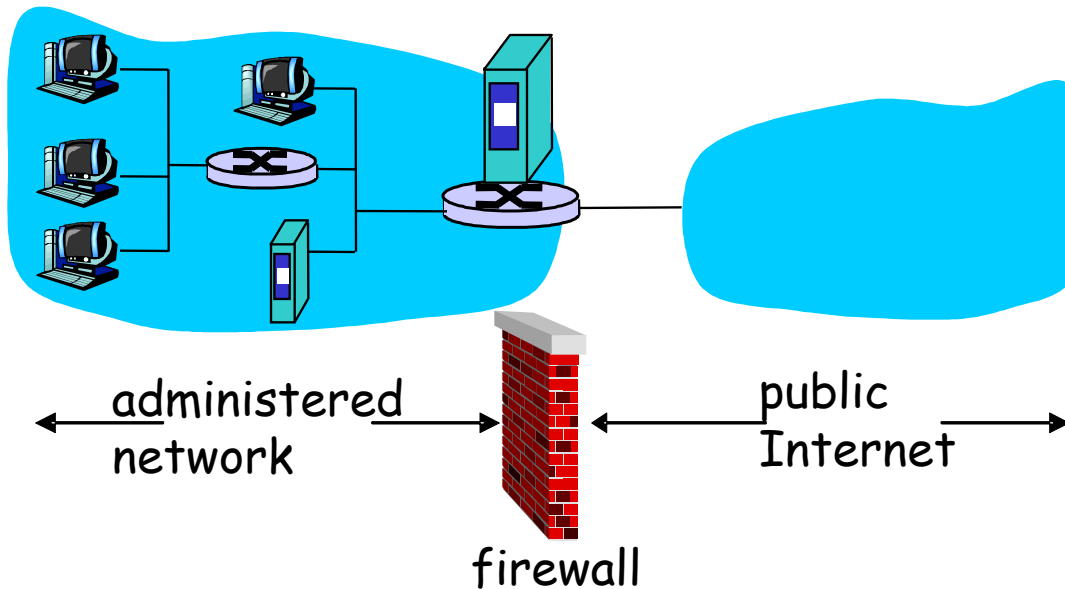
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Firewalls

firewall

isolates organization's internal net from larger Internet, allowing some packets to pass, blocking others



Firewalls: Why

prevent denial of service attacks:

- ❖ SYN flooding: attacker establishes many bogus TCP connections, no resources left for "real" connections

prevent illegal modification/access of internal data.

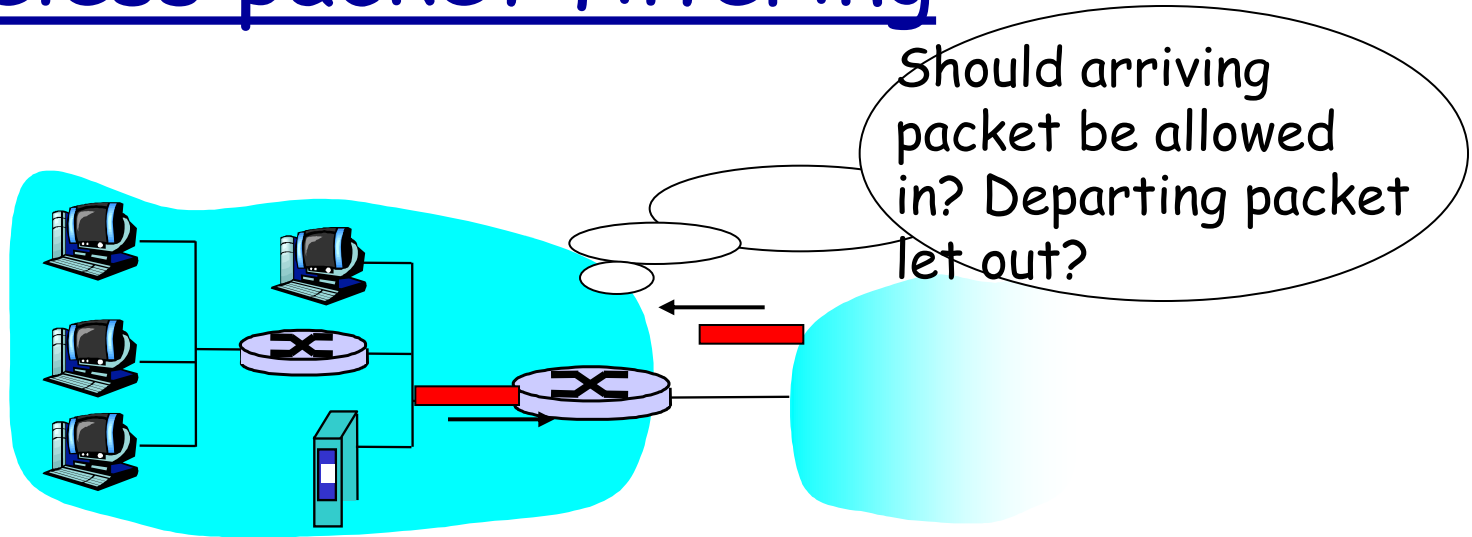
- ❖ e.g., attacker replaces CIA's homepage with something else

allow only authorized access to inside network (set of authenticated users/hosts)

three types of firewalls:

- ❖ stateless packet filters
- ❖ stateful packet filters
- ❖ application gateways

Stateless packet filtering



- ❖ internal network connected to Internet via **router firewall**
- ❖ router **filters packet-by-packet**, decision to forward/drop packet based on:
 - source IP address, destination IP address
 - TCP/UDP source and destination port numbers
 - ICMP message type
 - TCP SYN and ACK bits

Stateless packet filtering: more examples

<u>Policy</u>	<u>Firewall Setting</u>
No outside Web access.	Drop all outgoing packets to any IP address, port 80
No incoming TCP connections, except those for institution's public Web server only.	Drop all incoming TCP SYN packets to any IP except 130.207.244.203, port 80
Prevent Web-radios from eating up the available bandwidth.	Drop all incoming UDP packets - except DNS and router broadcasts.
Prevent your network from being used for a smurf DoS attack.	Drop all ICMP packets going to a "broadcast" address (e.g. 130.207.255.255).
Prevent your network from being tracerouted	Drop all outgoing ICMP TTL expired traffic

