

Chapter 8

Network Security

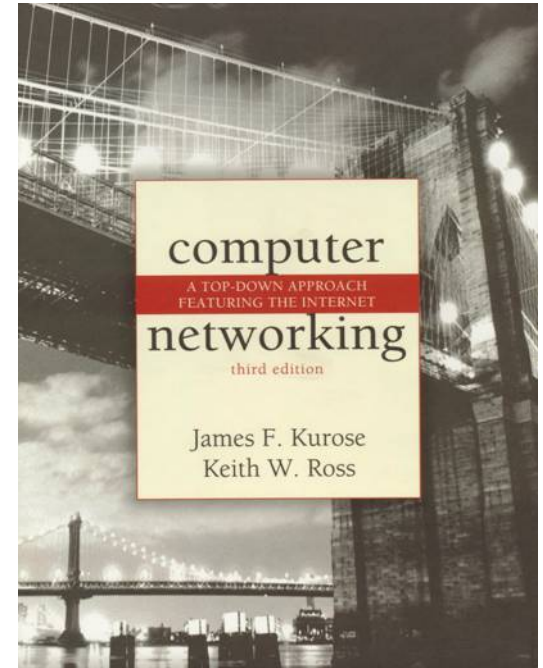
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*Computer Networking:
A Top Down Approach
Featuring the Internet,
3rd edition.*

*Jim Kurose, Keith Ross
Addison-Wesley, July
2004.*

Chapter 8: Network Security

Chapter goals:

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

Chapter 8 roadmap

8.1 What is network security?

8.2 Principles of cryptography

8.3 Authentication

8.4 Integrity

8.5 Key Distribution and certification

8.6 Access control: firewalls

8.7 Attacks and counter measures

8.8 Security in many layers

What is network security?

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

- sender encrypts message
- receiver decrypts message

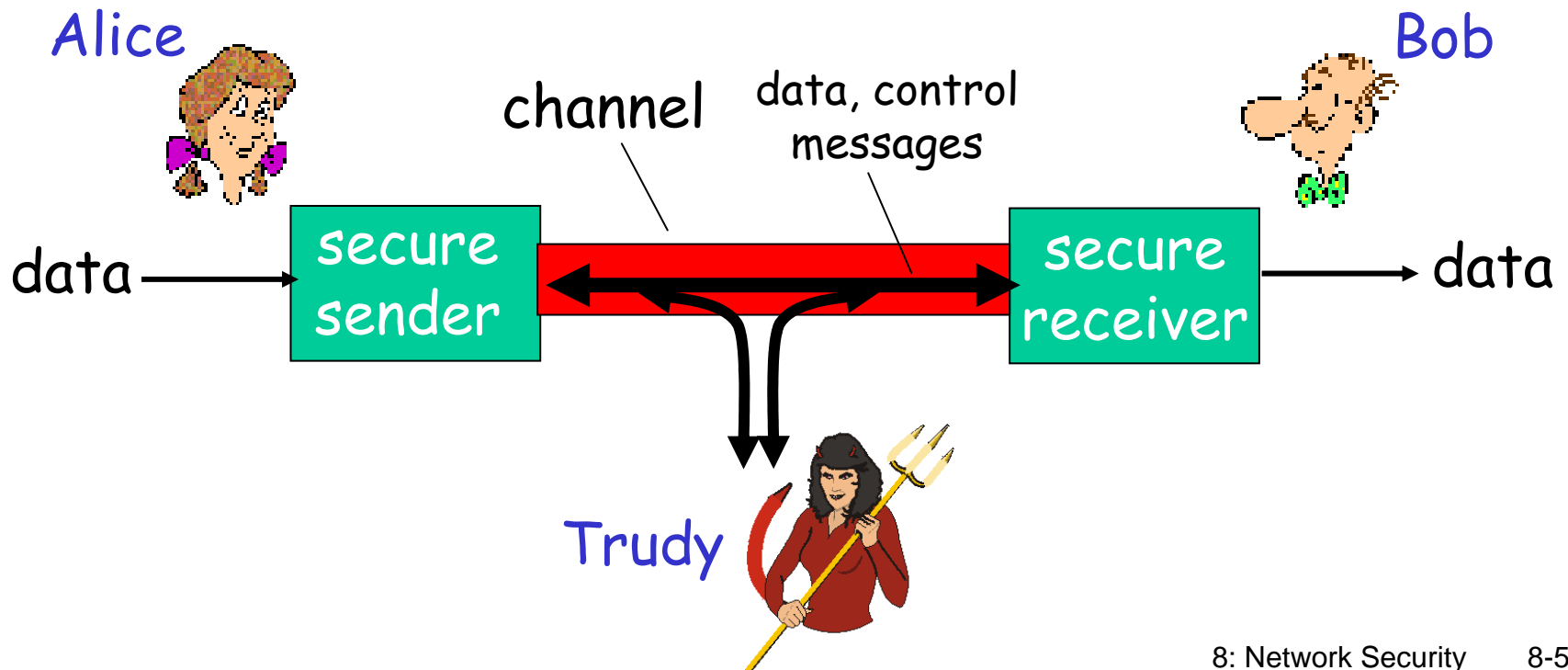
Authentication: sender, receiver want to confirm identity of each other

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



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
- ❑ other examples?

There are bad guys (and girls) out there!

Q: What can a "bad guy" do?

A: a lot!

- *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)

more on this later

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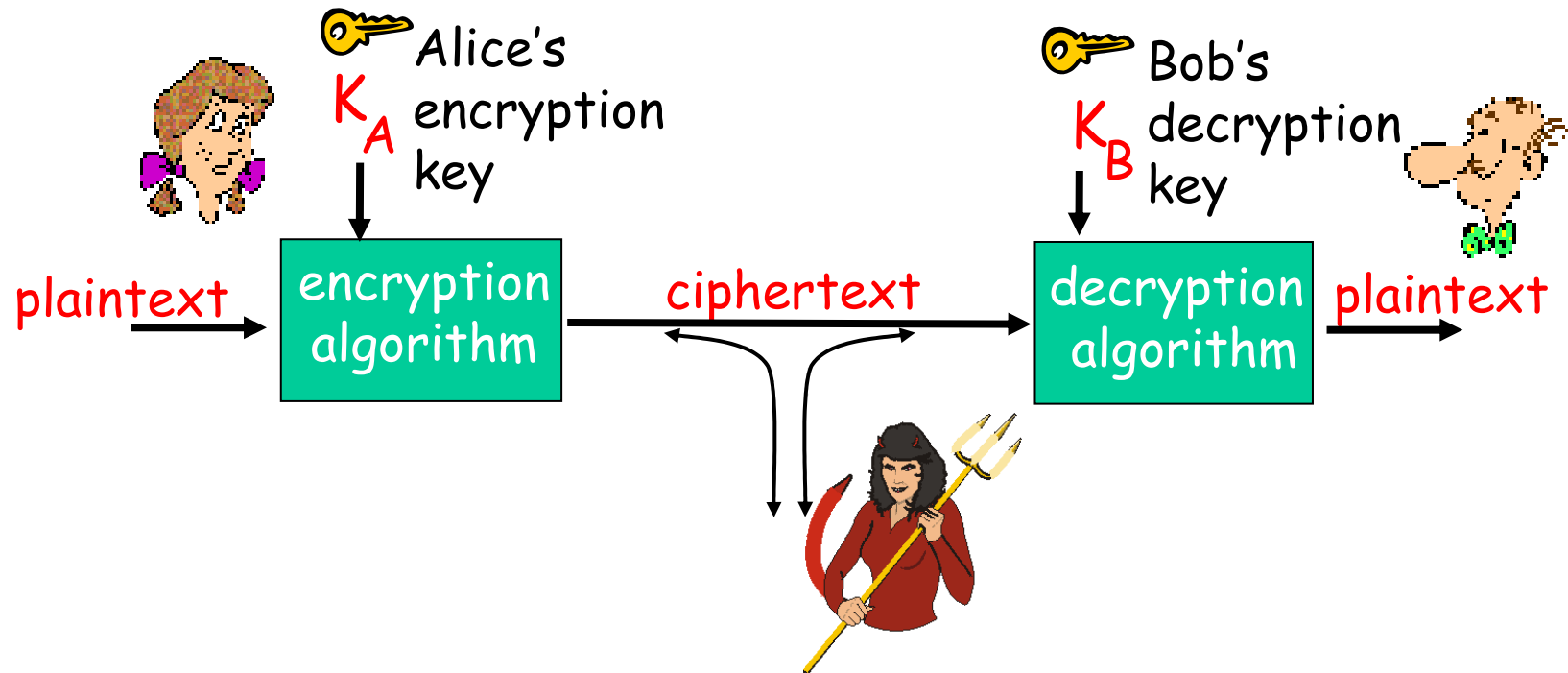
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8.7 Attacks and counter measures

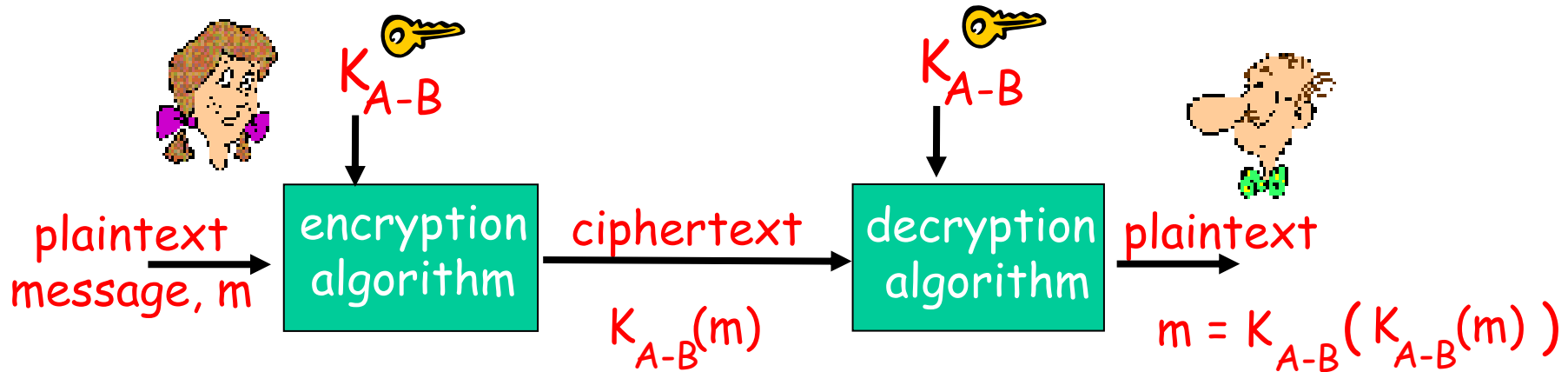
8.8 Security in many layers

The language of cryptography



symmetric key crypto: sender, receiver keys *identical*
public-key crypto: encryption key *public*, decryption key *secret* (private)

Symmetric key cryptography



symmetric key crypto: Bob and Alice share know same (symmetric) key: K_{A-B}

- 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
- ❑ How secure is DES?
 - DES Challenge: 56-bit-key-encrypted phrase ("Strong cryptography makes the world a safer place") decrypted (brute force) in 4 months
 - no known "backdoor" decryption approach
- ❑ making DES more secure:
 - use three keys sequentially (3-DES) on each datum
 - use cipher-block chaining

