COMP 3331/9331: Computer Networks and Applications

Week 10

Network Security

Reading Guide: Chapter 8: 8.1 – 8.5

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Network Security: Overview

Our goals:

- understand principles of network security:
  - cryptography and its *many* uses beyond "confidentiality"
  - authentication
  - message integrity

Network Security: roadmap

8.1 What is network security?

8.2 Principles of cryptography

8.3 Message integrity

8.4 Authentication

8.5 Securing email

8.6 - 8.9 SSL, IPSec, Firewall/IDS **- not covered.**

There are several security electives offered

What is network security?

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

- sender encrypts message
- receiver decrypts message

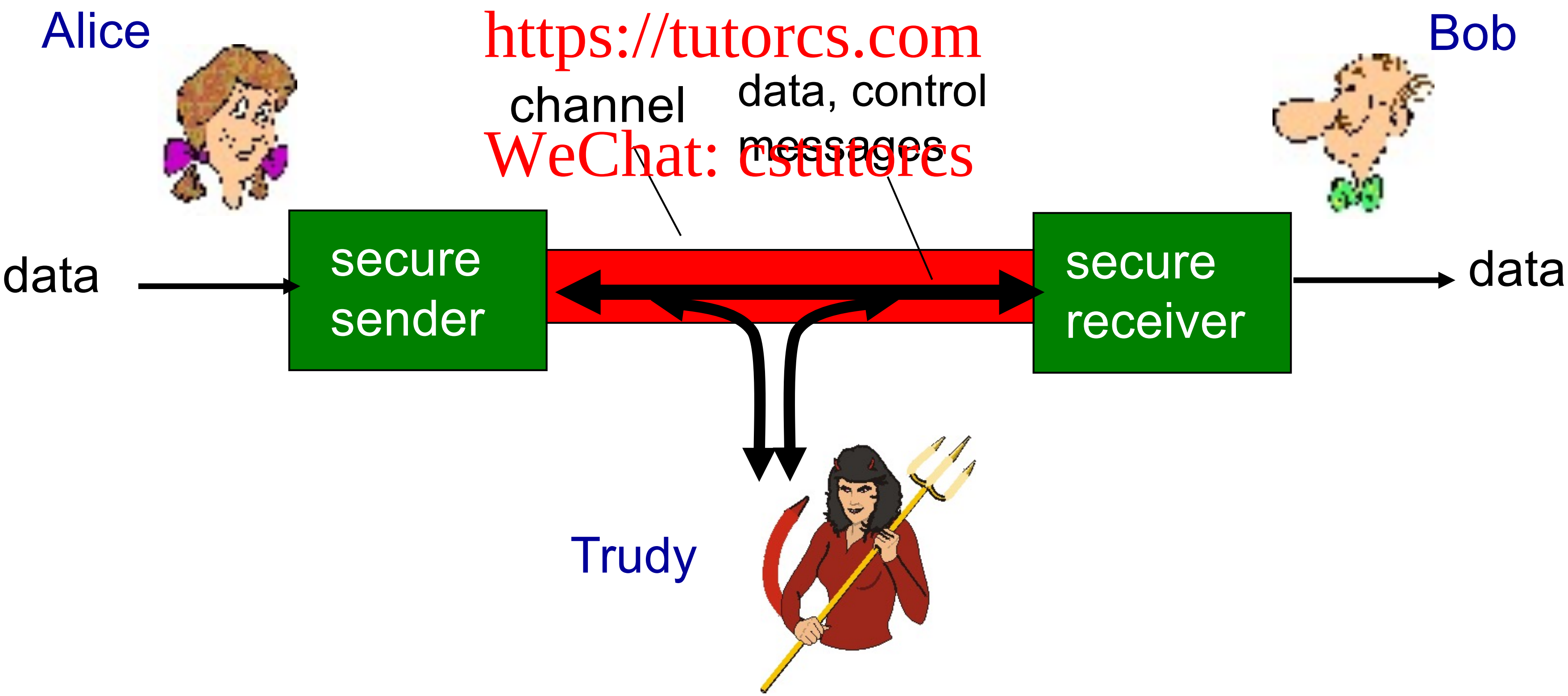
authentication: sender, receiver want to confirm identity of each other

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 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
- etc.

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)

Network Security: roadmap

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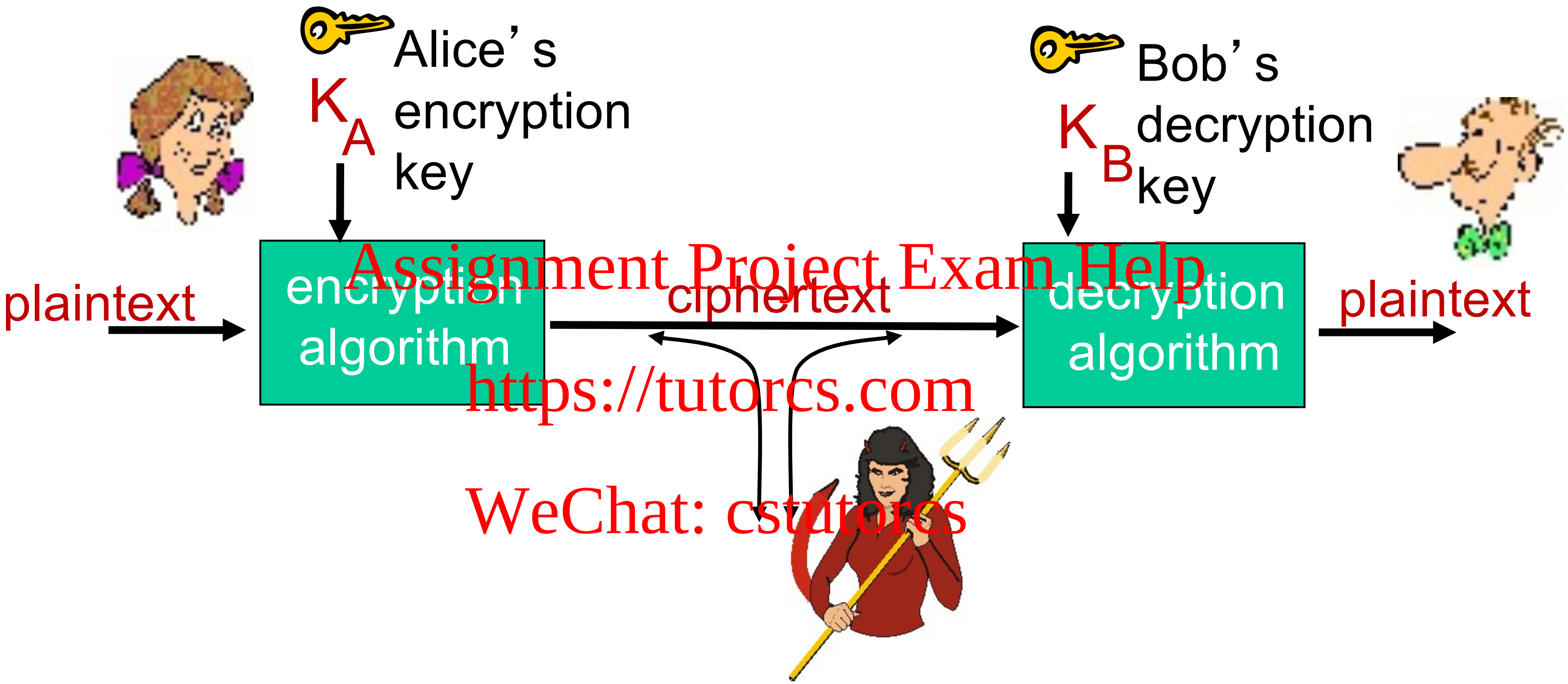
The language of cryptography

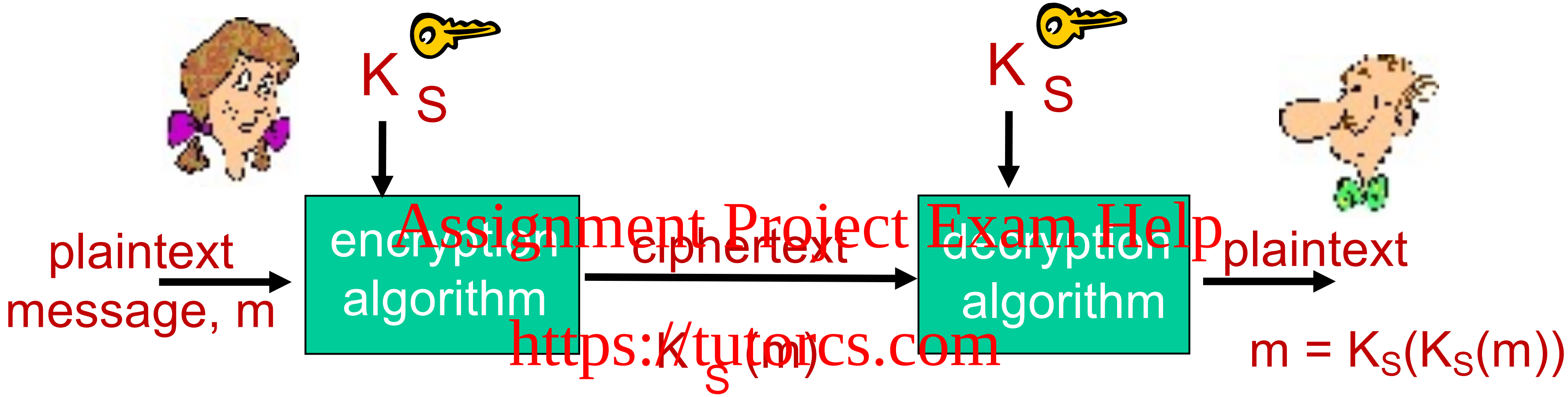


m plaintext message

$K_A(m)$ 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

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

Simple encryption scheme

substitution cipher: substituting one thing for another

- monoalphabetic cipher: substitute one letter for another
- Ceaser Cipher: replace each letter of the alphabet with the letter standing three places further down the alphabet.

