

Chapter 8: Network Security

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 roadmap

- 8.1 *What is network security?***
- 8.2 Principles of cryptography**
- 8.3 Message integrity, authentication**
- 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**

What is network security?

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

- sender encrypts message
- receiver decrypts message

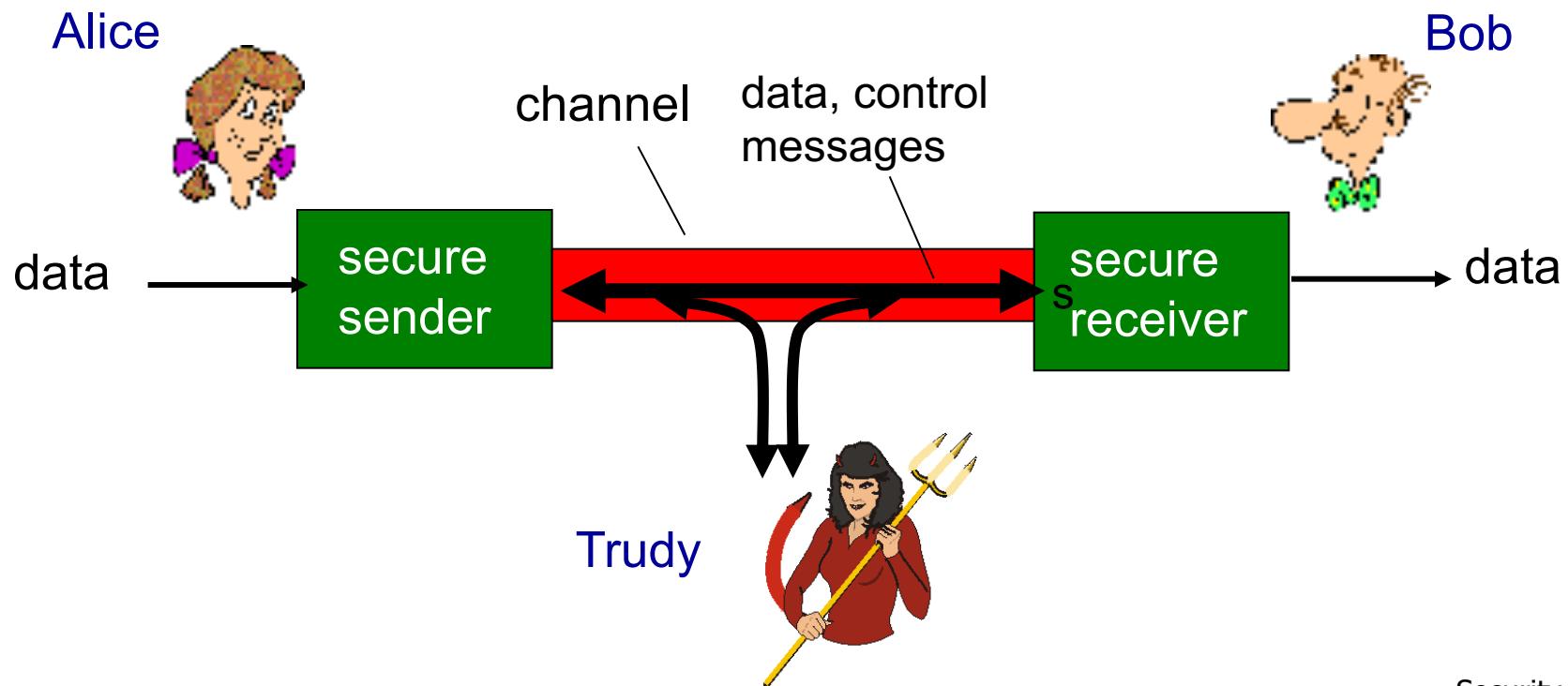
authentication: sender, receiver want to confirm identity of each other

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



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)

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8.2 *Principles of cryptography*

8.3 Message integrity, authentication

8.4 ~~Securing e-mail~~

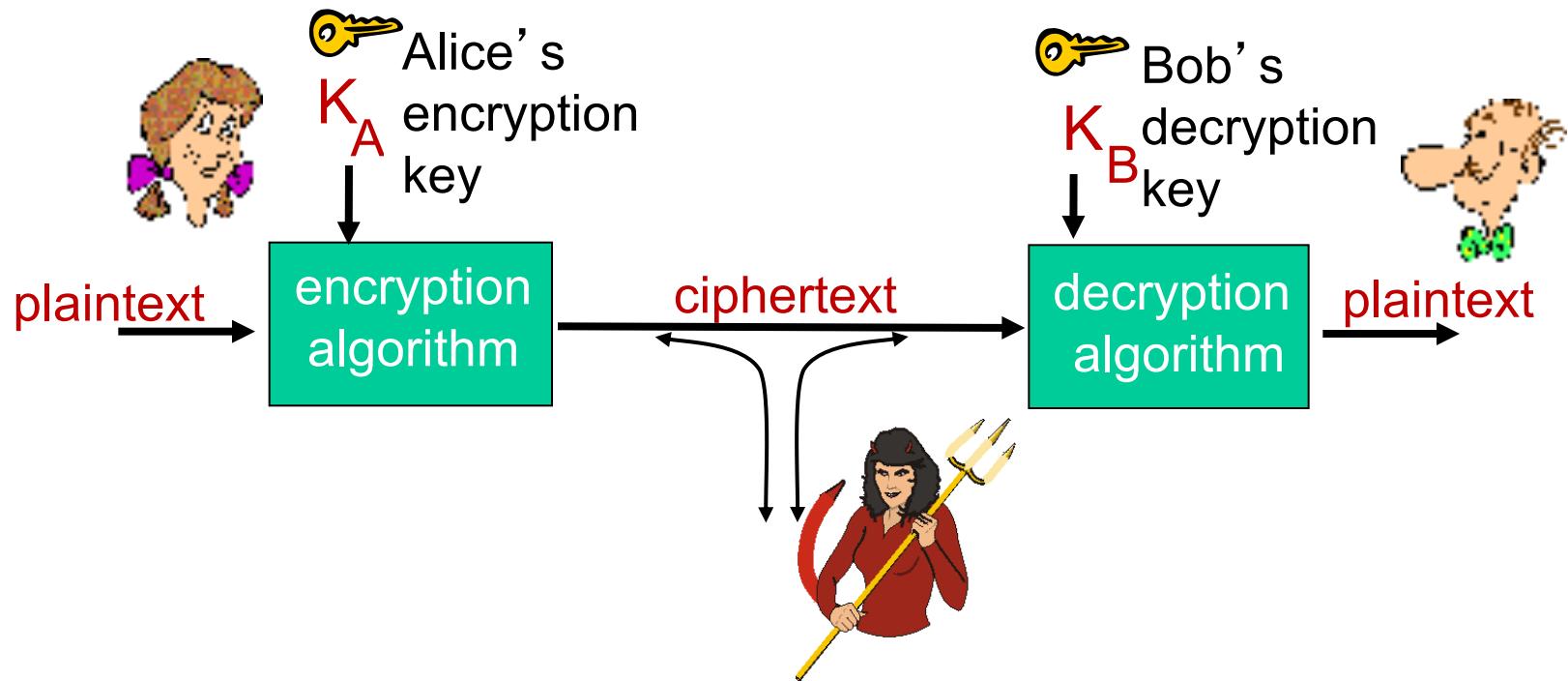
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The language of cryptography

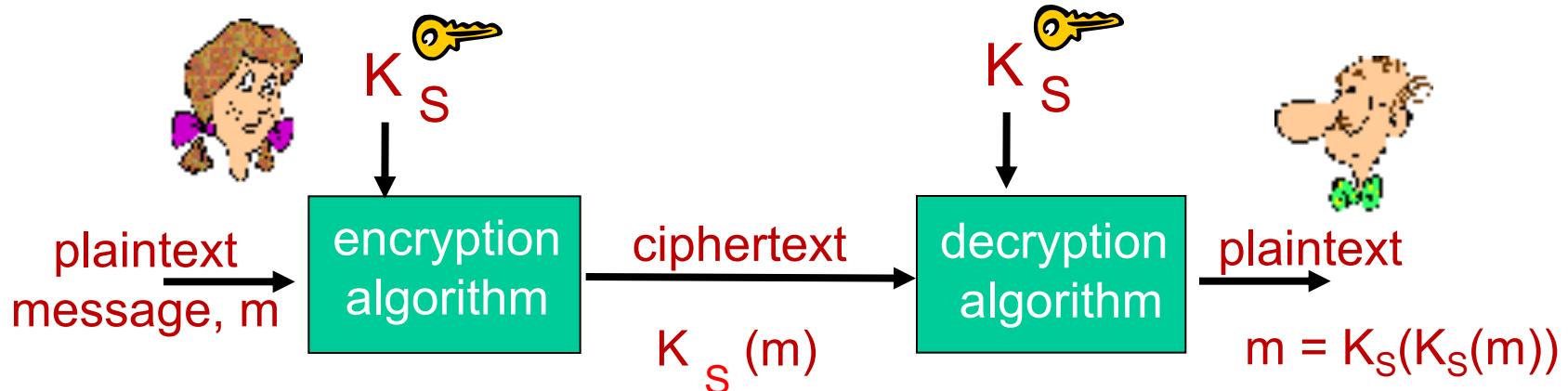


m plaintext message

$K_A(m)$ 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

- e.g., key is knowing substitution pattern in mono alphabetic substitution cipher

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

Symmetric key crypto: DES

DES: Data Encryption Standard

- US encryption standard [NIST 1993]
- 56-bit symmetric key, 64-bit plaintext input
- block cipher with cipher block chaining
- how secure is DES?
 - DES Challenge: 56-bit-key-encrypted phrase decrypted (brute force) in less than a day
 - no known good analytic attack
- making DES more secure:
 - 3DES: encrypt 3 times with 3 different keys

AES: Advanced Encryption Standard

- symmetric-key NIST standard, replaced DES (Nov 2001)
- processes data in 128 bit blocks
- 128, 192, or 256 bit keys
- brute force decryption (try each key) taking 1 second on DES, takes 149 trillion years for AES

Public Key Cryptography

symmetric key crypto

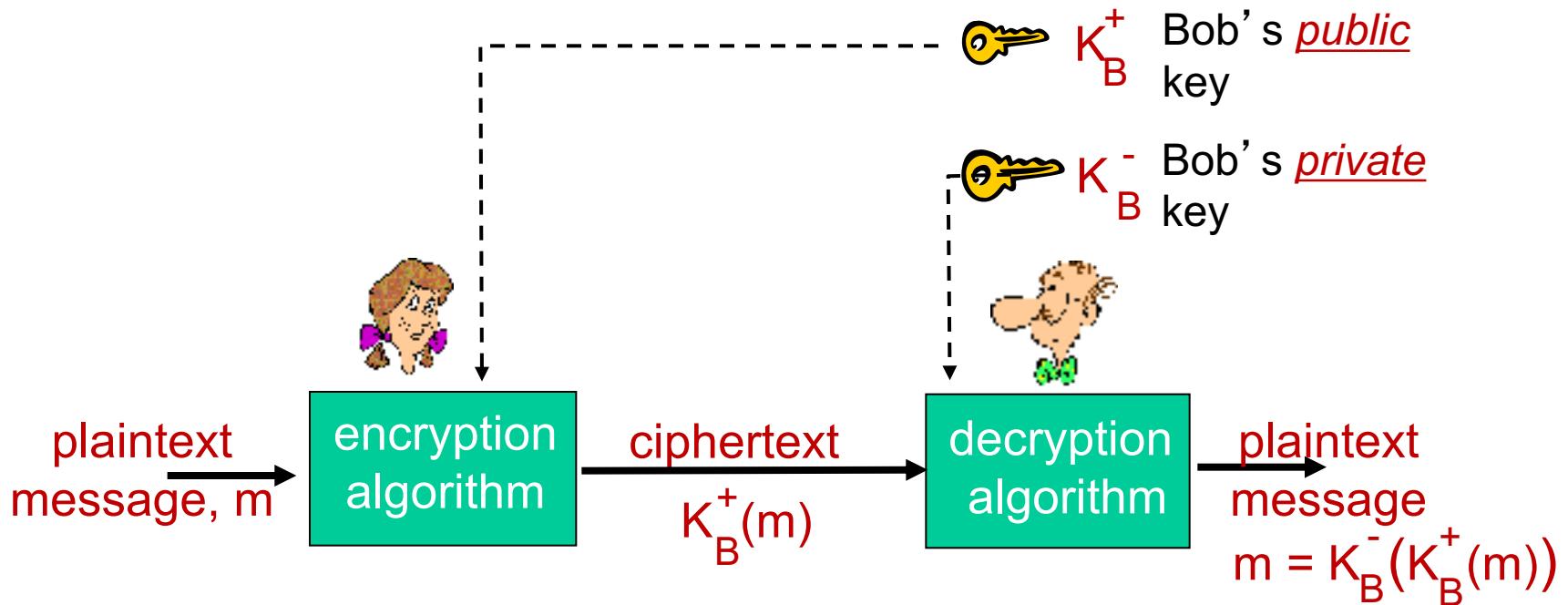
- requires sender, receiver know shared secret key
- Q: how to agree on key in first place (particularly if never “met”)?

public key crypto

- 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



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Authentication

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

Protocol 1.0: Alice says “I am Alice”



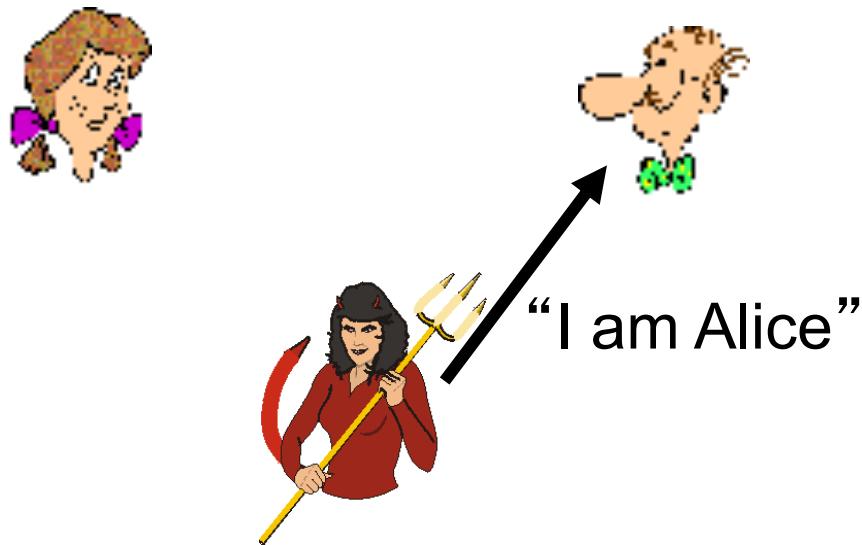
Failure scenario??