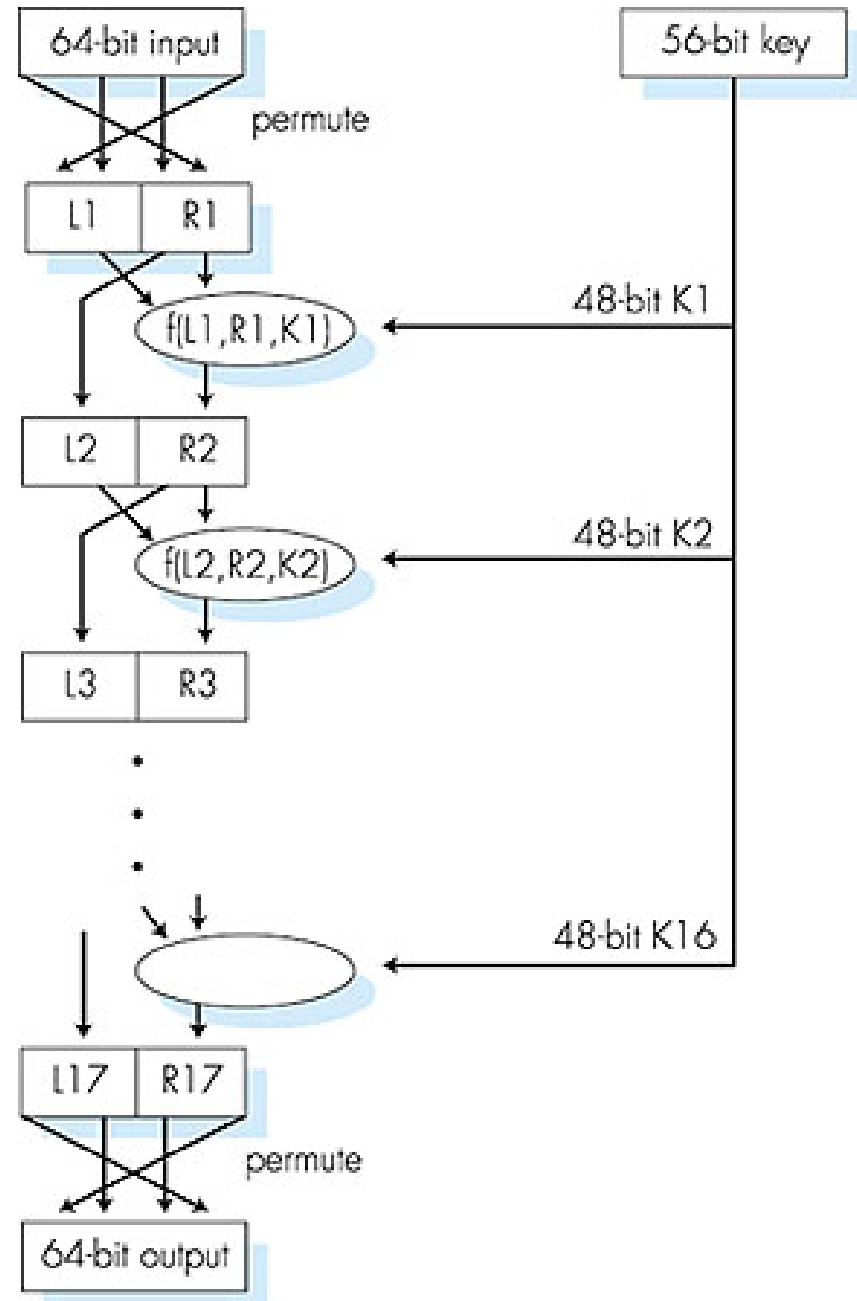
Symmetric key crypto: DES

DES operation

initial permutation

16 identical "rounds" of
function application,
each using different
48 bits of key

final permutation



AES: Advanced Encryption Standard

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

Public Key Cryptography

symmetric key crypto

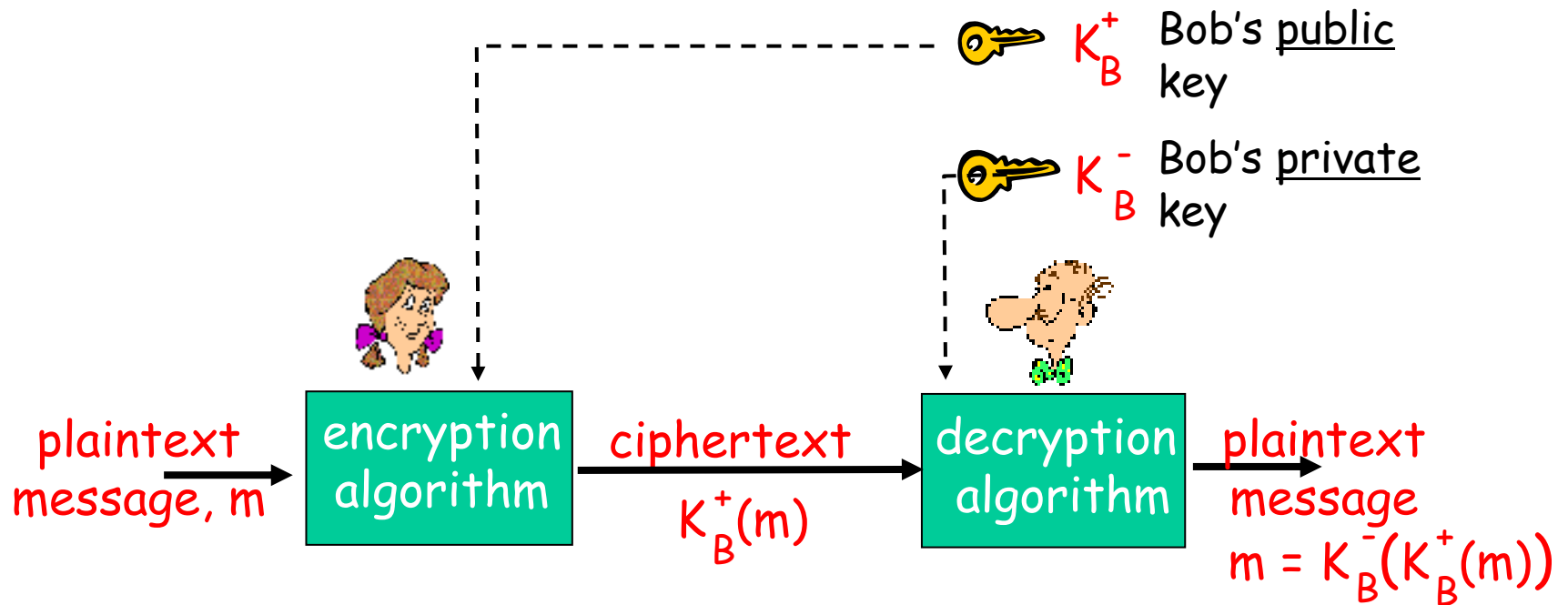
- ❑ requires sender, receiver know shared secret key
- ❑ Q: how to agree on key in first place (particularly if never "met")?

public key 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: Choosing keys

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) .


RSA: Encryption, decryption

0. Given (n,e) and (n,d) as computed above
1. To encrypt bit pattern, m , compute
 $c = m^e \bmod n$ (i.e., remainder when m^e is divided by n)
2. To decrypt received bit pattern, c , compute
 $m = c^d \bmod n$ (i.e., remainder when c^d is divided by 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).

encrypt:

<u>letter</u>	<u>m</u>	<u>m^e</u>	<u>c = m^e mod n</u>
I	12	1524832	17

decrypt:

<u>c</u>	<u>c^d</u>	<u>m = c^d mod n</u>	<u>letter</u>
17	481968572106750915091411825223071697	12	I

RSA: Why is that $m = (m^e \bmod n)^d \bmod n$

Useful number theory result: If p, q prime and $n = pq$, then:

$$x^y \bmod n = x^{y \bmod (p-1)(q-1)} \bmod n$$

$$\begin{aligned} (m^e \bmod n)^d \bmod n &= m^{ed} \bmod n \\ &= m^{ed \bmod (p-1)(q-1)} \bmod n \\ &\quad \text{(using number theory result above)} \\ &= m^1 \bmod n \\ &\quad \text{(since we chose } ed \text{ to be divisible by} \\ &\quad \text{(} p-1)(q-1 \text{) with remainder 1)} \\ &= m \end{aligned}$$

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!

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Authentication

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

Protocol ap1.0: Alice says "I am Alice"



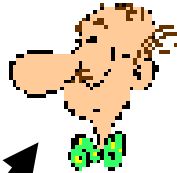
Failure scenario??



Authentication

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Protocol ap1.0: Alice says "I am Alice"

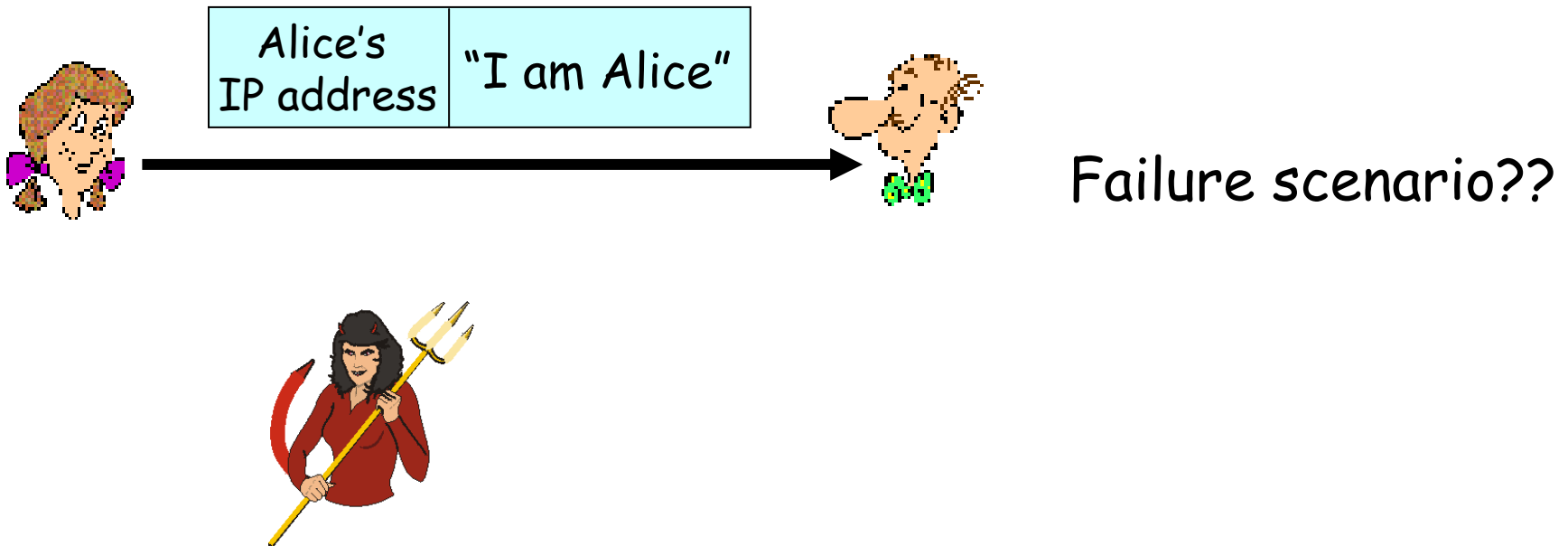


"I am Alice"

