# Chapter 8
# Security

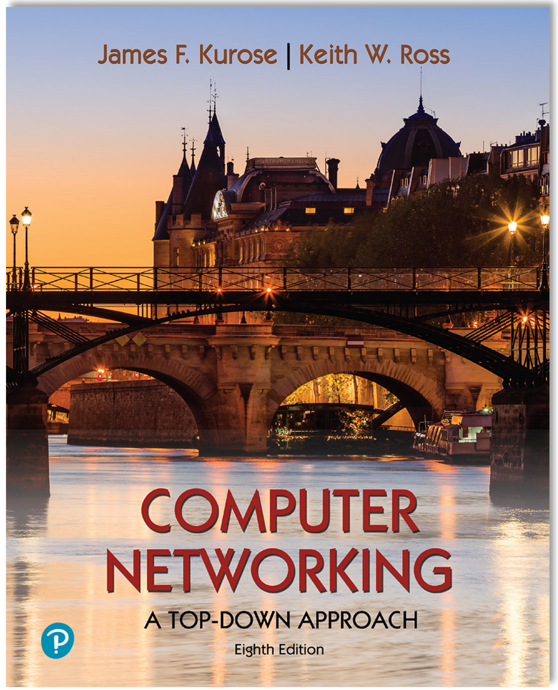
A note on the use of these PowerPoint slides:
We're making these slides freely available to all (faculty, students, readers). They're in PowerPoint form so you see the animations; and can add, modify, and delete slides (including this one) and slide content to suit your needs. They obviously represent a *lot* of work on our part. In return for use, we only ask the following:

- If you use these slides (e.g., in a class) that you mention their source (after all, we'd like people to use our book!)
- If you post any slides on a www site, that you note that they are adapted from (or perhaps identical to) our slides, and note our copyright of this material.

For a revision history, see the slide note for this page.

Thanks and enjoy! JFK/KWR






*Computer Networking: A Top-Down Approach*
8th edition
Jim Kurose, Keith Ross
Pearson, 2020

# Security: overview

## Chapter goals:

- understand principles of network security:
  - cryptography and its *many* uses beyond “confidentiality”
  - authentication
  - message integrity
- security in practice:
  - firewalls and intrusion detection systems
  - security in application, transport, network, link layers

# Chapter 8 outline

- What is network security?
- Principles of cryptography
- Message integrity, authentication
- Securing e-mail
- Securing TCP connections: TLS
- Network layer security: IPsec
- Security in wireless and mobile networks
- Operational security: firewalls and IDS

# What is network security?

confidentiality: only sender, intended receiver should "understand" message contents

- sender encrypts message
- receiver decrypts message

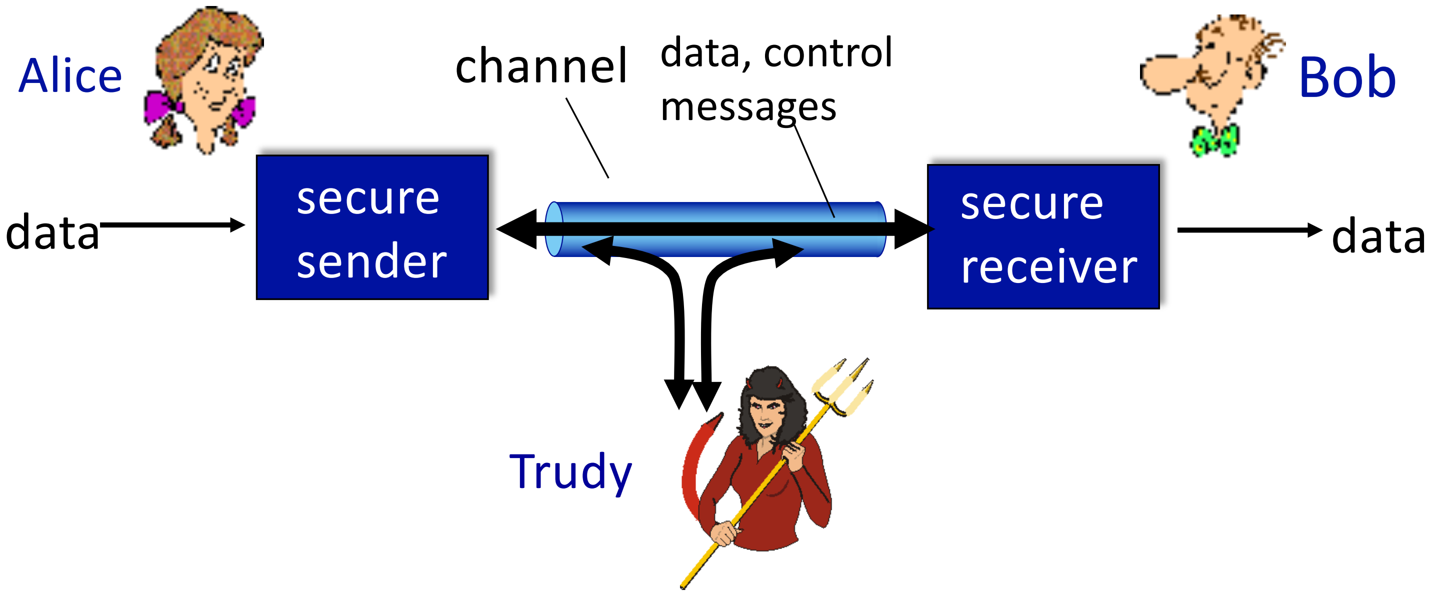
authentication: sender, receiver want to confirm identity of each other

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

access and availability: services must be accessible and available to users

# 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



# Friends and enemies: Alice, Bob, Trudy

Who might Bob and 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
- BGP routers exchanging routing table updates
- other examples?

# There are bad guys (and girls) out there!

*Q:* What can a “bad guy” do?

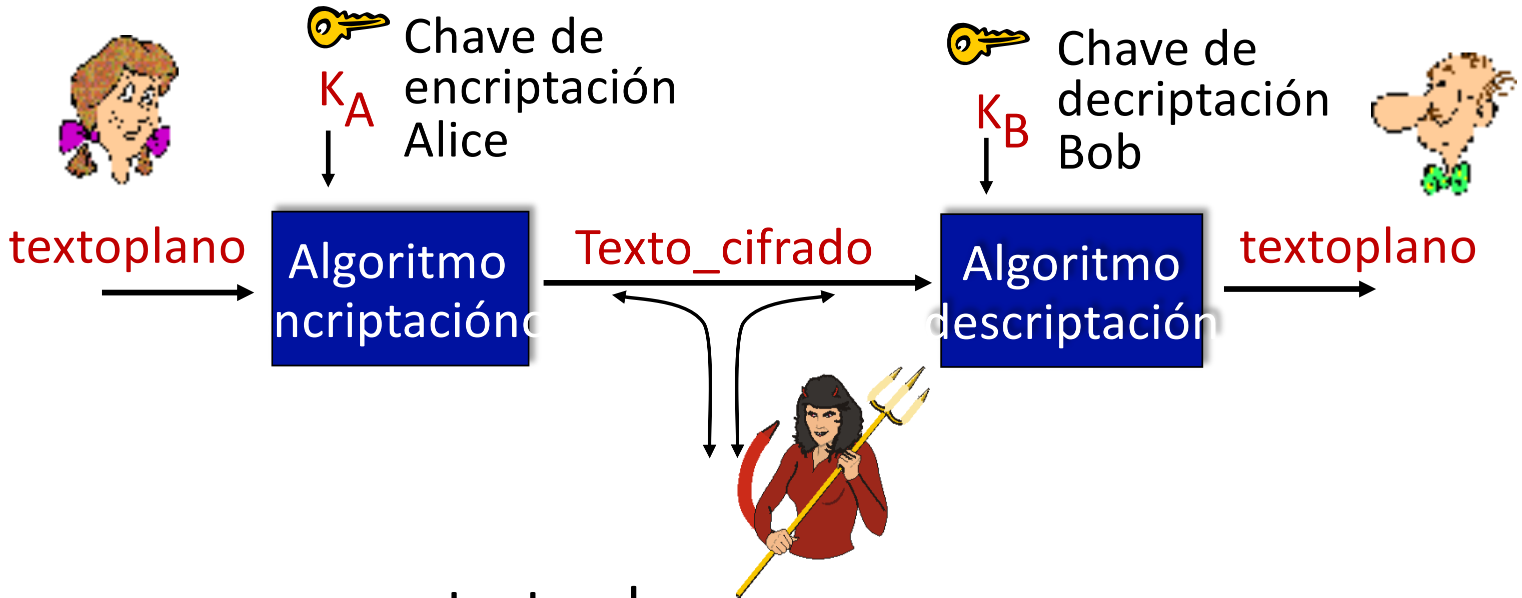
*A:* A lot! (recall section 1.6)

- 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)

# Chapter 8 outline

- What is network security?
- Principles of cryptography
- Message integrity, authentication
- Securing e-mail
- Securing TCP connections: TLS
- Network layer security: IPsec
- Security in wireless and mobile networks
- Operational security: firewalls and IDS

# A Linguaxe da Criptografía




m: mensaxe en texto plano

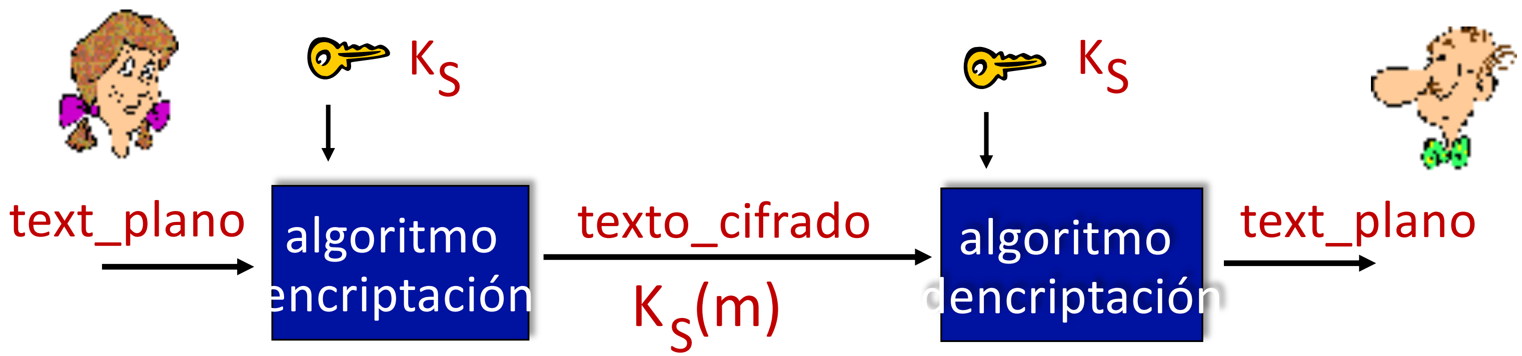
$K_A(m)$: texto cifrado, encriptado coa chave $K_A$

$m = K_B(K_A(m))$

# Rompendo a encriptación

- Ataque con texto cifrado: Trudy ten texto cifrado que analizar
- Duas opcións:
  - Forza bruta: buscar entre todas as chaves
  - Análise estatístico
- Texto plano coñecido: Trudy ten texto plano correspondente ao cifrado
  - *p.e., e*n cifrados monoalfabeticos, Trudy determina os pares para a,l,i,c,e,b,o,
- Texto plano escollido: Trudy pode cifrar o texto plano escollido

# Criptografía de chave simétrica




Crypto de chave simétrica: Bob e Alice comparten a mesma chave (symmetric): K

- *p.e.,* a chave é un patron de subtitución monoalfabética coñecido

*Q: como se poñen de acordo na chave*?

# Encriptación sinxela

*Cifrado de subtitución:* substituir unha cousa por otra:
monoalfabetico: substitute unha letra por outra

```
    text_plano:   abcdefghijklmnopqrstuvwxyz

texto_cifrado:    mnbvcxzasdfghjklpoiuytrewq
```

e.g.: `text_plano: bob. i love you. alice`
`texto_cifrado: nkn. s gktc wky. mgsbc`

*Chave de encriptación:* o mapa desde o conxunto de 26 letras ao conxunto de 26 letras

# Unha maneira máis sofisticada

- n cifrados de subtitución, $M_1,M_2,\ldots,M_n$
- Patrón cíclico:
  - p.e., n=4: $M_1,M_3,M_4,M_3,M_2$;   $M_1,M_3,M_4,M_3,M_2$; ..
- Para cada novo símbolo text_plano, usar o seguinte patron de maneira cíclica
  - dog: d desede $M_1$, o desde $M_3$, g desde $M_4$

*Chave de encriptación:* n cifrados de subtitución, e patrón cíclico

- A chave non ter porque se so un patrón n-bit

# Chave simétrica: DES

## DES: Data Encryption Standard

- Estándar dos EUA [NIST 1993]
- 56-bit chave simétrica, entrada 64-bit text_plano
- Cifrado en bloque con encadeado de bloque
- Canto de Seguro é DES?
  - DES Challenge: frase 56-bit-key-encrypted desencriptada (forza bruta) en menos dun dia
  - Non se coñece un bo ataque analítico
- facer DES máis seguro:
  - 3DES: encriptart 3 veces con 3 chaves diferentes

# AES: Advanced Encryption Standard

- Estándar symmetric-key NIST, reemplazou DES (Nov 2001)
- Procesa os datos en bloques de 128 bit
- Chaves de 128, 192, ou 256 bit
- Desenciptación forza bruta (pobar cada chave) tarda 1 s en DES, tarda 149 billóns de anos para AES

# Criptografía de chave pública

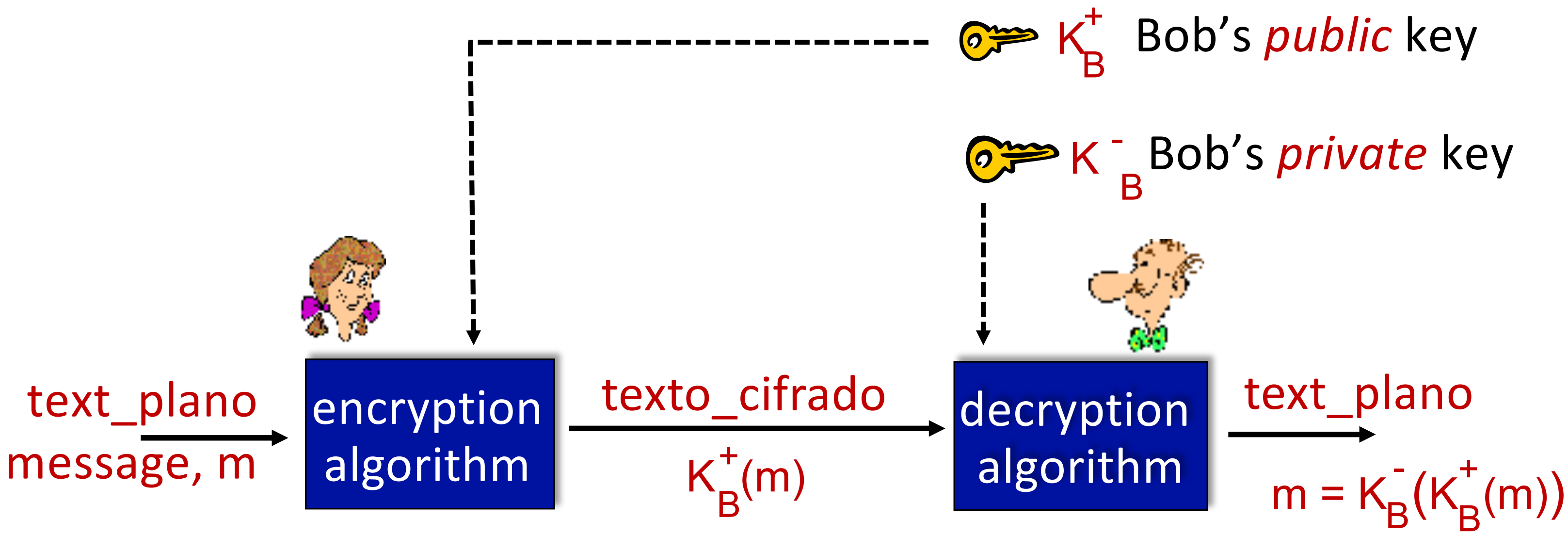
## Chave simétrica:

- Require que o emisor e receptor coñezan a mesma chave
- Q: como acordar unha chave a primeira vez (particularmente se nunca se "coñecen")?

## Chave pública

- *radicalmente* diferente idea [Diffie-Hellman76, RSA78]
- Emisor e receptor *non* comparten chave secreta
- *publica* chave de encriptación coñecida por *todos*
- *privada* chave de decriptación coñecida so polo receptor

# Criptografía de chave pública




*Guau* – a criptografía de chave pública revolucionou 2000 anos de criptografía (previamente so existia chave simétrica) !