Access Control Lists

- ❖ *ACL*: table of rules, applied top to bottom to incoming packets: (action, condition) pairs

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deny	all	all	all	all	all	all

Stateful packet filtering

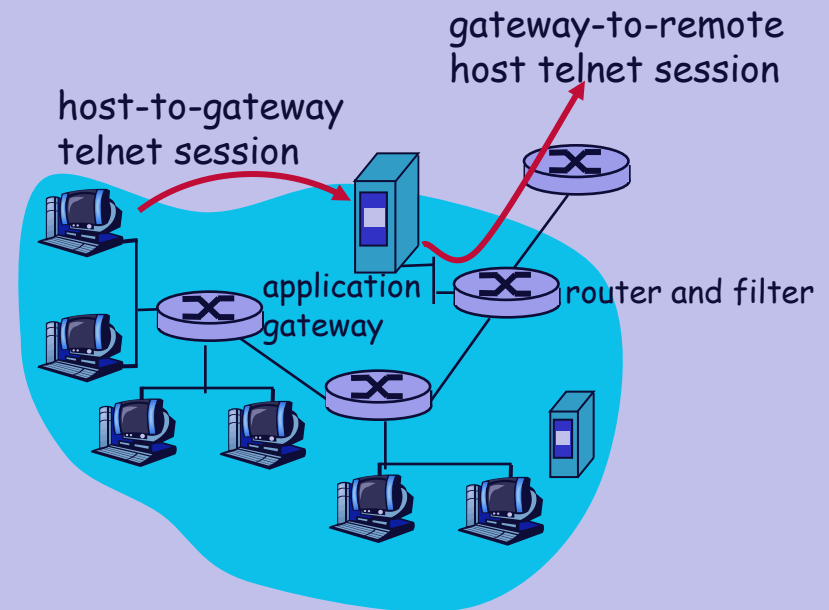
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 - admits packets that "make no sense," e.g., dest port = 80, ACK bit set, even though no TCP connection established:

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- ❖ *stateful packet filter*: track status of every TCP connection
 - track connection setup (SYN), teardown (FIN): can determine whether incoming, outgoing packets "makes sense"
 - timeout inactive connections at firewall: no longer admit packets

Application gateways

- ❖ filters packets on application data as well as on IP/TCP/UDP fields.
- ❖ example: allow select internal users to telnet outside.



1. require all telnet users to telnet through gateway.
2. for authorized users, gateway sets up telnet connection to dest host. Gateway relays data between 2 connections
3. router filter blocks all telnet connections not originating from gateway.

Limitations of firewalls and gateways

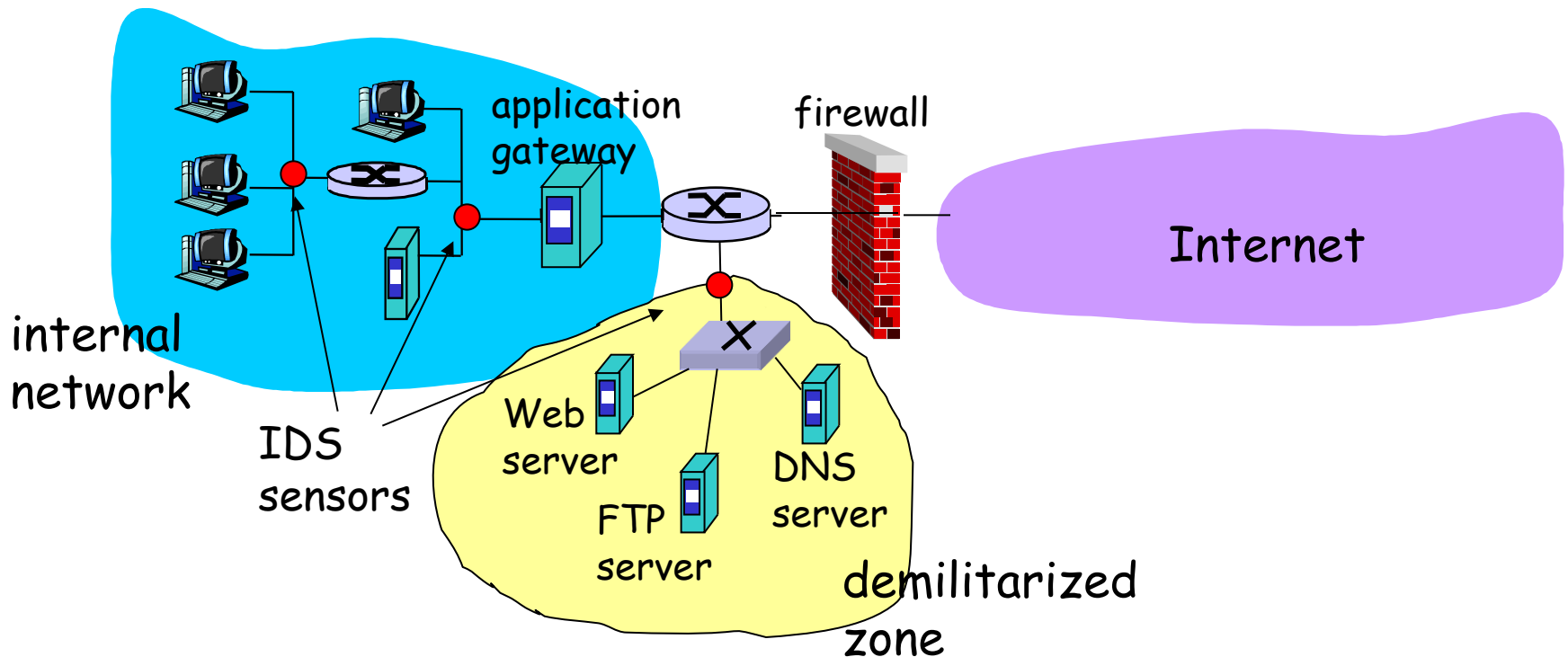
- ❖ IP spoofing: router can't know if data "really" comes from claimed source
- ❖ if multiple app's. need special treatment, each has own app. gateway.
- ❖ client software must know how to contact gateway.
 - e.g., must set IP address of proxy in Web browser
- ❖ filters often use all or nothing policy for UDP.
- ❖ tradeoff: **degree of communication with outside world, level of security**
- ❖ many highly protected sites still suffer from attacks.