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

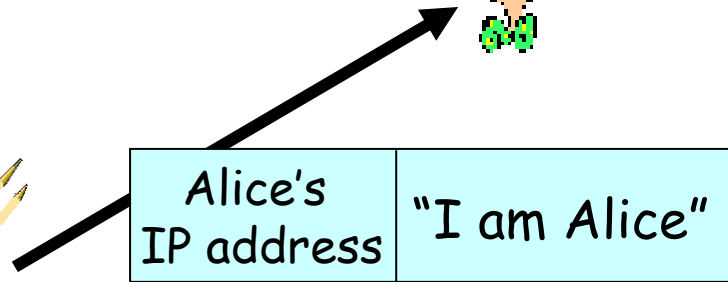
Authentication: another try

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



Authentication: another try

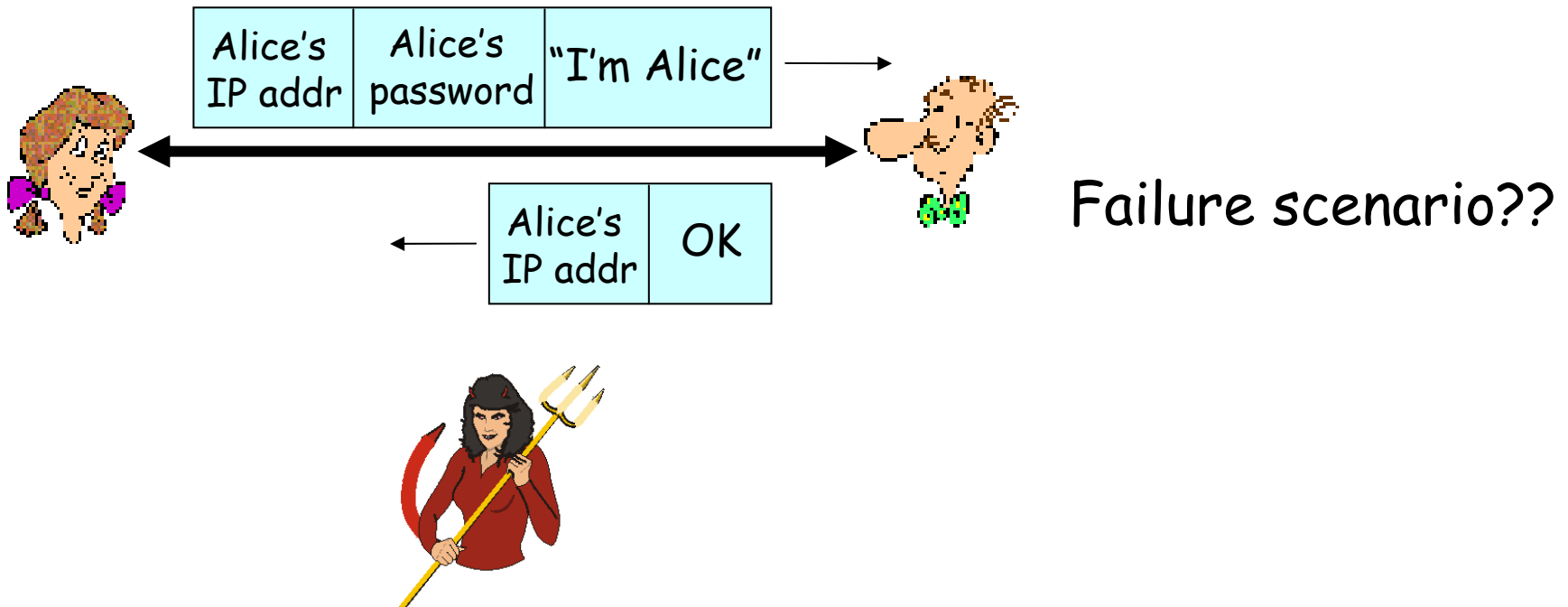
Protocol ap2.0: Alice says "I am Alice" in an IP packet containing her source IP address