Plain : a b c d e f g h i j k l m n o p q r s t u v w x y z
cipher: d e f g h i j k l m n o p q r s t u v w x y z a b c

e.g.: **Plaintext: meet me after the party**

ciphertext: phhw ph diwhu wkh sduwb

Encryption key: $c = (p+3) \bmod 26$

Each plaintext letter p substituted by the ciphertext letter c
In general, we have $c = (p+k)$ mode 26
where k is in range 1 to 25

Simple encryption scheme

- With only 25 possible keys, the Caeser cipher is vulnerable to brute force cryptanalysis
- Cipher can be any permutation of the 26 alphabet characters


```
plaintext:   abcdefghijklmnopqrstuvwxyz
ciphertext:  mnbvcxzasdfghjklpoiuytrewq
```


e.g.:

```
 Plaintext: bob. i love you. alice
ciphertext: nkn. s gktc wky. mgsbc
```

Encryption key: mapping from set of 26 letters to set of 26 letters

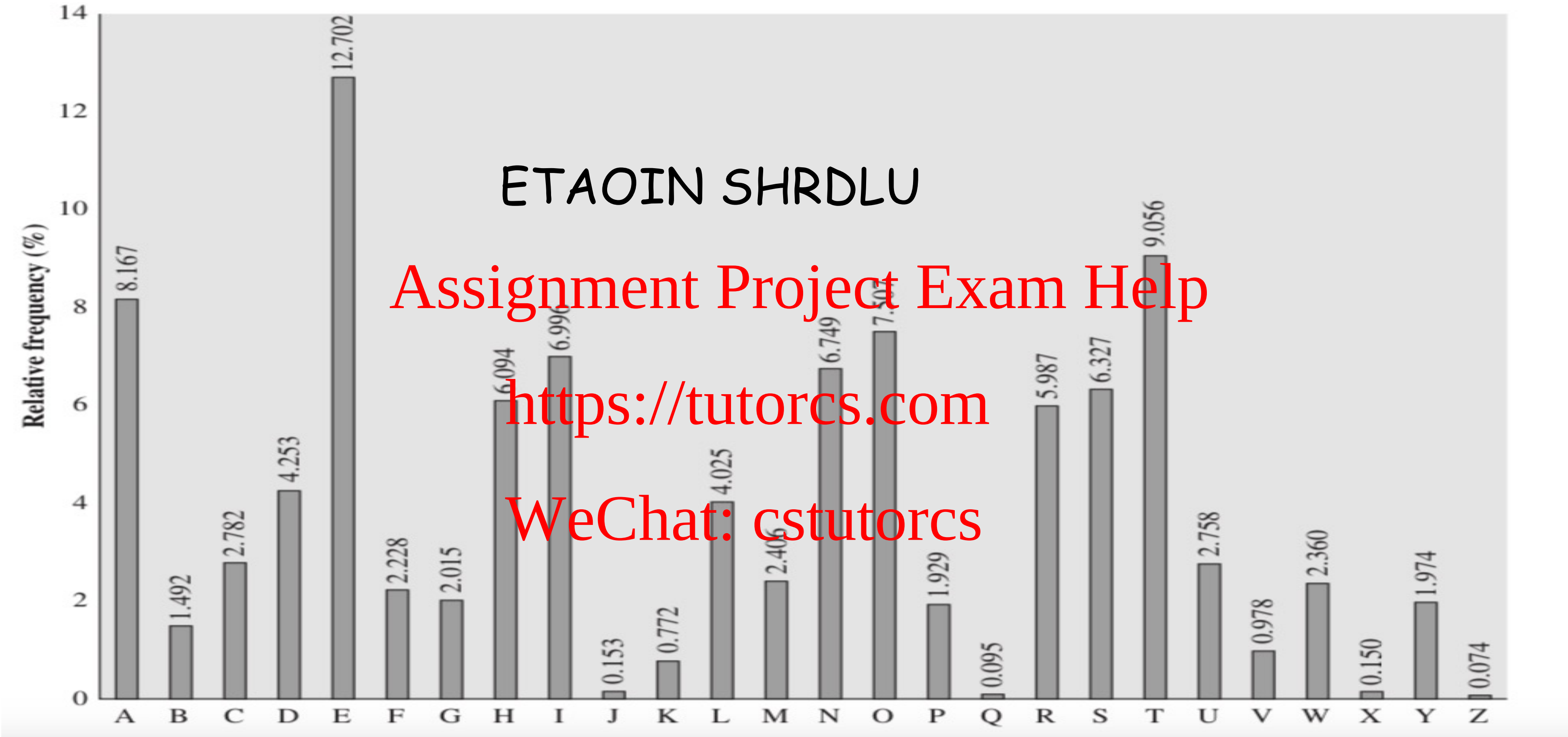
We have 26! (> 4 x10^{26}) possible keys

Breaking an encryption scheme

- cipher-text only attack: Trudy has ciphertext she can analyze
- two approaches:
  - brute force: search through all keys
  - statistical analysis

- known-plaintext attack: Trudy has (part of) plaintext corresponding to ciphertext
  - e.g., in monoalphabetic cipher, Trudy determines pairings for a,l,i,c,e,b,o,b
- chosen-plaintext attack: Trudy can get ciphertext for chosen plaintext

Breaking an encryption scheme



Frequency Histogram Analysis for letters in English language

Monoalphabetic ciphers are easy to break because they reflect the frequency data of the original alphabet

A more sophisticated encryption approach

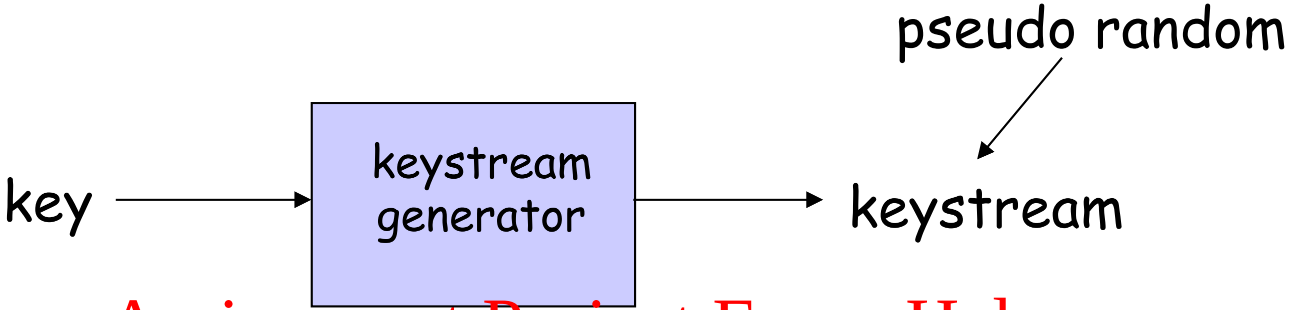
- Polyalphabet ciphers
- n substitution ciphers, $M_1, M_2, \ldots, M_n$
- cycling pattern:
  - e.g., n=4: and key is M_1, M_3, M_4, M_3, M_2; M_1, M_3, M_4, M_3, M_2; ..
- for each new plaintext symbol, use subsequent subsitution pattern in cyclic pattern
  - dog: d from M_1, o from M_3, g from M_4

Encryption key: n substitution ciphers, and cyclic pattern

Two types of symmetric ciphers

- **Stream ciphers**
  - encrypt one bit at time
- **Block ciphers**
  - Break plaintext message in equal-size blocks
  - Encrypt each block as a unit

Stream Ciphers



- Combine each bit of keystream with bit of plaintext to get bit of ciphertext
- m(i) = ith bit of message
- ks(i) = ith bit of keystream
- c(i) = ith bit of ciphertext
- c(i) = ks(i) ⊕ m(i) (⊕ = exclusive or)
- m(i) = ks(i) ⊕ c(i)