Authentication

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

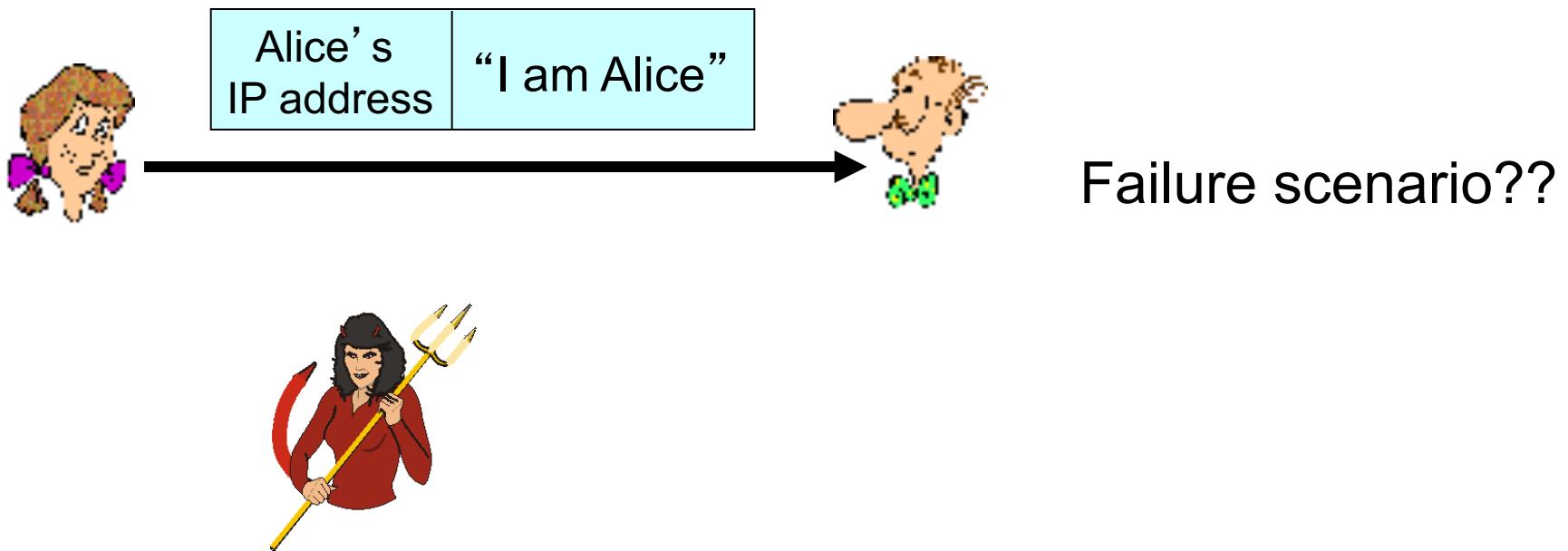
Protocol ap1.0: Alice says “I am Alice”



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

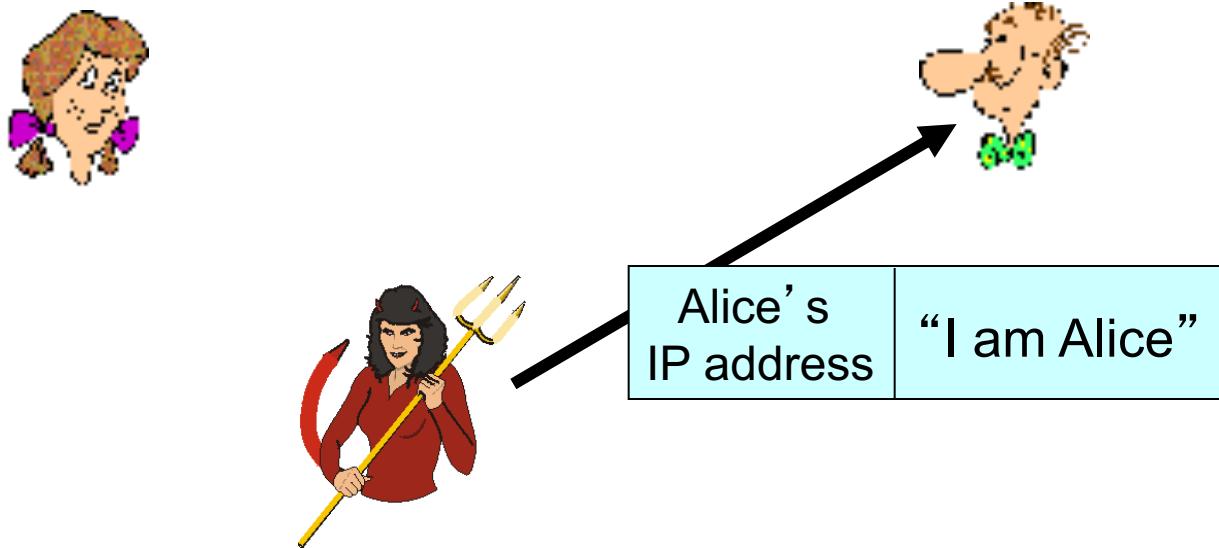
Authentication: another try

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



Authentication: another try

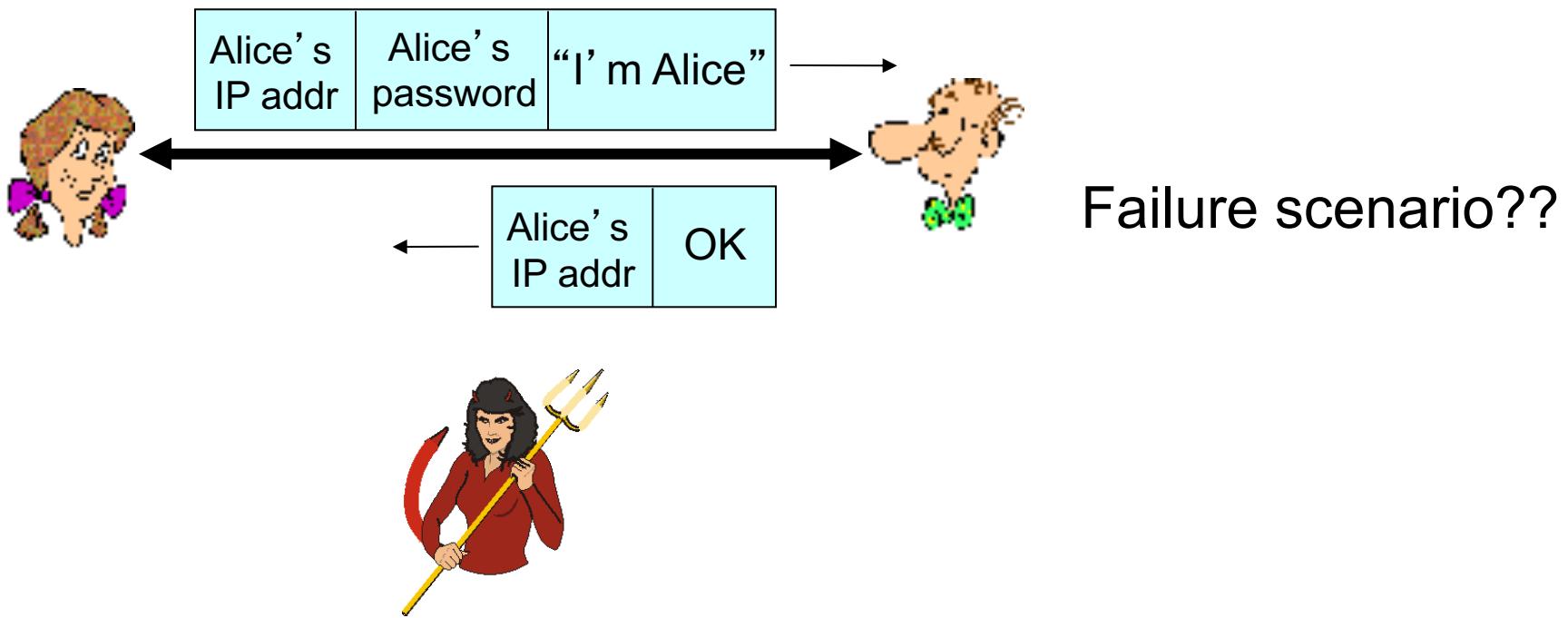
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Trudy can create
a packet
“spoofing”
Alice’s address