Intrusion detection systems

- ❖ packet filtering:
 - operates on TCP/IP headers only
 - no correlation check among sessions
- ❖ *IDS: intrusion detection system*
 - *deep packet inspection*: look at packet contents (e.g., check character strings in packet against database of known virus, attack strings)
 - *examine correlation* among multiple packets
 - port scanning
 - network mapping
 - DoS attack

Intrusion detection systems

- ❖ multiple IDSs: different types of checking at different locations



Network Security (summary)

basic techniques.....

- cryptography (symmetric and public)
- message integrity
- end-point authentication

.... used in many different security scenarios

- secure email
- secure transport (SSL)
- IP sec
- 802.11

operational security: firewalls and IDS

More slides ...

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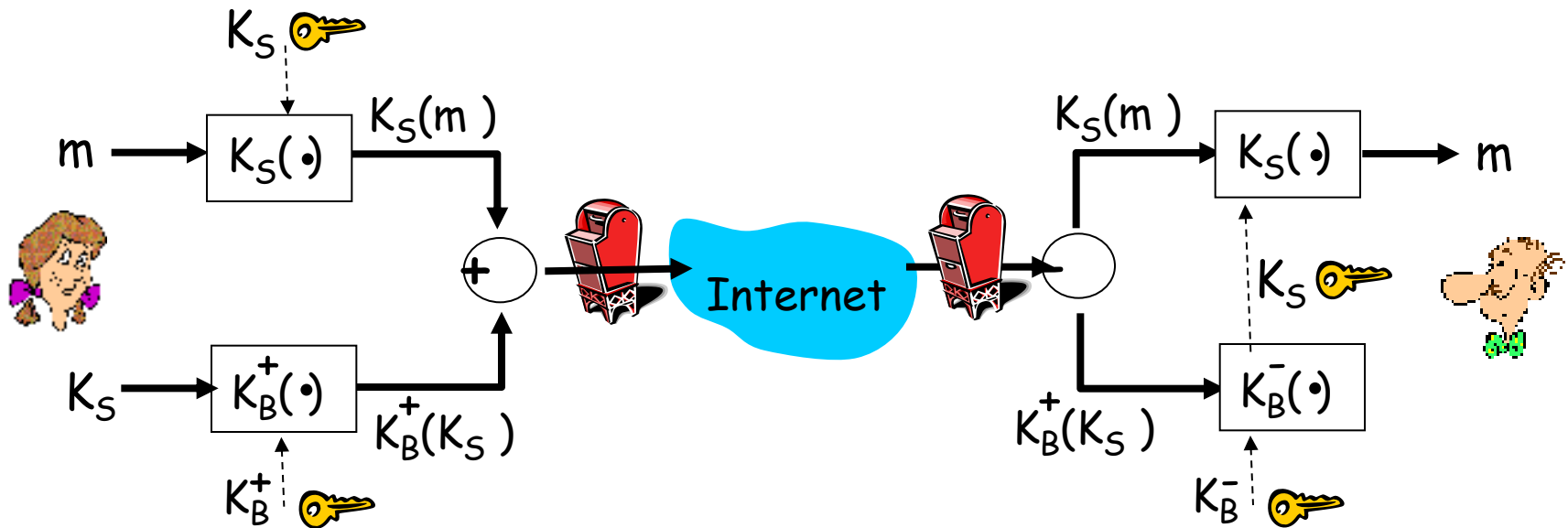
8.6 Network layer security: IPsec

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Secure e-mail

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

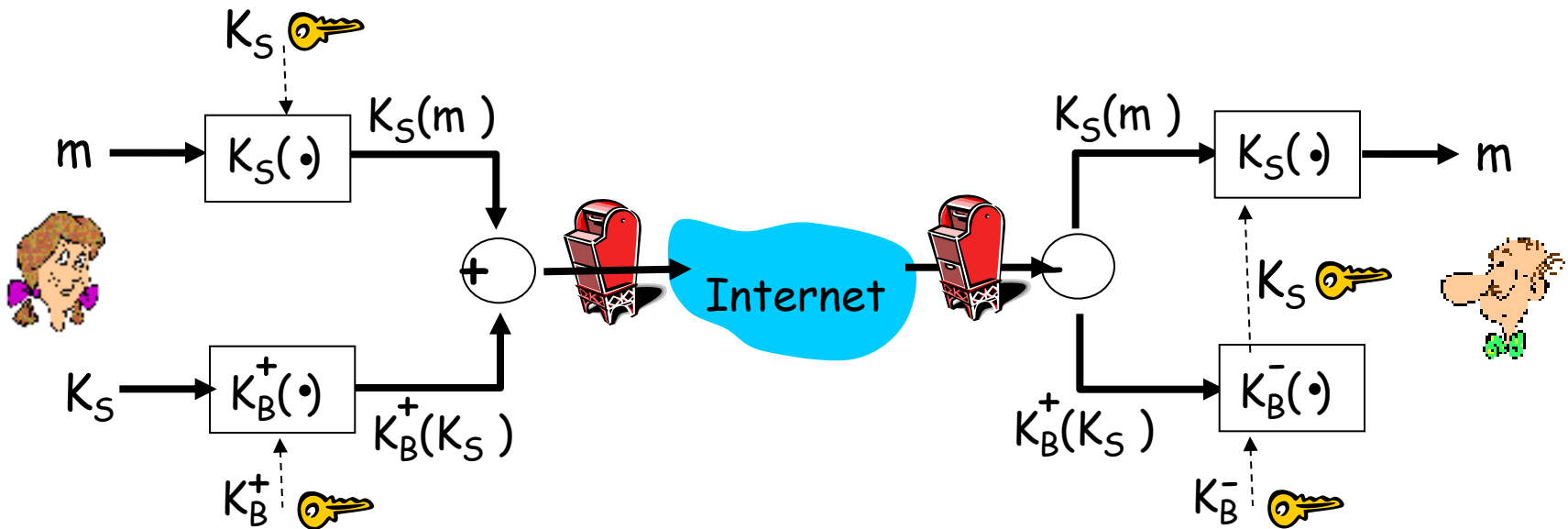


Alice:

- ❖ generates random *symmetric* private 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

Secure e-mail

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

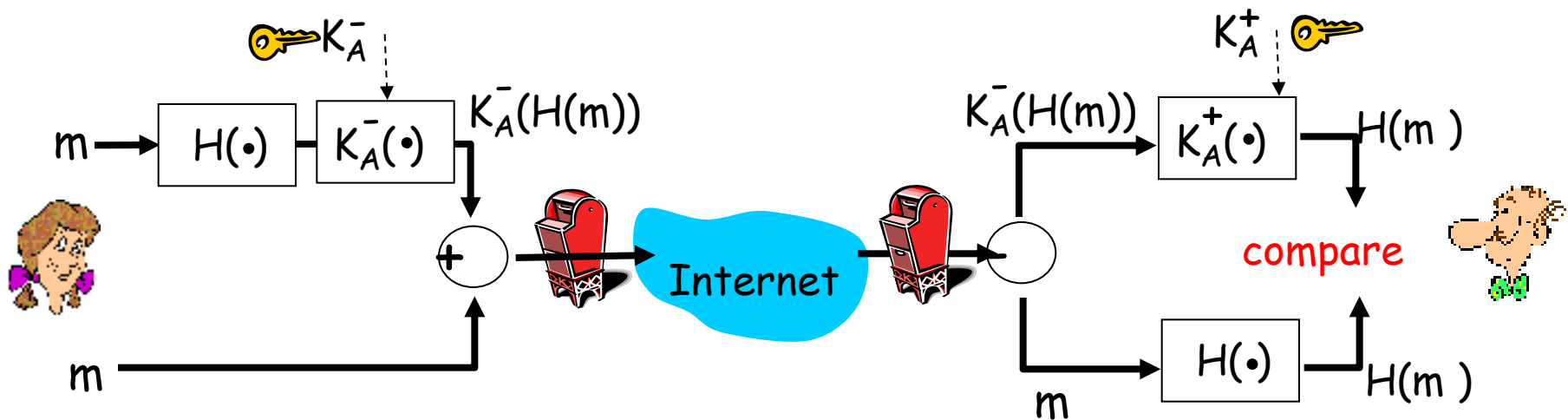


Bob:

- ❖ uses his private key to decrypt and recover K_S
- ❖ uses K_S to decrypt $K_S(m)$ to recover m

Secure e-mail (continued)

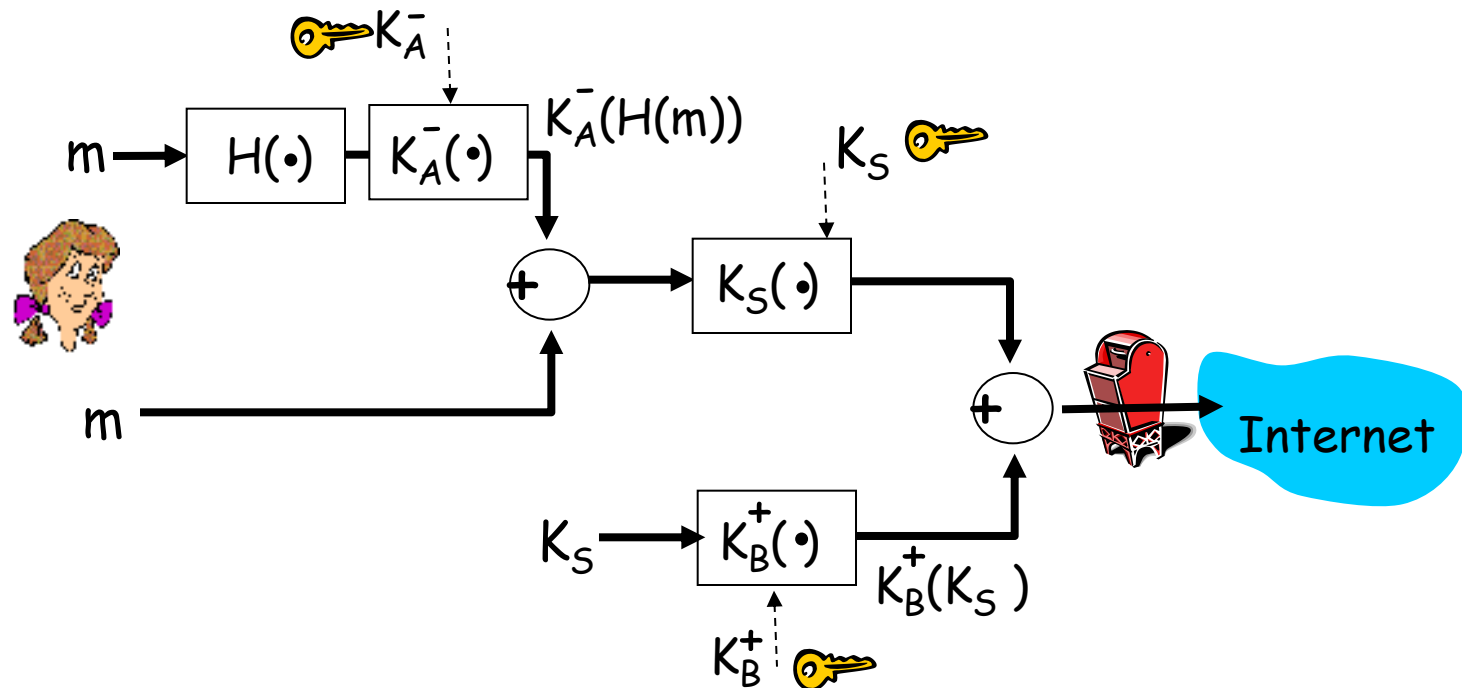
- ❖ Alice wants to provide sender authentication message integrity



- ❖ Alice digitally signs message
- ❖ sends both message (in the clear) and digital signature