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

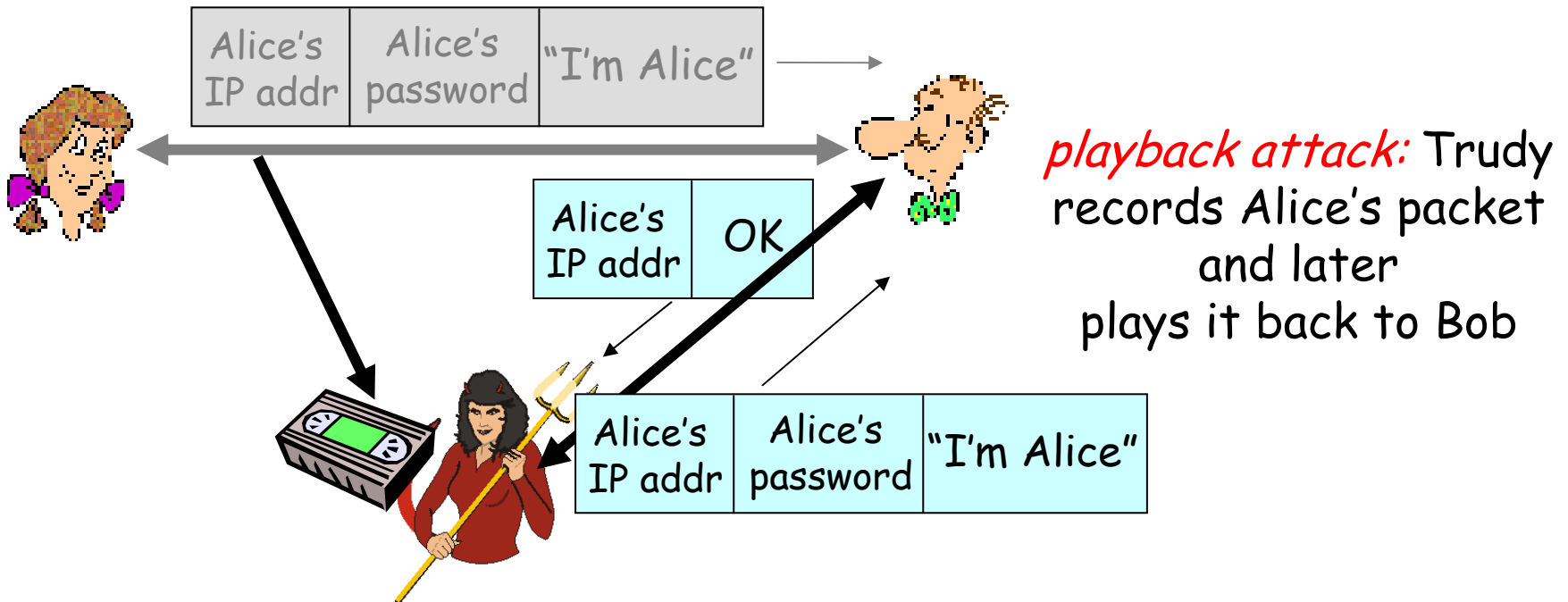
Authentication: another try

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



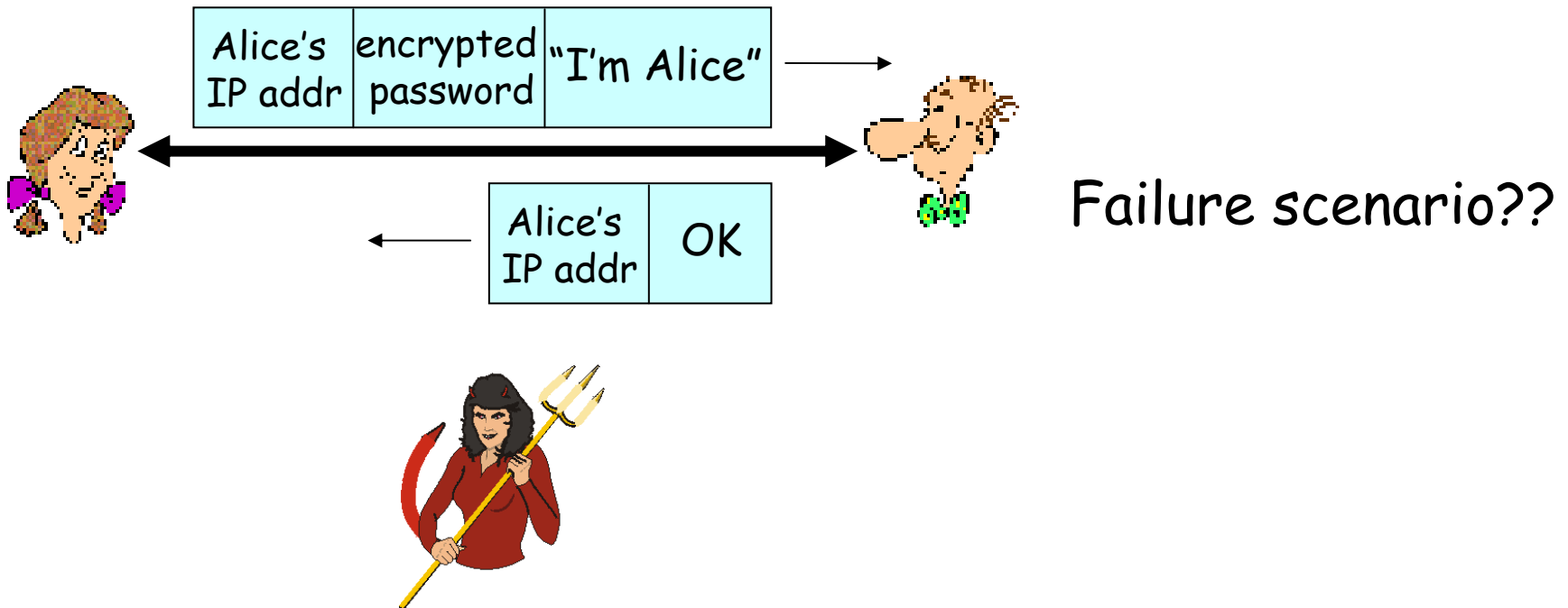
Authentication: another try

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



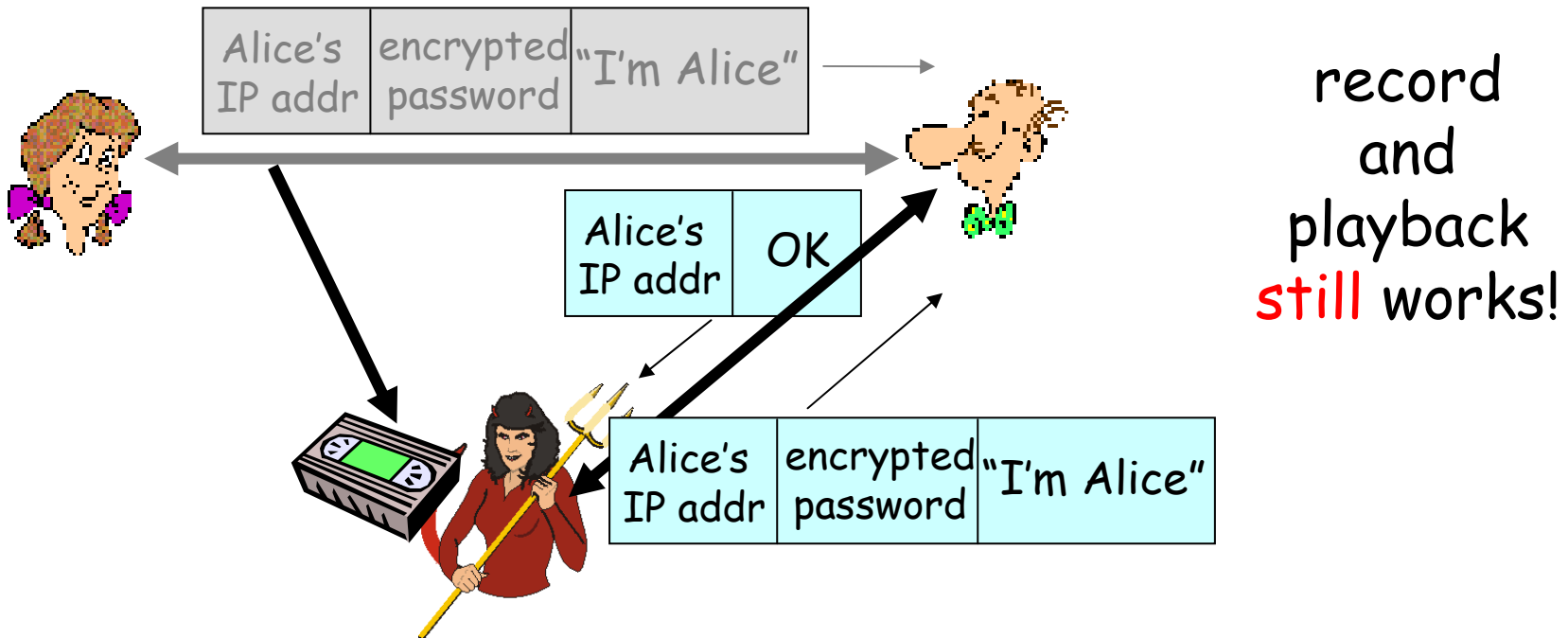
Authentication: yet another try

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



Authentication: another try

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

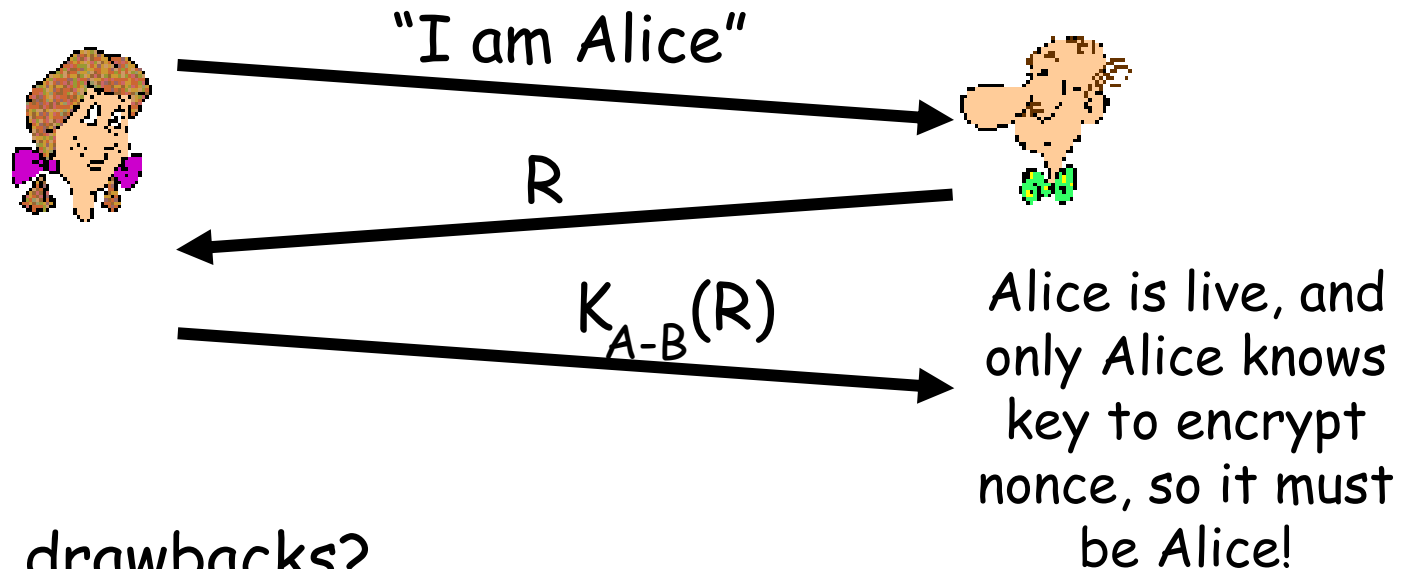


Authentication: yet another try

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



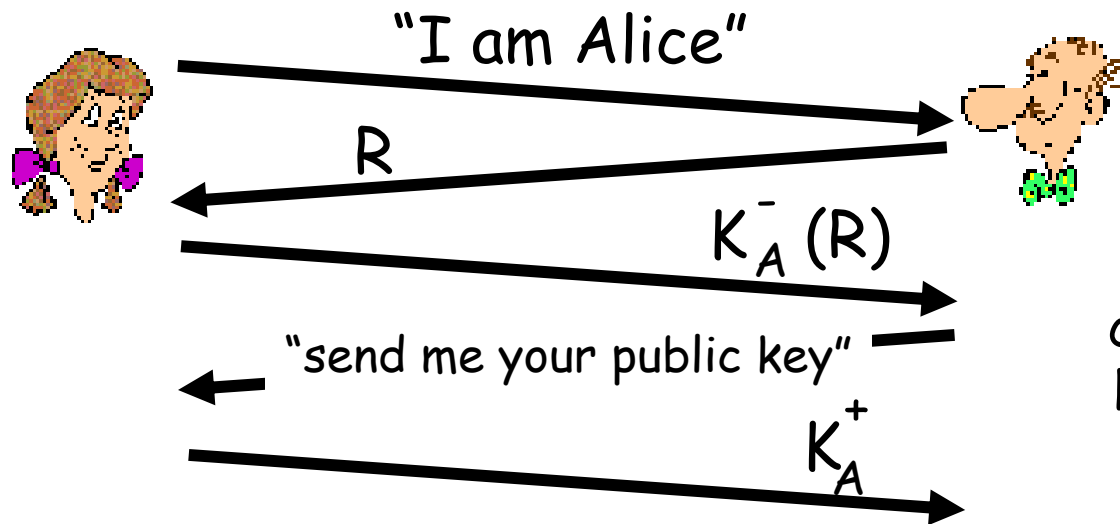
Failures, drawbacks?

Authentication: ap5.0

ap4.0 requires shared symmetric key

□ can we authenticate using public key techniques?

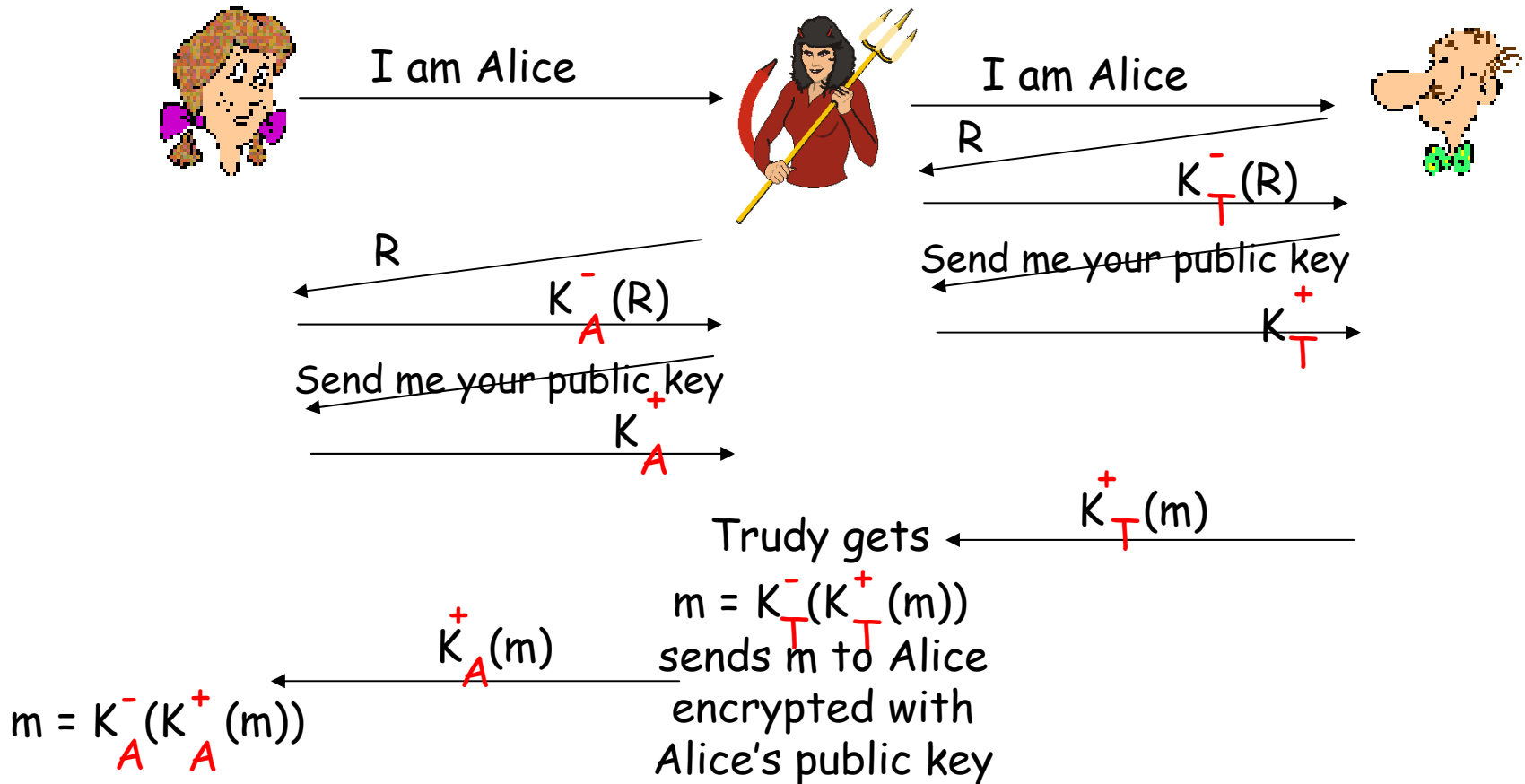
ap5.0: use nonce, public key cryptography



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

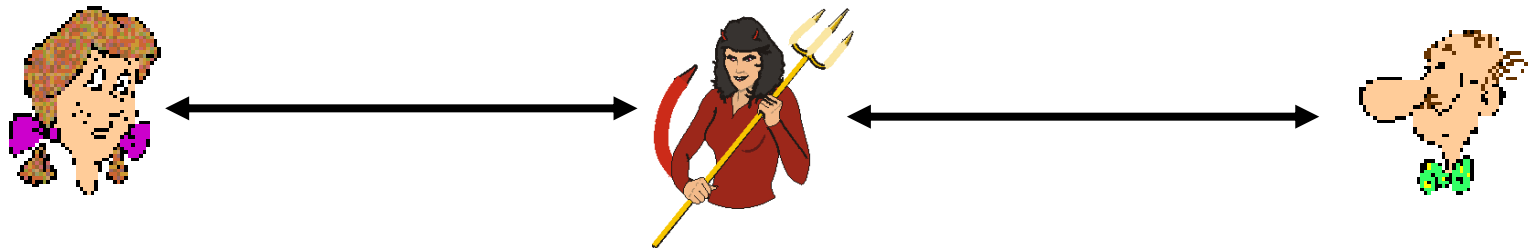
ap5.0: security hole

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



ap5.0: security hole

Man (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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8.4 *Message integrity*

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Digital Signatures

Cryptographic technique analogous to handwritten 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

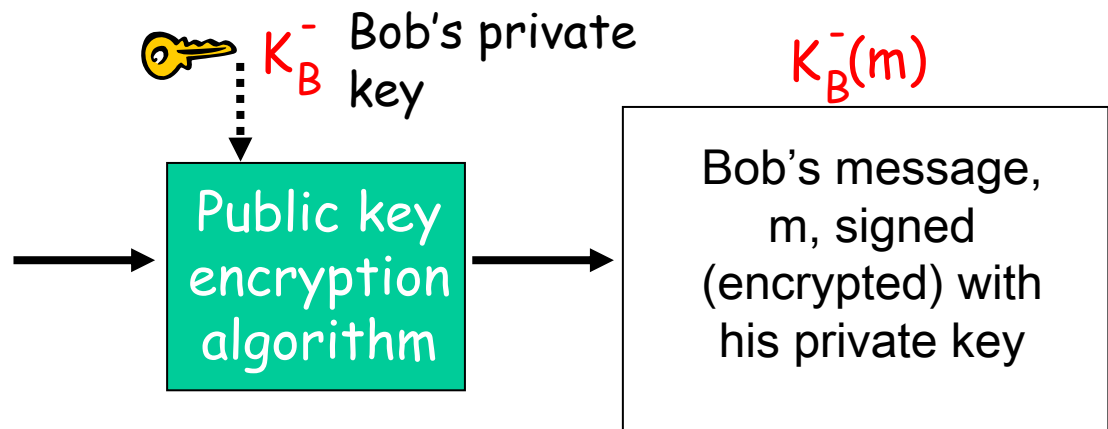
Digital Signatures

Simple digital signature for message m :

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

Bob's message, m

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



Digital Signatures (more)

- Suppose Alice receives msg m , digital signature $K_B^-(m)$
- 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:

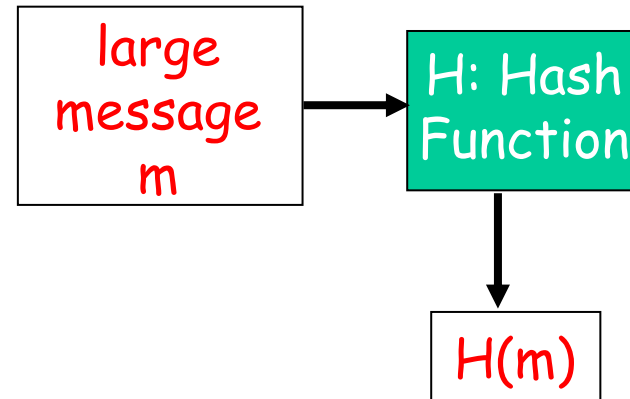
- ✓ Alice can take m , and signature $K_B^-(m)$ to court and prove that Bob signed m .