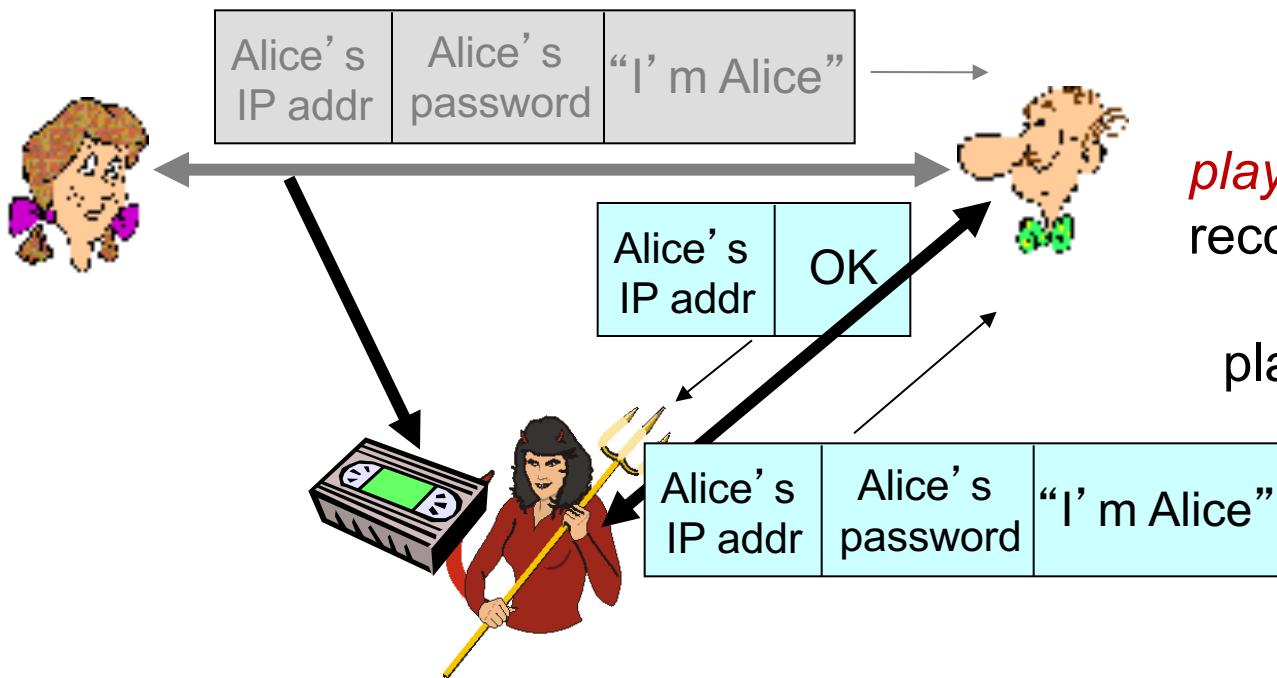
Authentication: another try

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



Authentication: another try

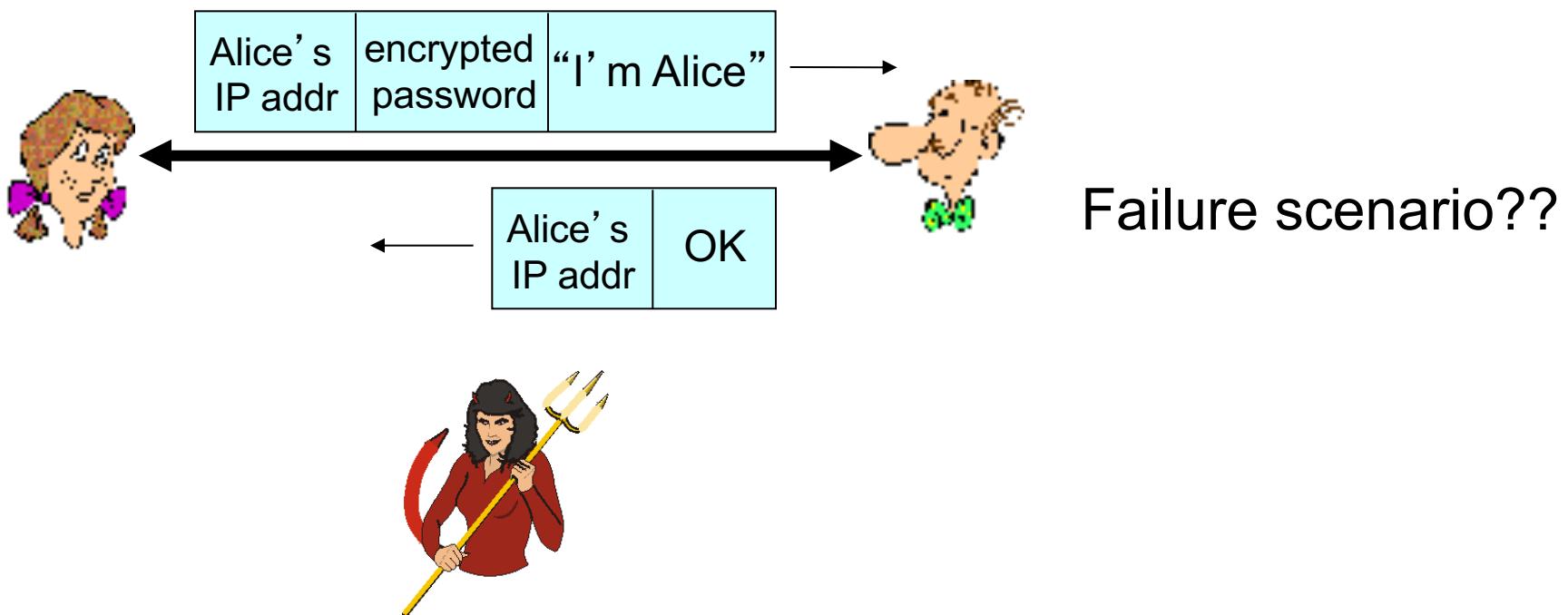
Protocol ap3.0: Alice says “I am Alice” and sends her secret password to “prove” it.



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

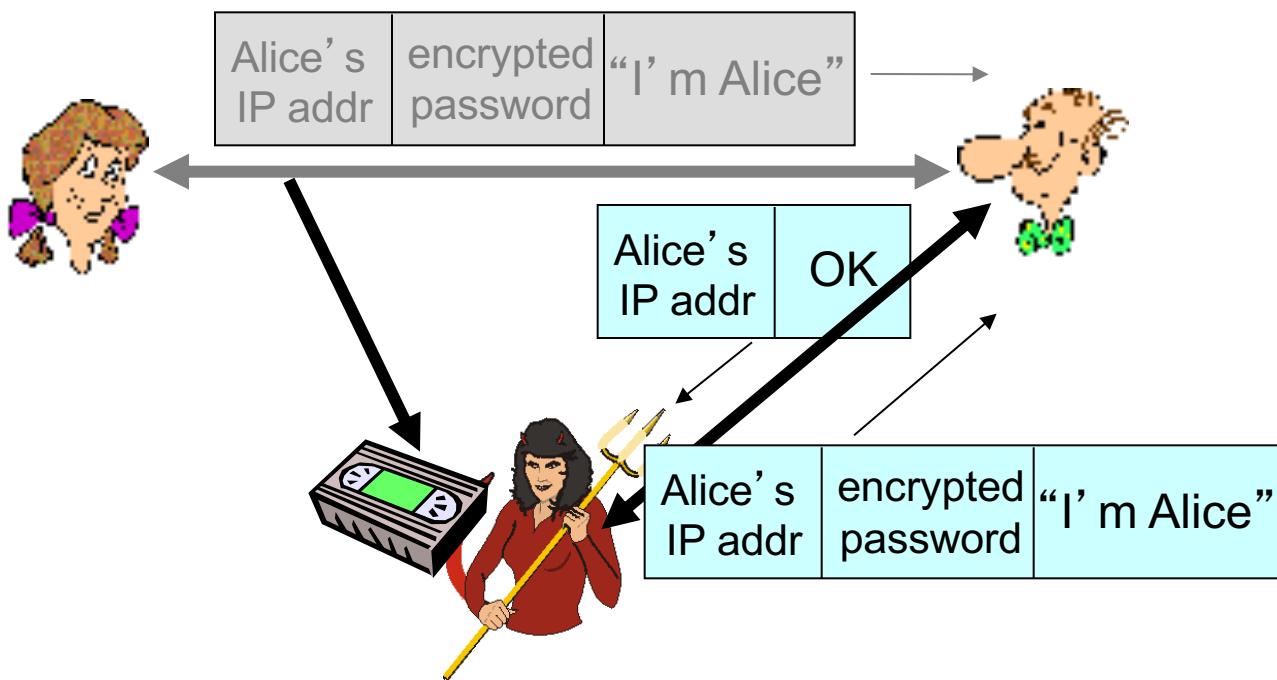
Authentication: yet another try

Protocol ap3.1: Alice says “I am Alice” and sends her **encrypted** secret password to “prove” it.



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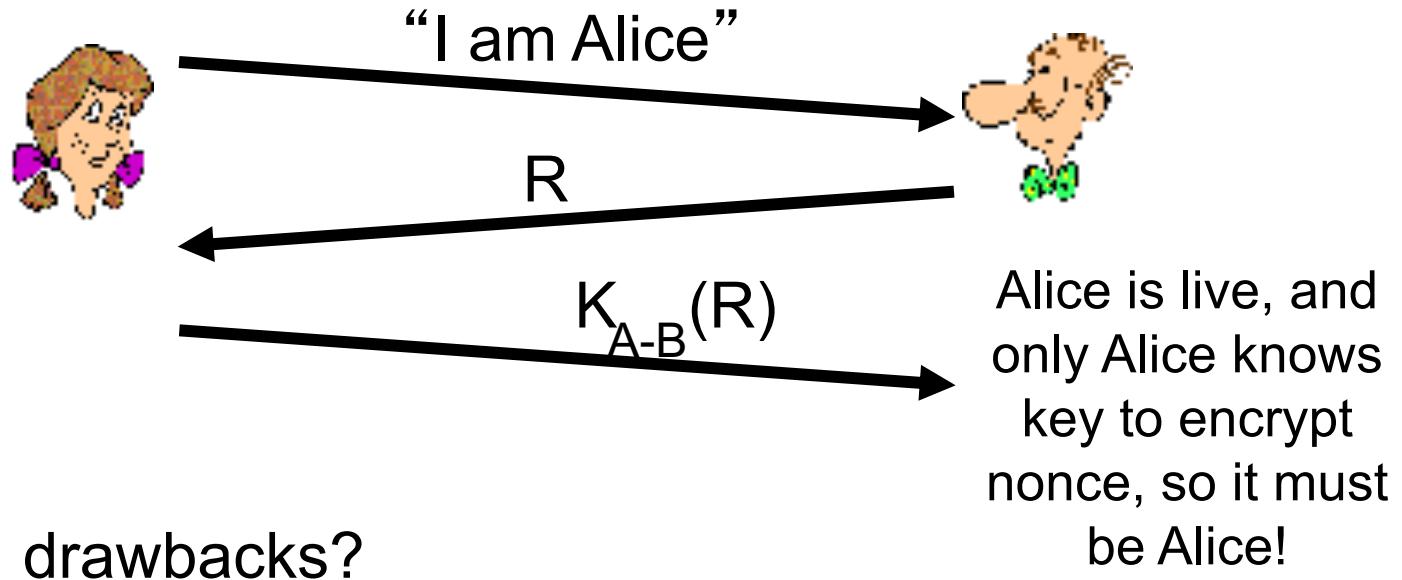
record
and
playback
still works!

Authentication: yet another try

Goal: avoid playback attack

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

ap4.0: to prove Alice “live”, Bob sends Alice **nonce**, R . Alice must return R , encrypted with shared secret key



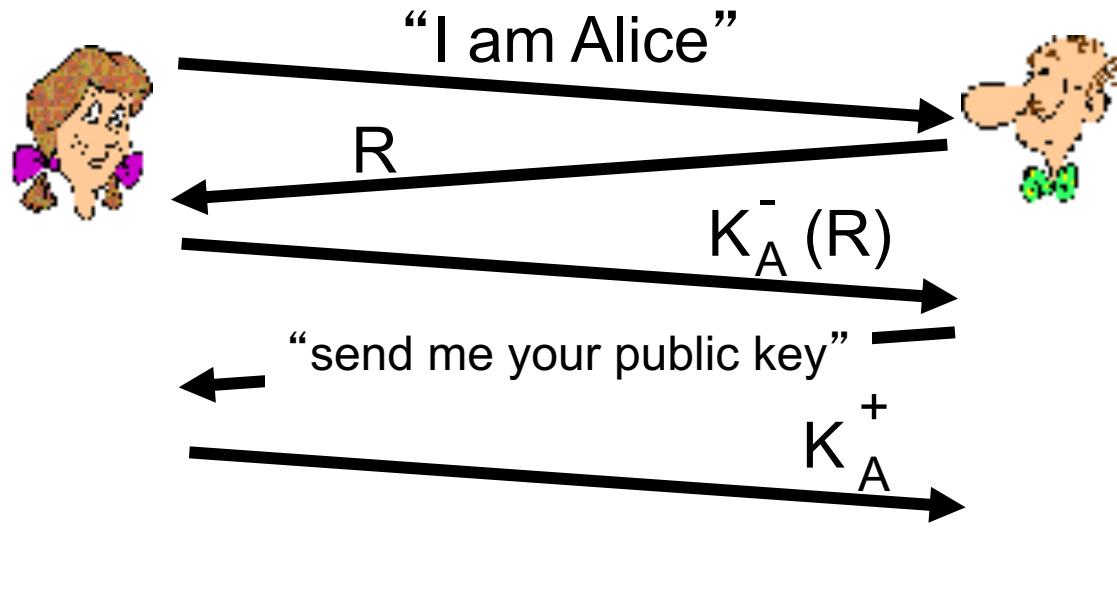
Failures, drawbacks?

Authentication: ap5.0

ap4.0 requires shared symmetric key

- can we authenticate using public key techniques?

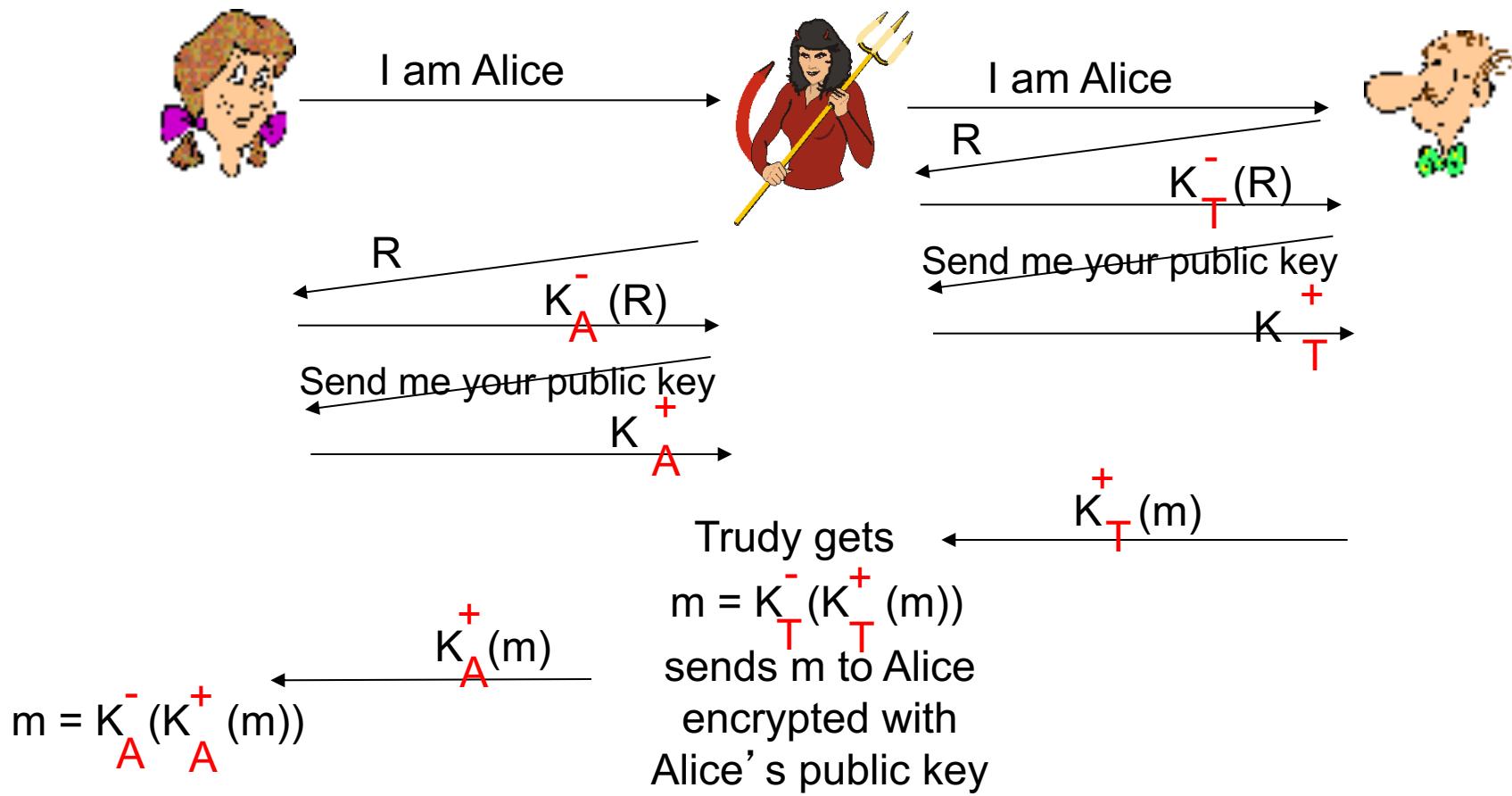
ap5.0: use nonce, public key cryptography