RC4 Stream Cipher

- RC4 is a popular stream cipher
  - Extensively analyzed and considered good
  - Key can be from 1 to 256 bytes
  - Used in WEP for 802.11
  - Known to have vulnerabilities
  - Many other alternatives: ChaCha, SOBER, SEAL, …

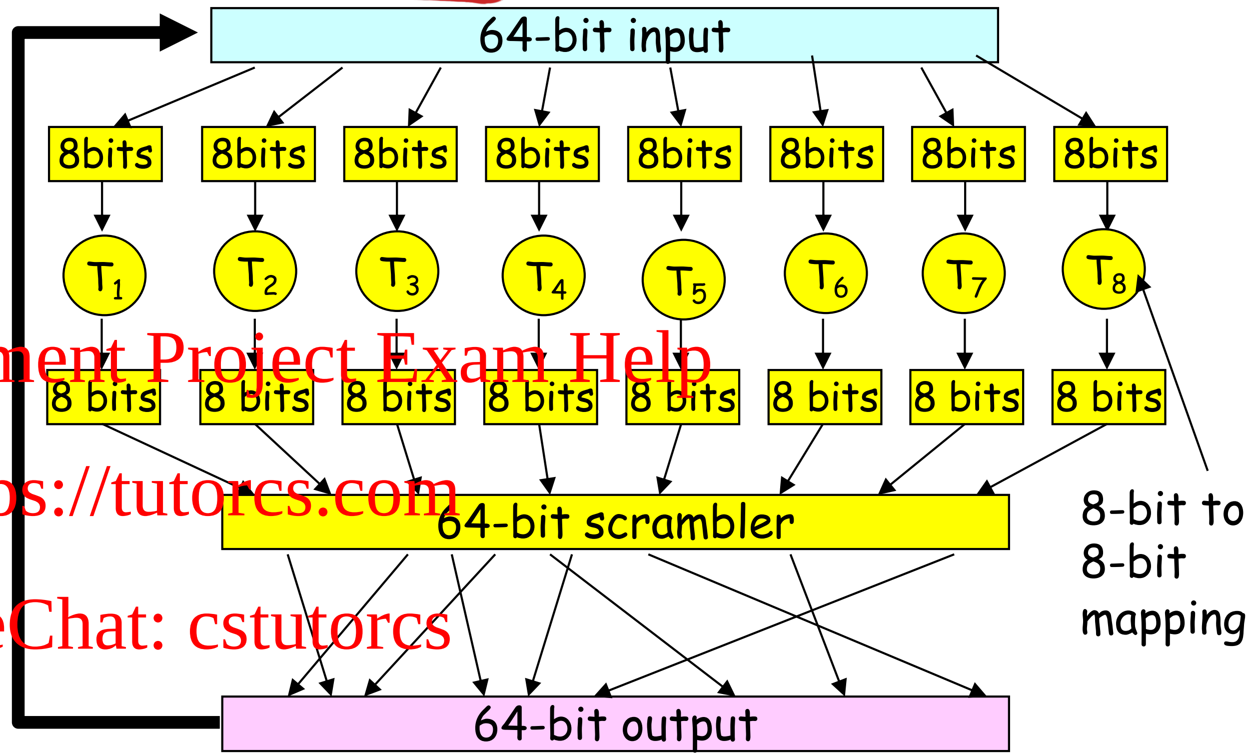
Block Cipher

- Ciphertext processed as *k* bit blocks
- 1-to-1 mapping is used to map k-bit block of plaintext to k-bit block of ciphertext
- E.g: k=3 (see table)
  - 010110001111 => 101000111001
- Possible permutations = 8! (40,320)
- To prevent brute force attacks
  - Choose large K (64, 128, etc)
- Full-table block ciphers not scalable
  - E.g., for k = 64, a table with 2^{64} entries required
  - instead use function that simulates a randomly permuted table

Input	Output
000	110
111	001
001	111
010	101
011	100
100	011
101	010
110	000

From Kaufman et al

Block Cipher (contd.)



- If only a single round, then one bit of input affects at most 8 bits of output
- In 2nd round, the 8 affected bits get scattered and inputted into multiple substitution boxes
- How many rounds?
  - How many times do you need to shuffle cards
  - Becomes less efficient as n increases

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 using distributed computing
  - no known good analytic attack
- making DES more secure:
  - 3DES: encrypt 3 times with 3 different keys

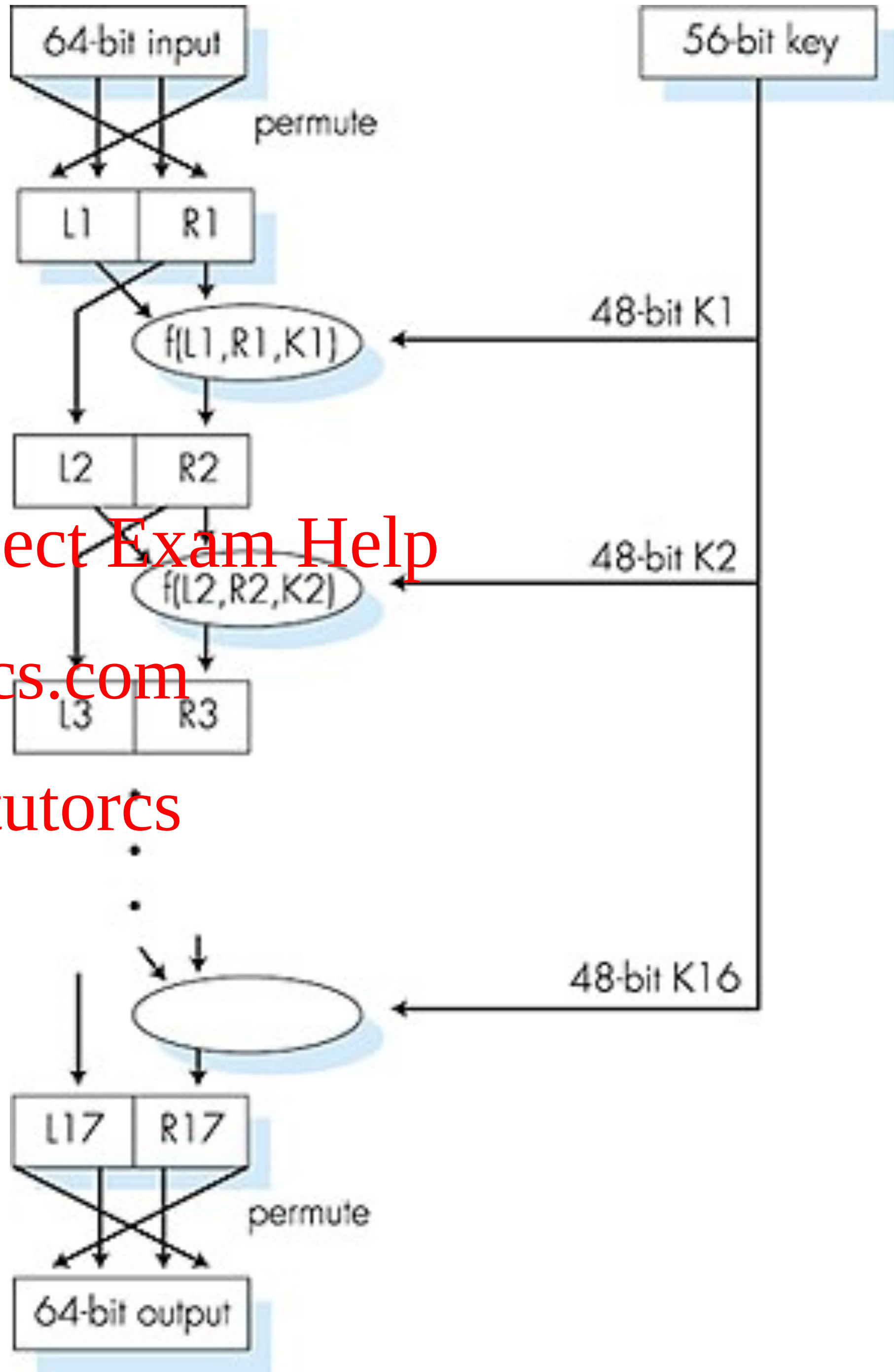
Symmetric key crypto: DES

DES operation

initial permutation

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

final permutation

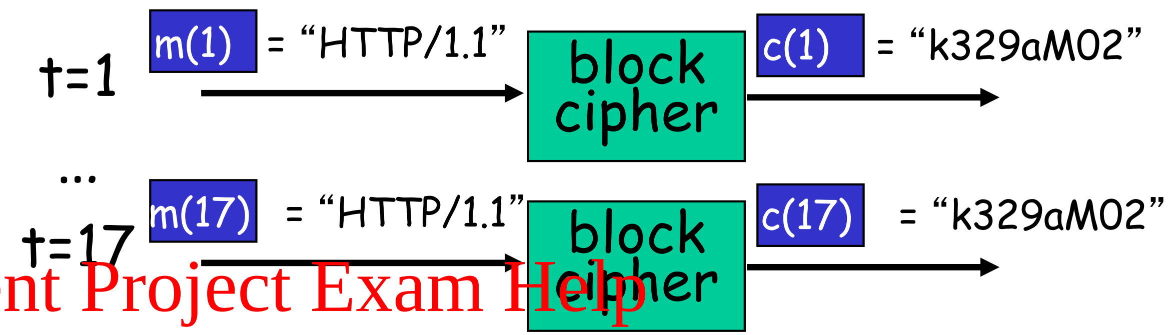


AES: Advanced Encryption Standard

- 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 sec on DES, takes 149 trillion years for AES