- Ideas similares apareceron aou mesmo tempo, independentemente nos EUA e RUGB (clasificados)

# Criptografía de chave pública: algoritmos

requerimentos:

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

# Prerequisito: arimética modular

- x mod n = resto de x cando se divide por n
- feitos:

  [(a mod n) + (b mod n)] mod n = (a+b) mod n
  [(a mod n) - (b mod n)] mod n = (a-b) mod n
  [(a mod n) * (b mod n)] mod n = (a*b) mod n
- entón

  $(a \bmod n)^d \bmod n = a^d \bmod n$
- exemplo: x=14, n=10, d=2:

  $(x \bmod n)^d \bmod n = 4^2 \bmod 10 = 6$

  $x^d = 14^2 = 196 \quad x^d \bmod 10 = 6$

# RSA: preparación

- mensaxe: so un patrón de bits
- Patrón de bits pode representarse por un enteiro
- entón, encriptar unha mensaxe é equivalente a encriptar un número

exemplo:

  - m= 10010001. Esta mensaxe e representada de maneira única polo número decimal 145.
  - Para encriptar m, encriptamos o número correspondente, o que nos da un novo número (o texto_cifrado).

# RSA: Creando o par publico/privado

1. Escoller dous números primos grandes *p, q.* (p.e., 1024 bits cada un)
2. computar $n = pq$, $z = (p-1)(q-1)$
3. escoller $e$ *(con* $e<n$*)* que non ten factores comúns con z (*e, z* son "primos relativos").
4. escoller $d$ tal que $ed-1$ é exactamente divisible por *z*. (noutras palabras: *ed* mod $z = 1$ ).
5. *publica* é $\underbrace{(n,e)}_{K_B^+}$. *privada* é $\underbrace{(n,d)}_{K_B^-}$.

# RSA: encriptación, decriptación

0. dados ($n,e$) e ($n,d$) computados coma antes

1. Para encriptar mensaxe $m$ $(<n)$, computar
   $c = m^e \bmod n$

2. Para desencriptar o patron de bits, $c$, computar
   $m = c^d \bmod n$

maxia! $m = (\underbrace{m^e \bmod n}_{c})^d \bmod n$

# RSA exemplo:

Bob escolle *p=5, q=7*. Entón *n=35, z=24*.

*e=5* (así *e, z* primos relativos).

*d=29* (así *ed-1* exactamente divisible por z).

encriptando mensaxes 8-bit.

encrypt: $\underbrace{\text{bit pattern}}_{\text{0000l000}}$ $\underbrace{m}_{12}$ $\underbrace{m^e}_{24832}$ $\underbrace{c = m^e \bmod\ n}_{17}$

decrypt: $\underbrace{c}_{17}$ $\underbrace{c^d}_{481968572106750915091411825223071697}$ $\underbrace{m = c^d \bmod\ n}_{12}$

# Porque funciona RSA?

- Debe demostrar que $c^d \bmod n = m$, onde $c = m^e \bmod n$
- feito: calquer x e y: $x^y \bmod n = x^{(y \bmod z)} \bmod n$
  - onde $n= pq$ e $z = (p-1)(q-1)$
- entón,

$$
\begin{aligned}
c^d \bmod n &= (m^e \bmod n)^d \bmod n \\
&= m^{ed} \bmod n \\
&= m^{(ed \bmod z)} \bmod n \\
&= m^1 \bmod n \\
&= m
\end{aligned}
$$

# RSA: outra propiedade importnte

A seguite propiedade é *moi* útil:

$$\underbrace{K_B^-(K_B^+(m))}_{\text{Usar pública primeiro, seguida por privada}} = m = \underbrace{K_B^+(K_B^-(m))}_{\text{Usar privada primeiro, seguida por pública}}$$

*O resultado é o mesmo!*

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

A partires da arimética modular:

$$(m^e \bmod n)^d \bmod n = m^{ed} \bmod n$$
$$= m^{de} \bmod n$$
$$= (m^d \bmod n)^e \bmod n$$

# Porqué RSA é segura?

- Supoñamos que coñecemos a chave pública de Bob (n,e). Qué dificil é determinar d?
- Esencialmente necesitar atopar factores de n sen coñecer os dous factores p e q
    - feito: factorizar un número grande é dificil

# RSA na práctica: chaves de sesións

- exponenciar en RSA é intensivo computacionalmente
- DES é polo menos 100 veces máis rápido que RSA
- Usar crypto de chave pública para establecer unha conexió segur, despois establecer unha segunda chave simétrica para encyptar os datos
- Sesión chave, $K_S$
  - Bob e Alice usan RSA para intercambiar a chave simétrica $K_S$
  - Cando os dous teñen $K_S$, poden usar criptografía de chave simétrica

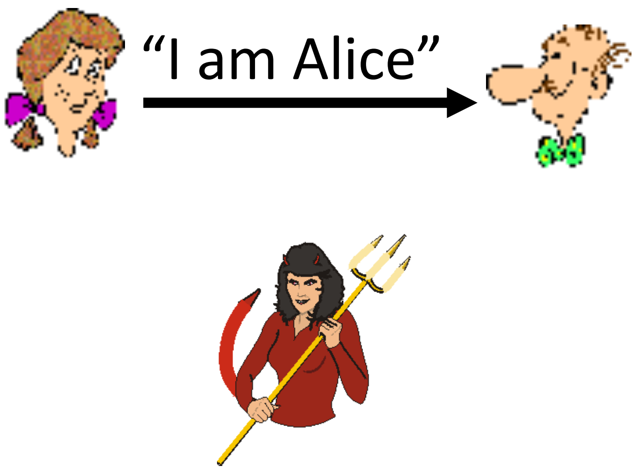
# Chapter 8 outline

- What is network security?
- Principles of cryptography
- **Authentication**, message integrity
- Securing e-mail
- Securing TCP connections: TLS
- Network layer security: IPsec
- Security in wireless and mobile networks
- Operational security: firewalls and IDS

# Authentication

Goal: Bob wants Alice to “prove” her identity to him

Protocol ap1.0: Alice says “I am Alice”

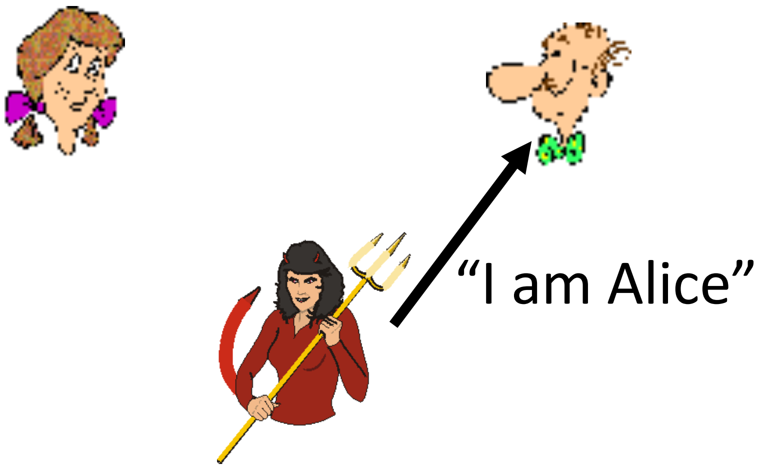



*failure scenario??*

# Authentication

Goal: Bob wants Alice to “prove” her identity to him

Protocol ap1.0: Alice says “I am Alice”




*in a network, Bob can not “see” Alice, so Trudy simply declares herself to be Alice*

# Authentication: another try

Goal: Bob wants Alice to "prove" her identity to him

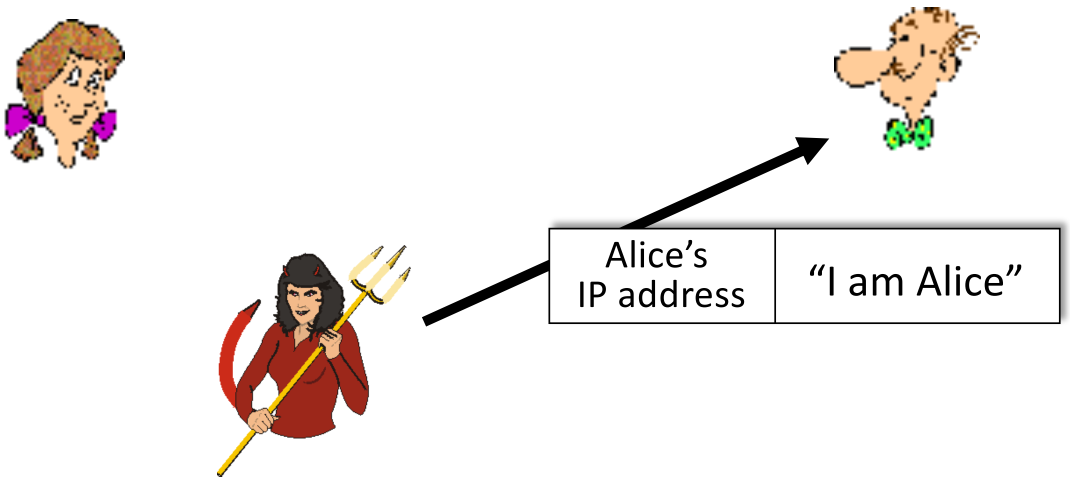
Protocol ap2.0: Alice says "I am Alice" in an IP packet containing her source IP address


*failure scenario??*

# Authentication: another try

Goal: Bob wants Alice to "prove" her identity to him

Protocol ap2.0: Alice says "I am Alice" in an IP packet containing her source IP address

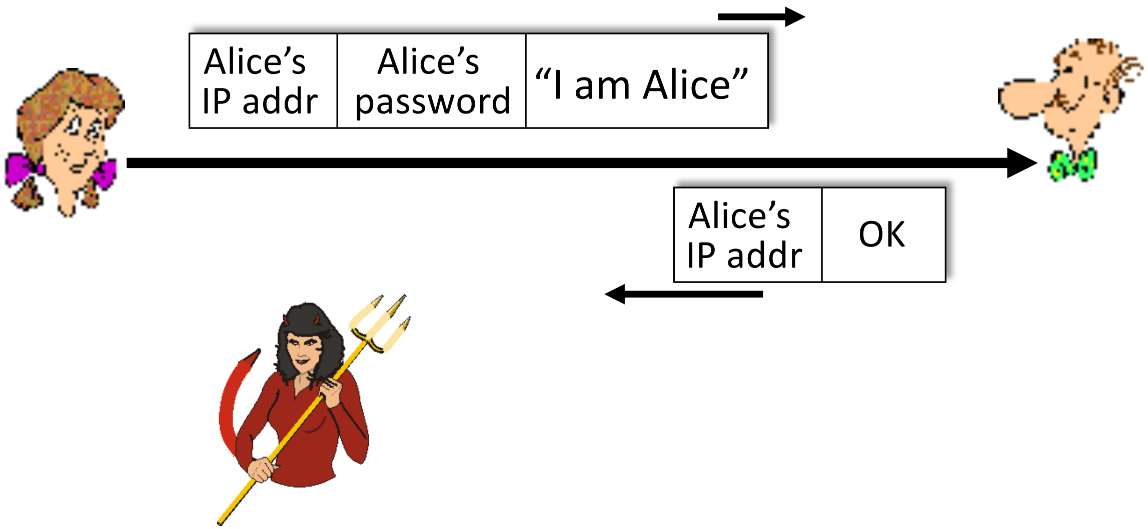



*Trudy can create a packet "spoofing" Alice's address*

# Authentication: a third try

Goal: Bob wants Alice to "prove" her identity to him

Protocol ap3.0: Alice says "I am Alice" Alice says "I am Alice" and sends her secret password to "prove" it.

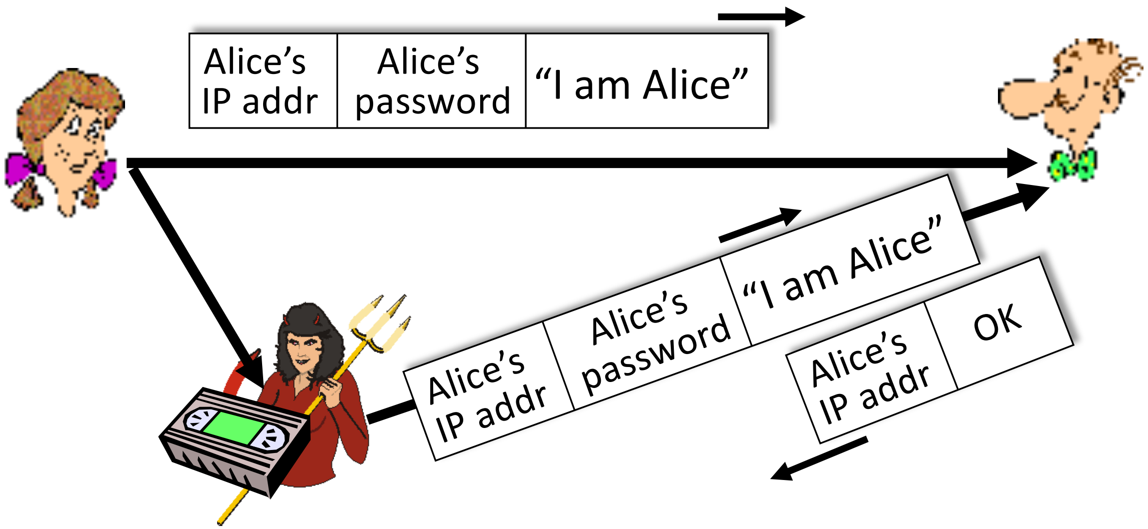



*failure scenario??*

# Authentication: a third try

Goal: Bob wants Alice to "prove" her identity to him

Protocol ap3.0: Alice says "I am Alice" Alice says "I am Alice" and sends her secret password to "prove" it.

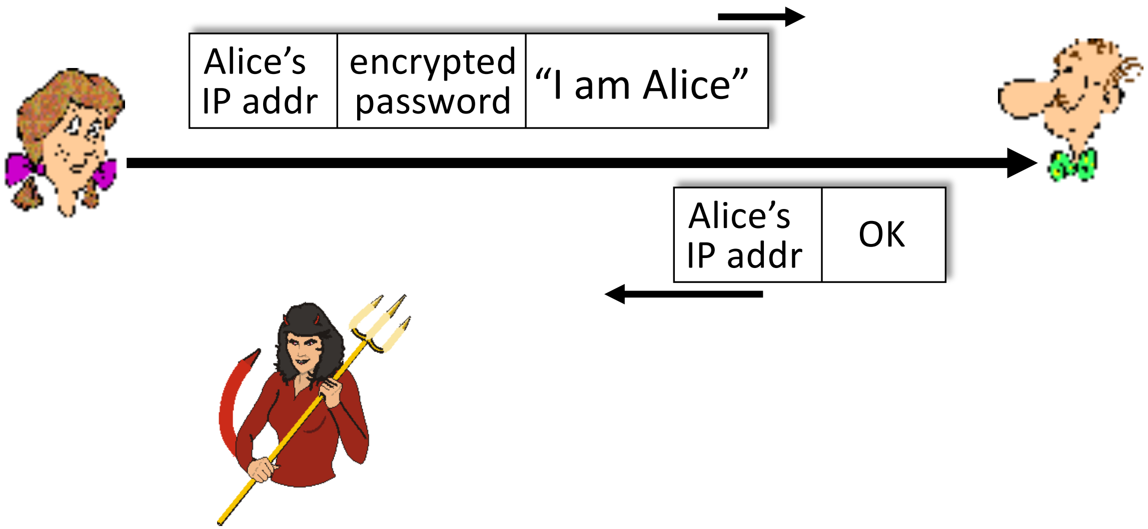



*playback attack:*
*Trudy records Alice's packet and later plays it back to Bob*

# Authentication: a modified third try

Goal: Bob wants Alice to "prove" her identity to him

Protocol ap3.0: Alice says "I am Alice" Alice says "I am Alice" and sends her encrypted secret password to "prove" it.

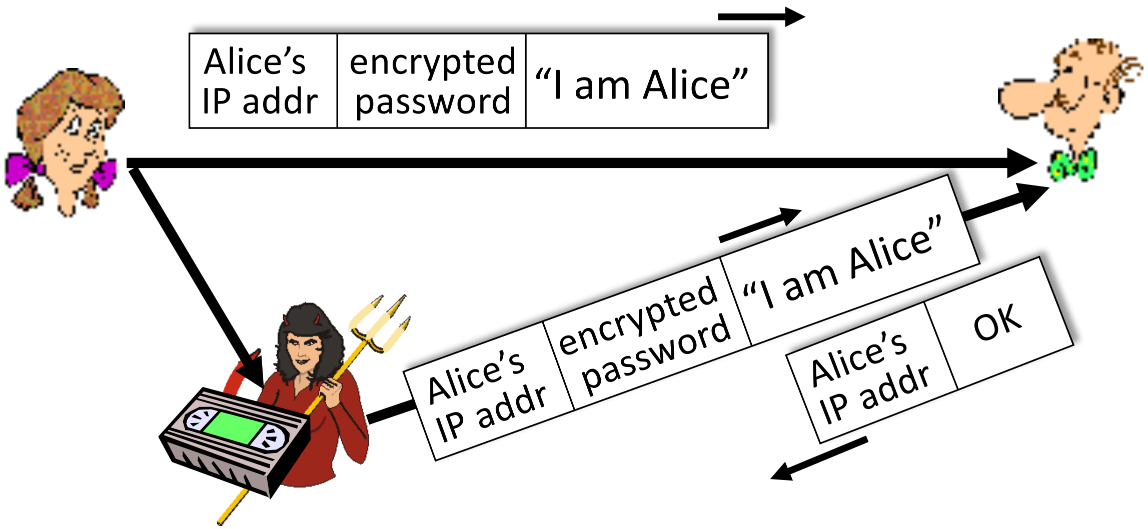



*failure scenario??*

# Authentication: a modified third try

Goal: Bob wants Alice to "prove" her identity to him

Protocol ap3.0: Alice says "I am Alice" Alice says "I am Alice" and sends her encrypted secret password to "prove" it.