Secure e-mail (continued)

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



Alice uses three keys: her private key, Bob's public key, newly created symmetric key

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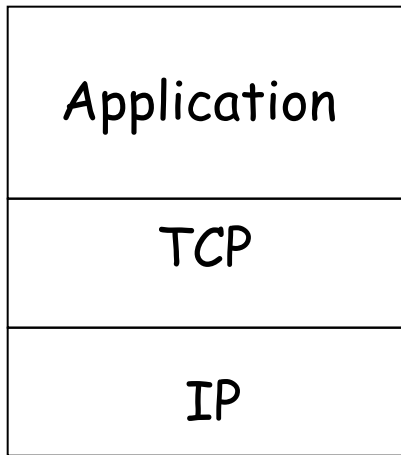
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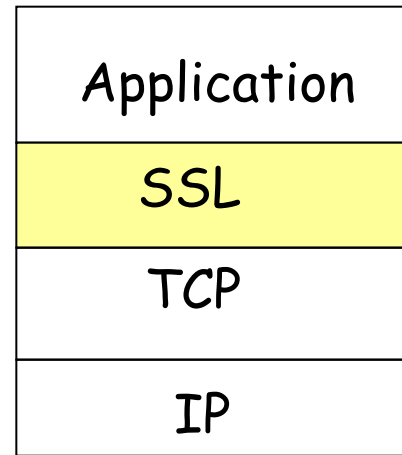
SSL: Secure Sockets Layer

- ❖ widely deployed security protocol
 - supported by almost all browsers, web servers
 - https
 - billions \$/year over SSL
- ❖ original design:
 - Netscape, 1993
- ❖ variation - TLS: transport layer security, RFC 2246
- ❖ provides
 - *confidentiality*
 - *integrity*
 - *authentication*
- ❖ original goals:
 - Web e-commerce transactions
 - encryption (especially credit-card numbers)
 - Web-server authentication
 - optional client authentication
 - minimum hassle in doing business with new merchant
- ❖ available to all TCP applications
 - secure socket interface

SSL and TCP/IP



Normal Application



Application
with SSL

- SSL provides application programming interface (API) to applications
- C and Java SSL libraries/classes readily available

Toy SSL: a simple secure channel

- ❖ *handshake*: Alice and Bob use their certificates, private keys to authenticate each other and exchange shared secret
- ❖ *key derivation*: Alice and Bob use shared secret to derive set of keys
- ❖ *data transfer*: data to be transferred is broken up into series of records
- ❖ *connection closure*: special messages to securely close connection

SSL Cipher Suite

❖ cipher suite

- public-key algorithm
- symmetric encryption algorithm
- MAC algorithm

❖ SSL supports several cipher suites

❖ negotiation: client, server agree on cipher suite

- client offers choice
- server picks one

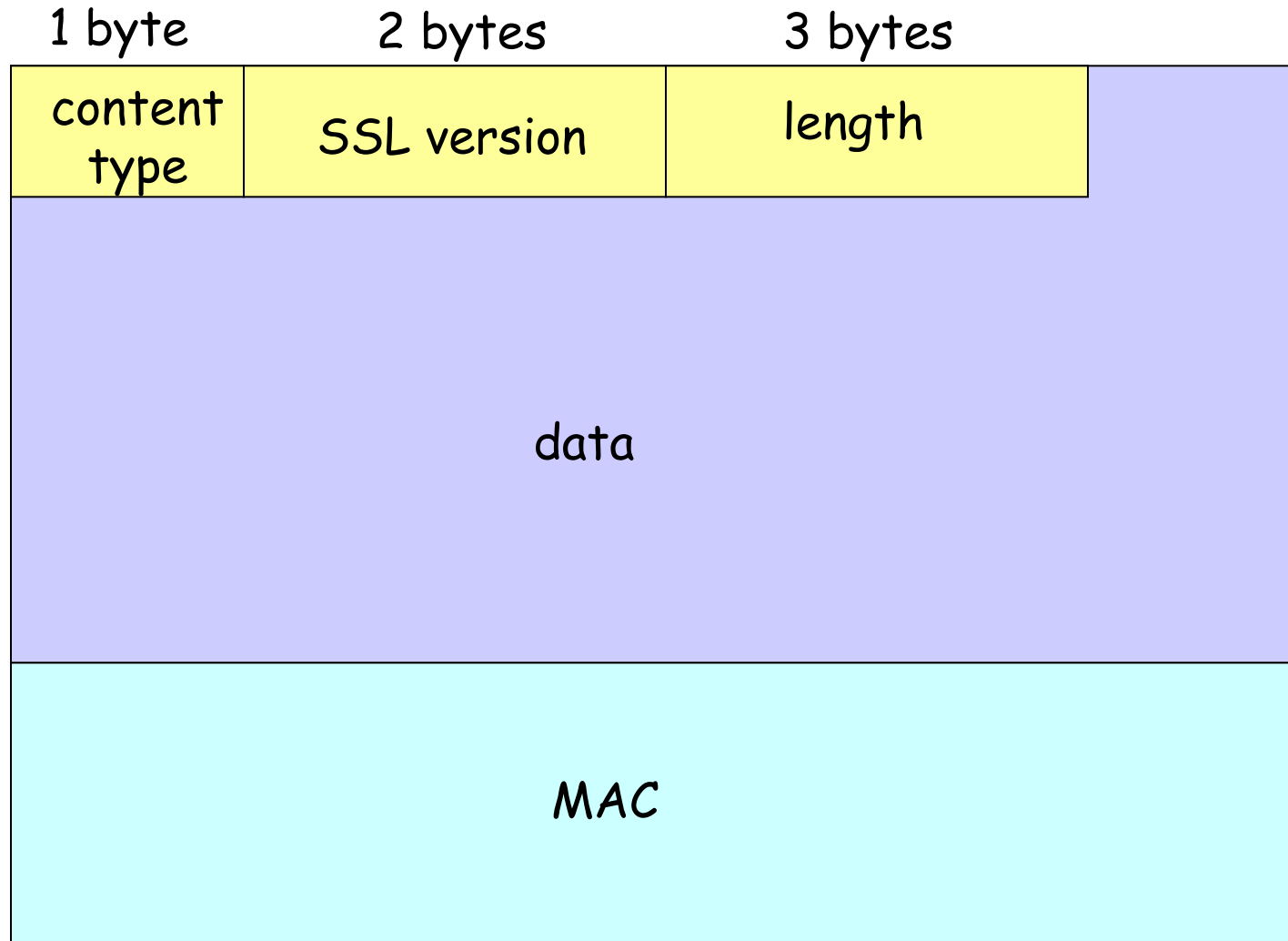
Common SSL symmetric ciphers

- DES - Data Encryption Standard: block
- 3DES - Triple strength: block
- RC2 - Rivest Cipher 2: block
- RC4 - Rivest Cipher 4: stream