Cipher Block Chaining

- cipher block: if input block repeated, will produce same cipher text:



- *Use random numbers:* XOR ith input block, m(i) and random number r(i) and apply block-cipher encryption algorithm
  - $C(i) = Ks(m(i) \oplus r(i))$
  - Send across c(i) and r(i)

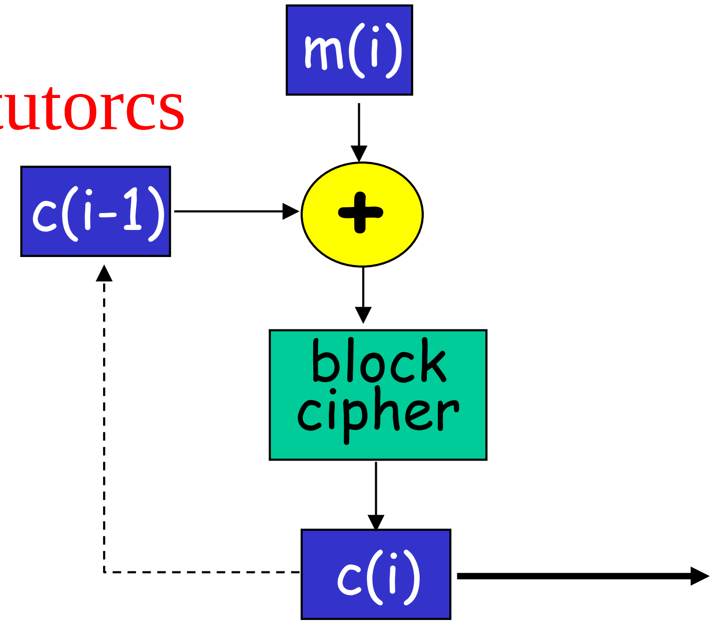
CBC Example

- Plaintext: 010 010 010
- If no CBC, sent txt : 101 101 101
  - 1-to-1 mapping table used
- Lets use the following random bits
  - r1: 001, r2: 111, r3: 100
  - XoR the plaintext with these random bits
  - 010 XoR 001 = 011
  - Now do table lookup for 011 -> 100
- We get c(1)=100, c(2)=010 and c(3)=000, although plaintext is the same (010)
- Need to transmit twice as many bits (c(i) as well as r(i))

Input	Output
000	110
111	001
001	111
010	101
011	100
100	011
101	010
110	000

Cipher Block Chaining

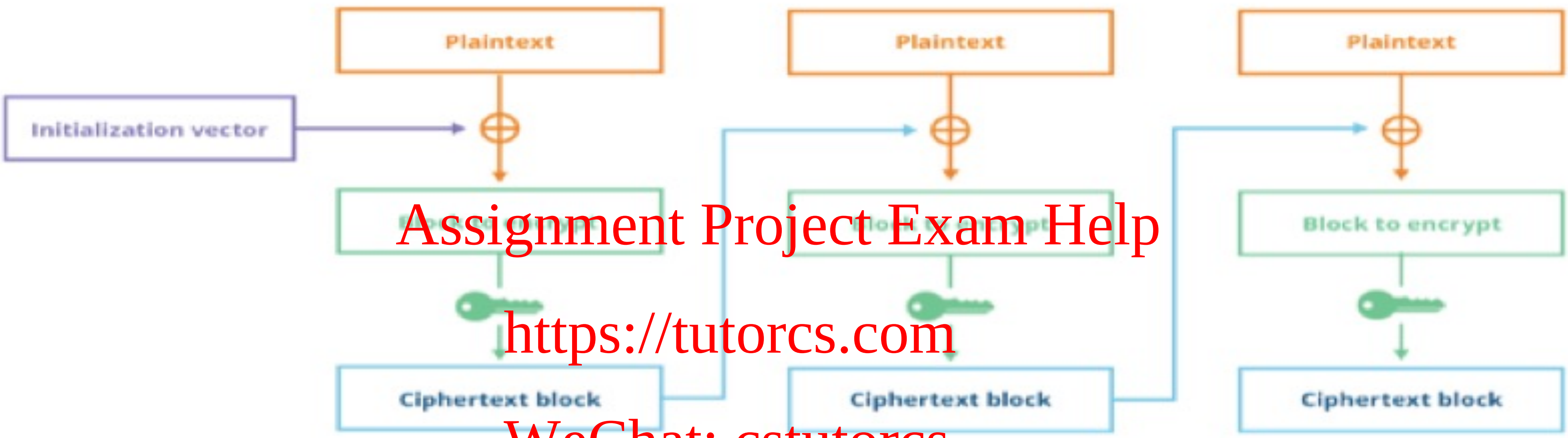
- *cipher block chaining:* send only one random value alongwith the very first message block, and then have the sender and receiver use the computed cipher block in place of the subsequent random number
- XOR ith input block, m(i), with previous block of cipher text, c(i-1)
  - c(0) is an initialisation vector (random) transmitted to receiver in clear

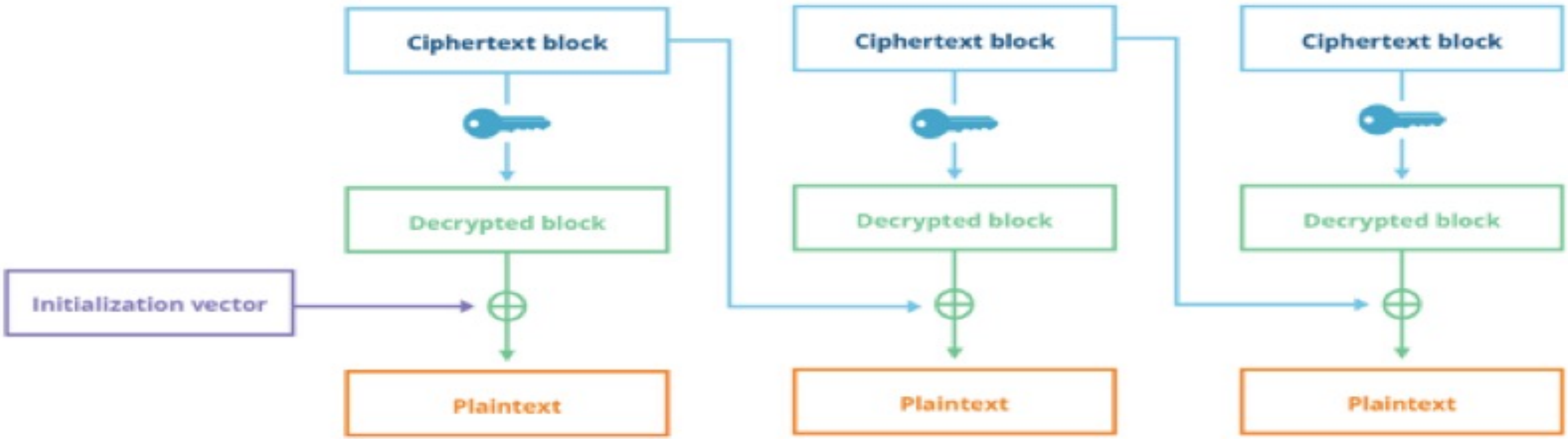


Cipher Block Chaining (CBC)

- CBC generates its own random numbers
  - Have encryption of current block depend on result of previous block
  - $c(i) = K_S(m(i) \oplus c(i-1))$
  - $m(i) = K_S(c(i)) \oplus c(i-1)$
- How do we encrypt first block?
  - Initialization vector (IV): random block = $c(0)$
  - IV does not have to be secret
- Change IV for each message (or session)
  - Guarantees that even if the same message is sent repeatedly, the ciphertext will be completely different each time

Cipher Block Chaining (CBC)