Bob computes
 $K_A^+(K_A^-(R)) = R$
and knows only Alice
could have the private
key, that encrypted R
such that
 $K_A^+(K_A^-(R)) = R$

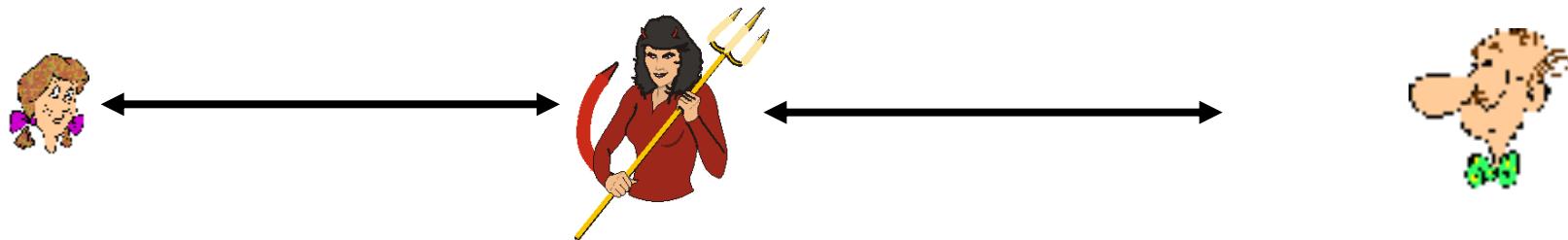
ap5.0: security hole

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



ap5.0: security hole

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



difficult to detect:

- Bob receives everything that Alice sends, and vice versa.
(e.g., so Bob, Alice can meet one week later and recall conversation!)
- problem is that Trudy receives all messages as well!

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Digital signatures

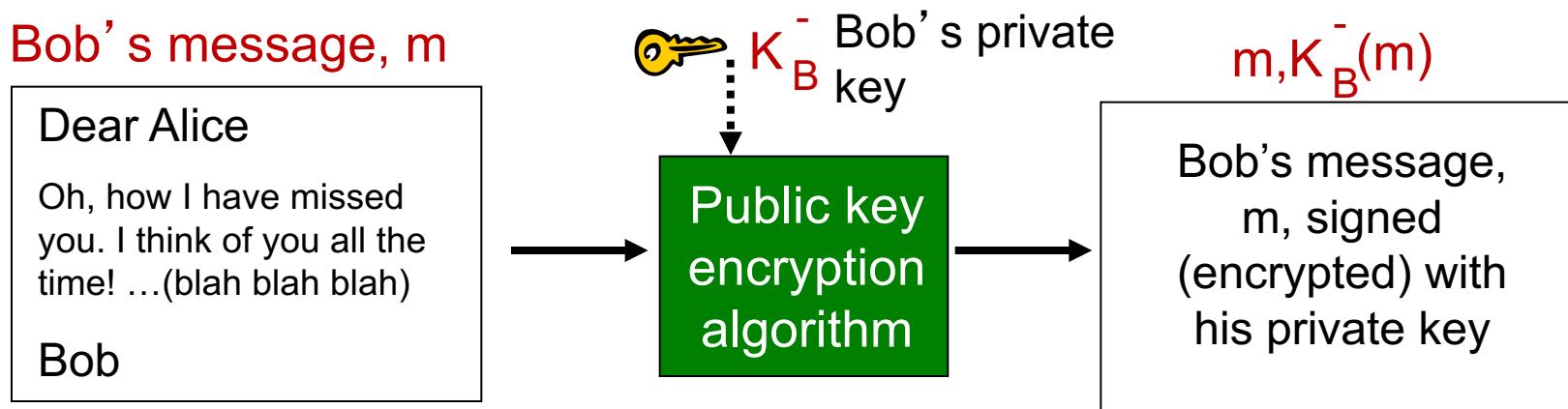
cryptographic technique analogous to hand-written signatures:

- sender (Bob) digitally signs document, establishing 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

Digital signatures

simple digital signature for message m :

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

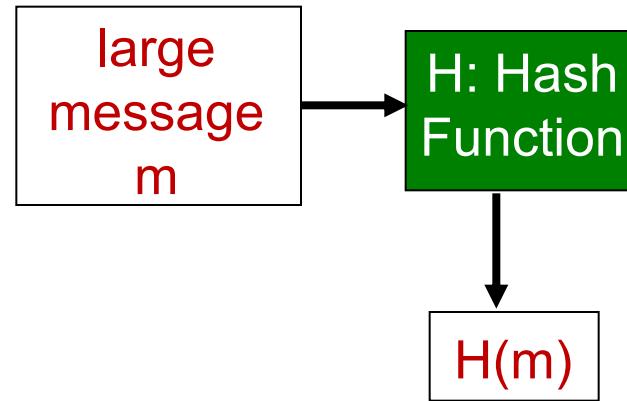


Message digests

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, $H(m)$.

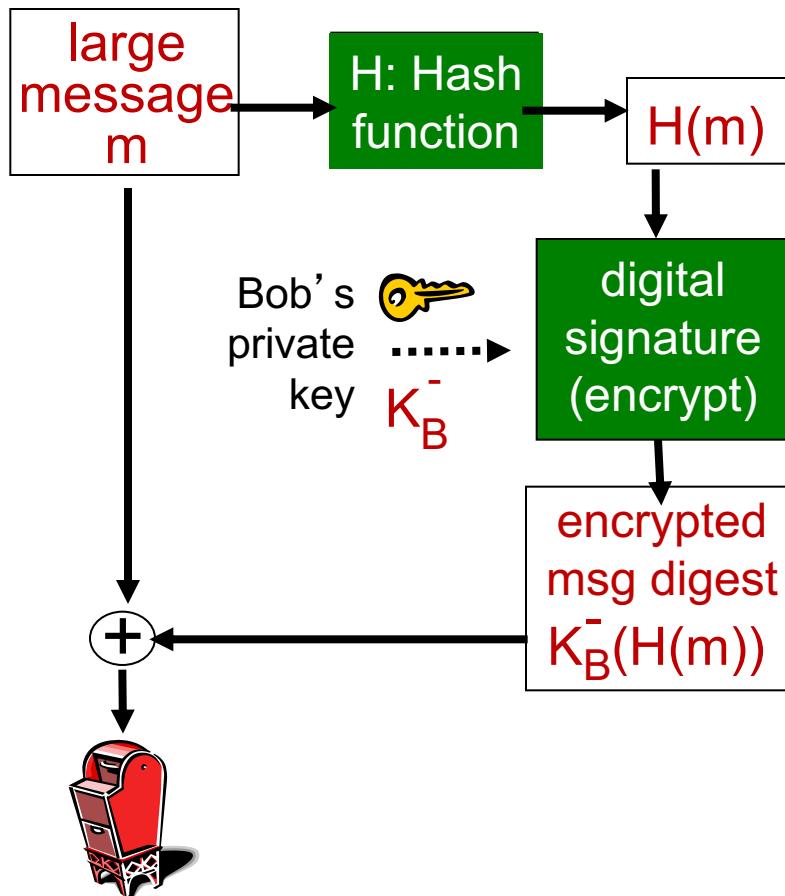


Hash function properties:

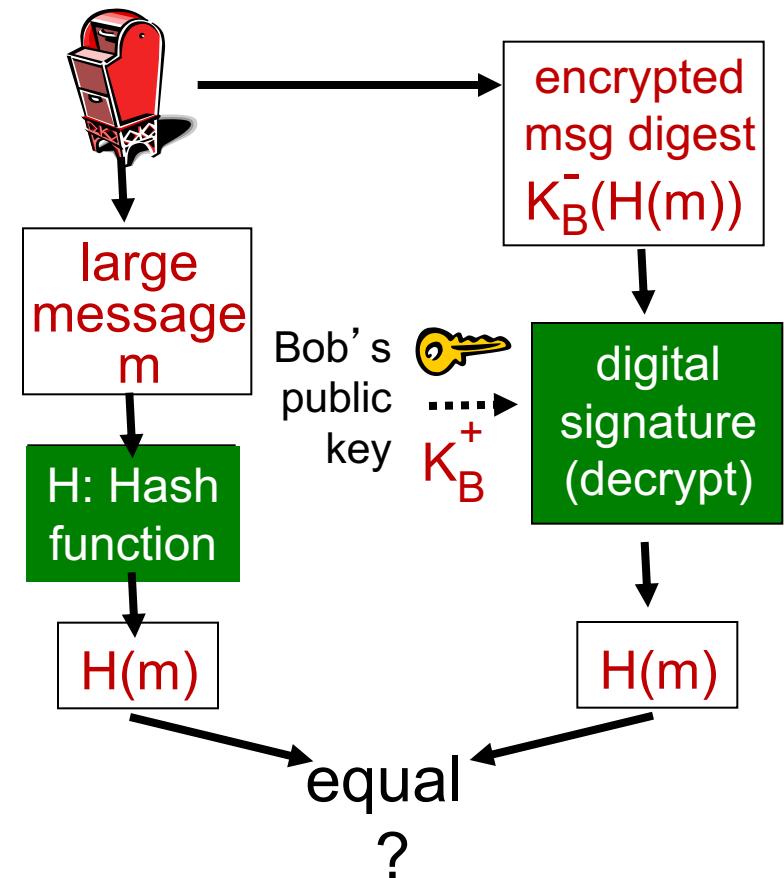
- many-to-1
- produces fixed-size msg digest (fingerprint)
- given message digest x , computationally infeasible to find m such that $x = H(m)$

Digital signature = signed message digest

Bob sends digitally signed message:



Alice verifies signature, integrity of digitally signed message:

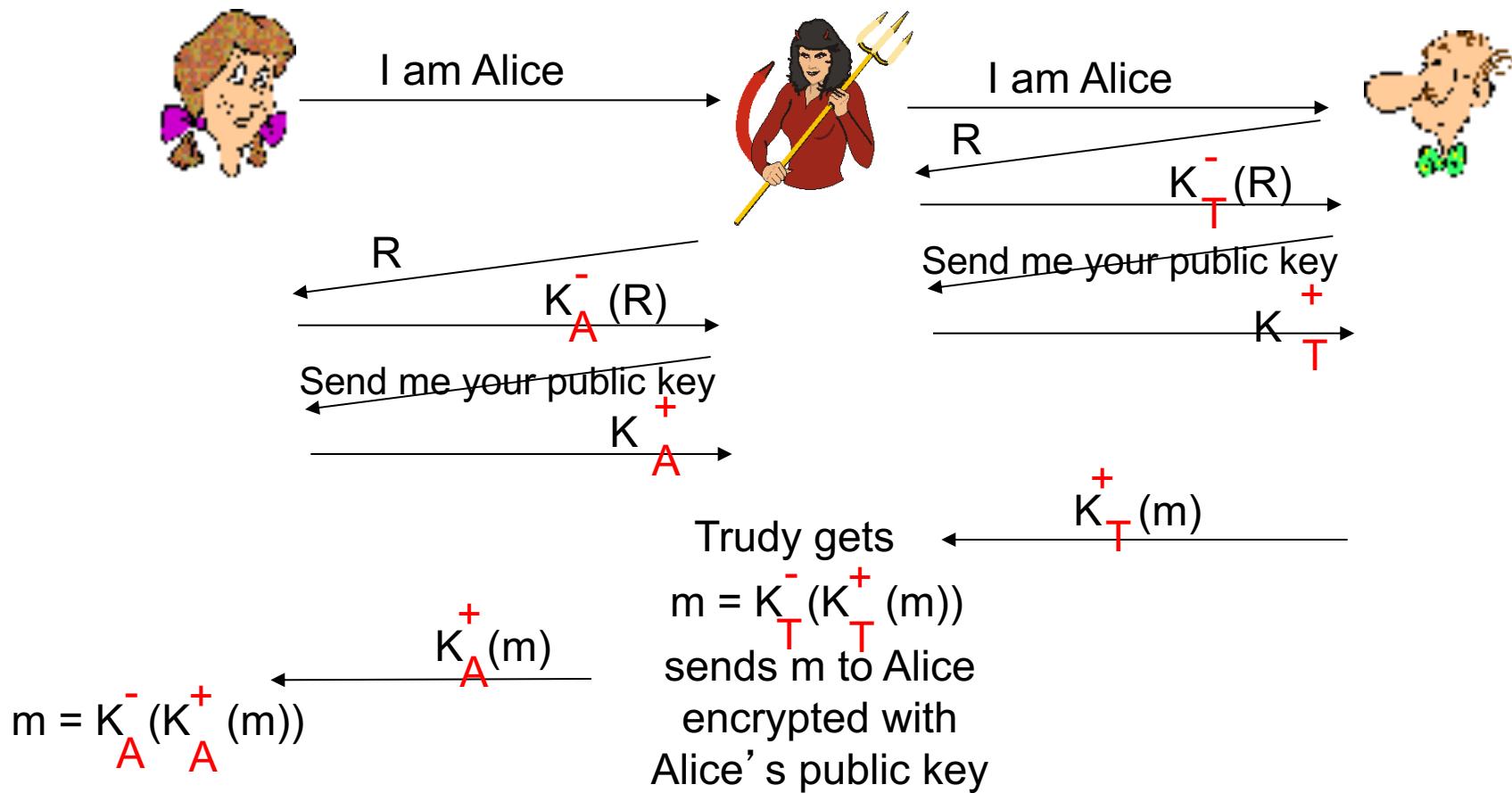


Hash function algorithms

- **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

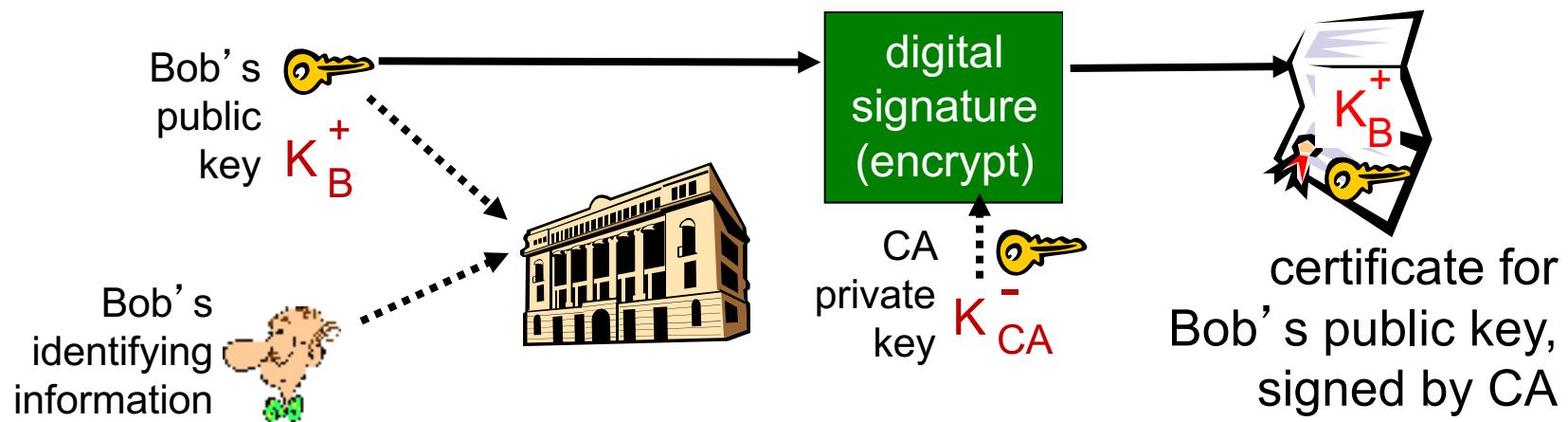
Recall: ap5.0 security hole

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



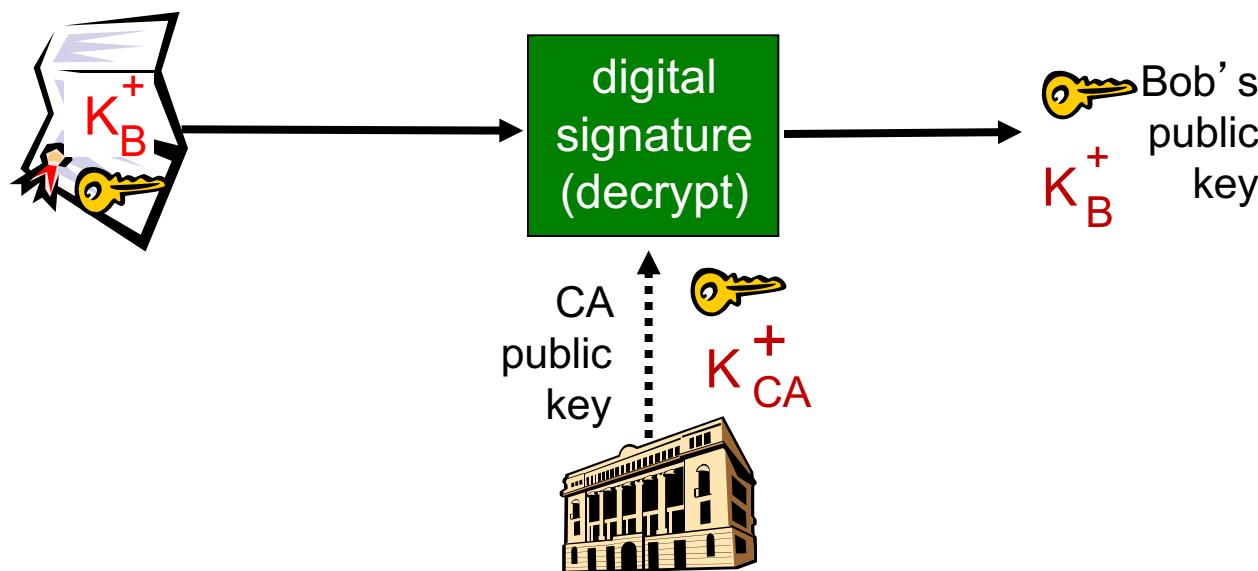
Certification authorities

- ***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



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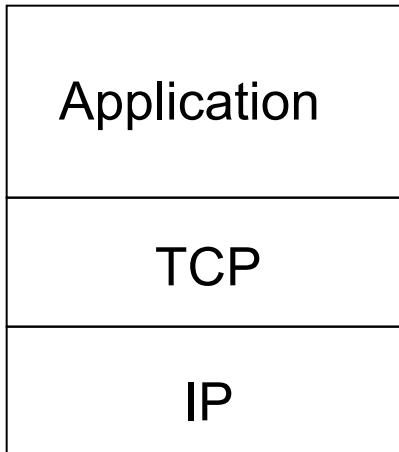
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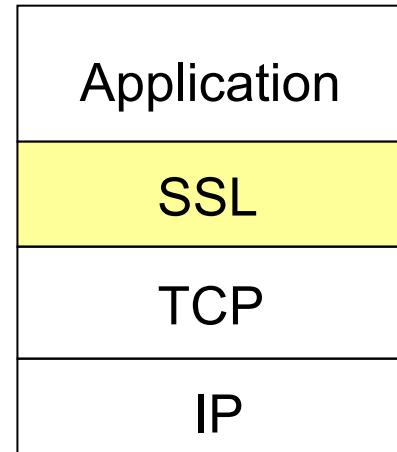
SSL: Secure Sockets Layer

- widely deployed security protocol
 - supported by almost all browsers, web servers
 - https
 - billions \$/year over SSL
- mechanisms: [Woo 1994], implementation: Netscape
- variation -TLS: transport layer security, RFC 2246
- provides
 - *confidentiality*
 - *integrity*
 - *authentication*

SSL and TCP/IP



normal application



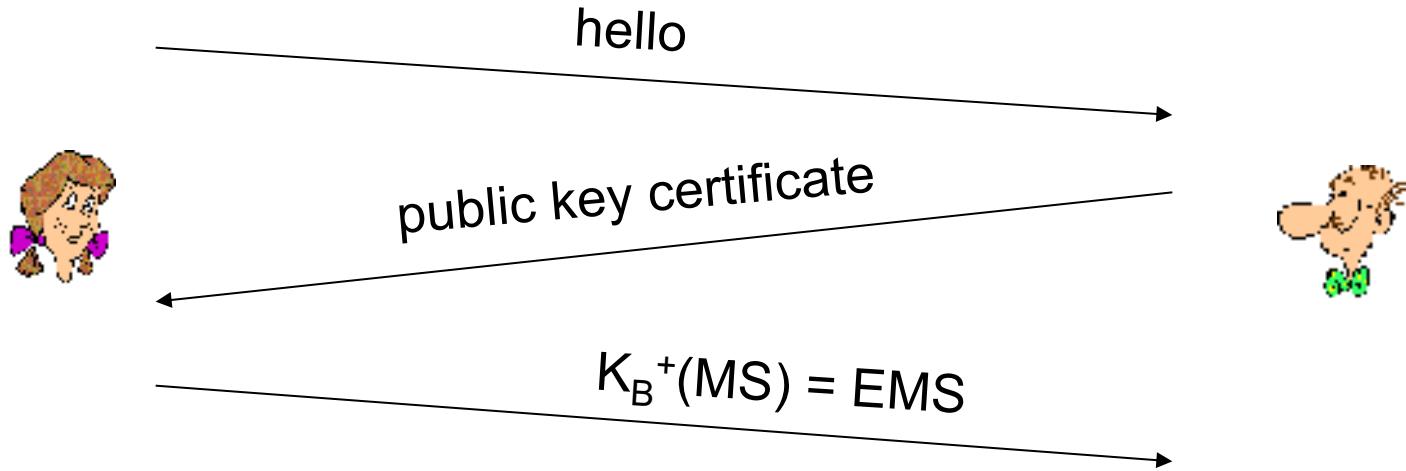
application with SSL

- 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

Toy: a simple handshake



MS: master secret

EMS: encrypted master secret

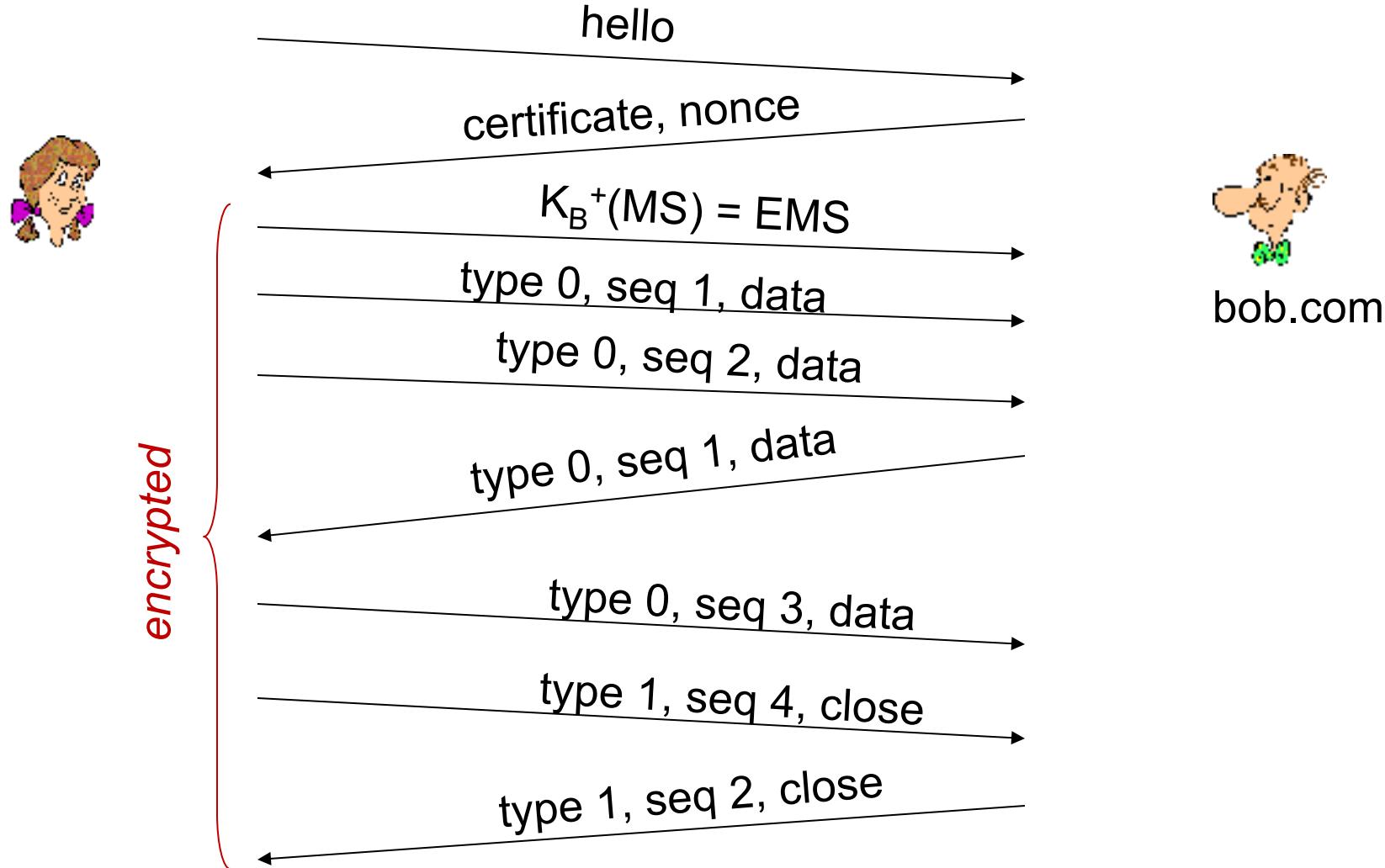
Toy: key derivation

- considered bad to use same key for more than one cryptographic operation
 - use 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 and creates the keys