SSL Public key encryption

- RSA

SSL Record Format



data and MAC encrypted (symmetric algorithm)

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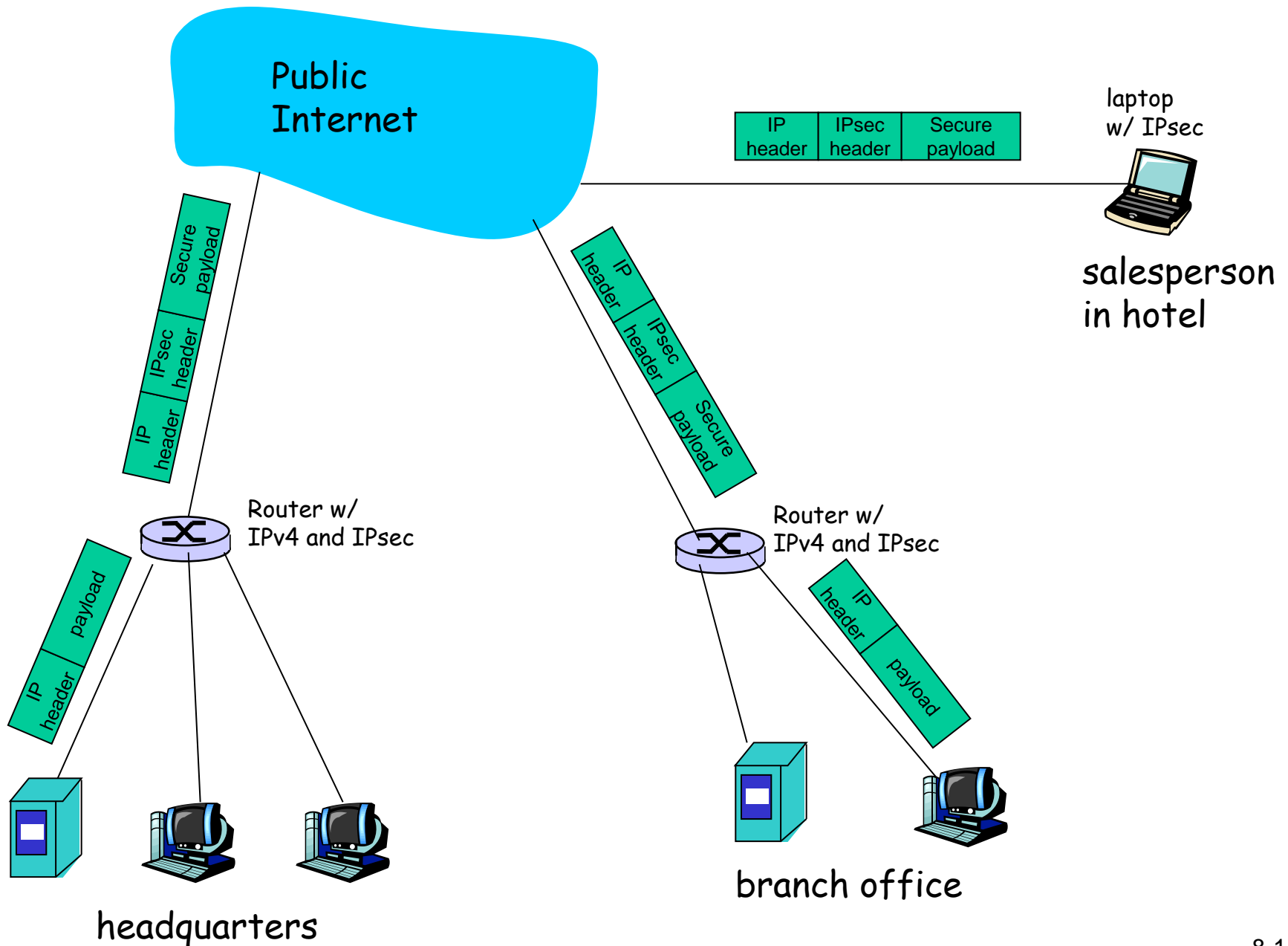
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Virtual Private Networks (VPNs)

- ❖ institutions often want private networks for security.
 - costly: separate routers, links, DNS infrastructure.
- ❖ VPN: institution's inter-office traffic is sent over public Internet instead
 - encrypted before entering public Internet
 - logically separate from other traffic

Virtual Private Network (VPN)