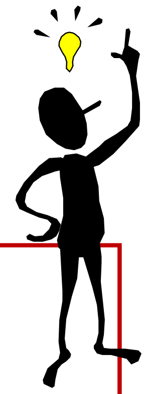


Public Key Cryptography

symmetric key crypto

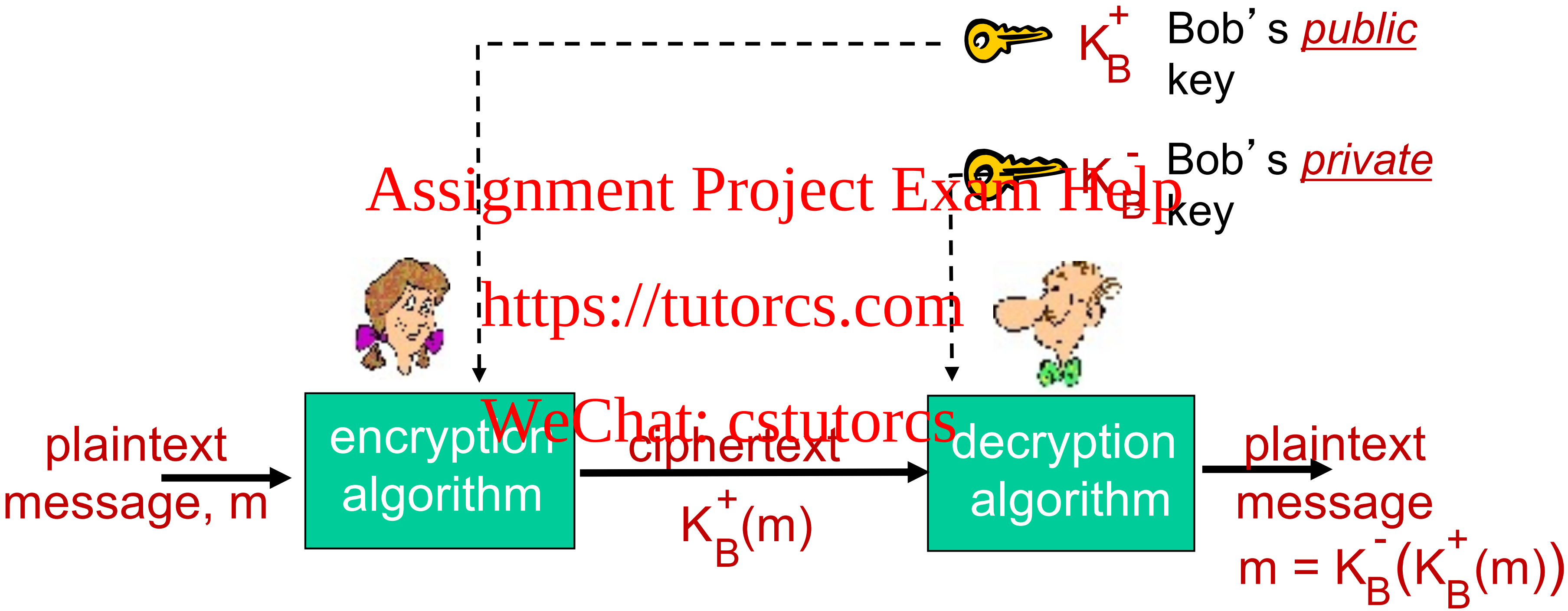
- requires sender, receiver know shared secret key
- Q: how to agree on key in first place (particularly if never "met")?

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



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

Prerequisite: modular arithmetic

- x mod n = remainder of x when divide by n
- facts:

  [(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

- thus

  $(a \bmod n)^d \bmod n = a^d \bmod n$

- example: x=14, n=10, d=2:

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

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

Note: You don't need to know this for the exam

RSA: getting ready

- message: just a bit pattern
- bit pattern can be uniquely represented by an integer number

- thus, encrypting a message is equivalent to encrypting a number.

example:

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

RSA: Creating public/private key pair

1. choose two large prime numbers p, q. (e.g., 1024 bits each)
2. compute $n = pq$, $z = (p-1)(q-1)$

3. choose e (with $e<n$) that has no common factors with z (e, z are "relatively prime").

4. choose d such that $ed-1$ is exactly divisible by z. (in other words: $ed \bmod z = 1$).
5. *public* key is $\underbrace{(n,e)}_{K_B^+}$. *private* key is $\underbrace{(n,d)}_{K_B^-}$.

RSA: encryption, decryption

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

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

   $c = m^e \bmod n$

2. to decrypt received bit pattern, c, compute

   $m = c^d \bmod n$

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

Proof of Correctness: Fermat's Little Theorem or Euler's Theorem (not on exam)

RSA example:

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

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

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

encrypting 8-bit messages.

	bit pattern	m	m^e	$c = m^e \bmod n$
encrypt:	00001100	12	248832	17

	c	c^d	$m = c^d \bmod n$
decrypt:	17	481968572106750915091411825223071697	12

RSA: another important property

The following property will be *very* useful later:

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

use public key first, followed by private key

use private key first, followed by public key

result is the same!

Why is RSA secure?

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

RSA in practice: session keys

- exponentiation in RSA is computationally intensive
- DES is at least 100 times faster than RSA
- use public key crypto to establish secure connection, then establish second key – symmetric session key – for encrypting data

session key, K_S

- Bob and Alice use RSA to exchange a symmetric key K_S
- once both have K_S, they use symmetric key cryptography

Network Security: roadmap

Authentication

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

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

Failure scenario??

Note: In some applications, both end points may need to authenticate each other

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

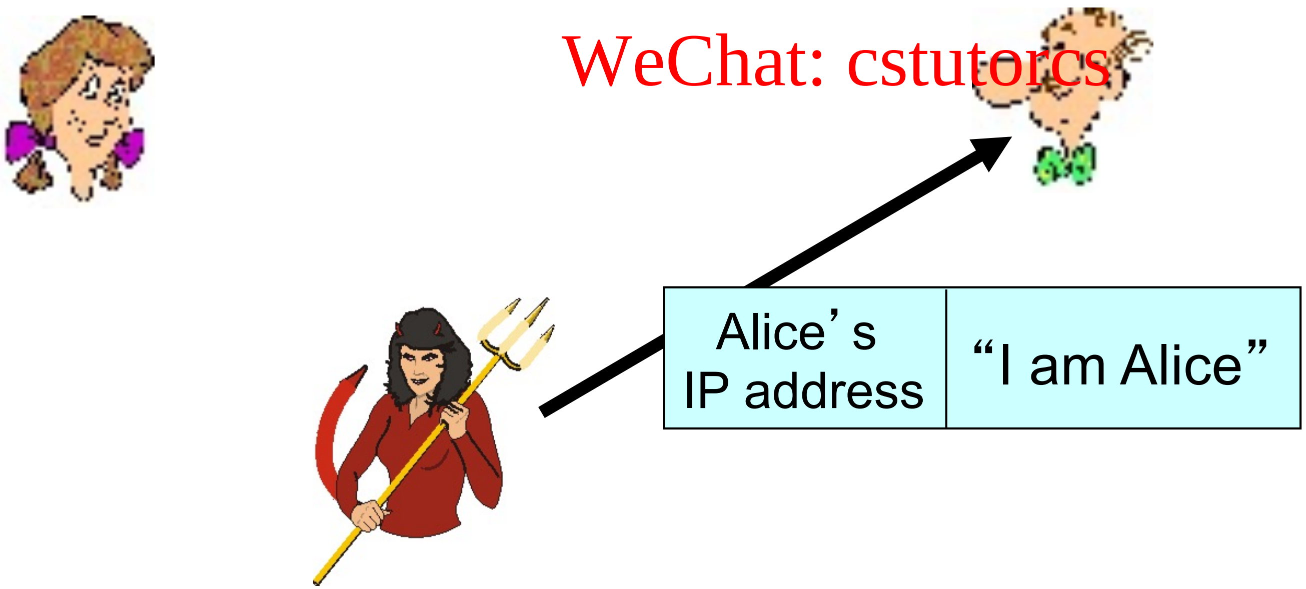
Authentication: another try

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

Failure scenario??