*playback attack still works: Trudy records Alice's packet and later plays it back to Bob*

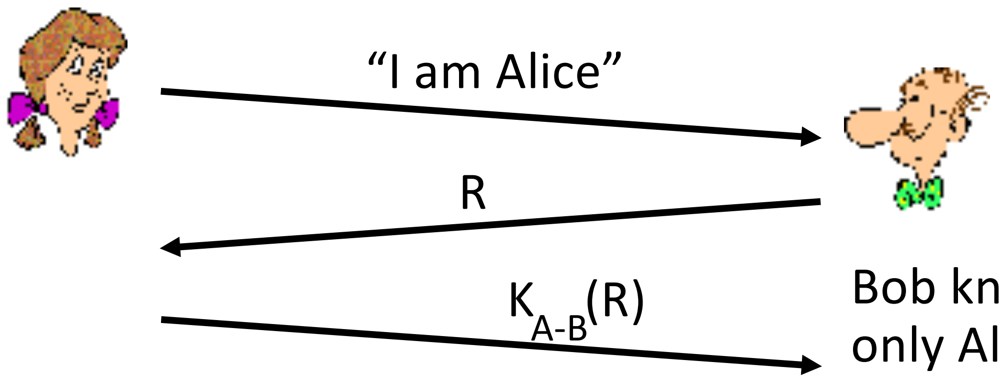
# Authentication: a fourth try

Goal: avoid playback attack

nonce: number (R) used only once-in-a-lifetime

protocol ap4.0: to prove Alice "live", Bob sends Alice nonce, R

- Alice must return R, encrypted with shared secret key



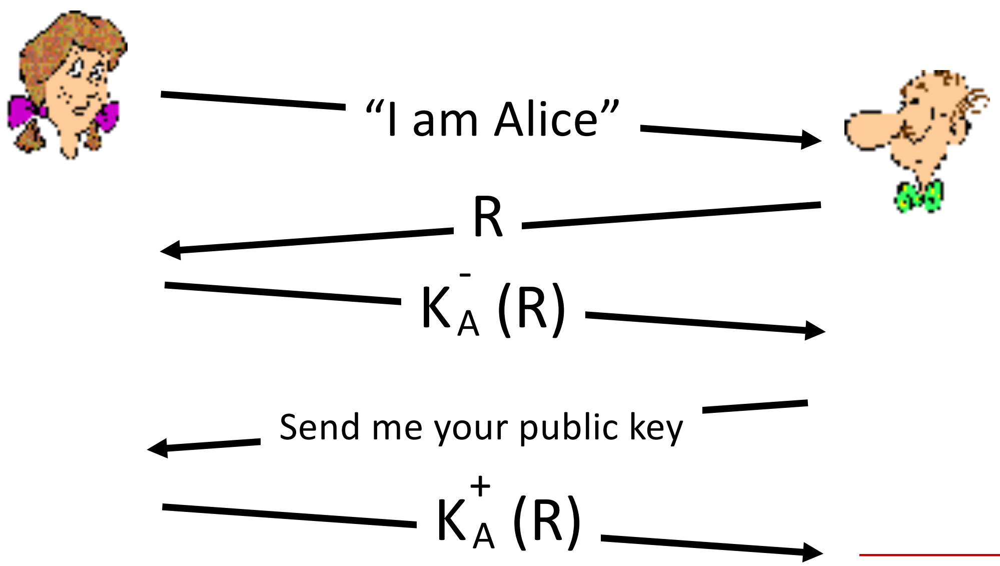

Bob know Alice is live, and only Alice knows key to encrypt nonce, so it must be Alice!

*Failures, drawbacks?*

# Authentication: ap5.0

ap4.0 requires shared symmetric key - can we authenticate using public key techniques?

ap5.0: use nonce, public key cryptography




Bob computes

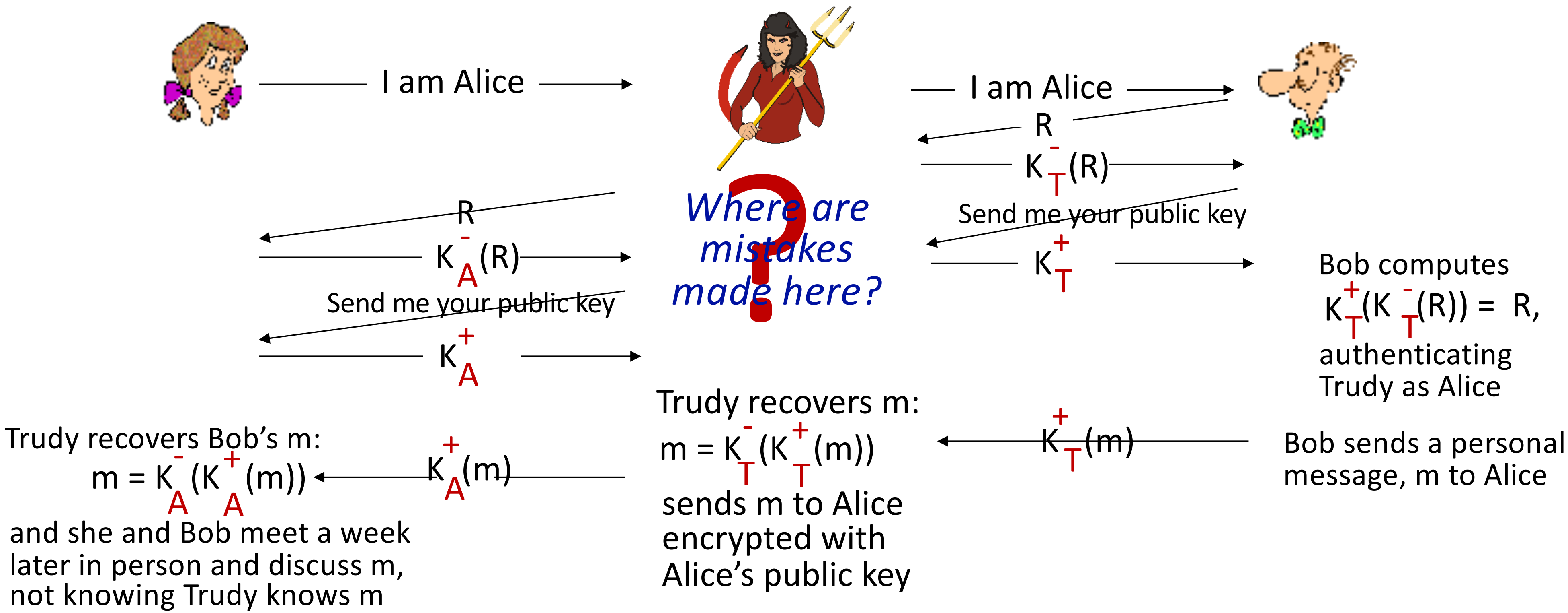
$$K_A^+(K_A^-(R)) = R$$

and knows only Alice could have the private key, that encrypted R such that

$$K_A^+(K_A^-(R)) = R$$

# Authentication: ap5.0 – there's still a flaw!

man (or woman) in the middle attack: Trudy poses as Alice (to Bob) and as Bob (to Alice)



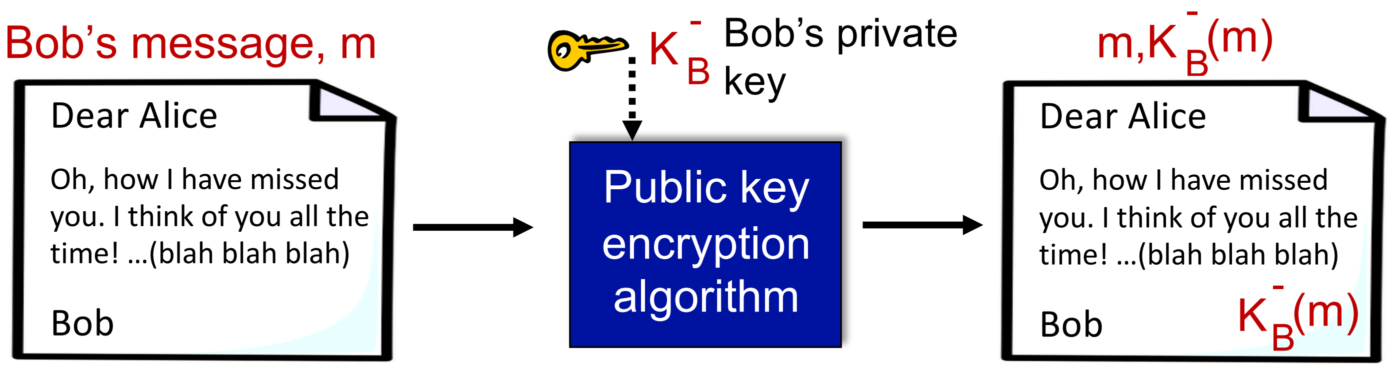
# Chapter 8 outline

- What is network security?
- Principles of cryptography
- Authentication, message integrity
- Securing e-mail
- Securing TCP connections: TLS
- Network layer security: IPsec
- Security in wireless and mobile networks
- Operational security: firewalls and IDS

# Digital signatures

cryptographic technique analogous to hand-written signatures:

- sender (Bob) digitally signs document: he is document owner/creator.
- *verifiable, nonforgeable:* recipient (Alice) can prove to someone that Bob, and no one else (including Alice), must have signed document
- simple digital signature for message m:
  - Bob signs m by encrypting with his private key $K_B$, creating "signed" message, $K_B^-(m)$



# Digital signatures

- suppose Alice receives msg m, with signature: m, $K_B^-(m)$
- Alice verifies m signed by Bob by applying Bob's public key $K_B^+$ to $K_B^-(m)$ then checks $K_B^+(K_B^-(m)) = m$.
- If $K_B^+(K_B^-(m)) = m$, whoever signed m must have used Bob's private key

Alice thus verifies that:

- Bob signed m
- no one else signed m
- Bob signed m and not m'

non-repudiation:

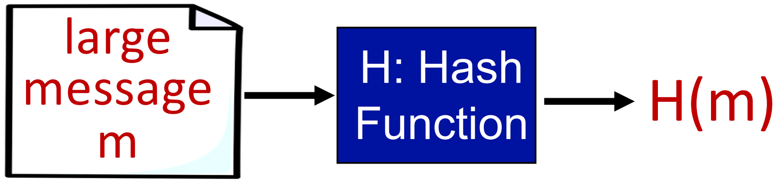
✓ Alice can take m, and signature $K_B^-(m)$ to court and prove that Bob signed m

# Message digests

computationally expensive to public-key-encrypt long messages

goal: fixed-length, easy- to-compute digital "fingerprint"

- apply hash function H to *m*, get fixed size message digest, *H(m)*




Hash function properties:

- many-to-1
- produces fixed-size msg digest (fingerprint)
- given message digest *x*, computationally infeasible to find *m* such that *x = H(m)*

# Internet checksum: poor crypto hash function

Internet checksum has some properties of hash function:

- produces fixed length digest (16-bit sum) of message
- is many-to-one

but given message with given hash value, it is easy to find another message with same hash value:

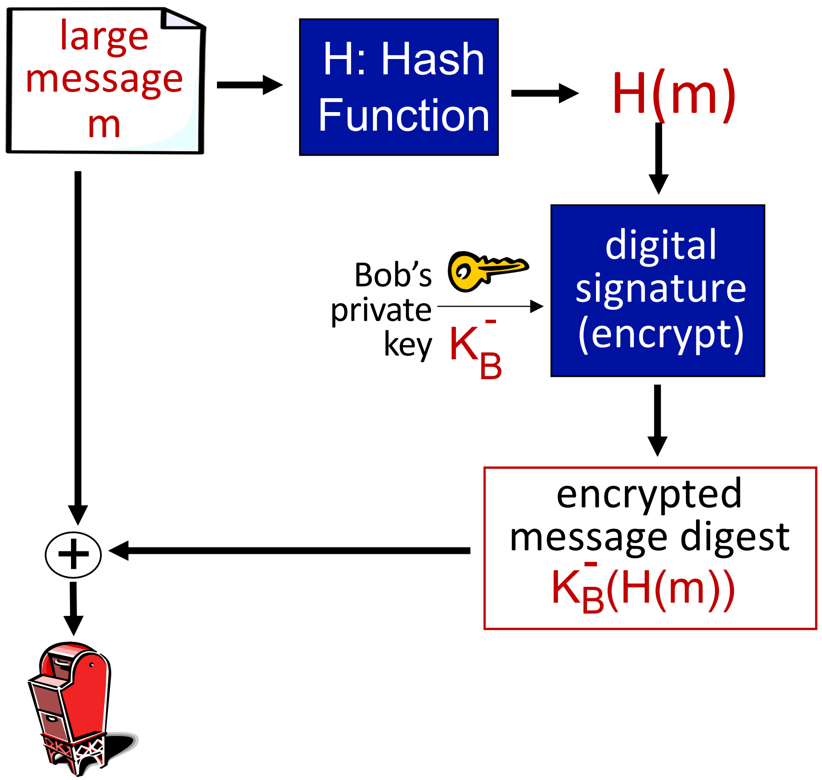
| message | ASCII format | message | ASCII format |
|---|---|---|---|
| I O U 1 | 49 4F 55 31 | I O U 9 | 49 4F 55 39 |
| 0 0 . 9 | 30 30 2E 39 | 0 0 . 1 | 30 30 2E 31 |
| 9 B O B | 39 42 D2 42 | 9 B O B | 39 42 D2 42 |
| | B2 C1 D2 AC | | B2 C1 D2 AC |

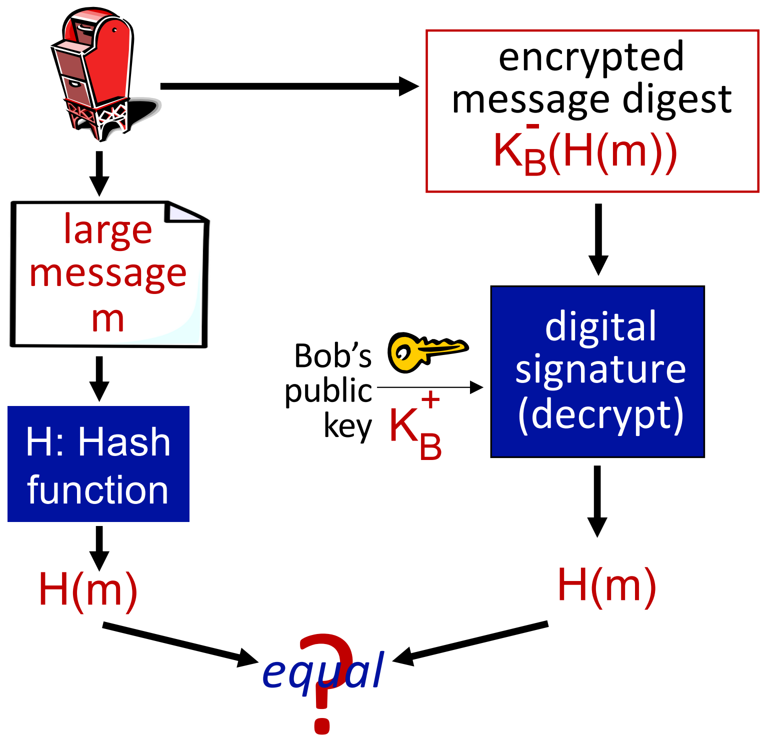
*different messages but identical checksums!*

# Digital signature = signed message digest

Bob sends digitally signed message:

Alice verifies signature, integrity of digitally signed message:



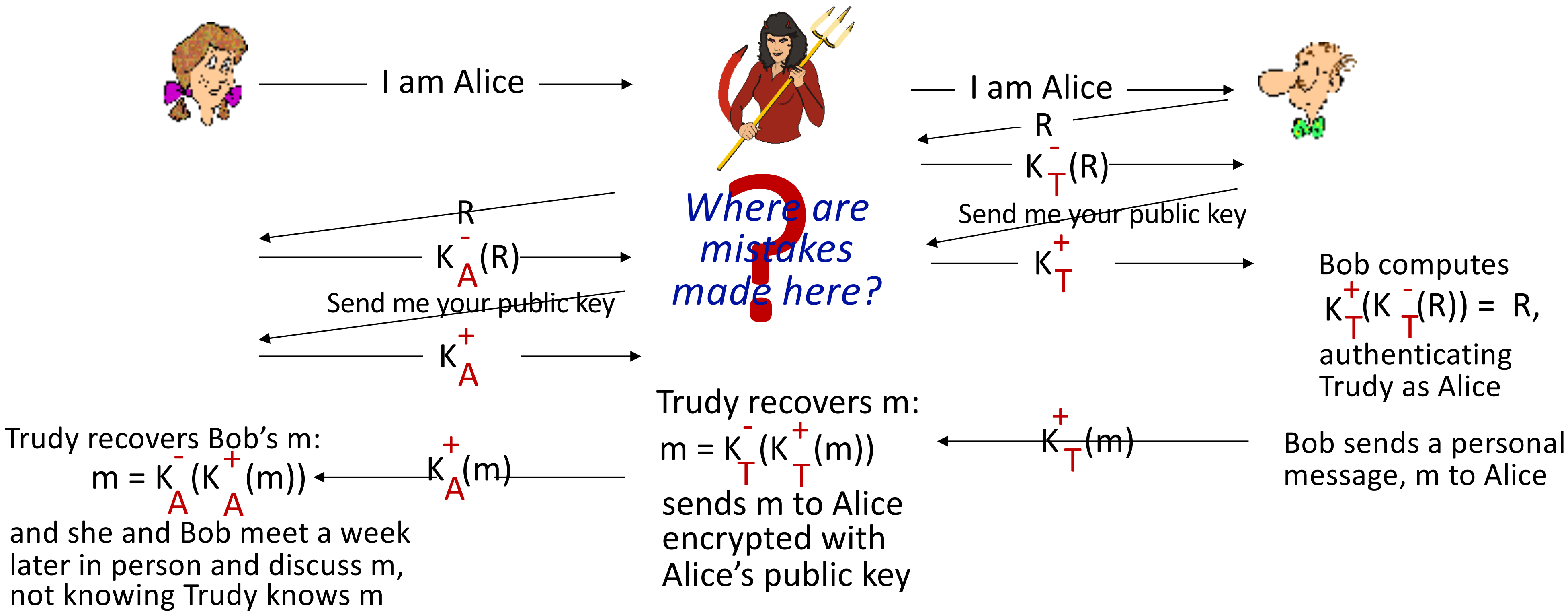



# Hash function algorithms

- MD5 hash function widely used (RFC 1321)
  - computes 128-bit message digest in 4-step process.
  - arbitrary 128-bit string x, appears difficult to construct msg m whose MD5 hash is equal to x
- SHA-1 is also used
  - US standard [NIST, FIPS PUB 180-1]
  - 160-bit message digest

# Authentication: ap5.0 – let's fix it!!

Recall the problem: Trudy poses as Alice (to Bob) and as Bob (to Alice)

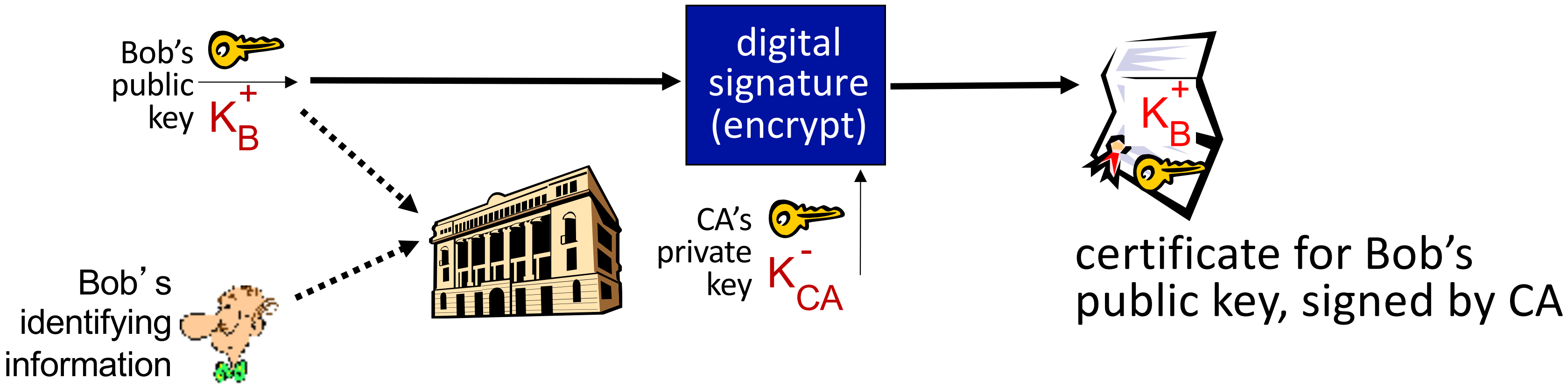


# Need for certified public keys

- motivation: Trudy plays pizza prank on Bob
  - Trudy creates e-mail order:
    *Dear Pizza Store, Please deliver to me four pepperoni pizzas. Thank you, Bob*
  - Trudy signs order with her private key
  - Trudy sends order to Pizza Store
  - Trudy sends to Pizza Store her public key, but says it's Bob's public key
  - Pizza Store verifies signature; then delivers four pepperoni pizzas to Bob
  - Bob doesn't even like pepperoni

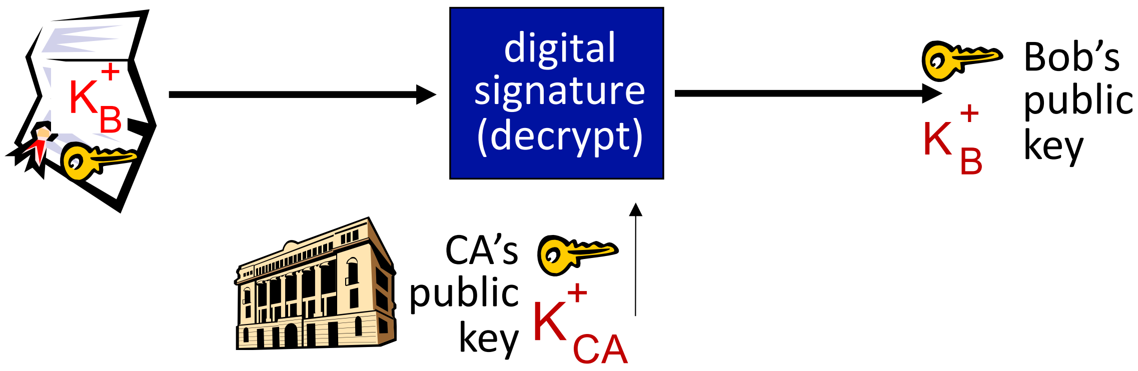
# Public key Certification Authorities (CA)

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



# Public key Certification Authorities (CA)

- 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

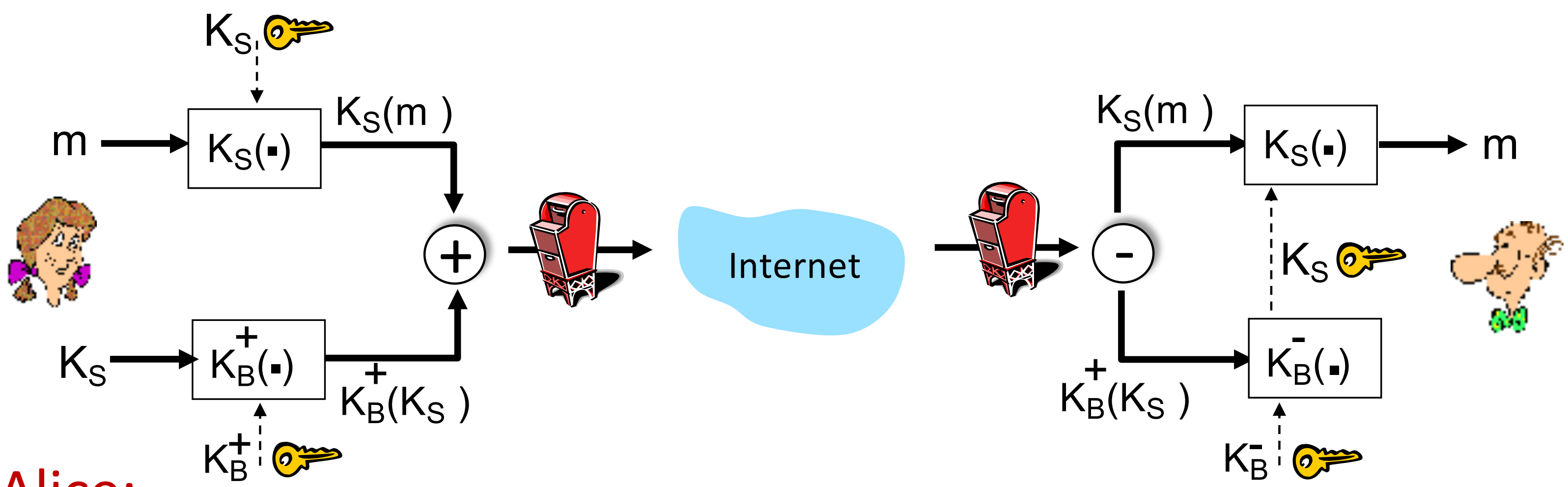


# Chapter 8 outline

- What is network security?
- Principles of cryptography
- Authentication, message integrity
- **Securing e-mail**
- Securing TCP connections: TLS
- Network layer security: IPsec
- Security in wireless and mobile networks
- Operational security: firewalls and IDS

# Secure e-mail: confidentiality

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

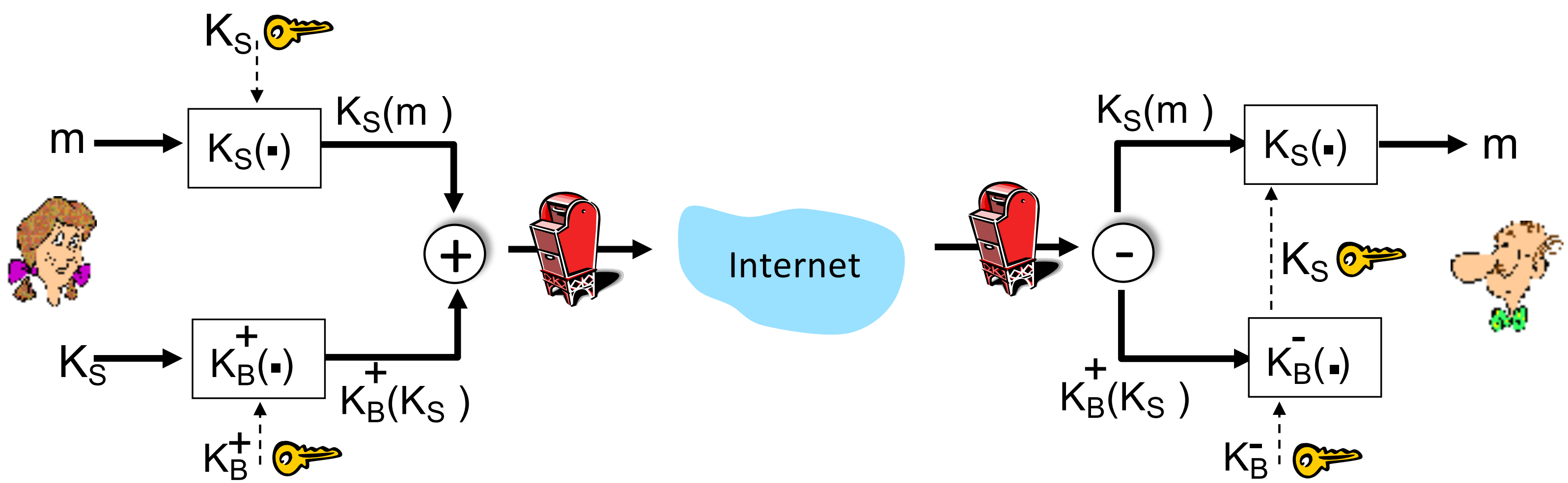



Alice:

- 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: confidentiality (more)

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

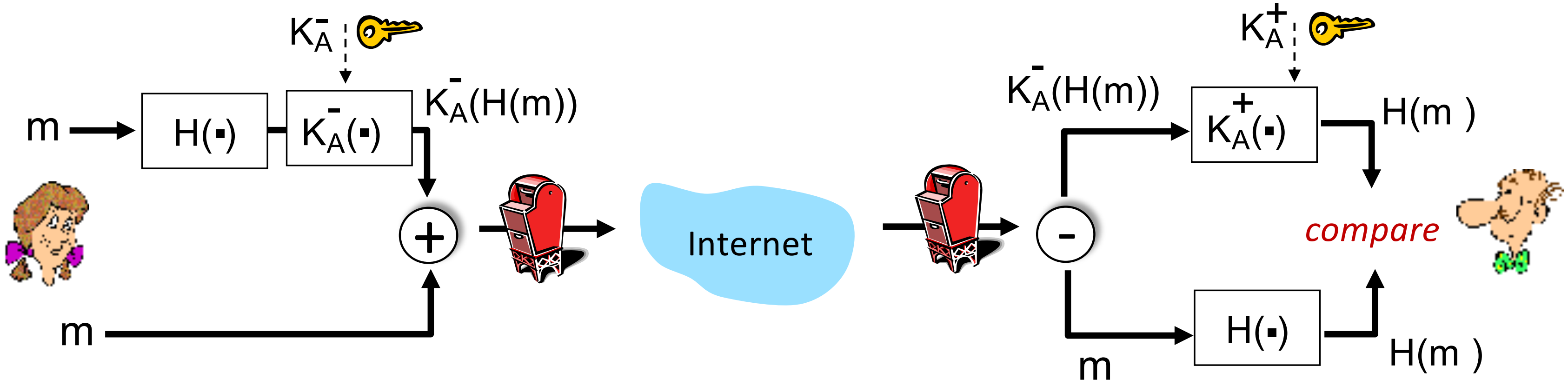



Bob:

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

# Secure e-mail: integrity, authentication

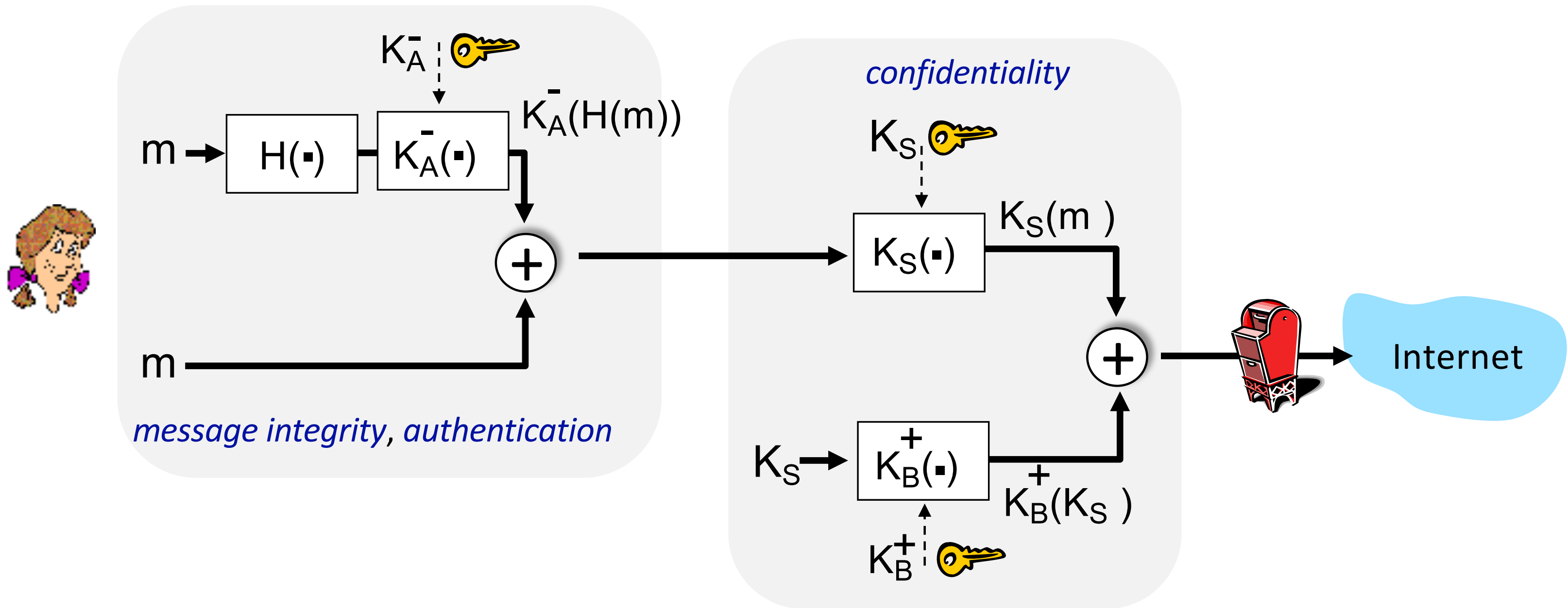
Alice wants to send m to Bob, with *message integrity*, *authentication*




- Alice digitally signs hash of her message with her private key, providing integrity and authentication
- sends both message (in the clear) and digital signature

# Secure e-mail: integrity, authentication

Alice sends m to Bob, with *confidentiality, message integrity, authentication*




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

*What are Bob's complementary actions?*

# Chapter 8 outline

- What is network security?
- Principles of cryptography
- Authentication, message integrity
- Securing e-mail
- **Securing TCP connections: TLS**
- Network layer security: IPsec
- Security in wireless and mobile networks
- Operational security: firewalls and IDS

# Transport-layer security (TLS)

- widely deployed security protocol above the transport layer
  - supported by almost all browsers, web servers: https (port 443)
- provides:
  - confidentiality: via *symmetric encryption*
  - integrity: via *cryptographic hashing*
  - authentication: via *public key cryptography*

  *all techniques we have studied!*
- history:
  - early research, implementation: secure network programming, secure sockets
  - secure socket layer (SSL) deprecated [2015]
  - TLS 1.3: RFC 8846 [2018]