Toy: sequence numbers

- *problem:* attacker can capture and replay record or re-order records
- *solution:* put sequence number into MAC:
 - $\text{MAC} = \text{MAC}(M_x, \text{sequence} \parallel \text{data})$
 - note: no sequence number field
- *problem:* attacker could replay all records
- *solution:* use nonce

Toy SSL: summary



Toy SSL isn't complete

- how long are fields?
- which encryption protocols?
- want negotiation?
 - allow client and server to support different encryption algorithms
 - allow client and server to choose together specific algorithm before data transfer

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

Real SSL: handshake (I)

Purpose

1. server authentication
2. negotiation: agree on crypto algorithms
3. establish keys
4. client authentication (optional)

Real SSL: handshake (2)

1. client sends list of algorithms it supports, along with client nonce
2. server chooses algorithms from list; sends back: choice + certificate + server nonce
3. client verifies certificate, extracts server's public key, generates pre_master_secret, encrypts with server's public key, sends to server
4. client and server independently compute encryption and MAC keys from pre_master_secret and nonces
5. client sends a MAC of all the handshake messages
6. server sends a MAC of all the handshake messages

Real SSL: handshaking (3)

last 2 steps protect handshake from tampering

- client typically offers range of algorithms, some strong, some weak
- man-in-the middle could delete stronger algorithms from list
- last 2 steps prevent this
 - last two messages are encrypted

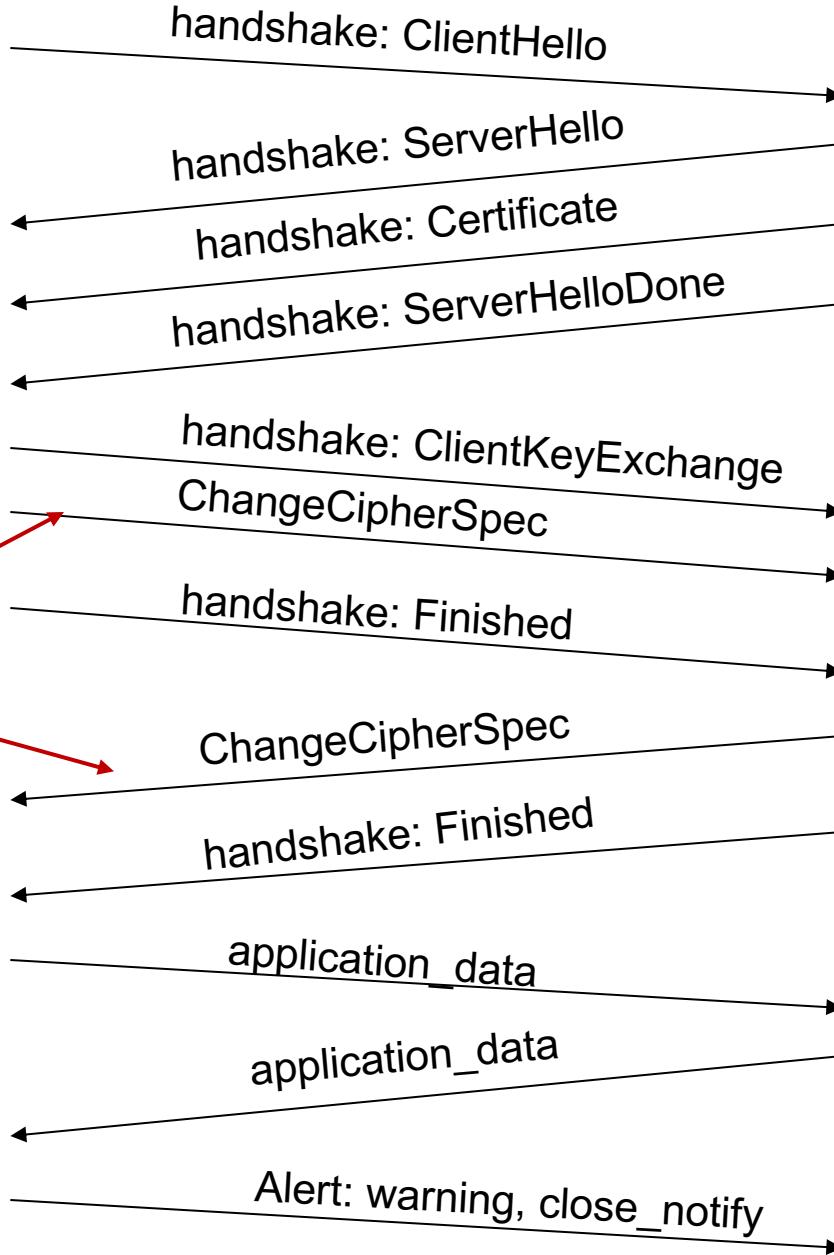
Real SSL: handshaking (4)

- why two random nonces?
- suppose Trudy sniffs all messages between Alice & Bob
- next day, Trudy sets up TCP connection with Bob, sends exact same sequence of records
 - Bob (Amazon) thinks Alice made two separate orders for the same thing
 - solution: Bob sends different random nonce for each connection. This causes encryption keys to be different on the two days
 - Trudy's messages will fail Bob's integrity check

Real SSL connection

*everything
henceforth
is encrypted*

TCP FIN follows



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What is network-layer confidentiality ?

between two network entities:

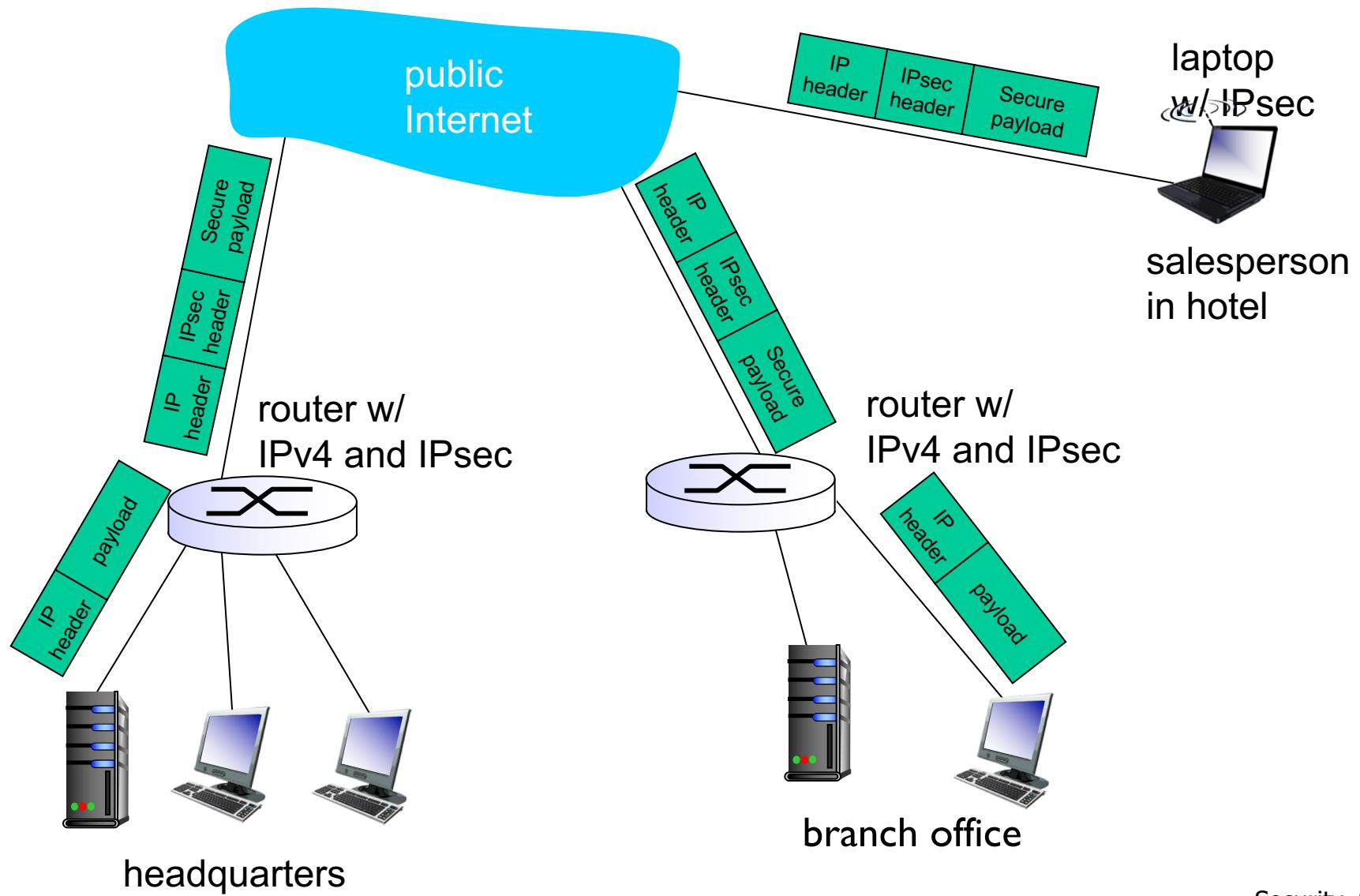
- sending entity encrypts datagram payload, payload could be:
 - TCP or UDP segment, ICMP message, OSPF message
- all data sent from one entity to other would be hidden:
 - web pages, e-mail, P2P file transfers, TCP SYN packets
 - ...
- “**blanket coverage**”

Virtual Private Networks (VPNs)

motivation:

- 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 Networks (VPNs)

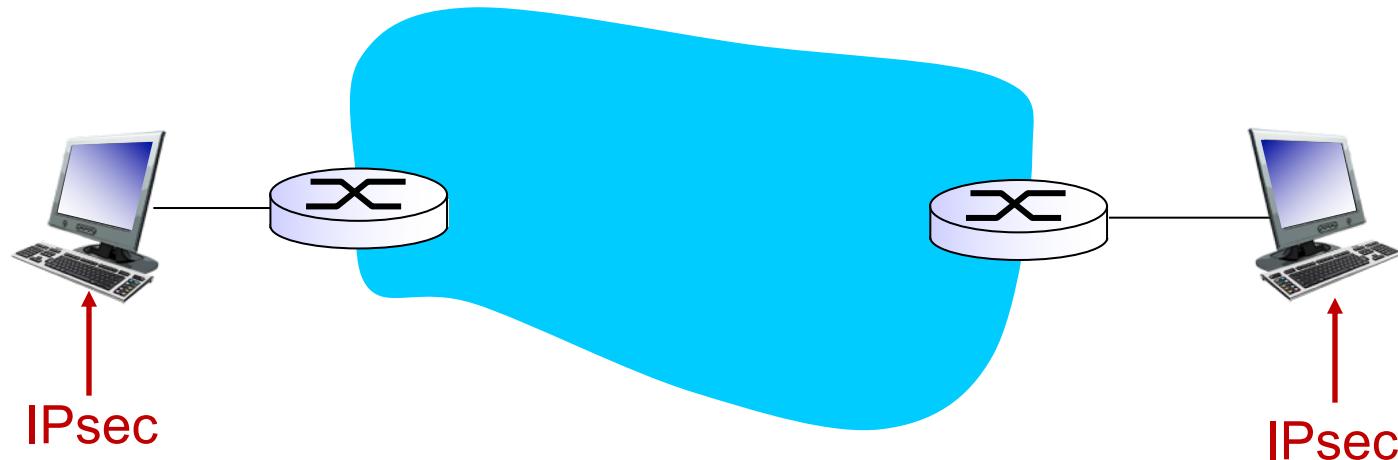


IPsec services

- data integrity
- origin authentication
- replay attack prevention
- confidentiality