Authentication: another try

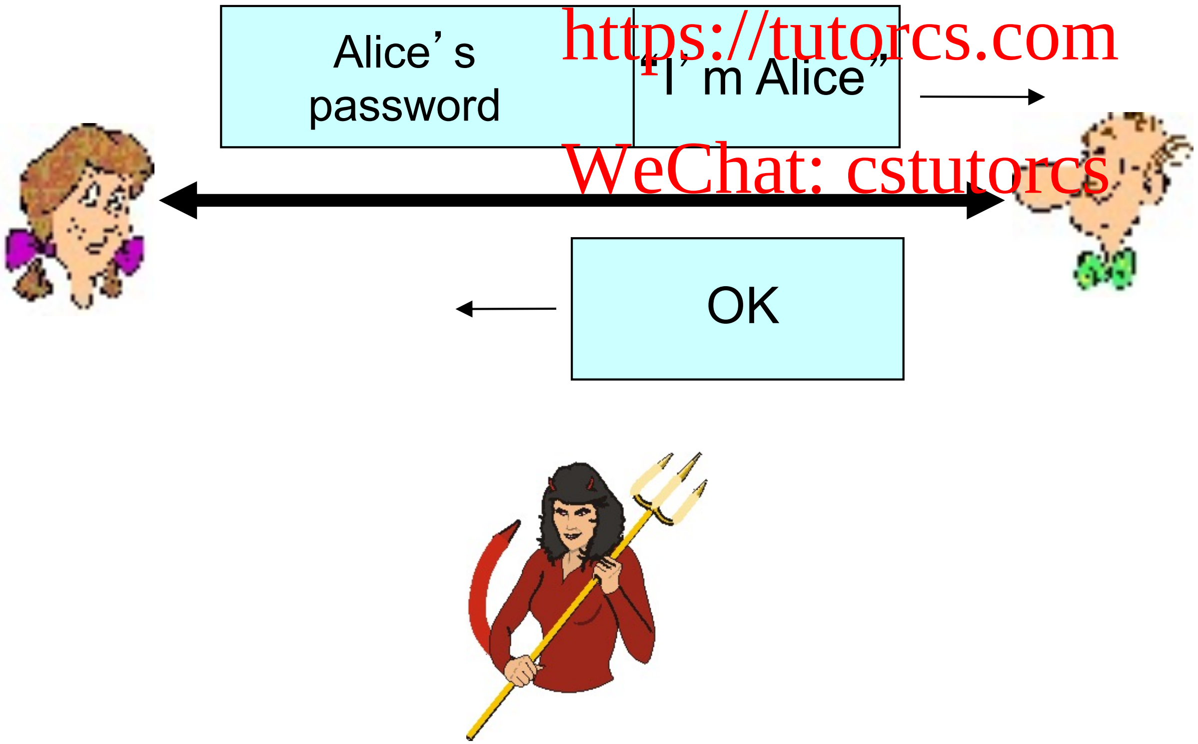
Protocol ap2.0: Alice says “I am Alice” in an IP packet containing her source IP address



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

Authentication: another try

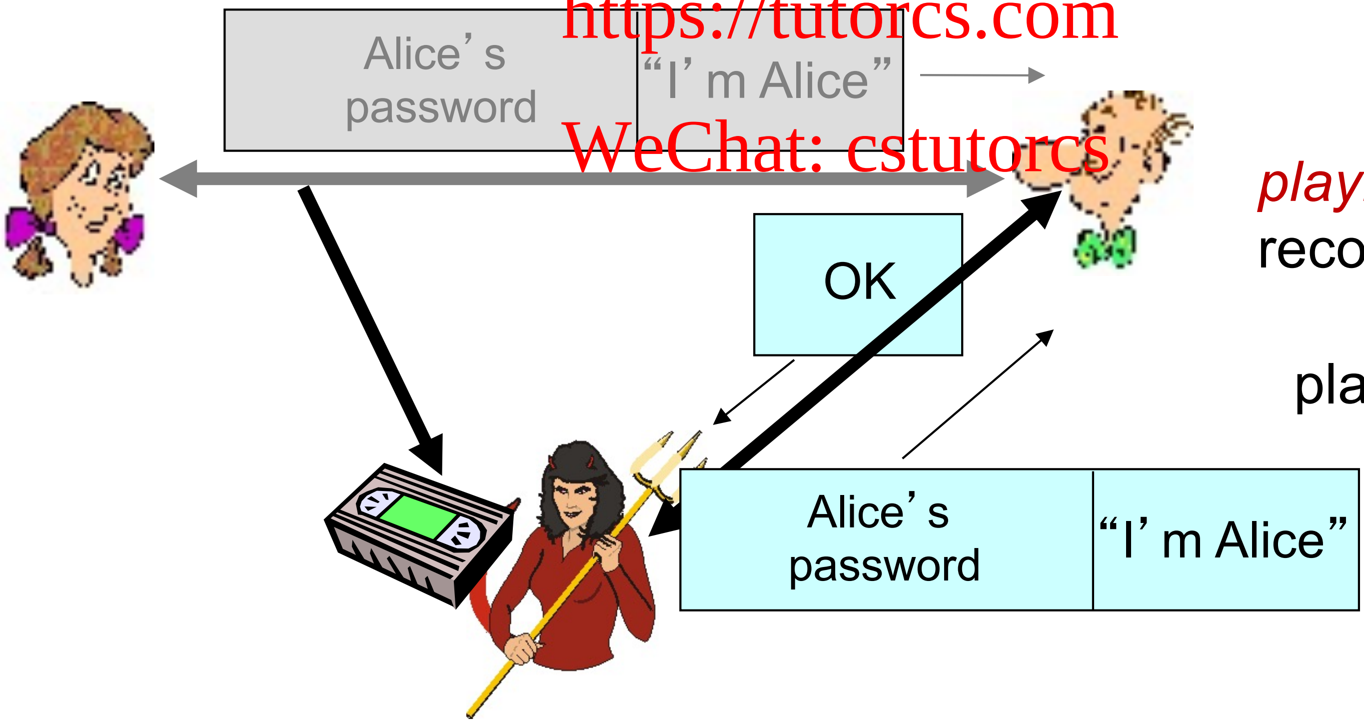
Protocol ap3.0: Alice says "I am Alice" and sends her secret password to "prove" it.



Failure scenario??

Authentication: another try

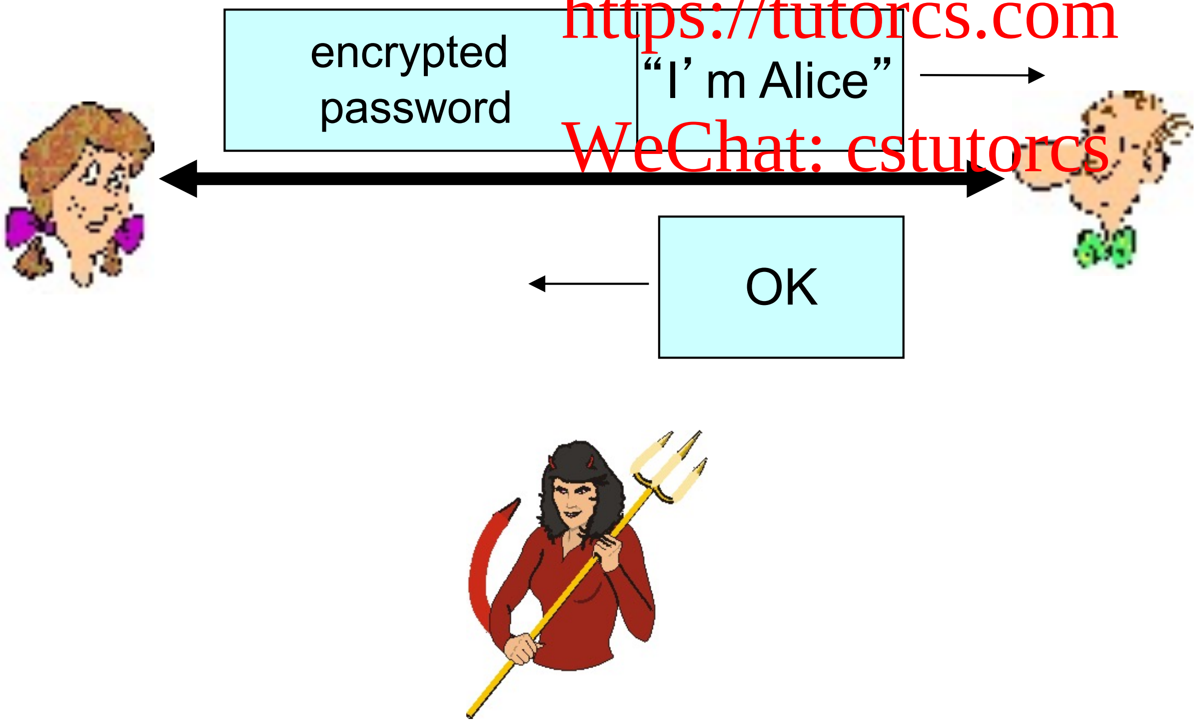
Protocol ap3.0: Alice says “I am Alice” and sends her secret password to “prove” it.