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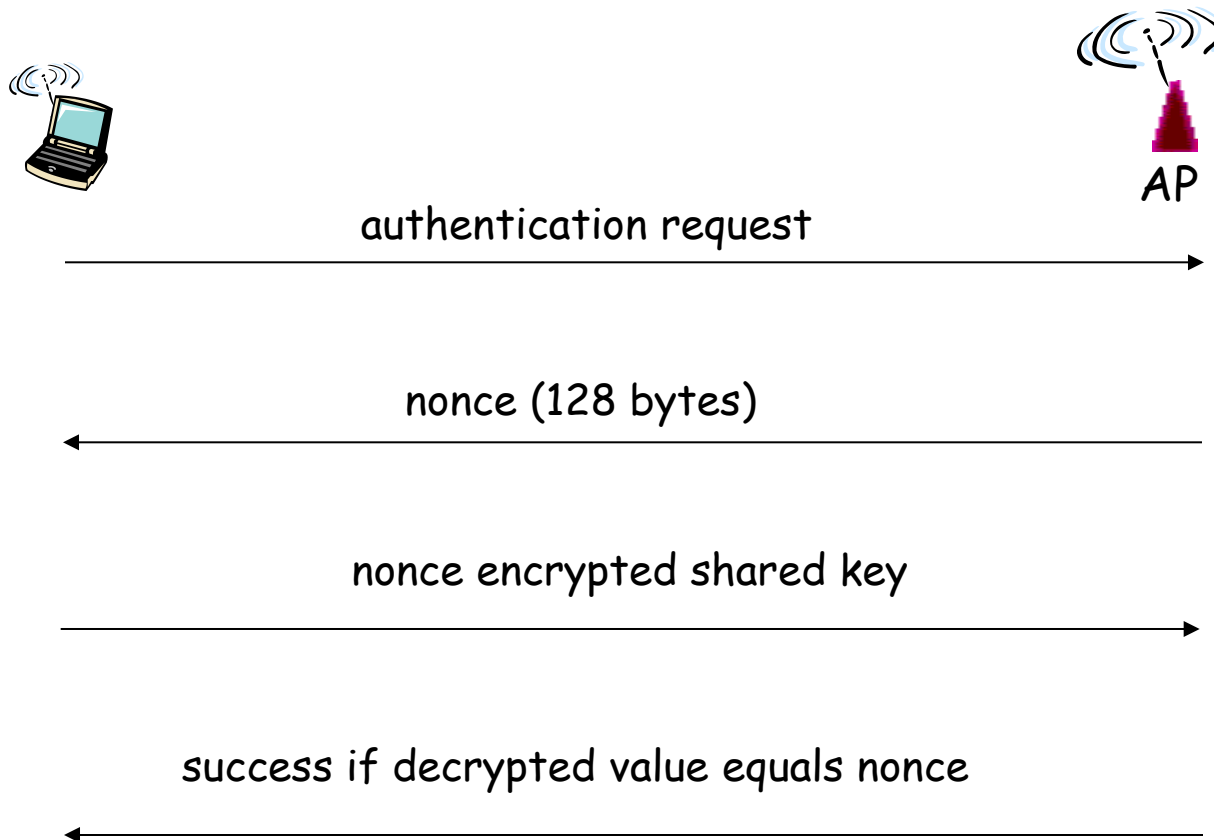
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WEP Authentication

Not all APs do it, even if WEP is being used. AP indicates if authentication is necessary in beacon frame. Done before association.