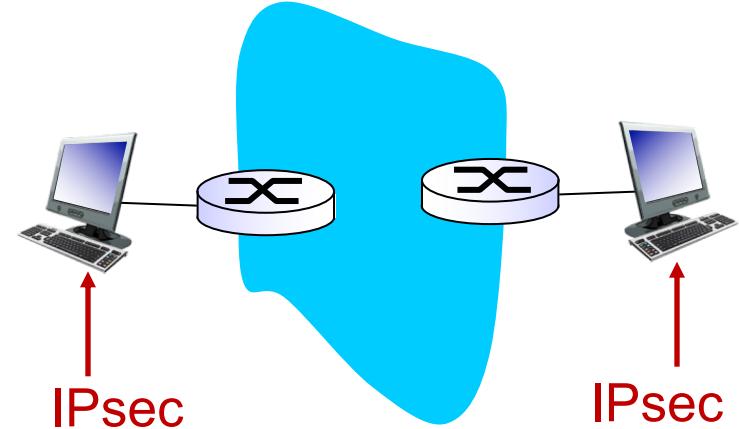
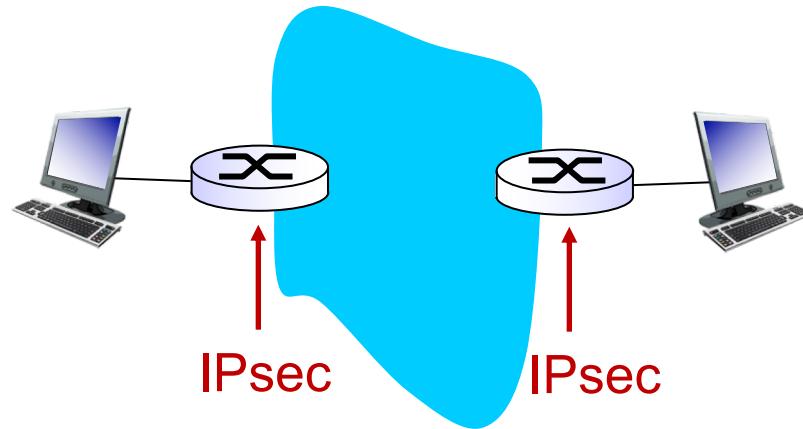
- two protocols providing different service models:
 - AH
 - ESP

IPsec transport mode



- IPsec datagram emitted and received by end-system
- protects upper level protocols

IPsec – tunneling mode



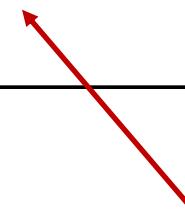
- edge routers IPsec-aware
- hosts IPsec-aware

Two IPsec protocols

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

Four combinations are possible!

Host mode with AH	Host mode with ESP
Tunnel mode with AH	Tunnel mode with ESP

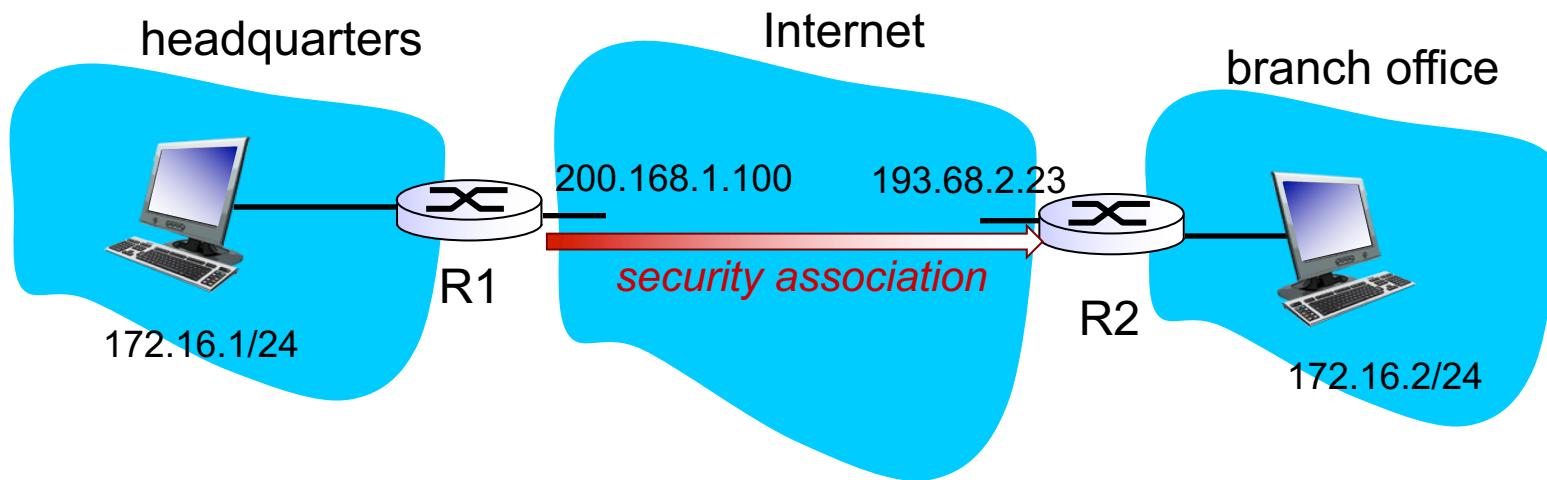


most common and
most important

Security associations (SAs)

- before sending data, “**security association (SA)**” established from sending to receiving entity
 - SAs are simplex: for only one direction
- ending, receiving entities maintain *state information* about SA
 - recall: TCP endpoints also maintain state info
 - IP is connectionless; IPsec is connection-oriented!
- how many SAs in VPN w/ headquarters, branch office, and n traveling salespeople?

Example SA from R1 to R2



R1 stores for SA:

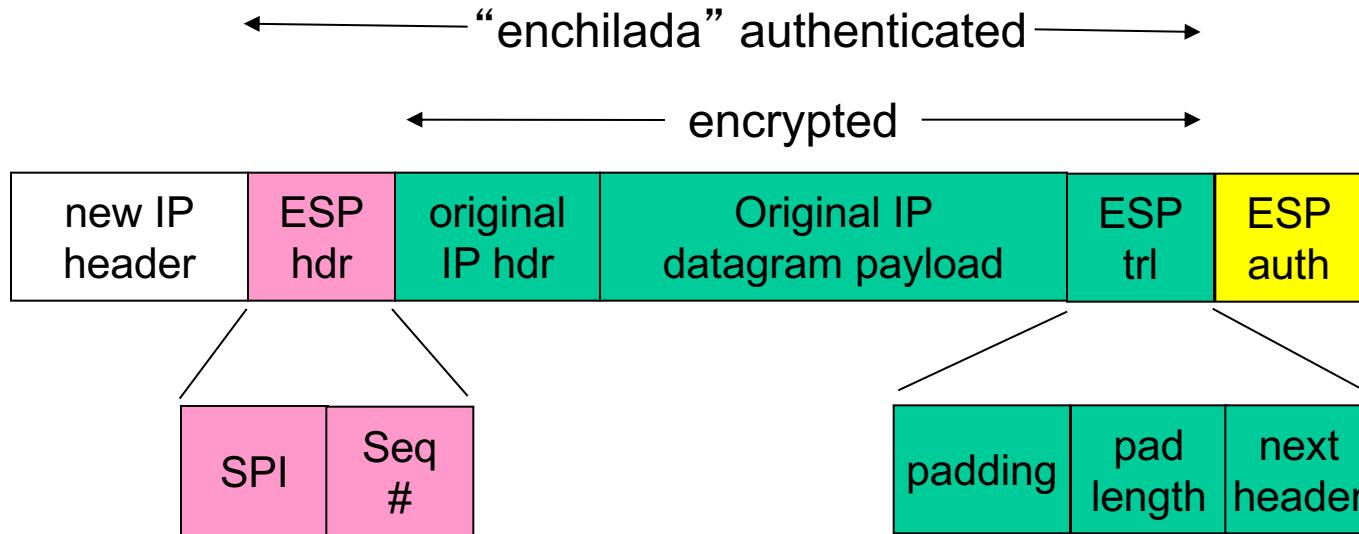
- 32-bit SA identifier: *Security Parameter Index (SPI)*
- origin SA interface (**200.168.1.100**)
- destination SA interface (**193.68.2.23**)
- type of encryption used (e.g., 3DES with CBC)
- encryption key
- type of integrity check used (e.g., HMAC with MD5)
- authentication key

Security Association Database (SAD)

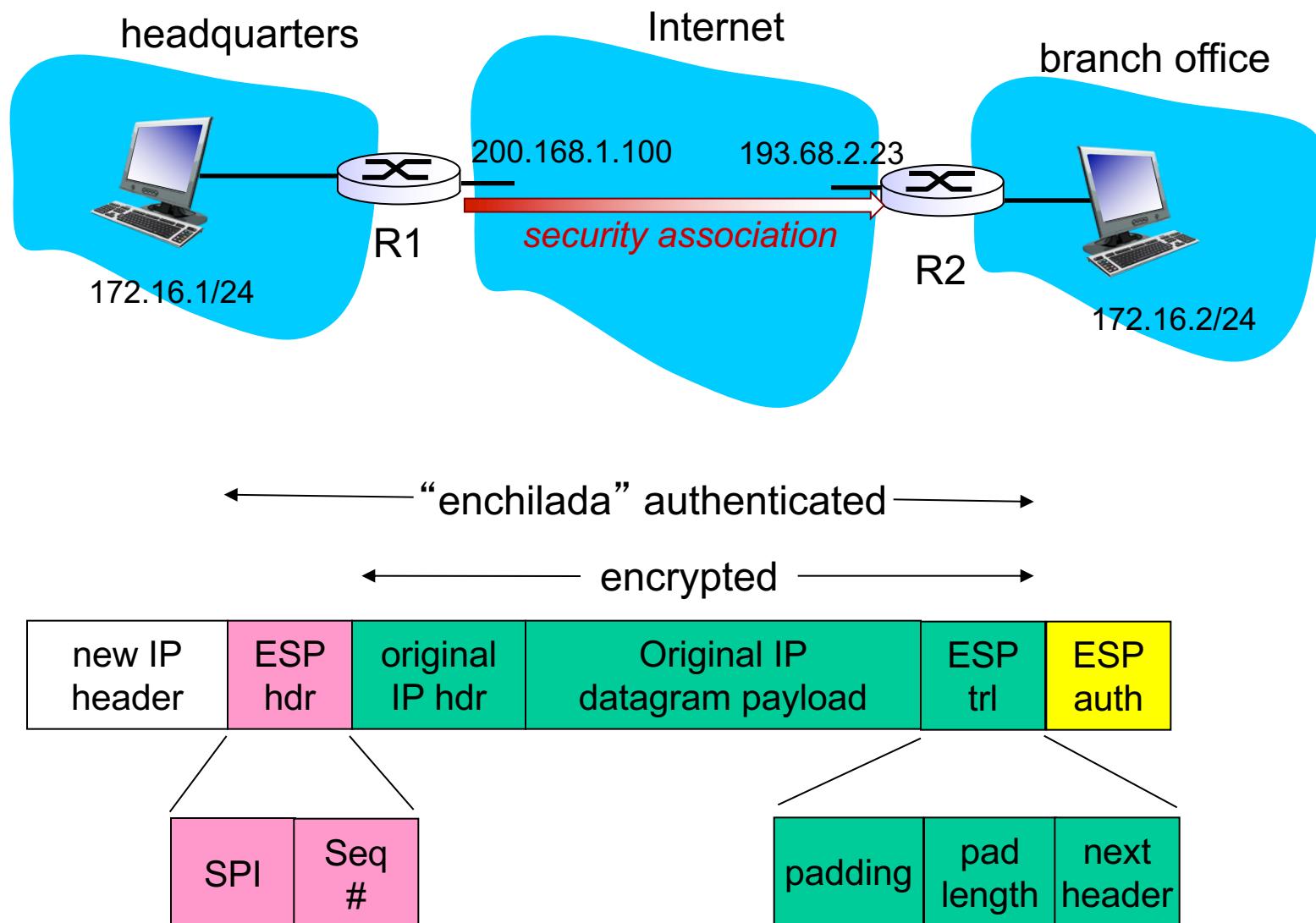
- endpoint holds SA state in *security association database (SAD)*, where it can locate them during processing.
- with n salespersons, $2 + 2n$ SAs in RI's SAD
- when sending IPsec datagram, RI accesses SAD to determine how to process datagram.
- when IPsec datagram arrives to R2, R2 examines SPI in IPsec datagram, indexes SAD with SPI, and processes datagram accordingly.