# Transport-layer security (TLS)

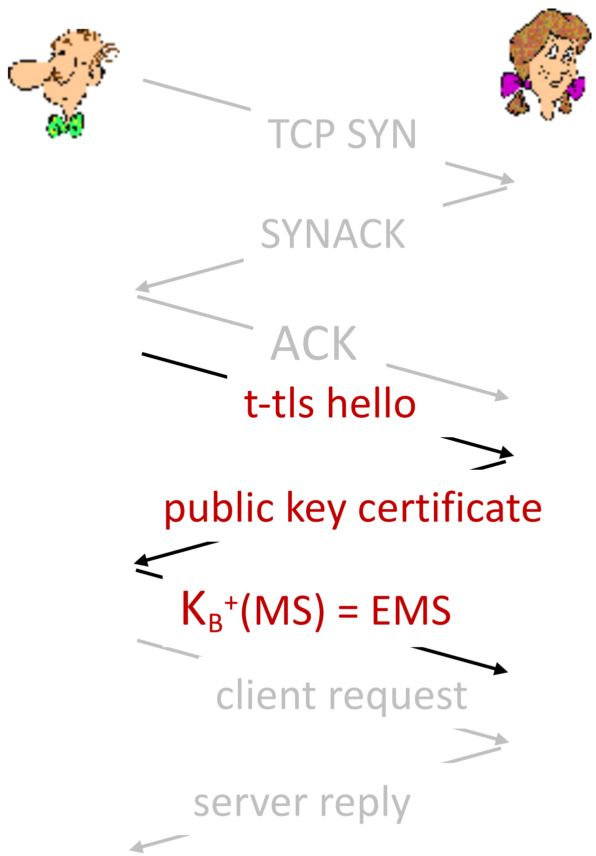
- widely deployed security protocol above the transport layer
  - supported by almost all browsers, web servers: https (port 443)
- provides:
  - confidentiality: via *symmetric encryption*
  - integrity: via *cryptographic hashing*
  - authentication: via *public key cryptography*

  *all techniques we have studied!*
- history:
  - early research, implementation: secure network programming, secure sockets
  - secure socket layer (SSL) deprecated [2015]
  - TLS 1.3: RFC 8846 [2018]

# Transport-layer security: what's needed?

- let's *build* a toy TLS protocol, *t-tls,* to see what's needed!
- we've seen the "pieces" already:
  - handshake: Alice, Bob use their certificates, private keys to authenticate each other, exchange or create shared secret
  - key derivation: Alice, Bob use shared secret to derive set of keys
  - data transfer: stream data transfer: data as a series of records
    - not just one-time transactions
  - connection closure: special messages to securely close connection

# t-tls: initial handshake




t-tls handshake phase:

- Bob establishes TCP connection with Alice
- Bob verifies that Alice is really Alice
- Bob sends Alice a master secret key (MS), used to generate all other keys for TLS session
- potential issues:
  - 3 RTT before client can start receiving data (including TCP handshake)

# t-tls: cryptographic keys

- considered bad to use same key for more than one cryptographic function
  - different keys for message authentication code (MAC) and encryption
- four keys:
  - $K_c$ : encryption key for data sent from client to server
  - $M_c$ : MAC key for data sent from client to server
  - $K_s$ : encryption key for data sent from server to client
  - $M_s$ : MAC key for data sent from server to client
- keys derived from key derivation function (KDF)
  - takes master secret and (possibly) some additional random data to create new keys

# t-tls: encrypting data

- recall: TCP provides data *byte stream* abstraction
- Q: can we encrypt data in-stream as written into TCP socket?
  - *A:* where would MAC go? If at end, no message integrity until all data received and connection closed!
  - *solution:* break stream in series of "records"
    - each client-to-server record carries a MAC, created using $M_c$
    - receiver can act on each record as it arrives
- t-tls record encrypted using symmetric key, $K_{c,}$ passed to TCP:

$K_c($ *length* | *data* | *MAC* $)$

# t-tls: encrypting data (more)

- possible attacks on data stream?
  - *re-ordering:* man-in middle intercepts TCP segments and reorders (manipulating sequence #s in unencrypted TCP header)
  - *replay*
- solutions:
  - use TLS sequence numbers (data, TLS-seq-# incorporated into MAC)
  - use nonce

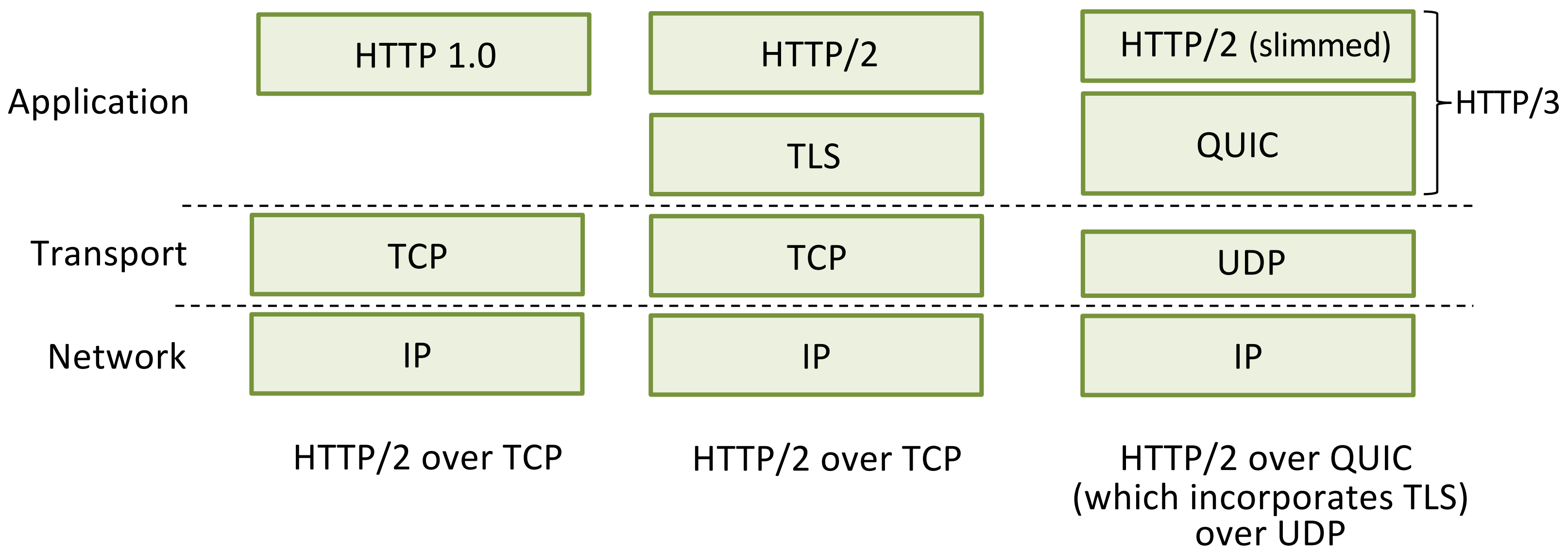
# t-tls: connection close

- truncation attack:
  - attacker forges TCP connection close segment
  - one or both sides thinks there is less data than there actually is
- solution: record types, with one type for closure
  - type 0 for data; type 1 for close
- MAC now computed using data, type, sequence #

$K_c($ | *length* | *type* | *data* | *MAC* | $)$

# Transport-layer security (TLS)

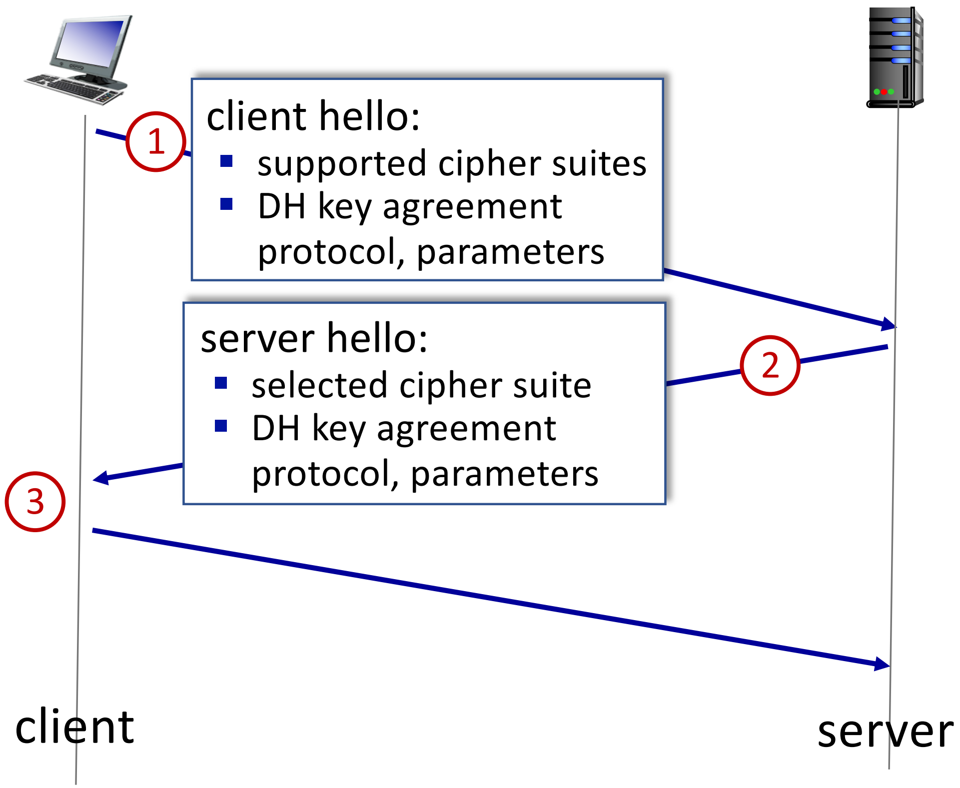
- TLS provides an API that *any* application can use
- an HTTP view of TLS:



# TLS: 1.3 cipher suite

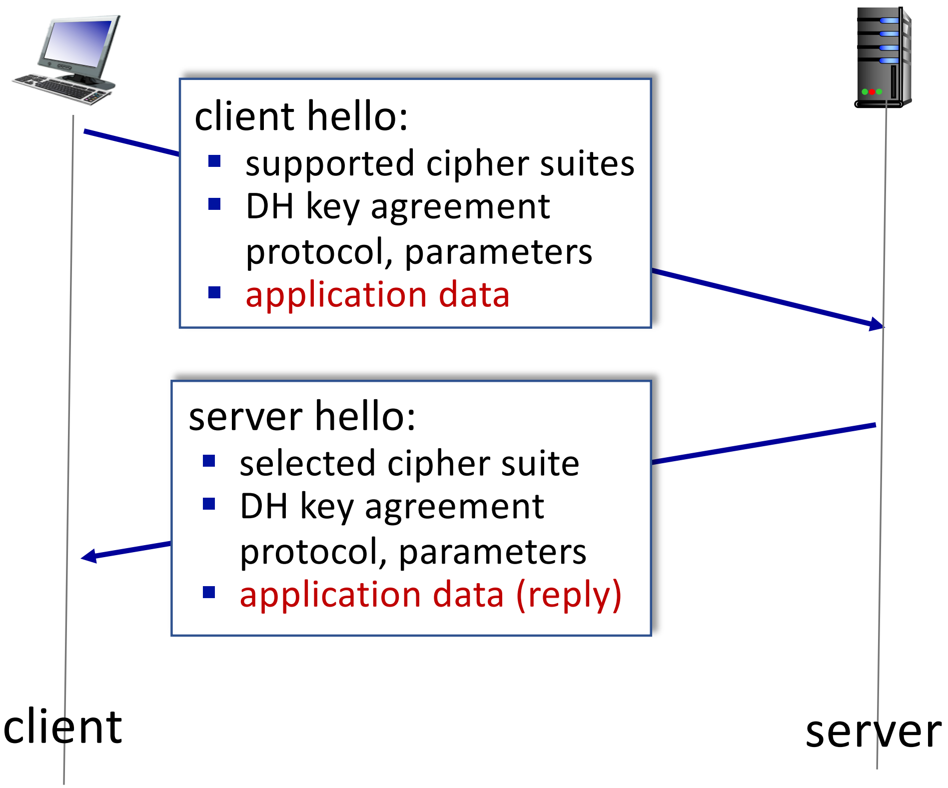
- "cipher suite": algorithms that can be used for key generation, encryption, MAC, digital signature
- TLS: 1.3 (2018): more limited cipher suite choice than TLS 1.2 (2008)
  - only 5 choices, rather than 37 choices
  - *requires* Diffie-Hellman (DH) for key exchange, rather than DH or RSA
  - combined encryption and authentication algorithm ("authenticated encryption") for data rather than serial encryption, authentication
    - 4 based on AES
  - HMAC uses SHA (256 or 284) cryptographic hash function

# TLS 1.3 handshake: 1 RTT




1. client TLS hello msg:
   - *guesses* key agreement protocol, parameters
   - indicates cipher suites it supports
2. server TLS hello msg chooses
   - key agreement protocol, parameters
   - cipher suite
   - server-signed certificate
3. client:
   - checks server certificate
   - generates key
   - can now make application request (e.g.., HTTPS GET)

# TLS 1.3 handshake: 0 RTT



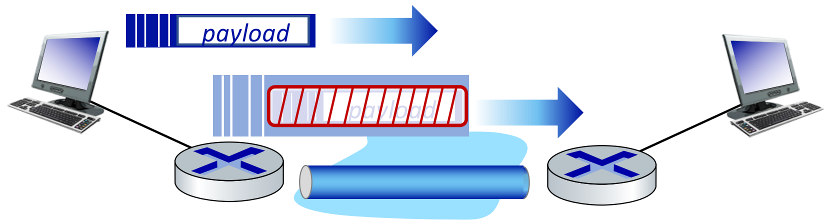

- initial hello message contains encrypted application data!
  - "resuming" earlier connection between client and server
  - application data encrypted using "resumption master secret" from earlier connection
- vulnerable to replay attacks!
  - maybe OK for get HTTP GET or client requests not modifying server state

# Chapter 8 outline

- What is network security?
- Principles of cryptography
- Authentication, message integrity
- Securing e-mail
- Securing TCP connections: TLS
- **Network layer security: IPsec**
- Security in wireless and mobile networks
- Operational security: firewalls and IDS

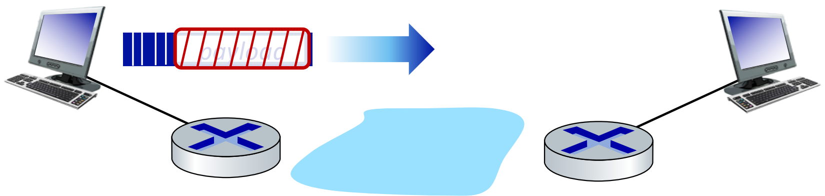
# IP Sec

- provides datagram-level encryption, authentication, integrity
  - for both user traffic and control traffic (e.g., BGP, DNS messages)
- two "modes":




tunnel mode:

- entire datagram is encrypted, authenticated
- encrypted datagram encapsulated in new datagram with new IP header, tunneled to destination



transport mode:

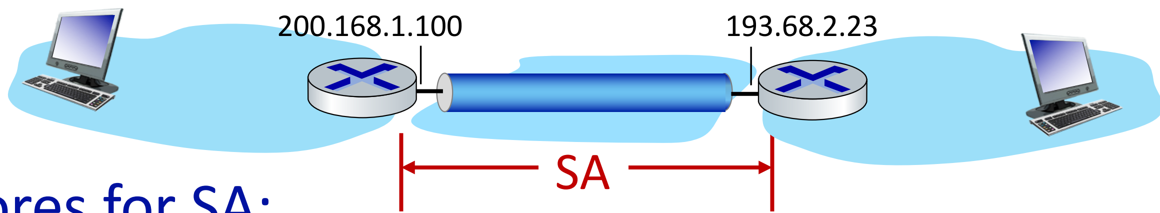
- *only* datagram *payload* is encrypted, authenticated

# Two IPsec protocols

- Authentication Header (AH) protocol [RFC 4302]
  - provides source authentication & data integrity but *not* confidentiality
- Encapsulation Security Protocol (ESP) [RFC 4303]
  - provides source authentication, data integrity, *and confidentiality*
  - more widely used than AH

# Security associations (SAs)

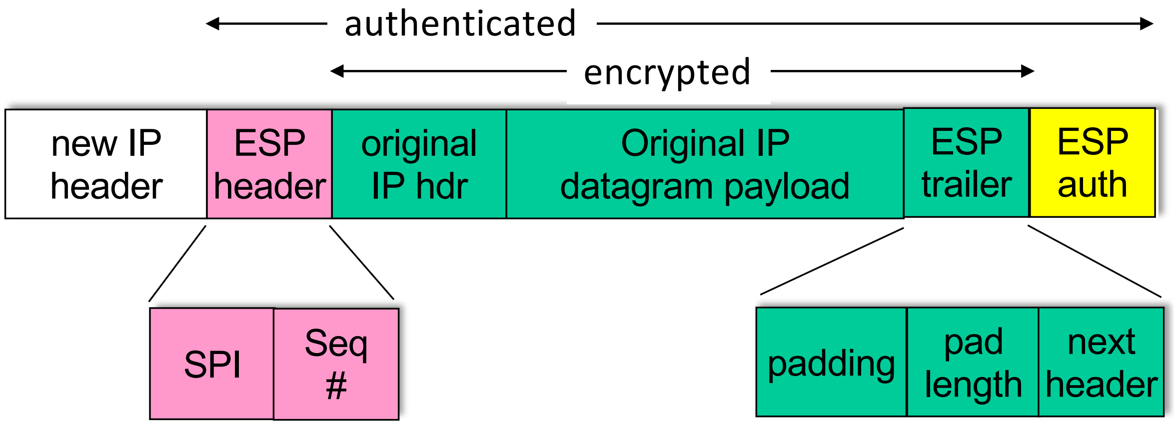
- before sending data, security association (SA) established from sending to receiving entity  (directional)
- ending, receiving entitles maintain *state information* about SA
  - recall: TCP endpoints also maintain state info
  - IP is connectionless; IPsec is connection-oriented!