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

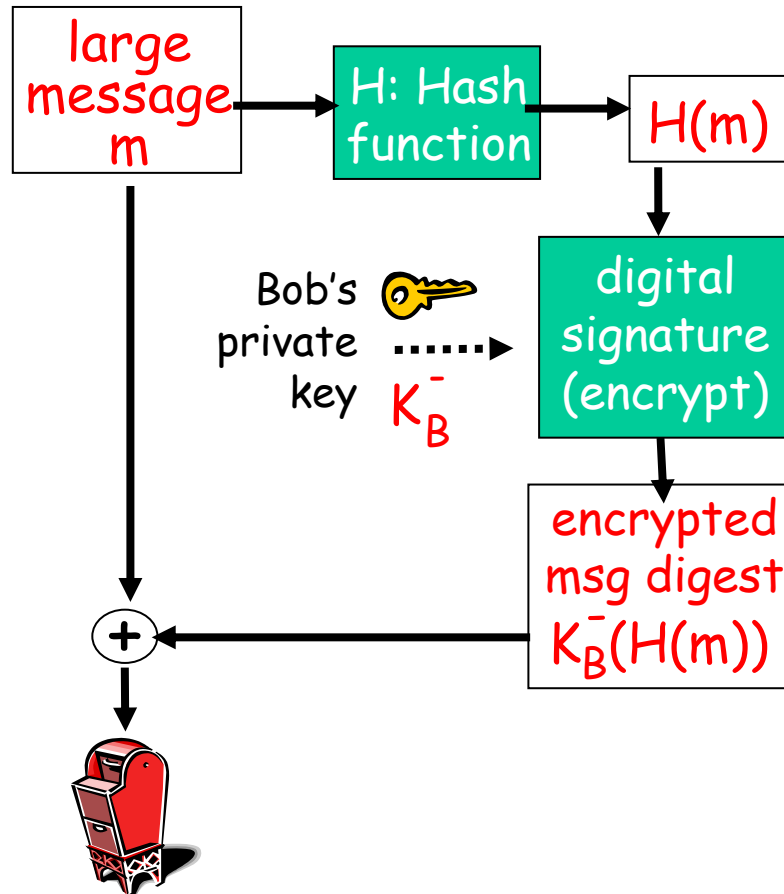
But given message with given hash value, it is easy to find another message with same hash value:

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

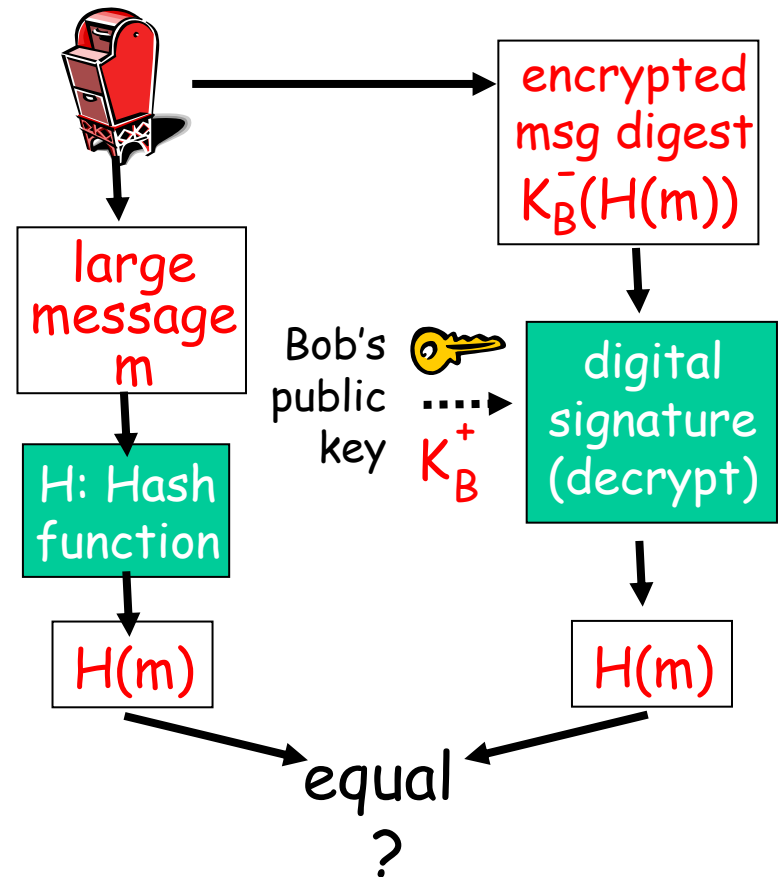
different messages
but identical checksums!

Digital signature = signed message digest

Bob sends digitally signed message:



Alice verifies signature and 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

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Trusted Intermediaries

Symmetric key problem:

- How do two entities establish shared secret key over network?

Solution:

- trusted key distribution center (KDC) acting as intermediary between entities

Public key problem:

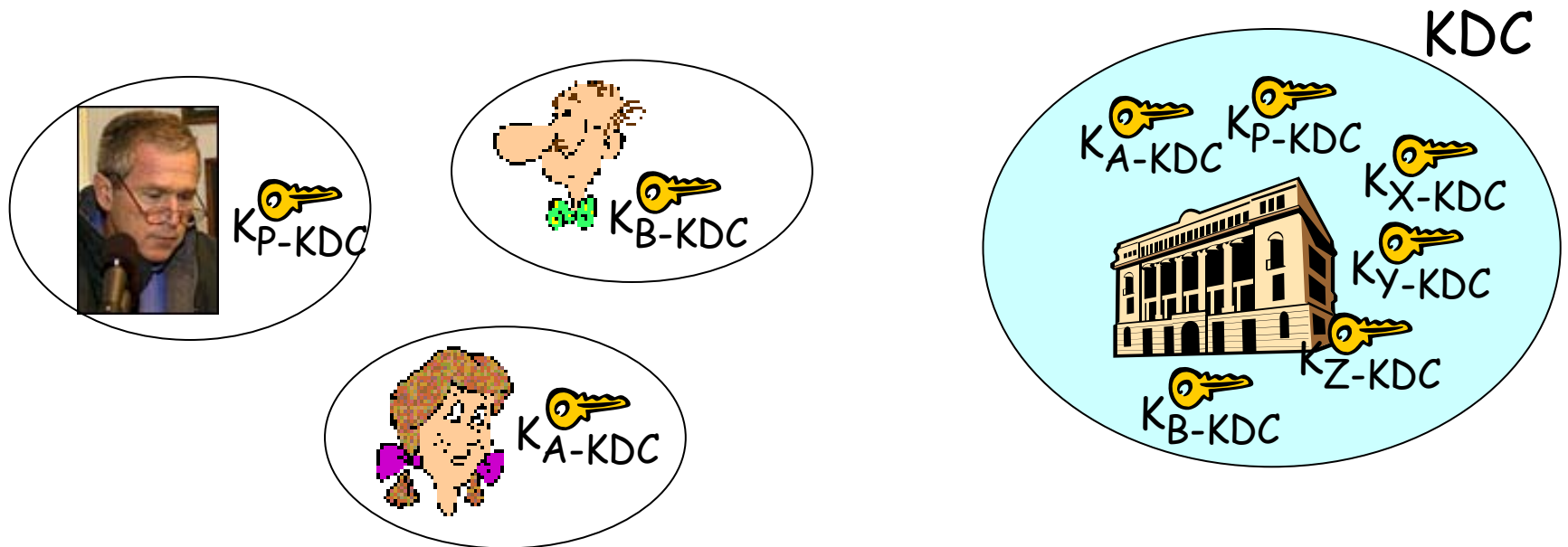
- When Alice obtains Bob's public key (from web site, e-mail, diskette), how does she know it is Bob's public key, not Trudy's?

Solution:

- trusted certification authority (CA)

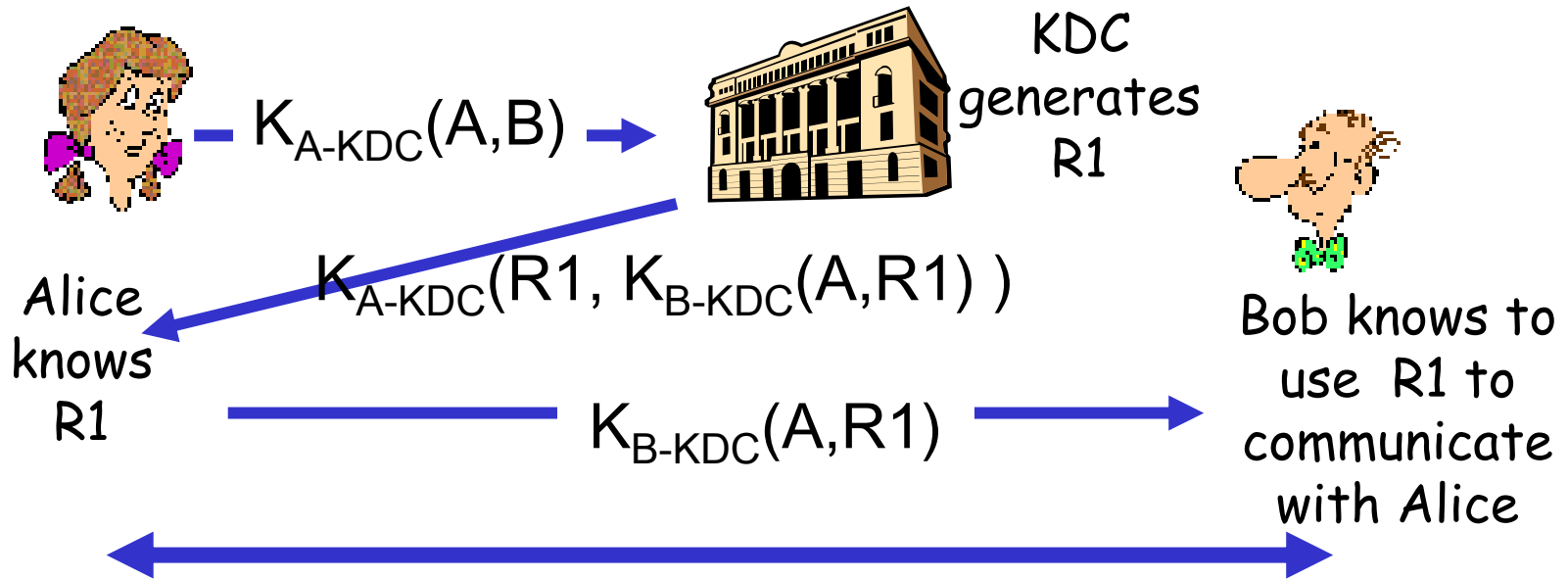
Key Distribution Center (KDC)

- Alice, Bob need shared symmetric key.
- **KDC**: server shares different secret key with *each* registered user (many users)
- Alice, Bob know own symmetric keys, K_{A-KDC} K_{B-KDC} , for communicating with KDC.