IPsec datagram

focus for now on tunnel mode with ESP



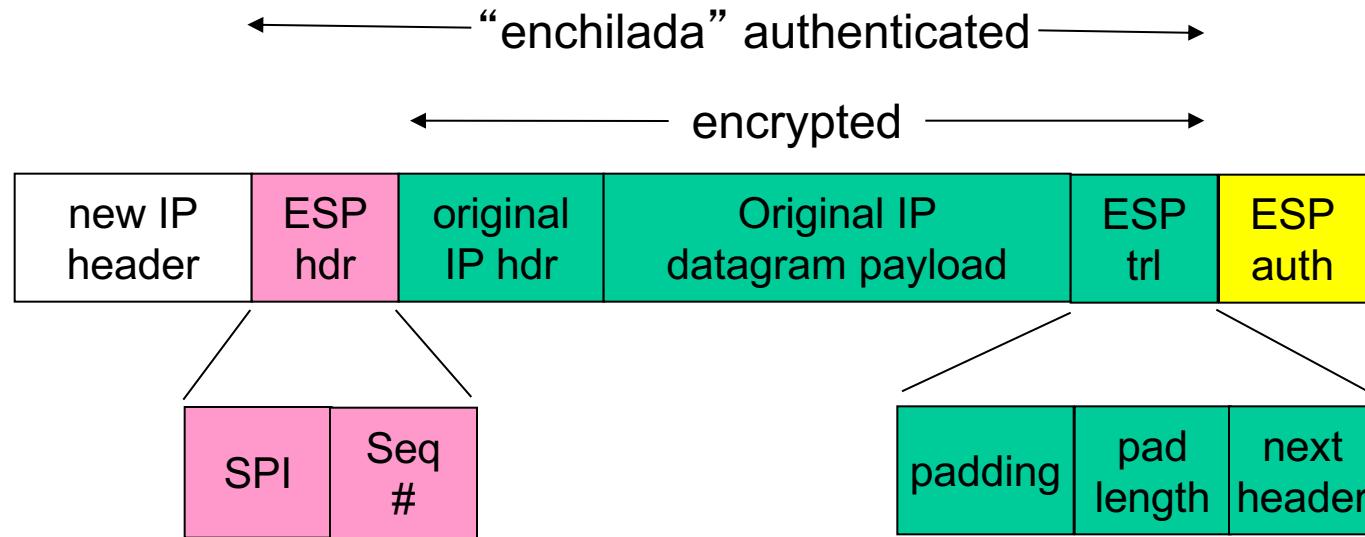
What happens?



R1: convert original datagram to IPsec datagram

- appends to back of original datagram (which includes original header fields!) an “ESP trailer” field.
- encrypts result using algorithm & key specified by SA.
- appends to front of this encrypted quantity the “ESP header, creating “enchilada”.
- creates authentication MAC over the *whole enchilada*, using algorithm and key specified in SA;
- appends MAC to back of *enchilada*, forming *payload*;
- creates brand new IP header, with all the classic IPv4 header fields, which it appends before *payload*

Inside the enchilada:



- 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 is created with shared secret key

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

Security Policy Database (SPD)

- policy: For a given datagram, sending entity needs to know if it should use IPsec
- needs also to know which SA to use
 - may use: source and destination IP address; protocol number
- info in SPD indicates “what” to do with arriving datagram
- info in SAD indicates “how” to do it

Summary: IPsec services



- suppose Trudy sits somewhere between R1 and 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?

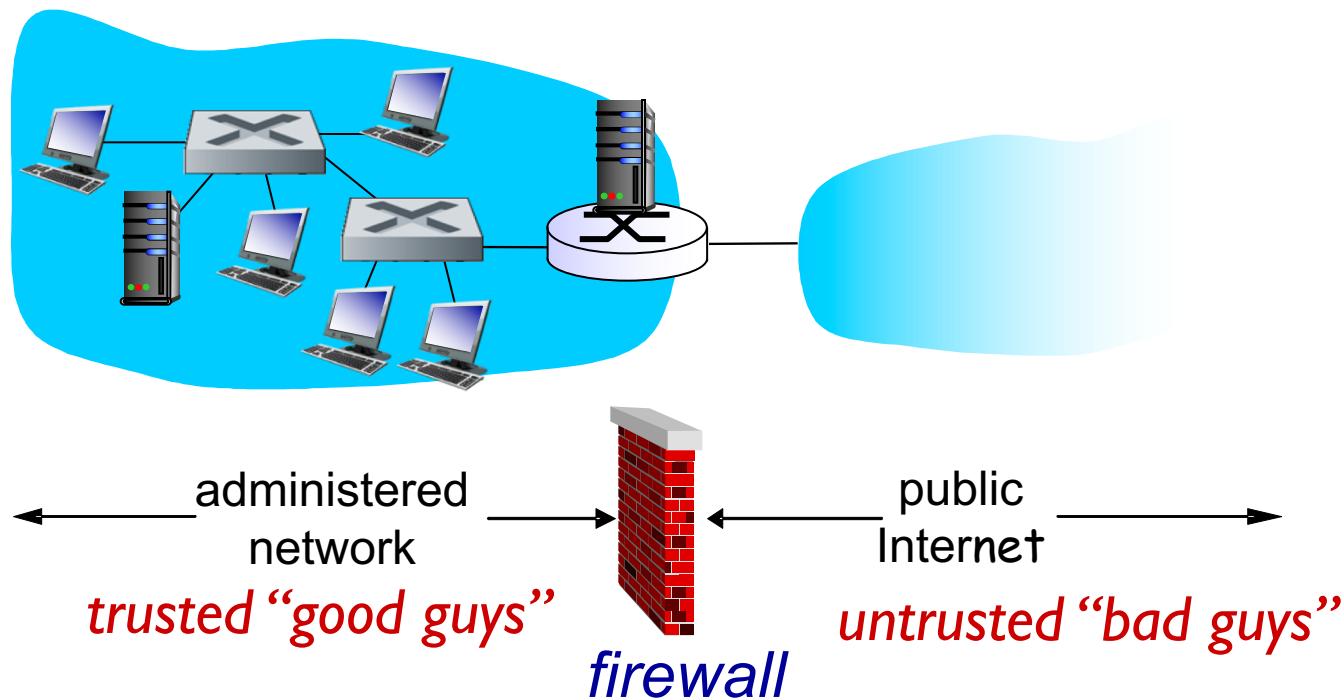
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Firewalls

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

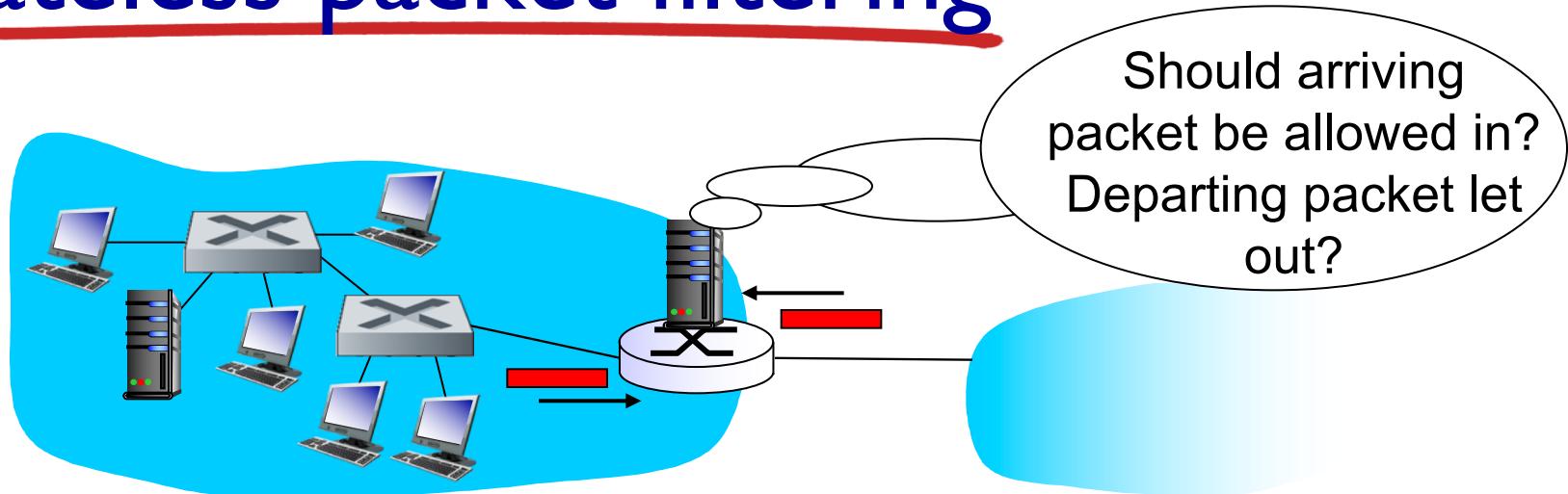
allow only authorized access to inside network

- 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: 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

<i>Policy</i>	<i>Firewall Setting</i>
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

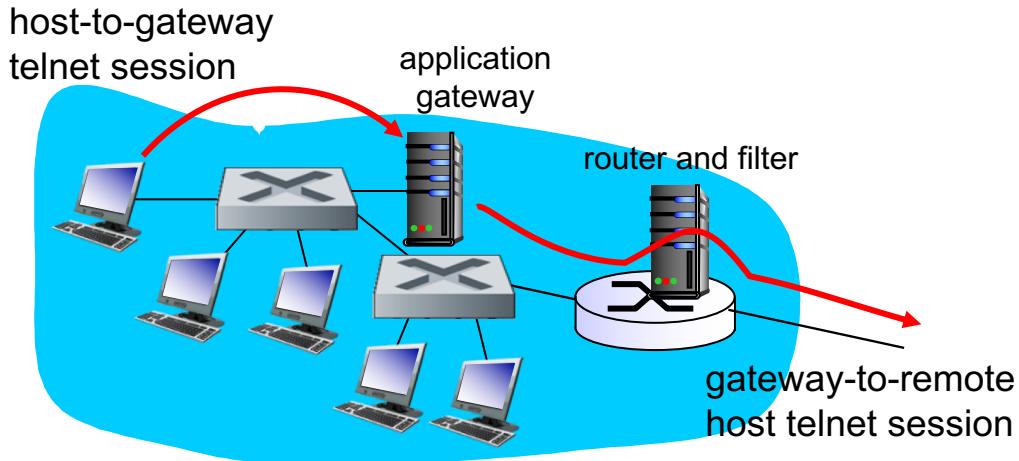
Stateful packet filtering

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 connxion
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

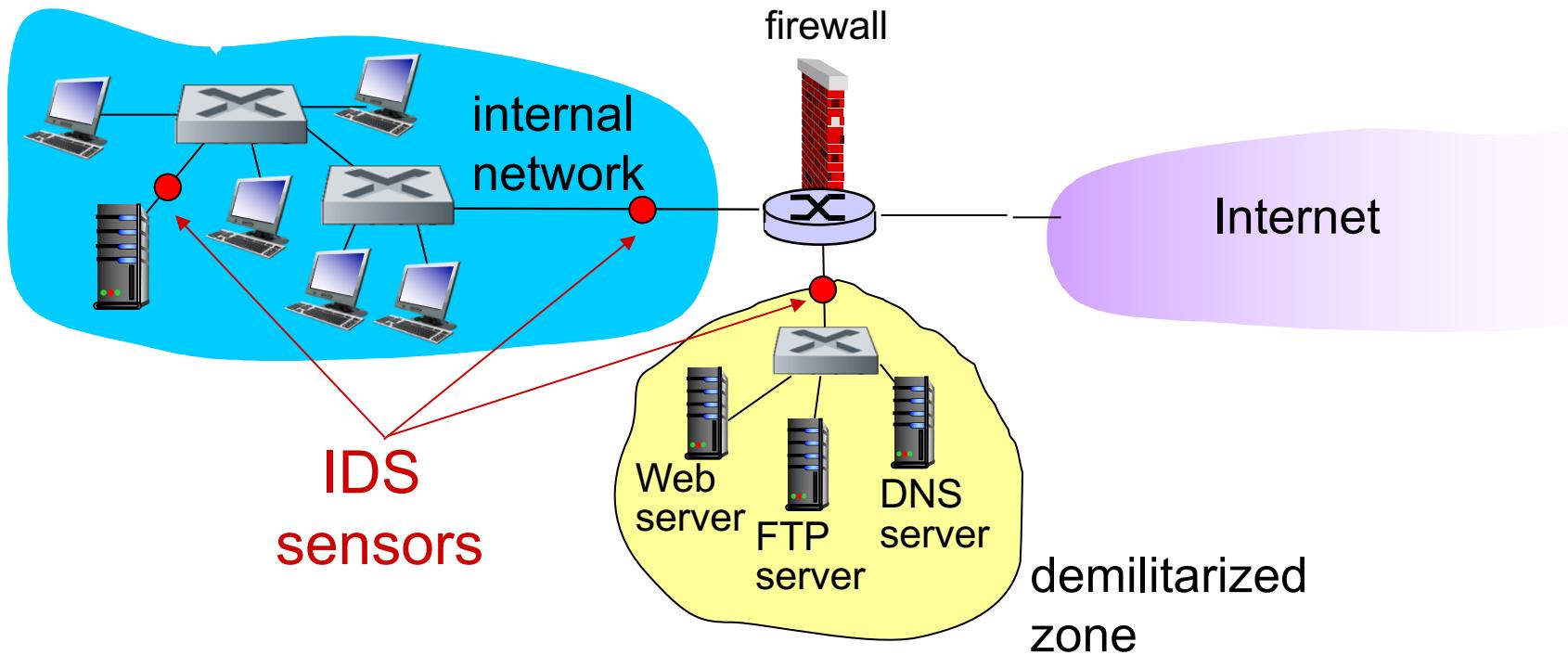
- *IP spoofing*: router can't know if data "really" comes from claimed source
- if multiple app's. need special treatment, each has own app. gateway
- client software must know how to contact gateway.
 - e.g., must set IP address of proxy in Web browser
- filters often use all or nothing policy for UDP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

operational security: firewalls and IDS