## R1 stores for SA:

- 32-bit identifier: *Security Parameter Index (SPI)*
- origin SA interface (200.168.1.100)
- destination SA interface (193.68.2.23)
- type of encryption used
- encryption key
- type of integrity check used
- authentication key

# IPsec datagram



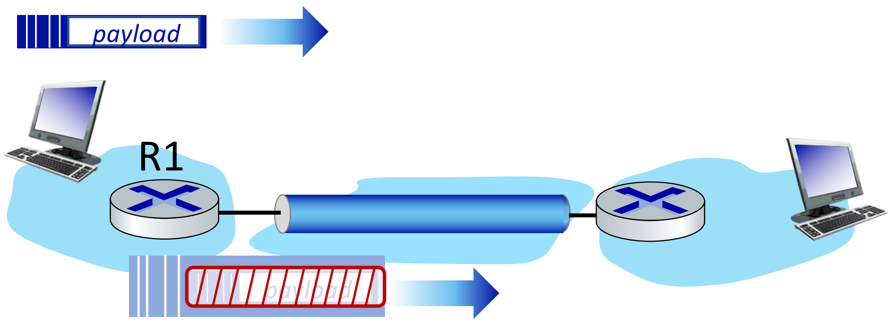

*tunnel mode ESP*

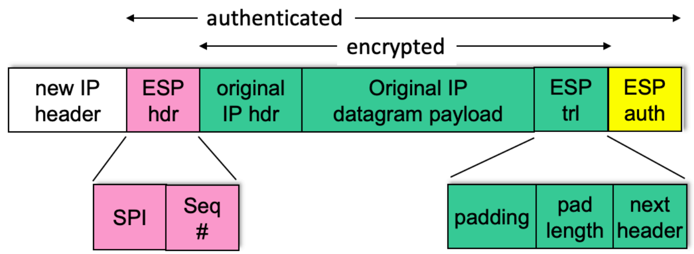
- ESP trailer: padding for block ciphers
- ESP header:
  - SPI, so receiving entity knows what to do
  - sequence number, to thwart replay attacks
- MAC in ESP auth field created with shared secret key

# ESP tunnel mode: actions

at R1:

- appends ESP trailer to original datagram (which includes original header fields!)
- encrypts result using algorithm & key specified by SA
- appends ESP header to front of this encrypted quantity
- creates authentication MAC using algorithm and key specified in SA
- appends MAC forming *payload*
- creates new IP header, new IP header fields, addresses to tunnel endpoint



# IPsec sequence numbers

- for new SA, sender initializes seq. # to 0
- each time datagram is sent on SA:
  - sender increments seq # counter
  - places value in seq # field
- goal:
  - prevent attacker from sniffing and replaying a packet
  - receipt of duplicate, authenticated IP packets may disrupt service
- method:
  - destination checks for duplicates
  - doesn't keep track of *all* received packets; instead uses a window

# IPsec security databases

## Security Policy Database (SPD)

- policy: for given datagram, sender needs to know if it should use IP sec
- policy stored in security policy database (SPD)
- needs to know which SA to use
  - may use: source and destination IP address; protocol number

*SAD: "how" to do it*

## Security Assoc. Database (SAD)

- endpoint holds SA state in security association database (SAD)
- when sending IPsec datagram, R1 accesses SAD to determine how to process datagram
- when IPsec datagram arrives to R2, R2 examines SPI in IPsec datagram, indexes SAD with SPI, processing
- datagram accordingly.

*SPD: "what" to do*

# Summary: IPsec services

Trudy sits somewhere between R1, R2. she doesn't know the keys

- will Trudy be able to see original contents of datagram? How about source, dest IP address, transport protocol, application port?
- flip bits without detection?
- masquerade as R1 using R1's IP address?
- replay a datagram?

# IKE: Internet Key Exchange

- *previous examples:* manual establishment of IPsec SAs in IPsec endpoints:

  *Example SA:*

  SPI: 12345
  Source IP: 200.168.1.100
  Dest IP: 193.68.2.23
  Protocol: ESP
  Encryption algorithm: 3DES-cbc
  HMAC algorithm: MD5
  Encryption key: 0x7aeaca…
  HMAC key:0xc0291f…

- manual keying is impractical for VPN with 100s of endpoints
- instead use IPsec IKE (Internet Key Exchange)

# IKE: PSK and PKI

- authentication (prove who you are) with either
  - pre-shared secret (PSK) or
  - with PKI (pubic/private keys and certificates).
- PSK: both sides start with secret
  - run IKE to authenticate each other and to generate IPsec SAs (one in each direction), including encryption, authentication keys
- PKI: both sides start with public/private key pair, certificate
  - run IKE to authenticate each other, obtain IPsec SAs (one in each direction).
  - similar with handshake in SSL.

# IKE phases

- IKE has two phases
  - *phase 1:* establish bi-directional IKE SA
    - note: IKE SA different from IPsec SA
    - aka ISAKMP security association
  - *phase 2:* ISAKMP is used to securely negotiate IPsec pair of SAs
- phase 1 has two modes: aggressive mode and main mode
  - aggressive mode uses fewer messages
  - main mode provides identity protection and is more flexible

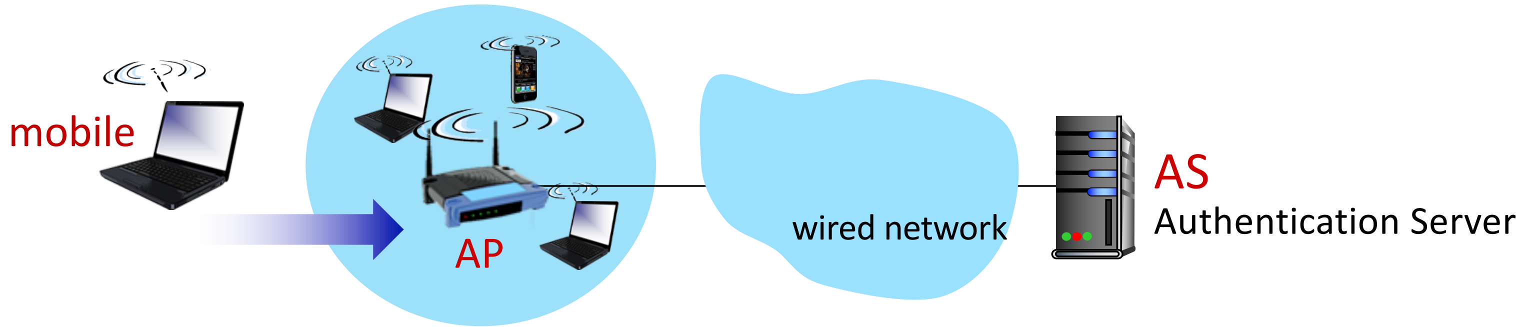
# IPsec summary

- IKE message exchange for algorithms, secret keys, SPI numbers
- either AH or ESP protocol  (or both)
  - AH provides integrity, source authentication
  - ESP protocol (with AH) additionally provides encryption
- IPsec peers can be two end systems, two routers/firewalls, or a router/firewall and an end system

# Chapter 8 outline

- What is network security?
- Principles of cryptography
- Authentication, message integrity
- Securing e-mail
- Securing TCP connections: TLS
- Network layer security: IPsec
- Security in wireless and mobile networks
  - 802.11 (WiFi)
  - 4G/5G
- Operational security: firewalls and IDS

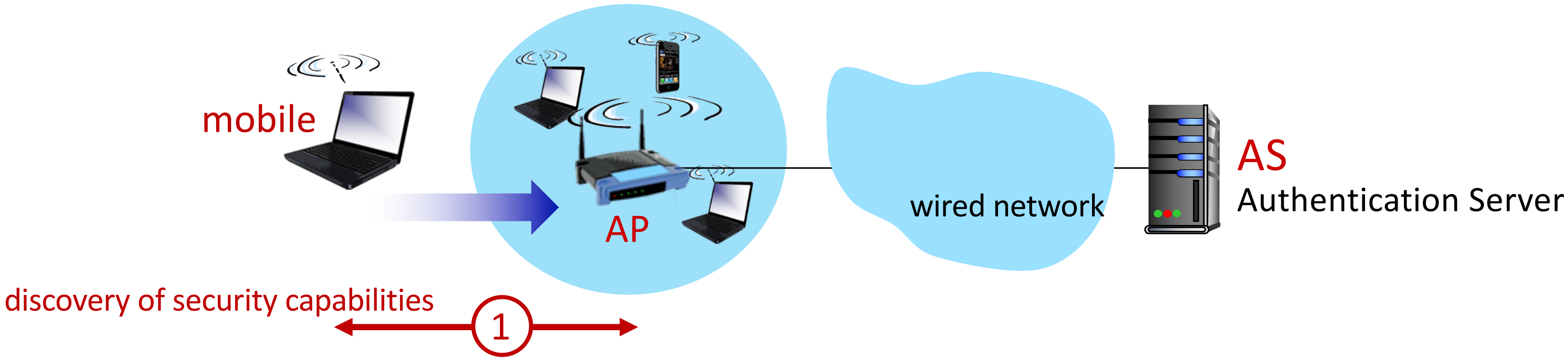
# 802.11: authentication, encryption




Arriving mobile must:

- associate with access point: (establish) communication over wireless link
- authenticate to network

# 802.11: authentication, encryption

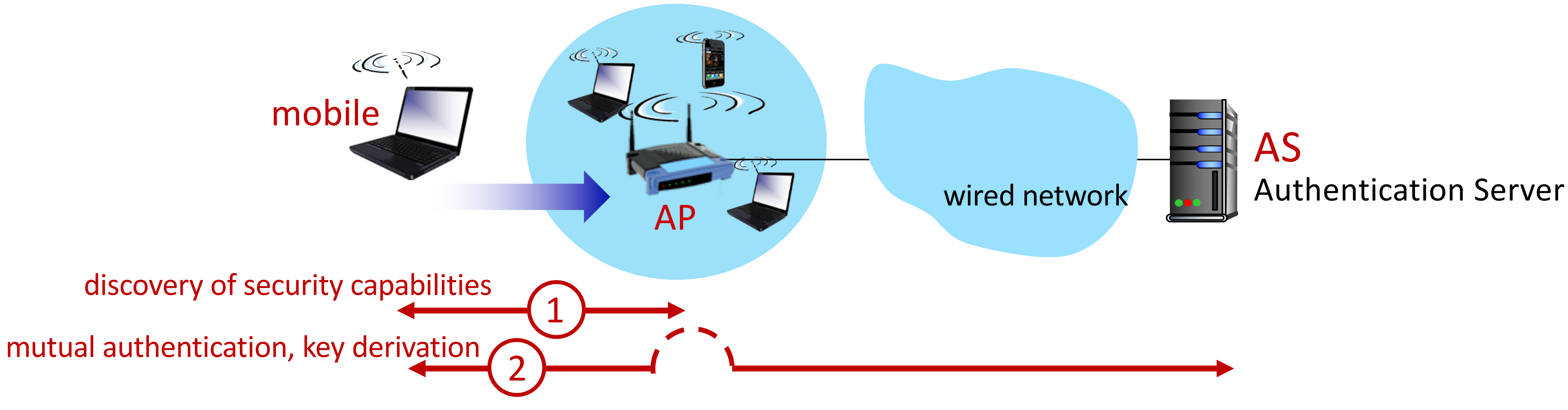



1 discovery of security capabilities:

- AP advertises its presence, forms of authentication and encryption provided
- device requests specific forms authentication, encryption desired

although device, AP already exchanging messages, device not yet authenticated, does not have encryption keys

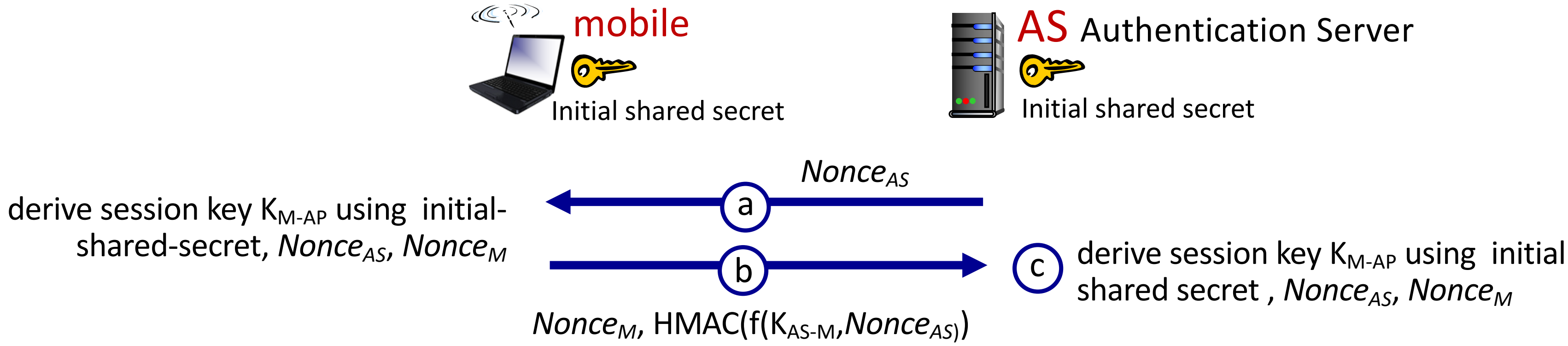
# 802.11: authentication, encryption




2 mutual authentication and shared symmetric key derivation:

- AS, mobile already have shared common secret (e.g., password)
- AS, mobile use shared secret, nonces (prevent relay attacks), cryptographic hashing (ensure message integrity) to authenticating each other
- AS, mobile derive symmetric session key

# 802.11: WPA3 handshake



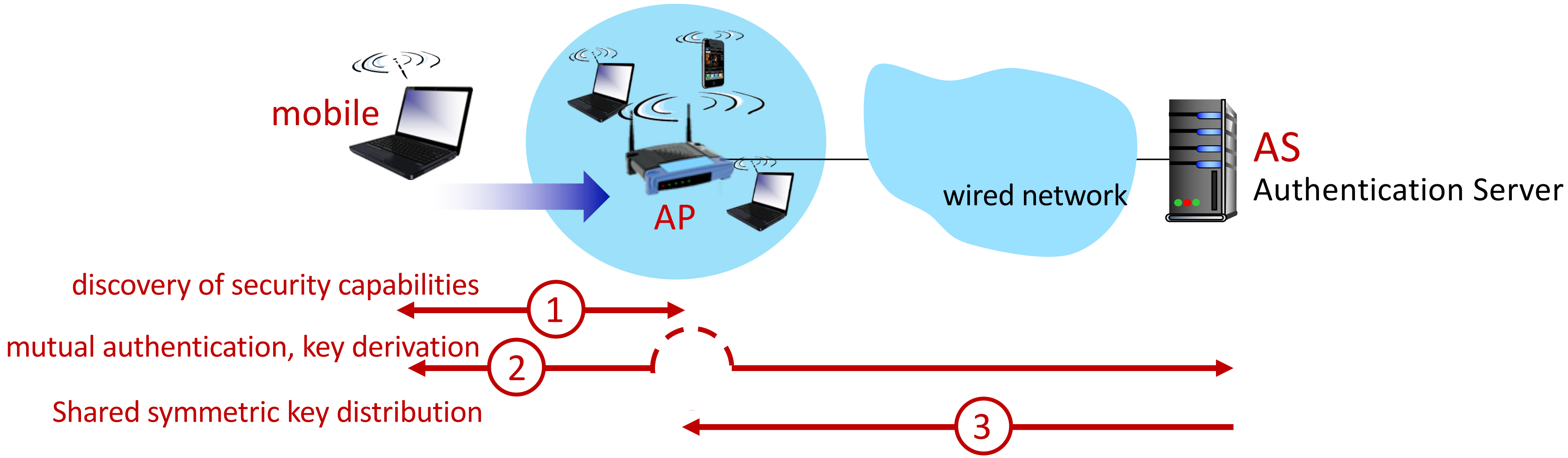

ⓐ AS generates $Nonce_{AS}$, sends to mobile

ⓑ mobile receives $Nonce_{AS}$

- generates $Nonce_M$
- generates symmetric shared session key $K_{M\text{-}AP}$ using $Nonce_{AS}$, $Nonce_M$, and initial shared secret
- sends $Nonce_M$, and HMAC-signed value using $\text{Nonce}_{AS}$ and initial shared secret