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

Authentication: yet another try

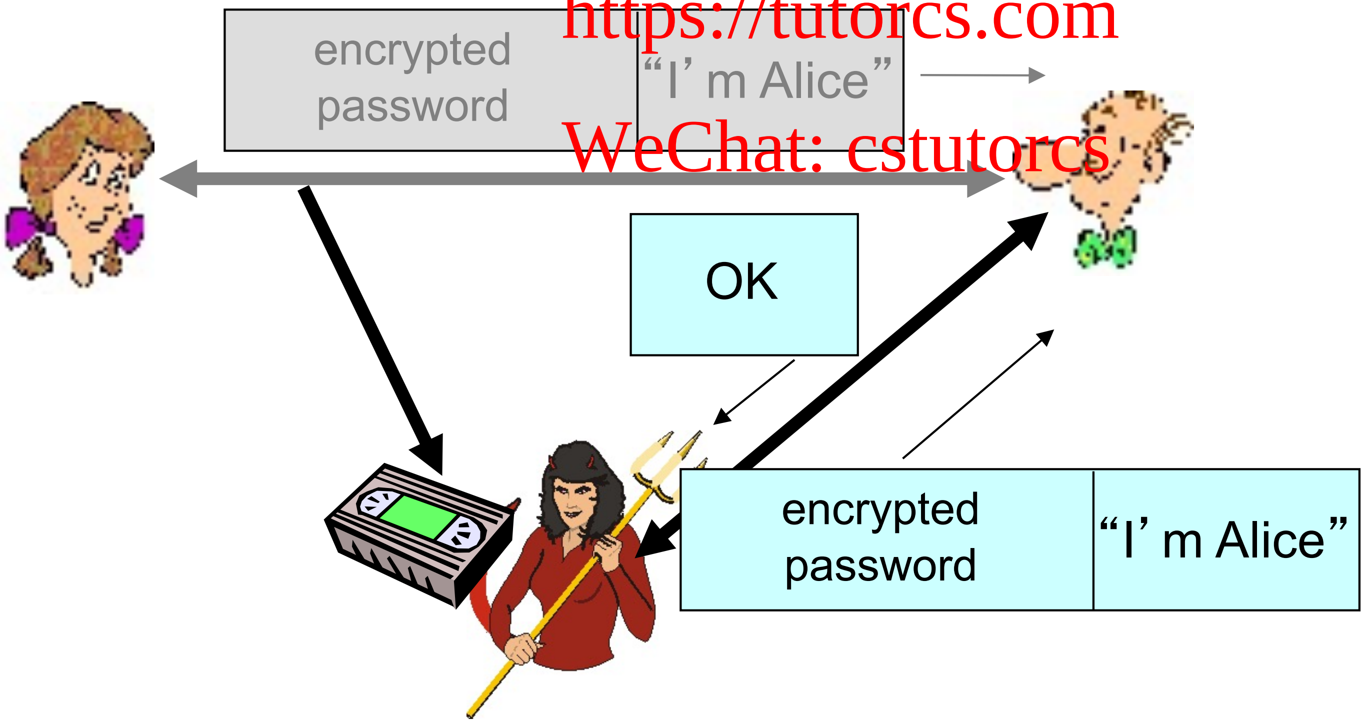
Protocol ap3.1: Alice says "I am Alice" and sends her *encrypted* secret password to "prove" it.



Failure scenario??

Authentication: yet another try

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



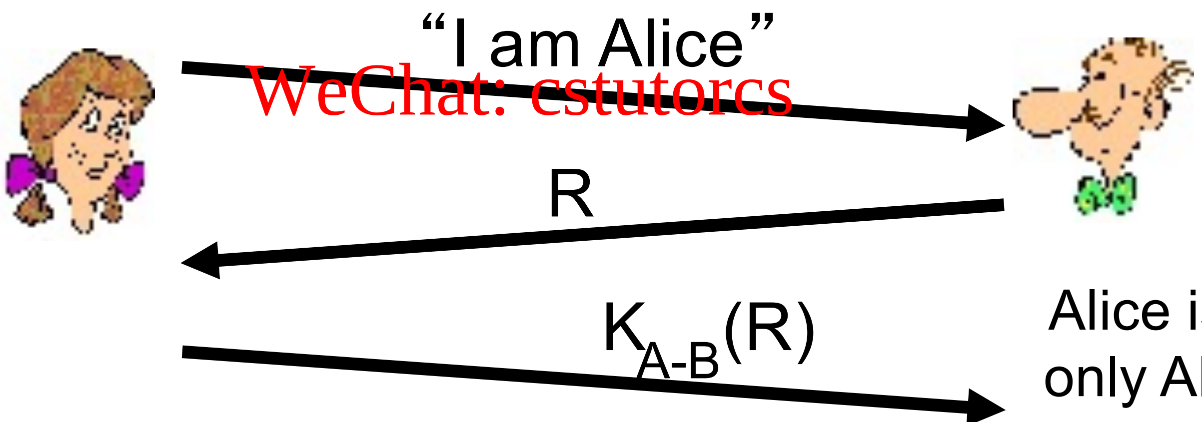
record and playback *still* works!

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



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

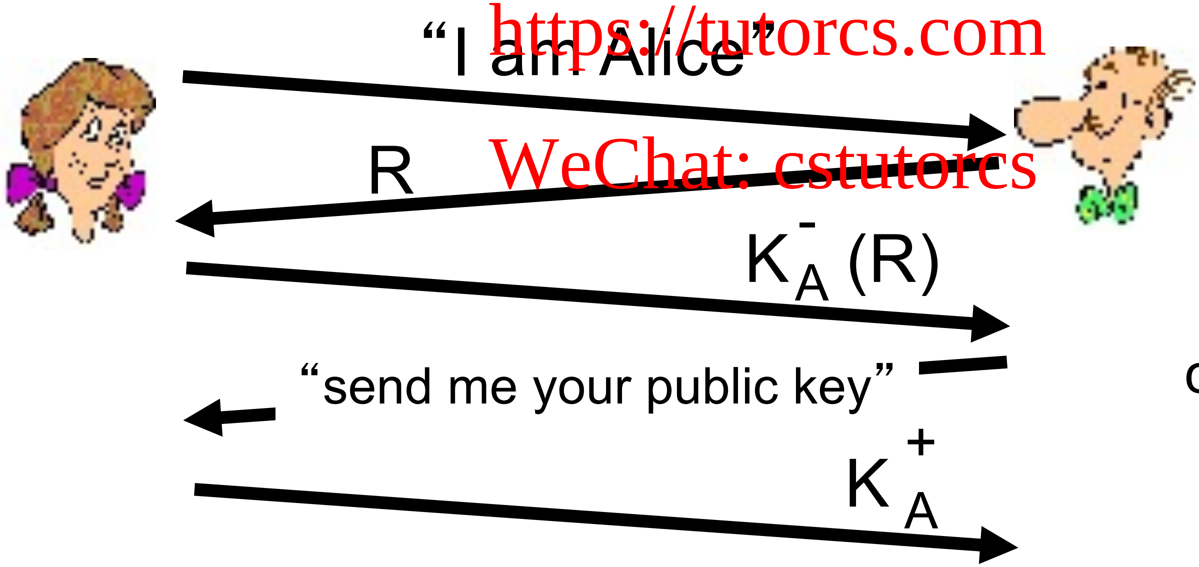
drawbacks?

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

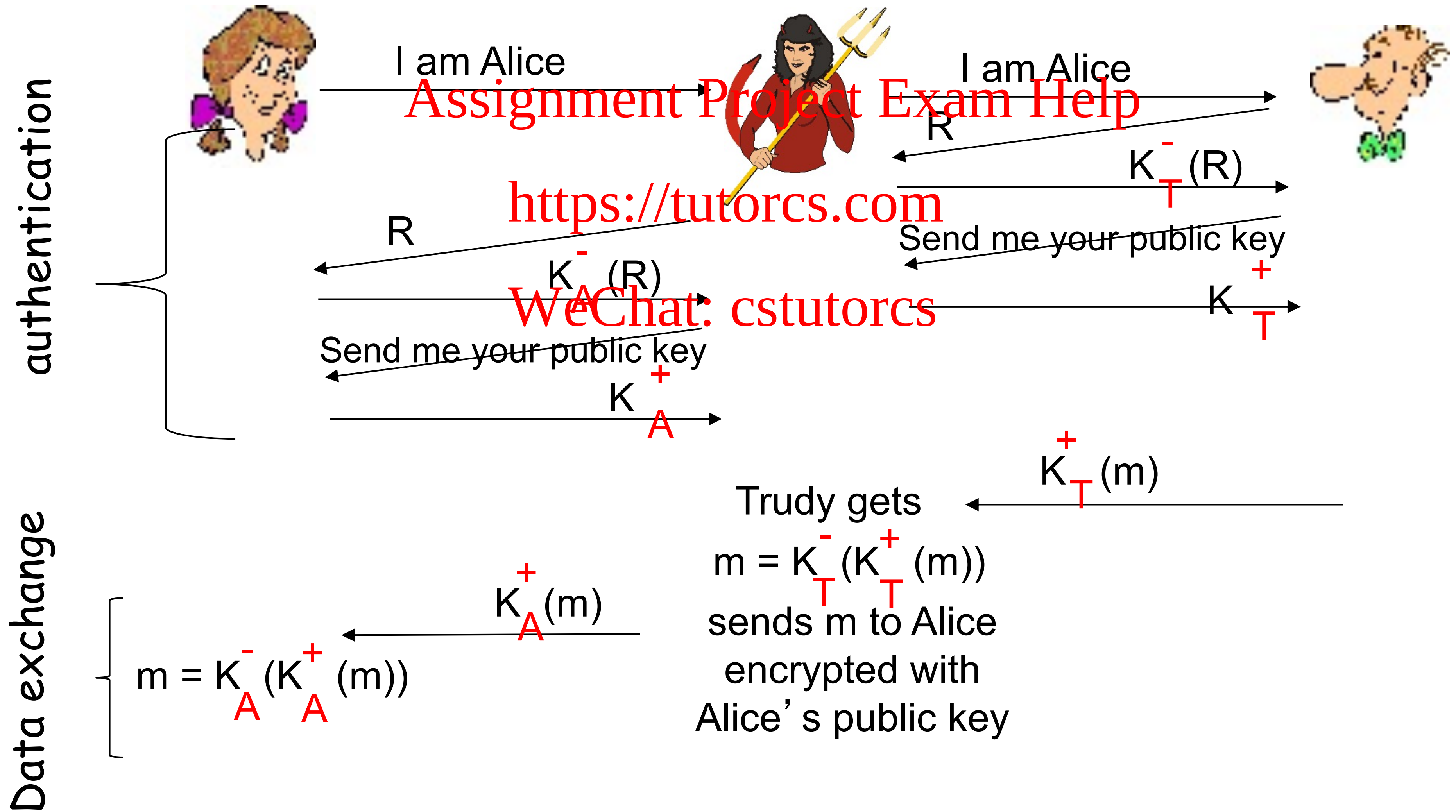
$$K_A^+(K_A^-(R)) = R$$

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!