Key Distribution Center (KDC)

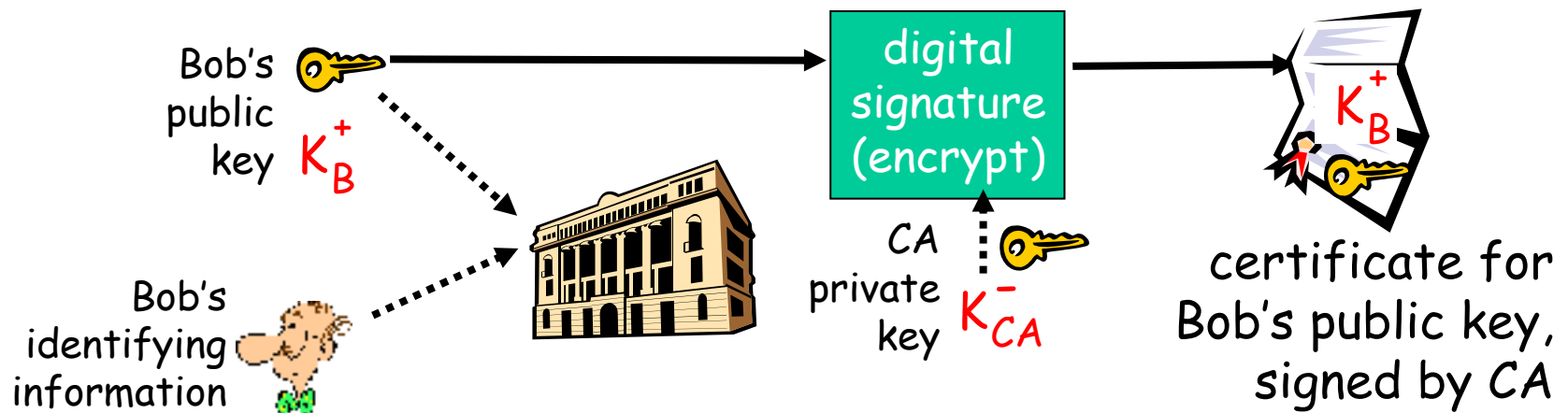
Q: How does KDC allow Bob, Alice to determine shared symmetric secret key to communicate with each other?



Alice and Bob communicate: using R1 as *session key* for shared symmetric encryption

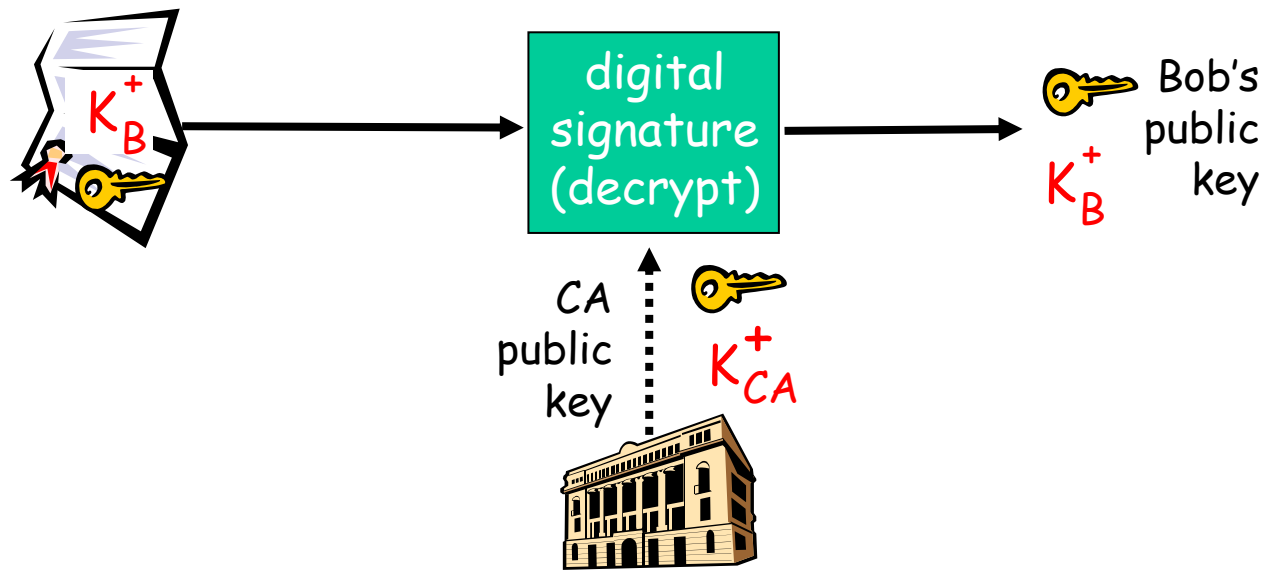
Certification Authorities

- ❑ **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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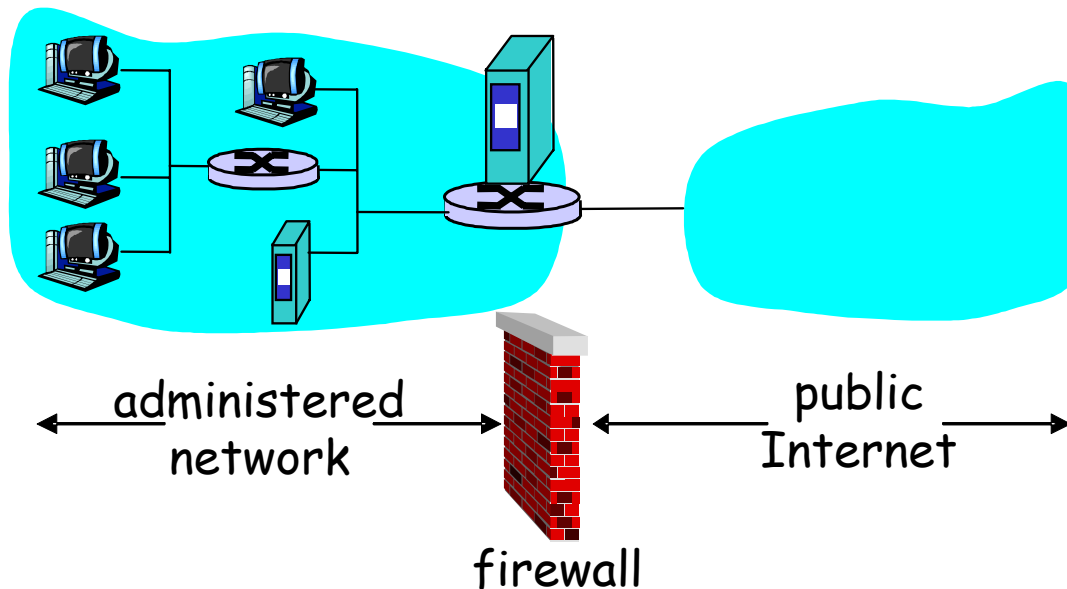
8.7 Attacks and counter measures

8.8 Security in many layers

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)

two types of firewalls:

- application-level
- packet-filtering

Packet Filtering

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

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.

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Internet security threats

Mapping:

- before attacking: "case the joint" - find out what services are implemented on network
- Use `ping` to determine what hosts have addresses on network
- Port-scanning: try to establish TCP connection to each port in sequence (see what happens)
- `nmap` (<http://www.insecure.org/nmap/>) mapper: "network exploration and security auditing"

Countermeasures?

Internet security threats

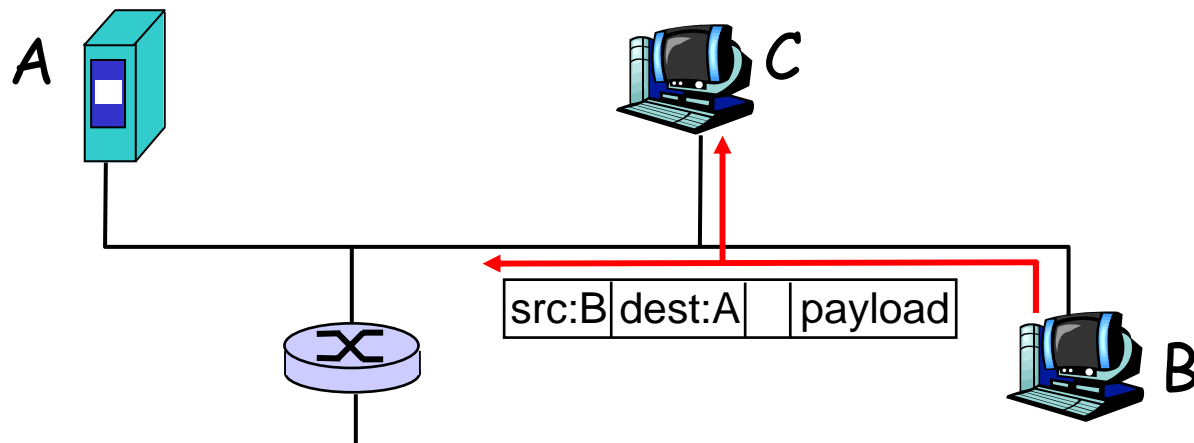
Mapping: countermeasures

- record traffic entering network
- look for suspicious activity (IP addresses, ports being scanned sequentially)

Internet security threats

Packet sniffing:

- broadcast media
- promiscuous NIC reads all packets passing by
- can read all unencrypted data (e.g. passwords)
- e.g.: C sniffs B's packets

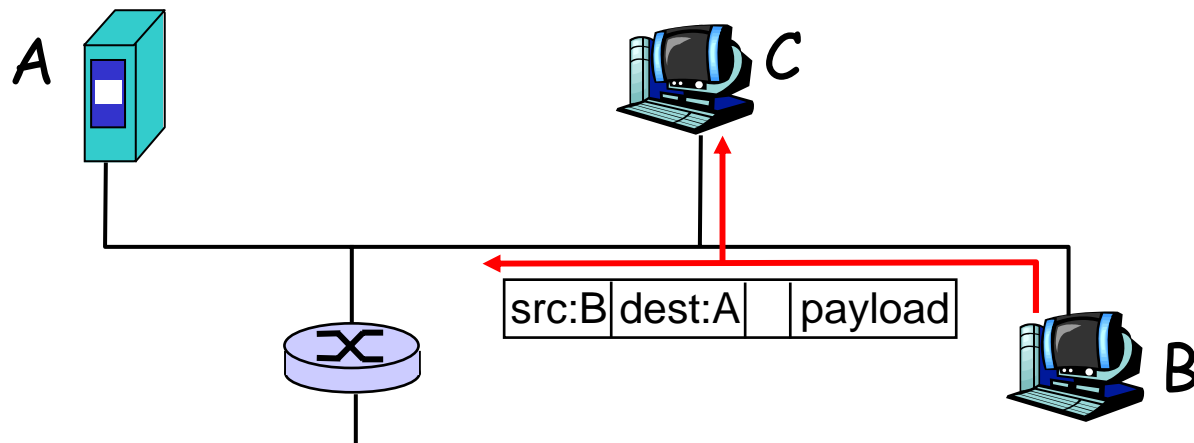


Countermeasures?