ⓒ AS derives symmetric shared session key $K_{M\text{-}AP}$

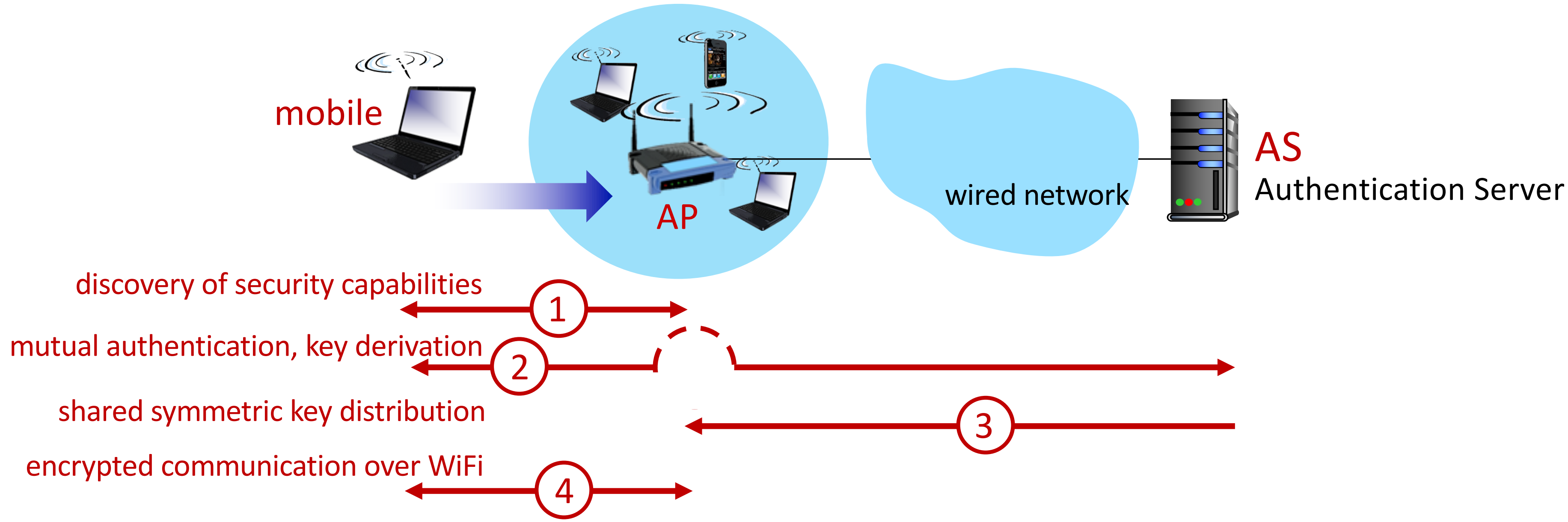
# 802.11: authentication, encryption




3 shared symmetric session key distribution (e.g., for AES encryption)

- same key derived at mobile, AS
- AS informs AP of the shared symmetric session

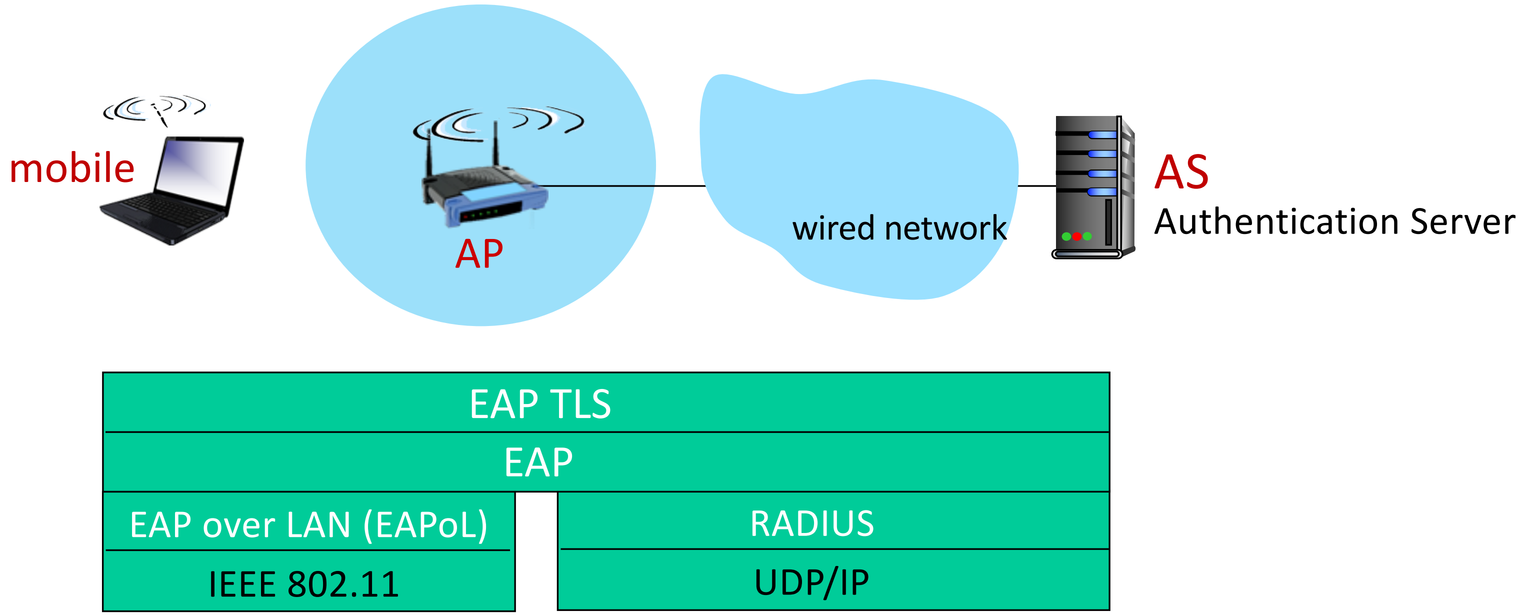
# 802.11: authentication, encryption




4 encrypted communication between mobile and remote host via AP

- same key derived at mobile, AS
- AS informs AP of the shared symmetric session

# 802.11: authentication, encryption

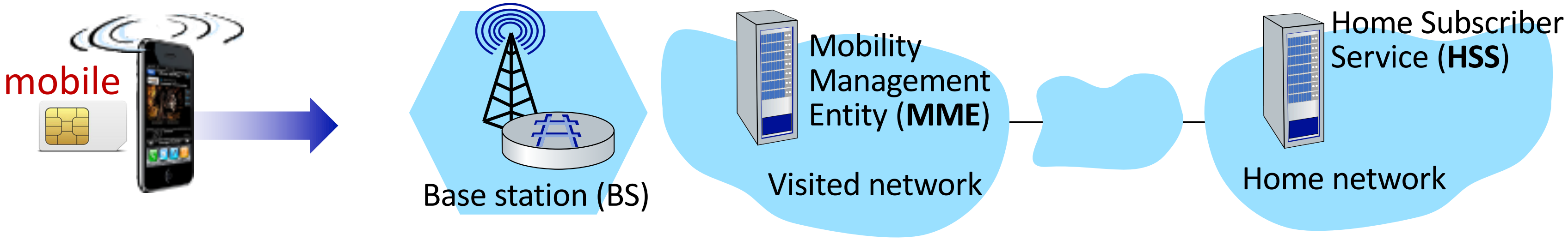



- Extensible Authentication Protocol (EAP) [RFC 3748] defines end-to-end request/response protocol between mobile device, AS

# Chapter 8 outline

- What is network security?
- Principles of cryptography
- Authentication, message integrity
- Securing e-mail
- Securing TCP connections: TLS
- Network layer security: IPsec
- Security in wireless and mobile networks
  - 802.11 (WiFi)
  - 4G/5G
- Operational security: firewalls and IDS

# Authentication, encryption in 4G LTE

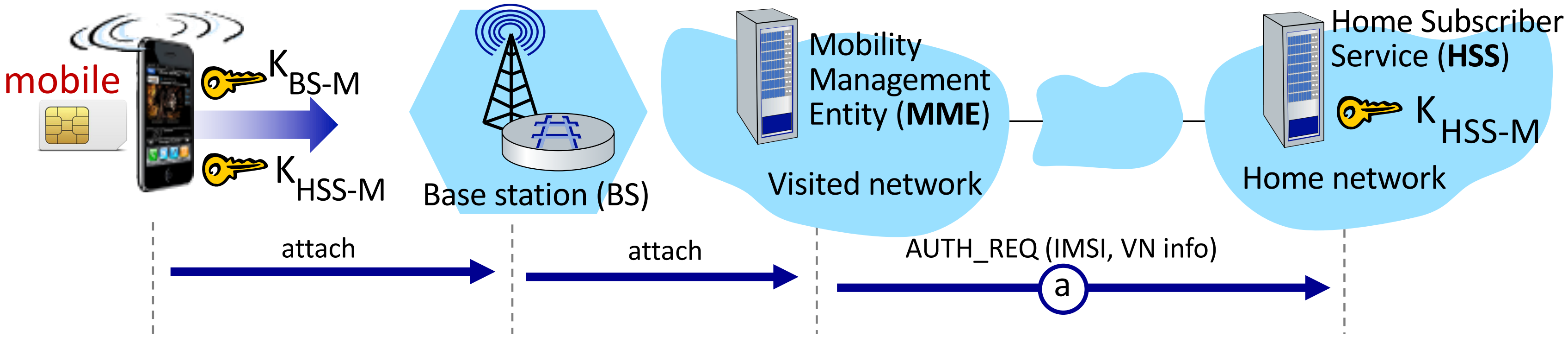



- arriving mobile must:
  - associate with BS: (establish) communication over 4G wireless link
  - authenticate itself to network, and authenticate network
- notable differences from WiFi
  - mobile's SIMcard provides global identity, contains shared keys
  - services in visited network depend on (paid) service subscription in home network

# Authentication, encryption in 4G LTE


- mobile, BS use derived session key $K_{BS-M}$ to encrypt communications over 4G link
- MME in visited network + HHS in home network, together play role of WiFi AS
  - ultimate authenticator is HSS
  - trust and business relationship between visited and home networks

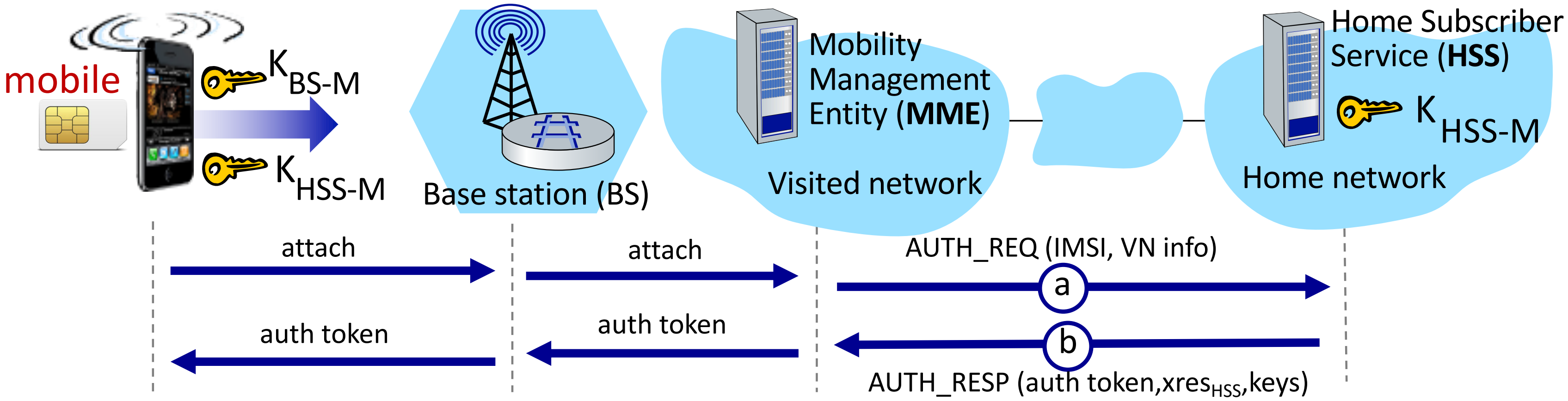
# Authentication, encryption in 4G LTE




ⓐ authentication request to home network HSS

- mobile sends attach message (containing its IMSI, visited network info) relayed from BS to visited MME to home HHS
- IMSI identifies mobile's home network

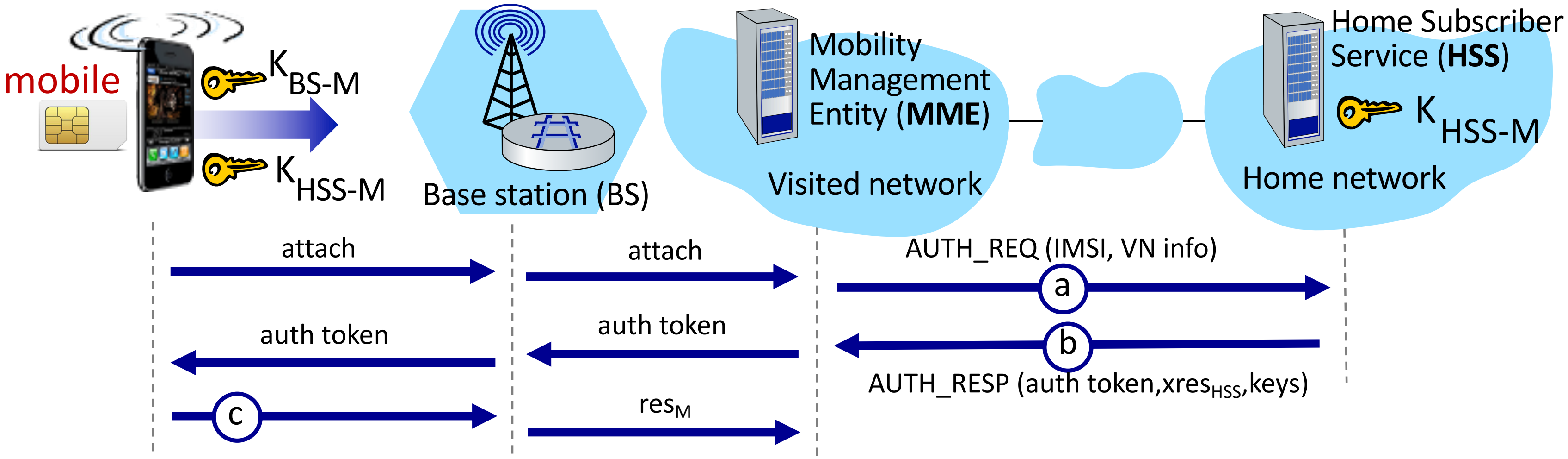
# Authentication, encryption in 4G LTE




b HSS use shared-in-advance secret key, $K_{HSS-M}$, to derive authentication token, *auth_token*, and expected authentication response token, *$xres_{HSS}$*

- *auth_token* contains info encrypted by HSS using $K_{HSS-M}$ , allowing mobile to know that whoever computed *auth_token* knows shared-in-advance secret
- mobile has authenticated network
- visited HSS keeps *$xres_{HSS}$* for later use

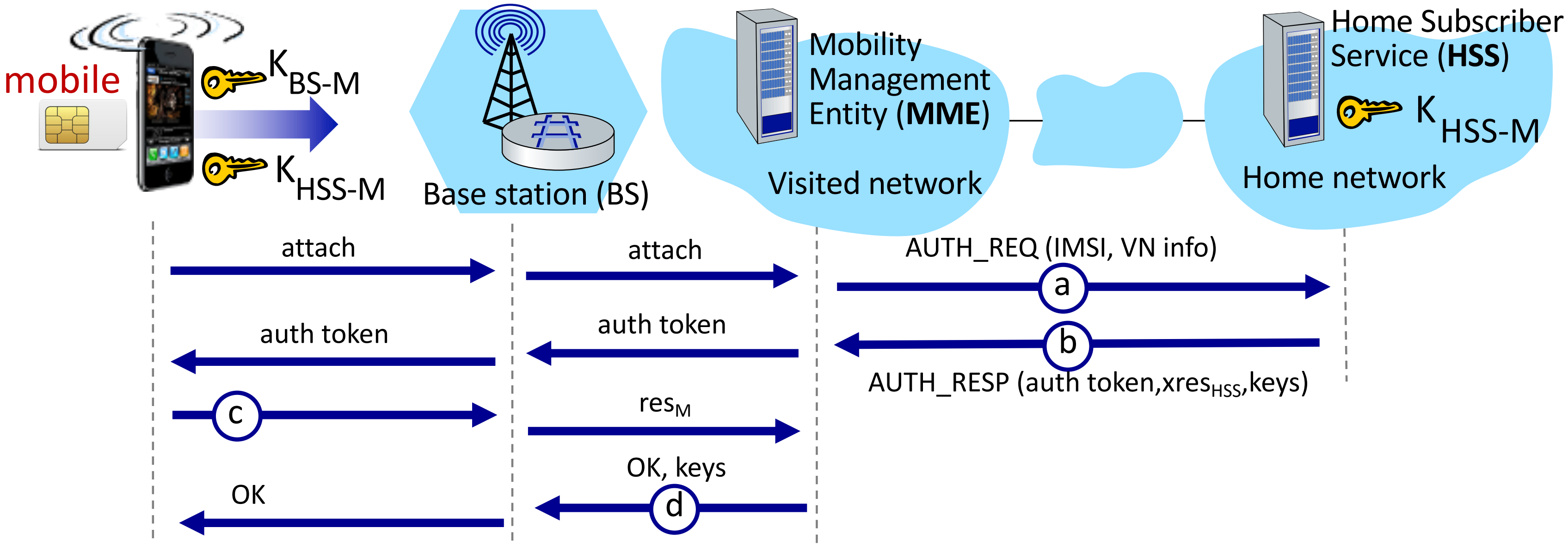
# Authentication, encryption in 4G LTE




ⓒ authentication response from mobile:

- mobile computes $res_M$ using its secret key to make same cryptographic calculation that HSS made to compute $xres_{HSS}$ and sends $res_M$ to MME

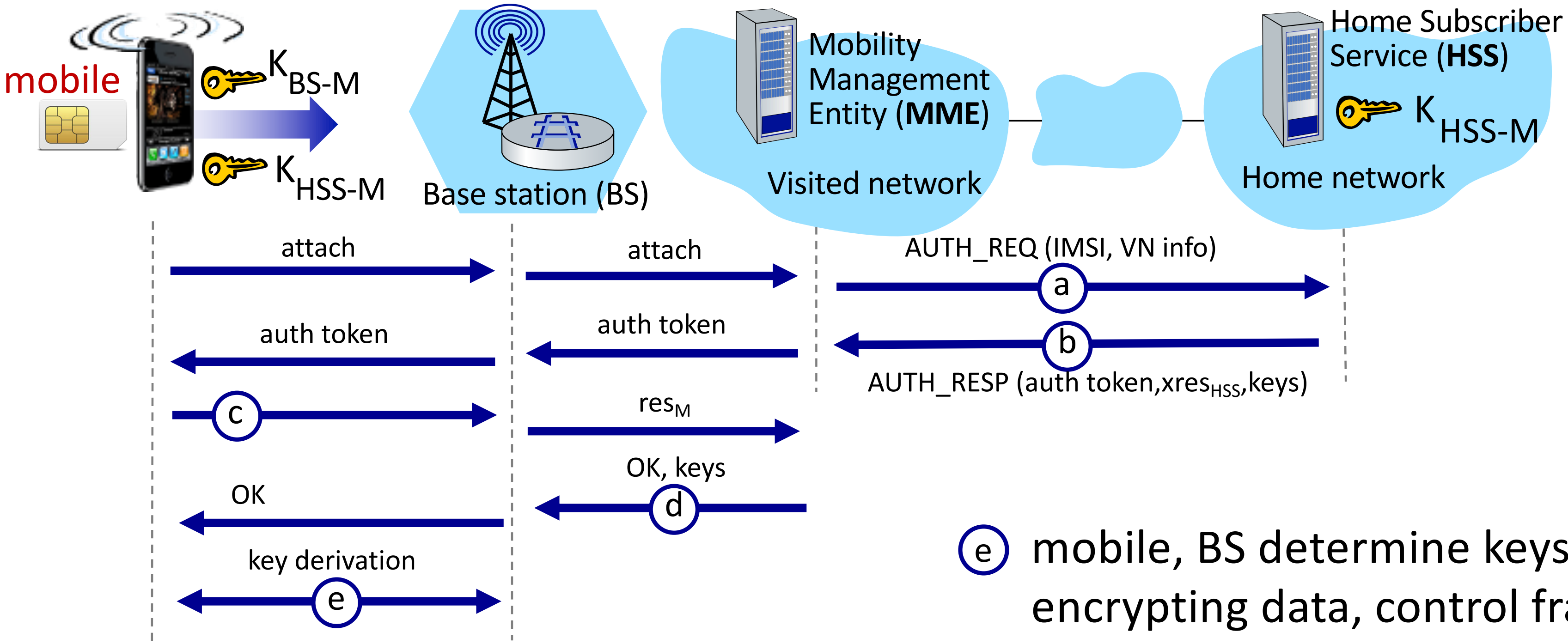
# Authentication, encryption in 4G LTE




ⓓ mobile is authenticated by network:

- MMS compares mobile-computed value of $res_M$ with the HSS-computed value of $xres_{HSS}$ . If they match, mobile is authenticated ! (why?)
- MMS informs BS that mobile is authenticated, generates keys for BS

# Authentication, encryption in 4G LTE




e mobile, BS determine keys for encrypting data, control frames over 4G wireless channel

- AES can be used

# Authentication, encryption: from 4G to 5G

- 4G: MME in visited network makes authentication decision
- 5G: home network provides authentication decision
  - visited MME plays "middleman" role but can still reject

- 4G: uses shared-in-advance keys
- 5G: keys not shared in advance for IoT

- 4G: device IMSI transmitted in cleartext to BS
- 5G: public key crypto used to encrypt IMSI

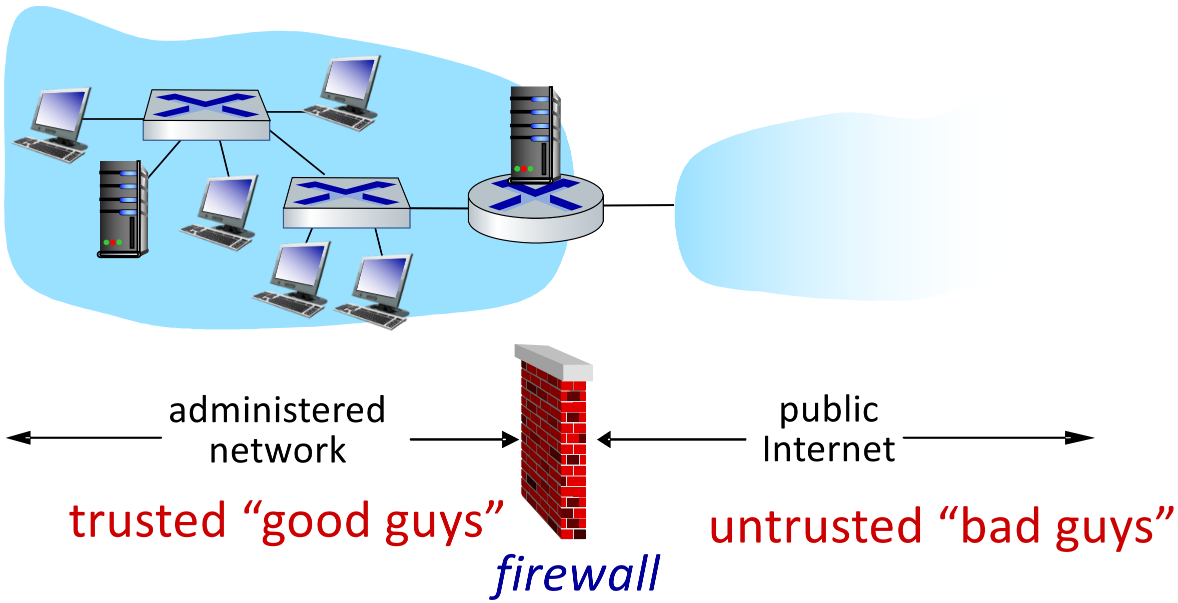
# Chapter 8 outline

- What is network security?
- Principles of cryptography
- Authentication, message integrity
- Securing e-mail
- Securing TCP connections: TLS
- Network layer security: IPsec
- Security in wireless and mobile networks
- Operational security: firewalls and IDS

# Firewalls

**firewall**

isolates organization's internal network 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

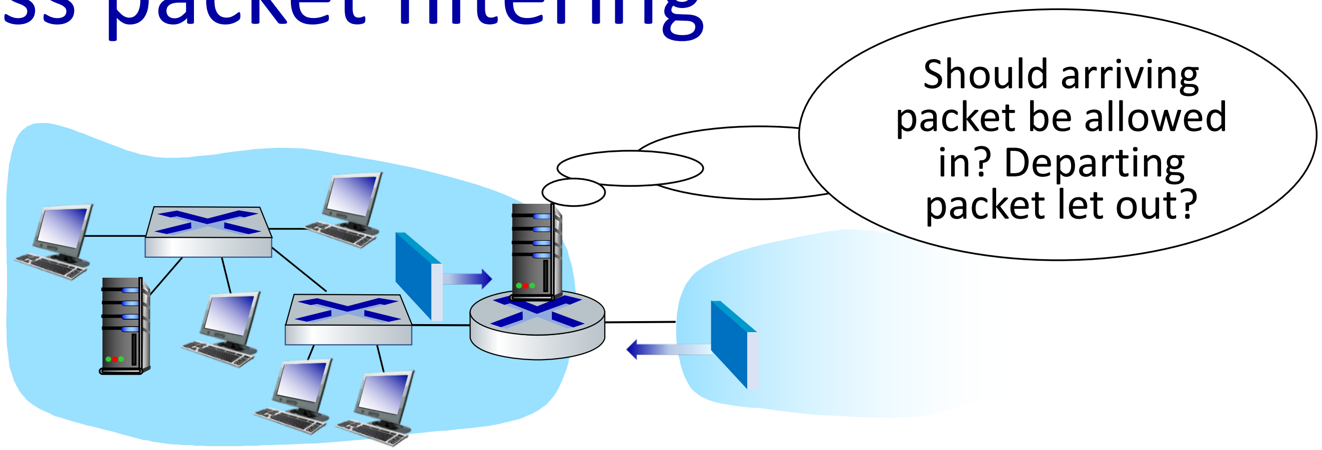
allow only authorized access to inside network

- set of authenticated users/hosts

three types of firewalls:

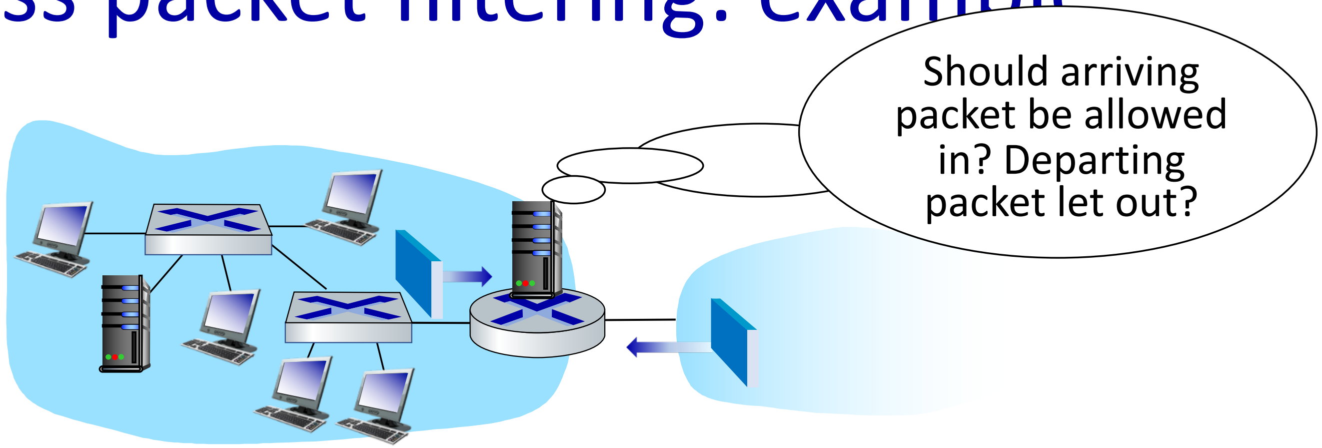
- stateless packet filters
- stateful packet filters
- application gateways

# Stateless packet filtering




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

# Stateless packet filtering: example




- example 1: block incoming and outgoing datagrams with IP protocol field = 17 and with either source or dest port = 23
  - result: all incoming, outgoing UDP flows and telnet connections are blocked
- example 2: block inbound TCP segments with ACK=0
  - result: prevents external clients from making TCP connections with internal clients, but allows internal clients to connect to outside

# Stateless packet filtering: more examples

| Policy | Firewall Setting |
| --- | --- |
| 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: looks like OpenFlow forwarding (Ch. 4)!

| action | source address | dest address | protocol | source port | dest port | flag bit |
|---|---|---|---|---|---|---|
| allow | 222.22/16 | outside of 222.22/16 | TCP | > 1023 | 80 | any |
| allow | outside of 222.22/16 | 222.22/16 | TCP | 80 | > 1023 | ACK |
| allow | 222.22/16 | outside of 222.22/16 | UDP | > 1023 | 53 | --- |
| allow | outside of 222.22/16 | 222.22/16 | UDP | 53 | > 1023 | ---- |
| deny | all | all | all | all | all | all |

# 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): determine whether incoming, outgoing packets "makes sense"
  - timeout inactive connections at firewall: no longer admit packets

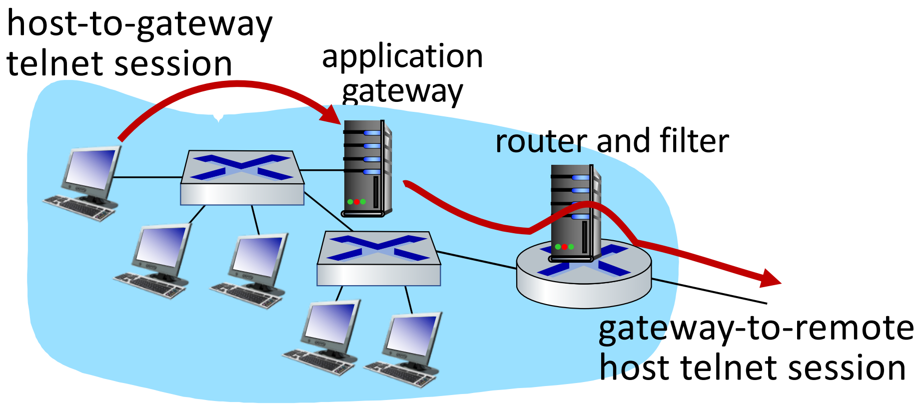
# Stateful packet filtering

ACL augmented to indicate need to check connection state table before admitting packet

| action | source address | dest address | proto | source port | dest port | flag bit | check connection |
|---|---|---|---|---|---|---|---|
| allow | 222.22/16 | outside of 222.22/16 | TCP | > 1023 | 80 | any | |
| allow | outside of 222.22/16 | 222.22/16 | TCP | 80 | > 1023 | ACK | X |
| allow | 222.22/16 | outside of 222.22/16 | UDP | > 1023 | 53 | --- | |
| allow | outside of 222.22/16 | 222.22/16 | UDP | 53 | > 1023 | ---- | X |
| deny | all | all | all | all | all | all | |

# Application gateways

- filter 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, gateways

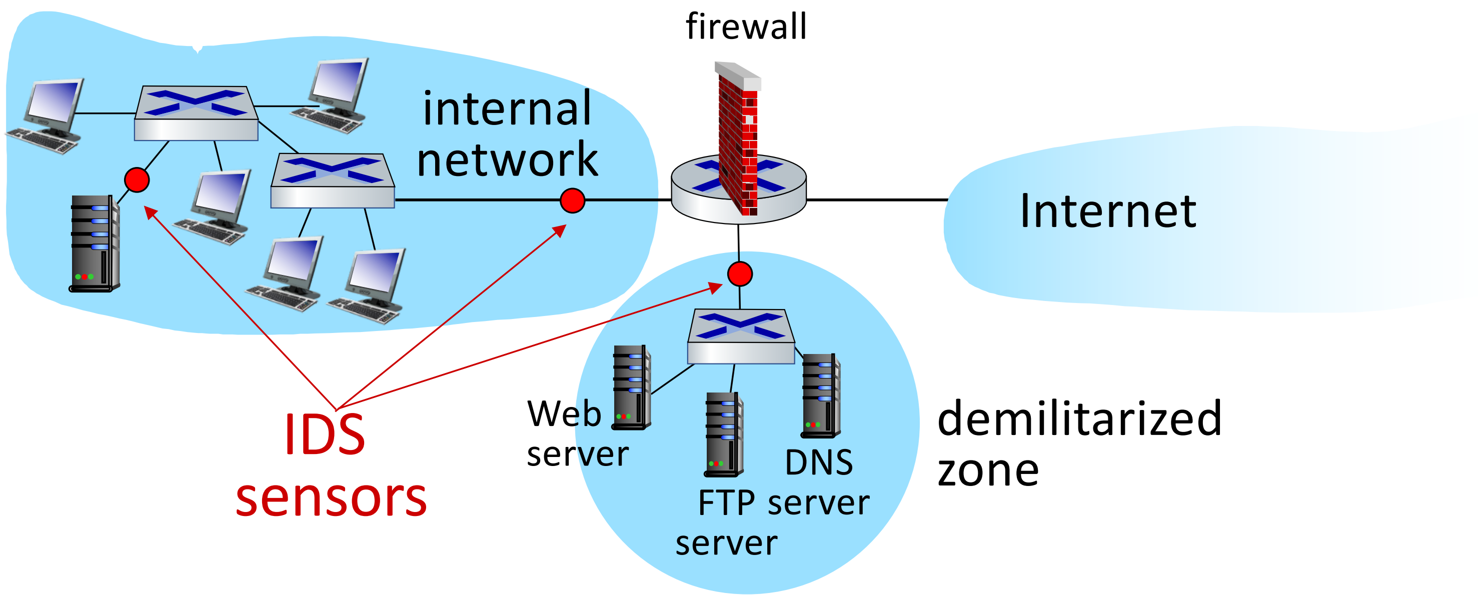
- IP spoofing: router can't know if data "really" comes from claimed source
- if multiple apps need special treatment, each has own app. gateway
- client software must know how to contact gateway
  - e.g., must set IP address of proxy in Web browser
- filters often use all or nothing policy for UDP
- *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 key)
- message integrity
- end-point authentication

.... used in many different security scenarios

- secure email
- secure transport (TLS)
- IP sec
- 802.11, 4G/5G

operational security: firewalls and IDS