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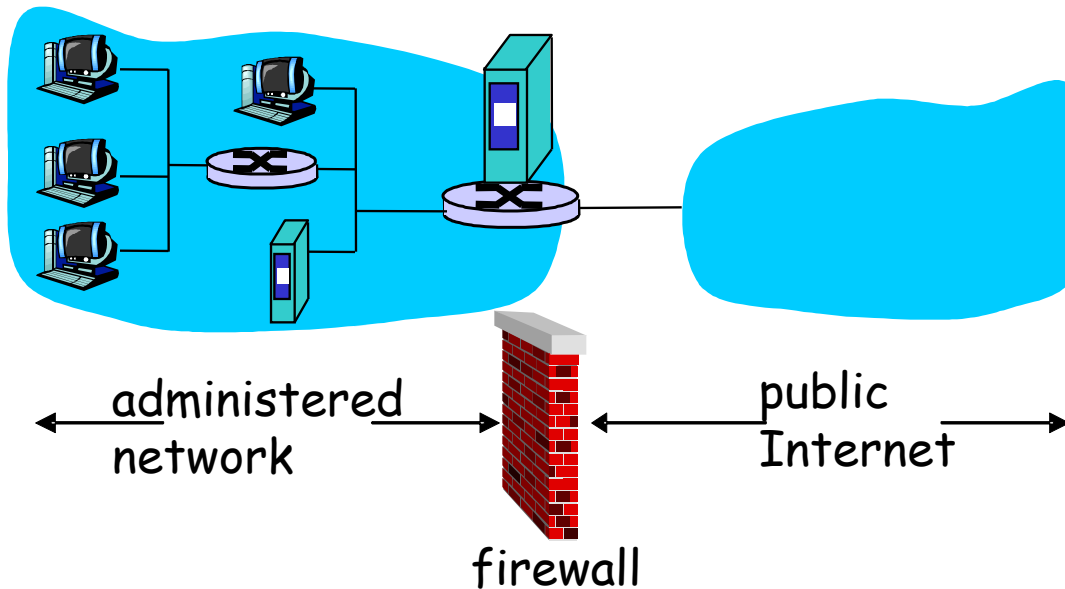
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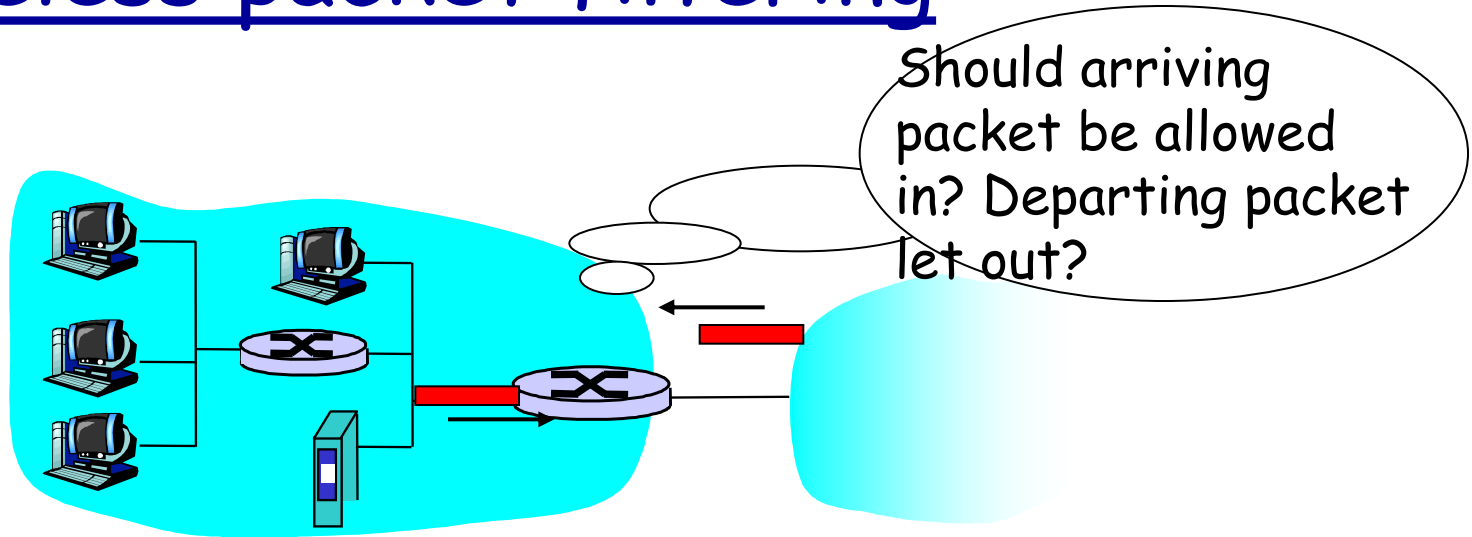
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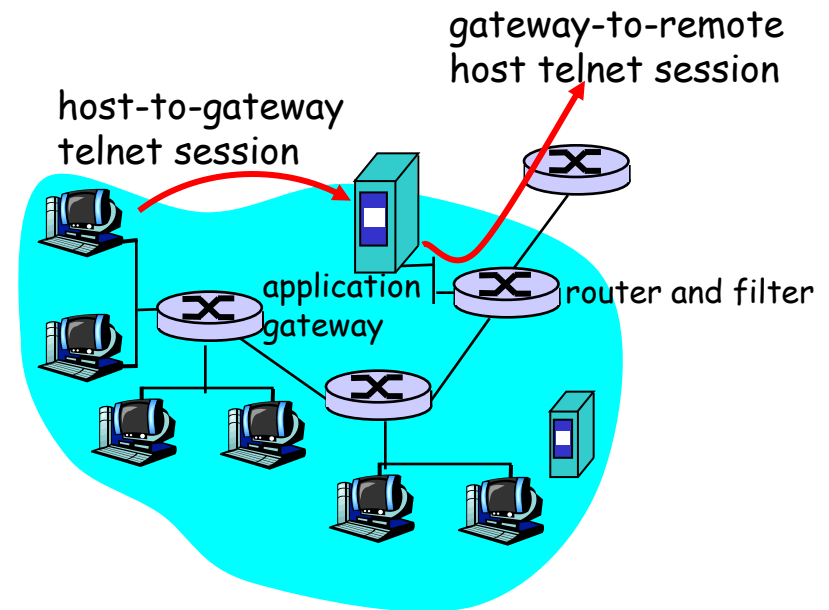
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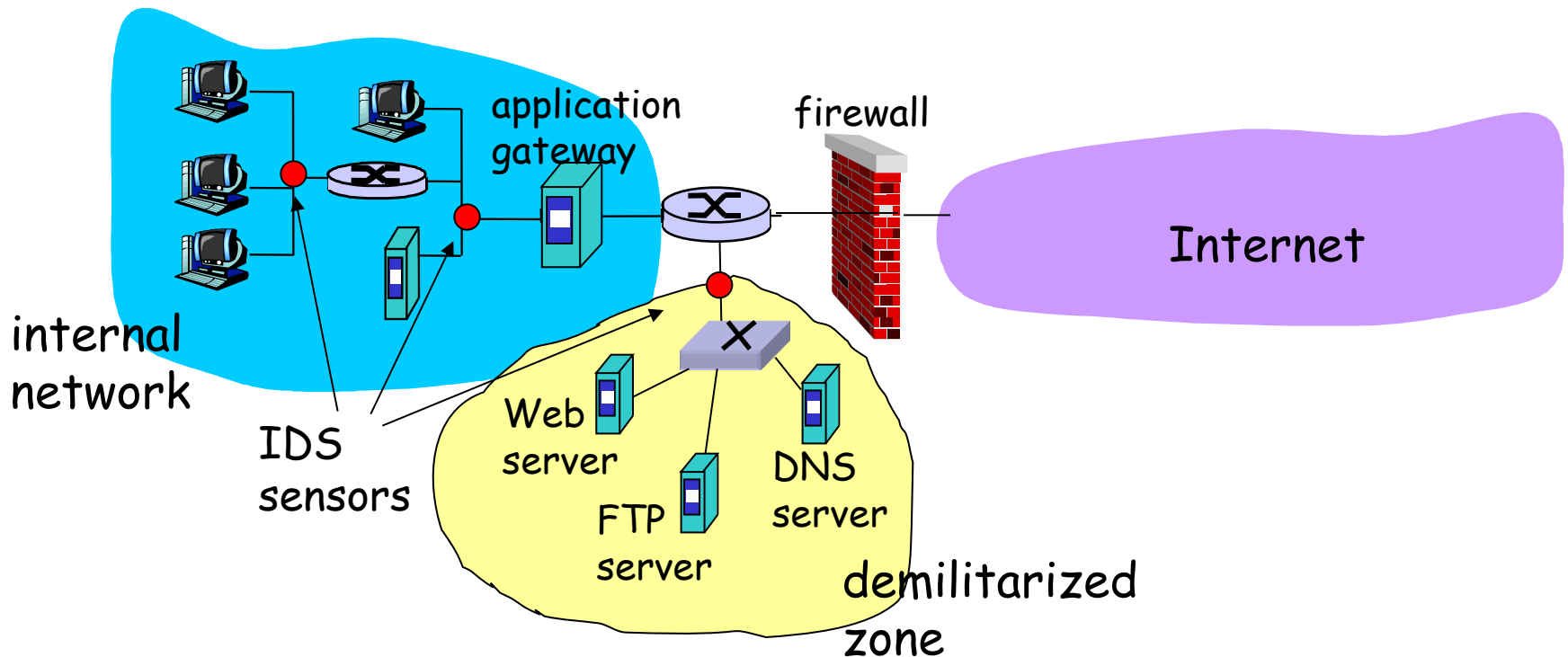
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