Internet security threats

Packet sniffing: countermeasures

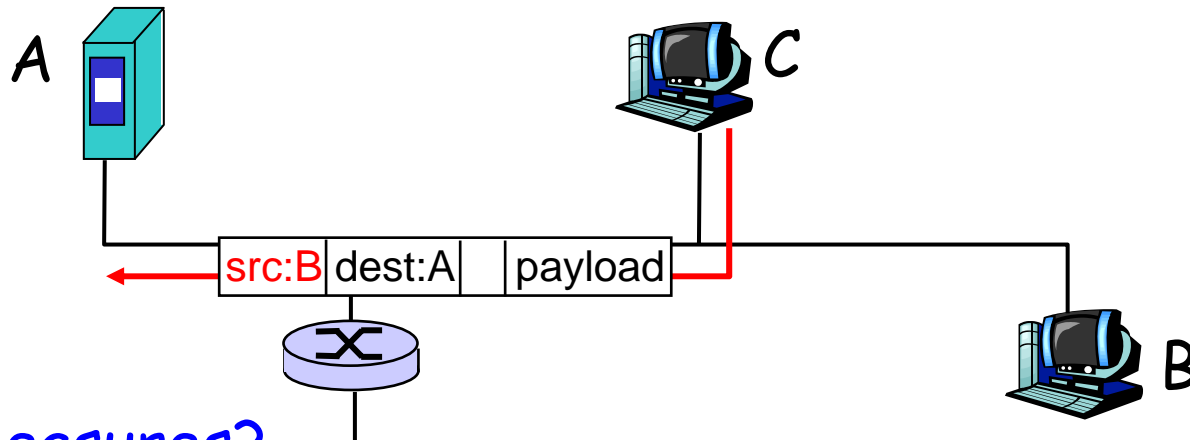
- all hosts in organization run software that checks periodically if host interface in promiscuous mode.
- one host per segment of broadcast media (switched Ethernet at hub)



Internet security threats

IP Spoofing:

- can generate "raw" IP packets directly from application, putting any value into IP source address field
- receiver can't tell if source is spoofed
- e.g.: C pretends to be B

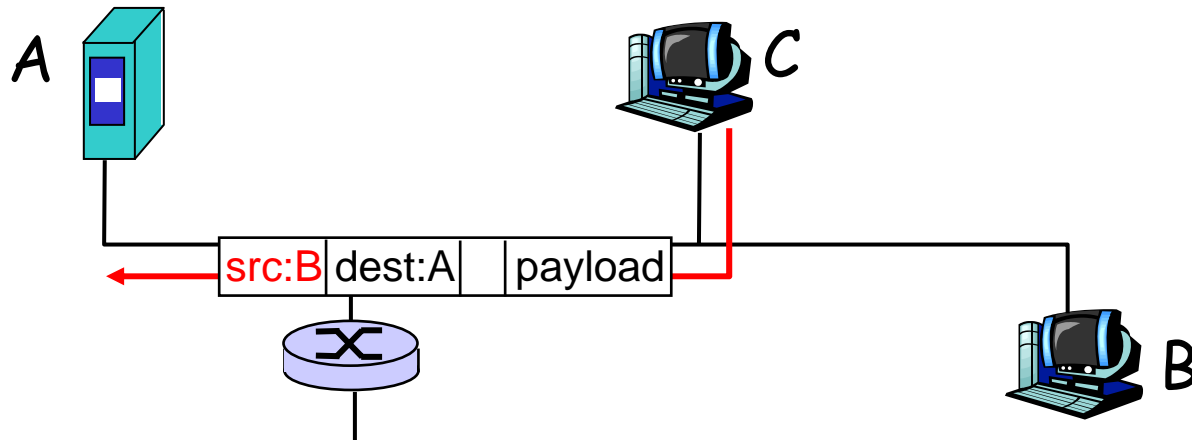


Countermeasures?

Internet security threats

IP Spoofing: ingress filtering

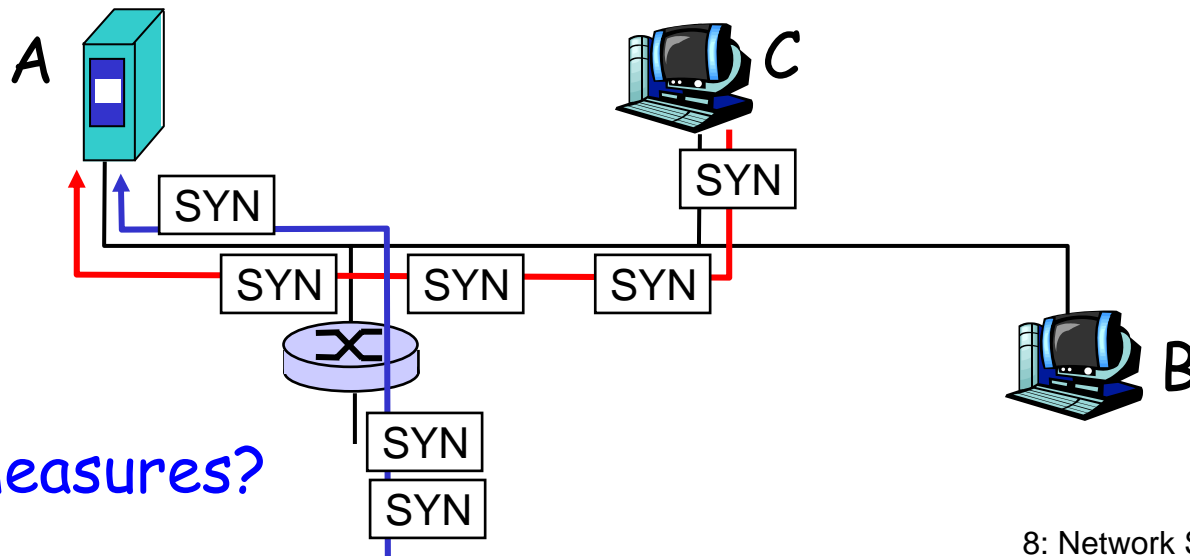
- routers should not forward outgoing packets with invalid source addresses (e.g., datagram source address not in router's network)
- great, but ingress filtering can not be mandated for all networks



Internet security threats

Denial of service (DOS):

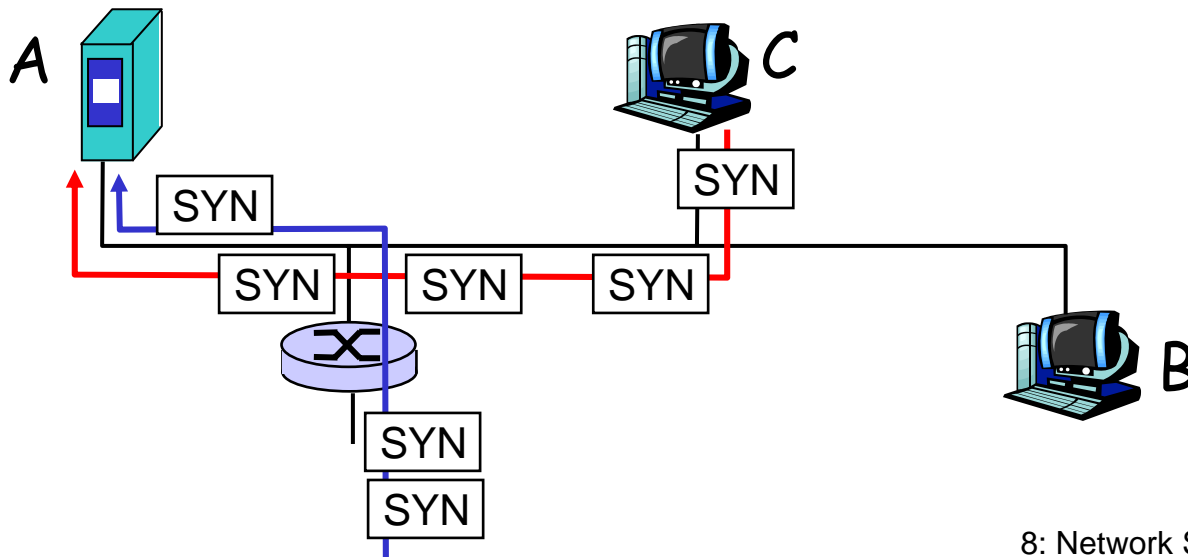
- flood of maliciously generated packets "swamp" receiver
- Distributed DOS (DDOS): multiple coordinated sources swamp receiver
- e.g., C and remote host SYN-attack A



Internet security threats

Denial of service (DOS): countermeasures

- filter out flooded packets (e.g., SYN) before reaching host: throw out good with bad
- **traceback** to source of floods (most likely an innocent, compromised machine)



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- 8.4 Integrity
- 8.5 Key Distribution and certification
- 8.6 Access control: firewalls
- 8.7 Attacks and counter measures
- 8.8 Security in many layers
 - 8.8.1. Secure email
 - 8.8.2. Secure sockets
 - 8.8.3. IPsec
 - 8.8.4. Security in 802.11

Pretty good privacy (PGP)

- ❑ Internet e-mail encryption scheme, de-facto standard.
- ❑ uses symmetric key cryptography, public key cryptography, hash function, and digital signature as described.
- ❑ provides secrecy, sender authentication, integrity.
- ❑ inventor, Phil Zimmerman, was target of 3-year federal investigation.

A PGP signed message:

```
---BEGIN PGP SIGNED MESSAGE---  
Hash: SHA1  
  
Bob:My husband is out of town  
    tonight.Passionately yours,  
    Alice  
  
---BEGIN PGP SIGNATURE---  
Version: PGP 5.0  
Charset: noconv  
yhHJRHhGJGhgg/12EpJ+1o8gE4vB3mqJ  
    hFEvZP9t6n7G6m5Gw2  
---END PGP SIGNATURE---
```

Secure sockets layer (SSL)

- ❑ transport layer security to any TCP-based app using SSL services.
- ❑ used between Web browsers, servers for e-commerce (shttp).
- ❑ security services:
 - server authentication
 - data encryption
 - client authentication (optional)

- ❑ server authentication:
 - SSL-enabled browser includes public keys for trusted CAs.
 - Browser requests server certificate, issued by trusted CA.
 - Browser uses CA's public key to extract server's public key from certificate.
- ❑ check your browser's security menu to see its trusted CAs.

SSL (continued)

Encrypted SSL session:

- ❑ Browser generates *symmetric session key*, encrypts it with server's public key, sends encrypted key to server.
- ❑ Using private key, server decrypts session key.
- ❑ Browser, server know session key
 - All data sent into TCP socket (by client or server) encrypted with session key.
- ❑ SSL: basis of IETF Transport Layer Security (TLS).
- ❑ SSL can be used for non-Web applications, e.g., IMAP.
- ❑ Client authentication can be done with client certificates.

IPsec: Network Layer Security

- **Network-layer secrecy:**
 - sending host encrypts the data in IP datagram
 - TCP and UDP segments; ICMP and SNMP messages.
- **Network-layer authentication**
 - destination host can authenticate source IP address
- **Two principle protocols:**
 - authentication header (AH) protocol
 - encapsulation security payload (ESP) protocol
- **For both AH and ESP, source, destination handshake:**
 - create network-layer logical channel called a security association (SA)
- **Each SA unidirectional.**
- **Uniquely determined by:**
 - security protocol (AH or ESP)
 - source IP address
 - 32-bit connection ID

Authentication Header (AH) Protocol

- ❑ provides source authentication, data integrity, no confidentiality
- ❑ AH header inserted between IP header, data field.
- ❑ protocol field: 51
- ❑ intermediate routers process datagrams as usual

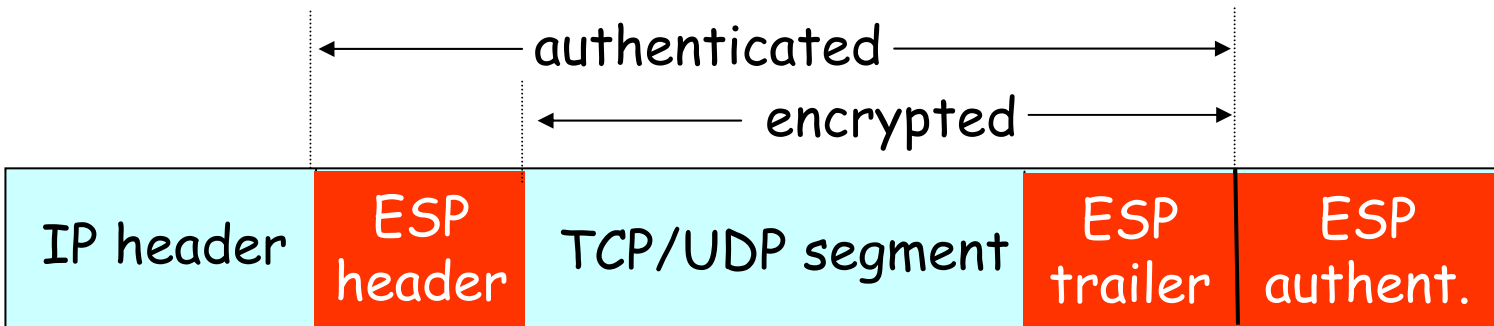
AH header includes:

- ❑ connection identifier
- ❑ authentication data: source- signed message digest calculated over original IP datagram.
- ❑ next header field: specifies type of data (e.g., TCP, UDP, ICMP)



ESP Protocol

- ❑ provides secrecy, host authentication, data integrity.
- ❑ data, ESP trailer encrypted.
- ❑ next header field is in ESP trailer.
- ❑ ESP authentication field is similar to AH authentication field.
- ❑ Protocol = 50.



IEEE 802.11 security

- *War-driving*: drive around Bay area, see what 802.11 networks available?
 - More than 9000 accessible from public roadways
 - 85% use no encryption/authentication
 - packet-sniffing and various attacks easy!
- *Securing 802.11*
 - encryption, authentication
 - first attempt at 802.11 security: Wired Equivalent Privacy (WEP): a failure
 - current attempt: 802.11i

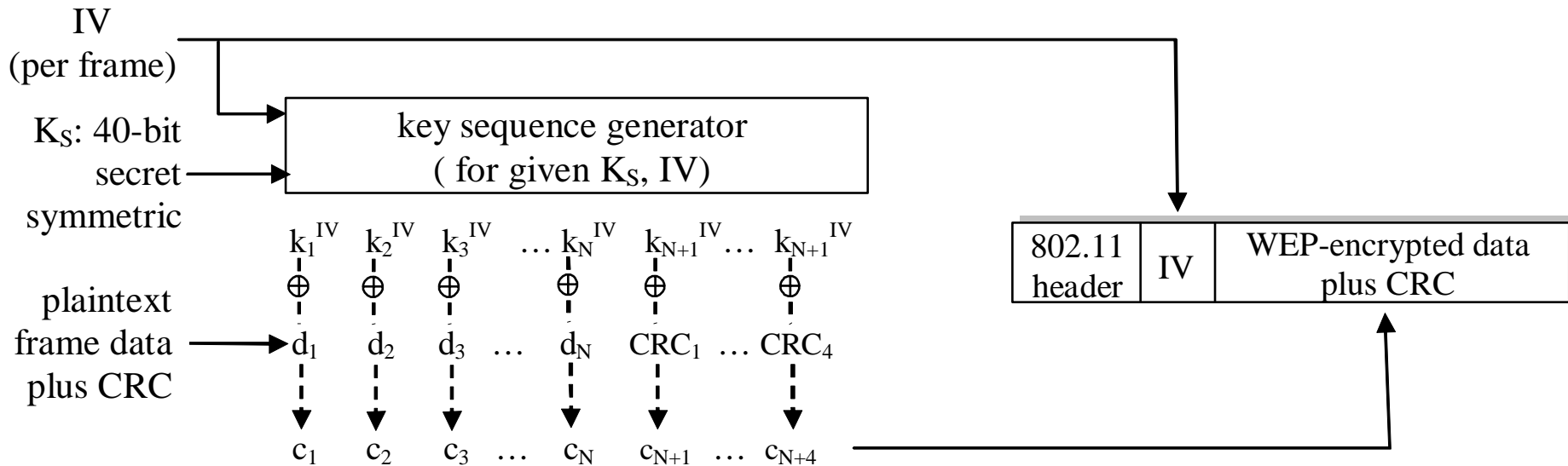
Wired Equivalent Privacy (WEP):

- ❑ authentication as in protocol *ap4.0*
 - host requests authentication from access point
 - access point sends 128 bit nonce
 - host encrypts nonce using shared symmetric key
 - access point decrypts nonce, authenticates host
- ❑ no key distribution mechanism
- ❑ authentication: knowing the shared key is enough

WEP data encryption

- ❑ Host/AP share 40 bit symmetric key (semi-permanent)
- ❑ Host appends 24-bit initialization vector (IV) to create 64-bit key
- ❑ 64 bit key used to generate stream of keys, k_i^{IV}
- ❑ k_i^{IV} used to encrypt ith byte, d_i , in frame:
$$c_i = d_i \text{ XOR } k_i^{\text{IV}}$$
- ❑ IV and encrypted bytes, c_i sent in frame

802.11 WEP encryption



Sender-side WEP encryption

Breaking 802.11 WEP encryption

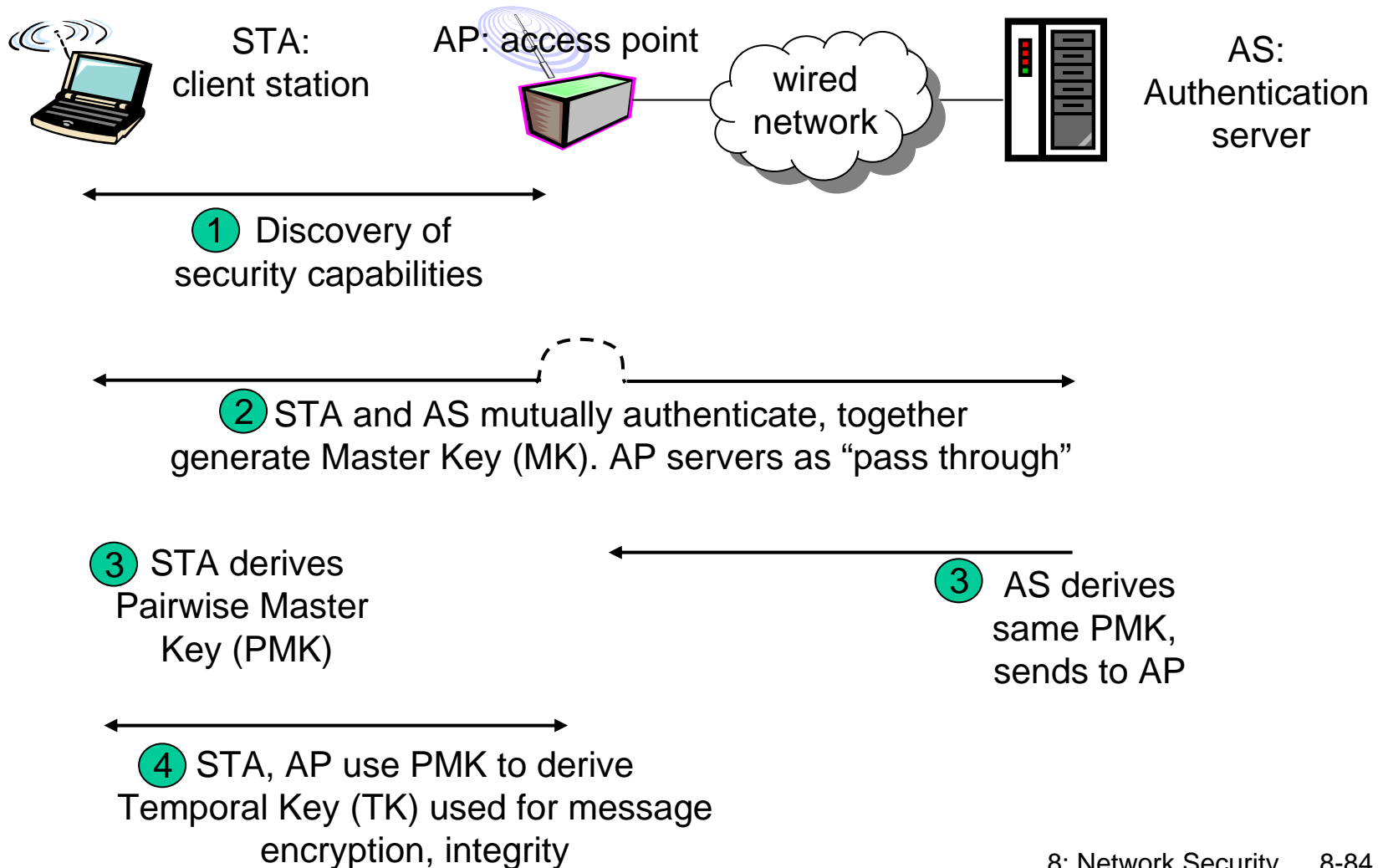
Security hole:

- ❑ 24-bit IV, one IV per frame, -> IV's eventually reused
- ❑ IV transmitted in plaintext -> IV reuse detected
- ❑ **Attack:**
 - Trudy causes Alice to encrypt known plaintext $d_1 d_2 d_3 d_4 \dots$
 - Trudy sees: $c_i = d_i \text{ XOR } k_i^{\text{IV}}$
 - Trudy knows $c_i d_i$, so can compute k_i^{IV}
 - Trudy knows encrypting key sequence $k_1^{\text{IV}} k_2^{\text{IV}} k_3^{\text{IV}} \dots$
 - Next time IV is used, Trudy can decrypt!

802.11i: improved security

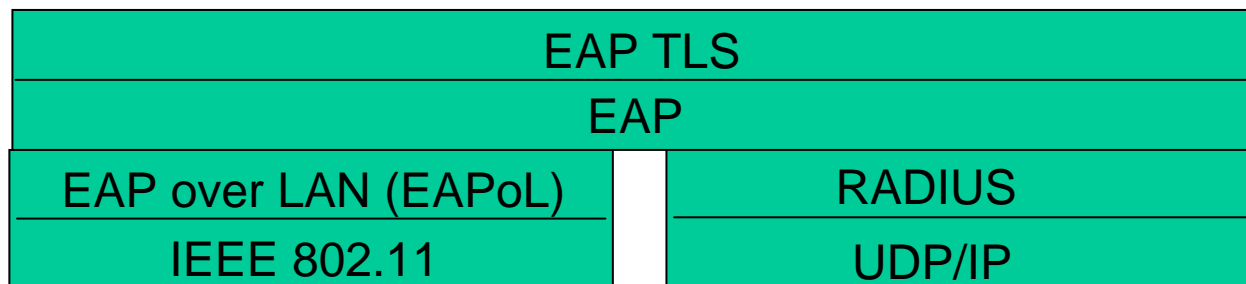
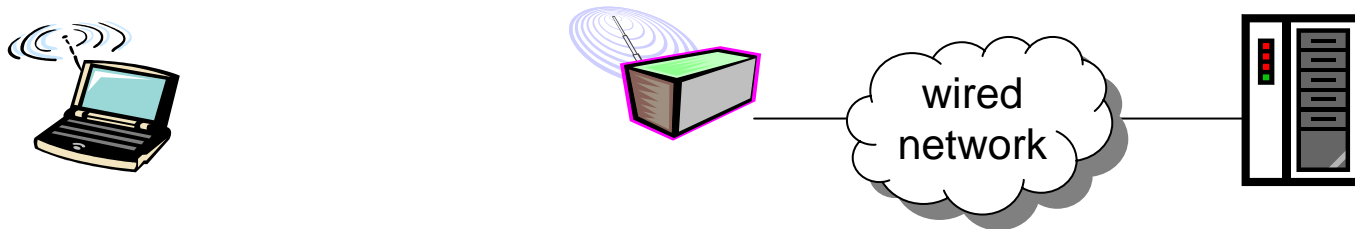
- ❑ numerous (stronger) forms of encryption possible
- ❑ provides key distribution
- ❑ uses authentication server separate from access point

802.11i: four phases of operation



EAP: extensible authentication protocol

- EAP: end-end client (mobile) to authentication server protocol
- EAP sent over separate "links"
 - mobile-to-AP (EAP over LAN)
 - AP to authentication server (RADIUS over UDP)



Network Security (summary)

Basic techniques.....

- cryptography (symmetric and public)
- authentication
- message integrity
- key distribution

.... used in many different security scenarios

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