Network Security: roadmap

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Confidentiality vs Integrity

- Confidentiality: message private and secret
- Integrity: protection against message tampering
- Encryption alone may not guarantee integrity
  - Attacker can modify message under encryption without learning what it is
- Public Key Crypto Standard (PKCS)
  - "RSA encryption is intended primarily to provide confidentiality …. It is not intended to provide integrity"
- Both confidentiality and integrity are needed for security

Digital signatures

cryptographic technique analogous to hand-written signatures:

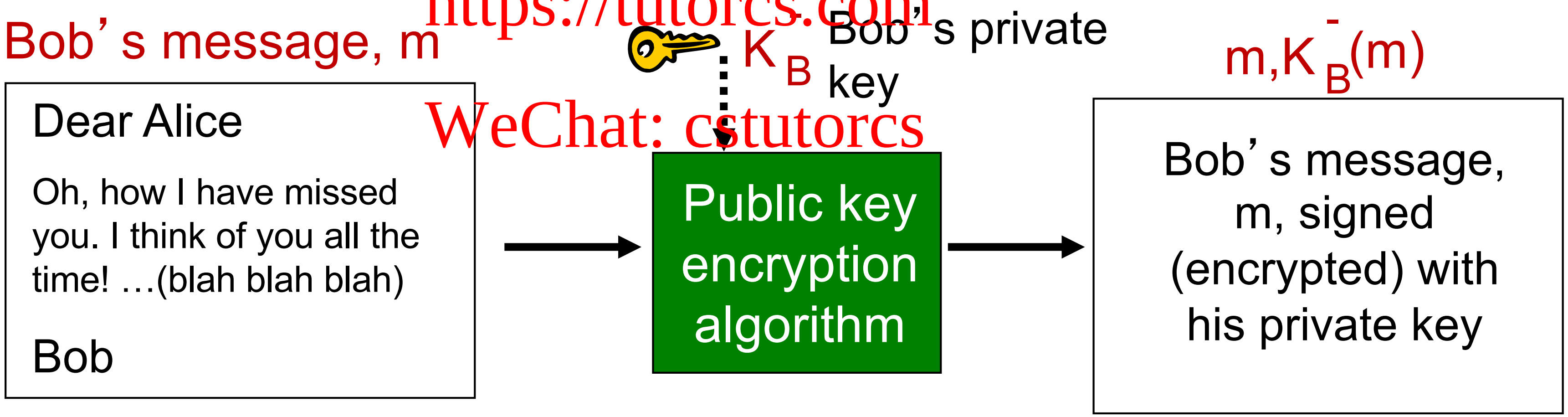
- sender (Bob) digitally signs document, establishing he is document owner/creator.

- *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, $K_B^-(m)$



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.

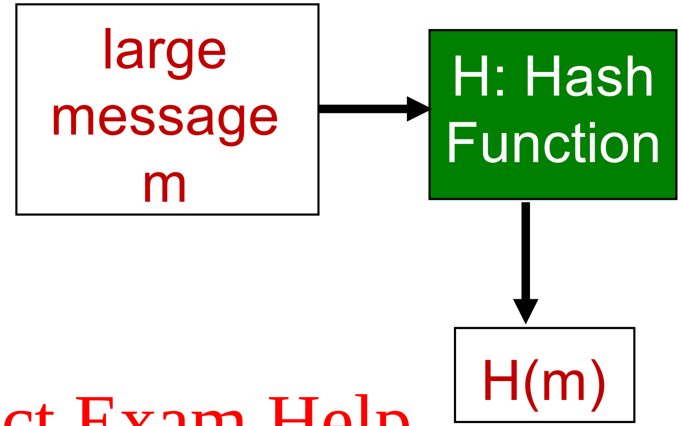
Alice thus verifies that:

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

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

different messages but identical checksums!

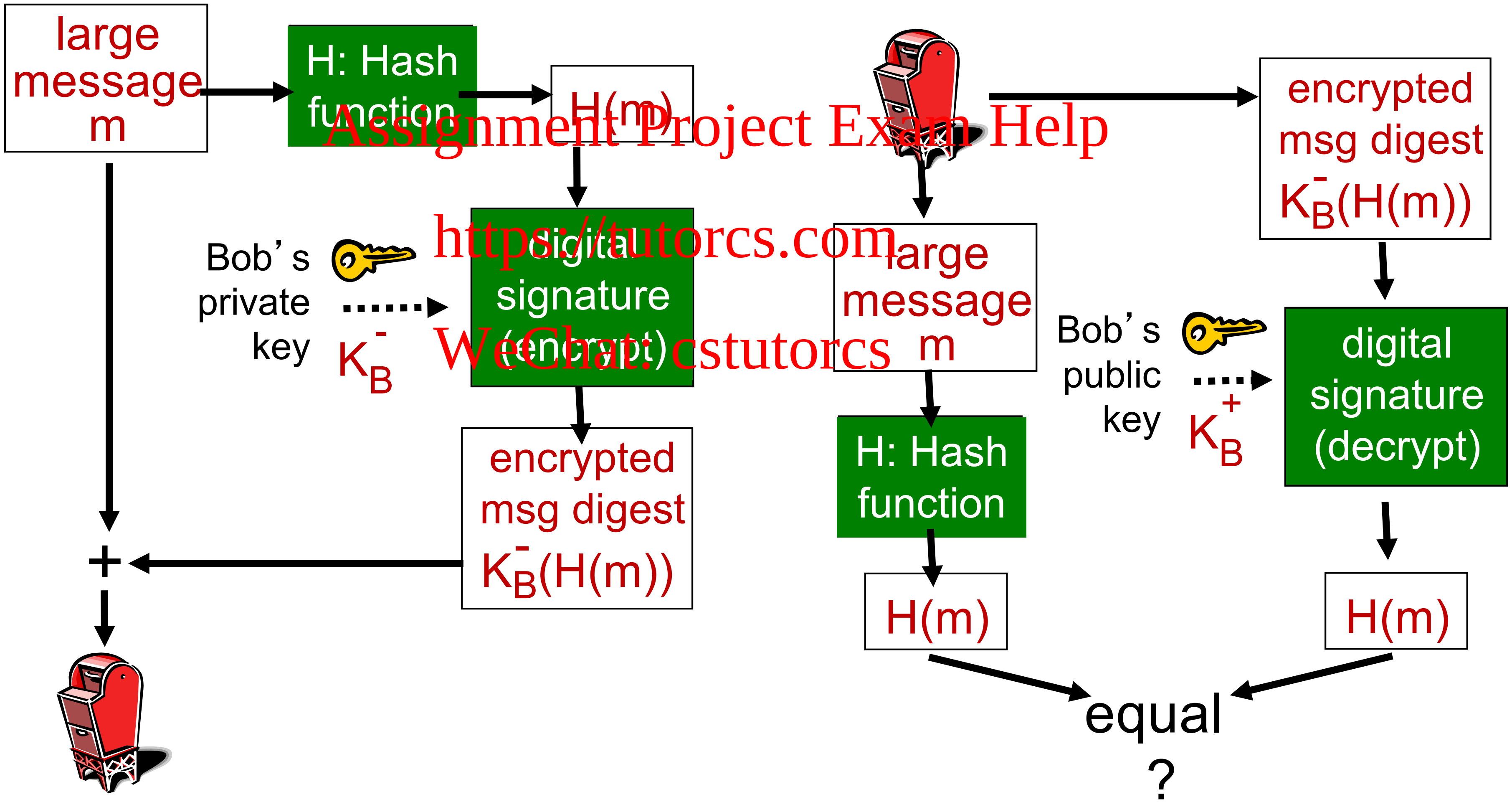
Hash function algorithms

- 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
- SHA-2 and SHA-3 (recent standard) are better - security

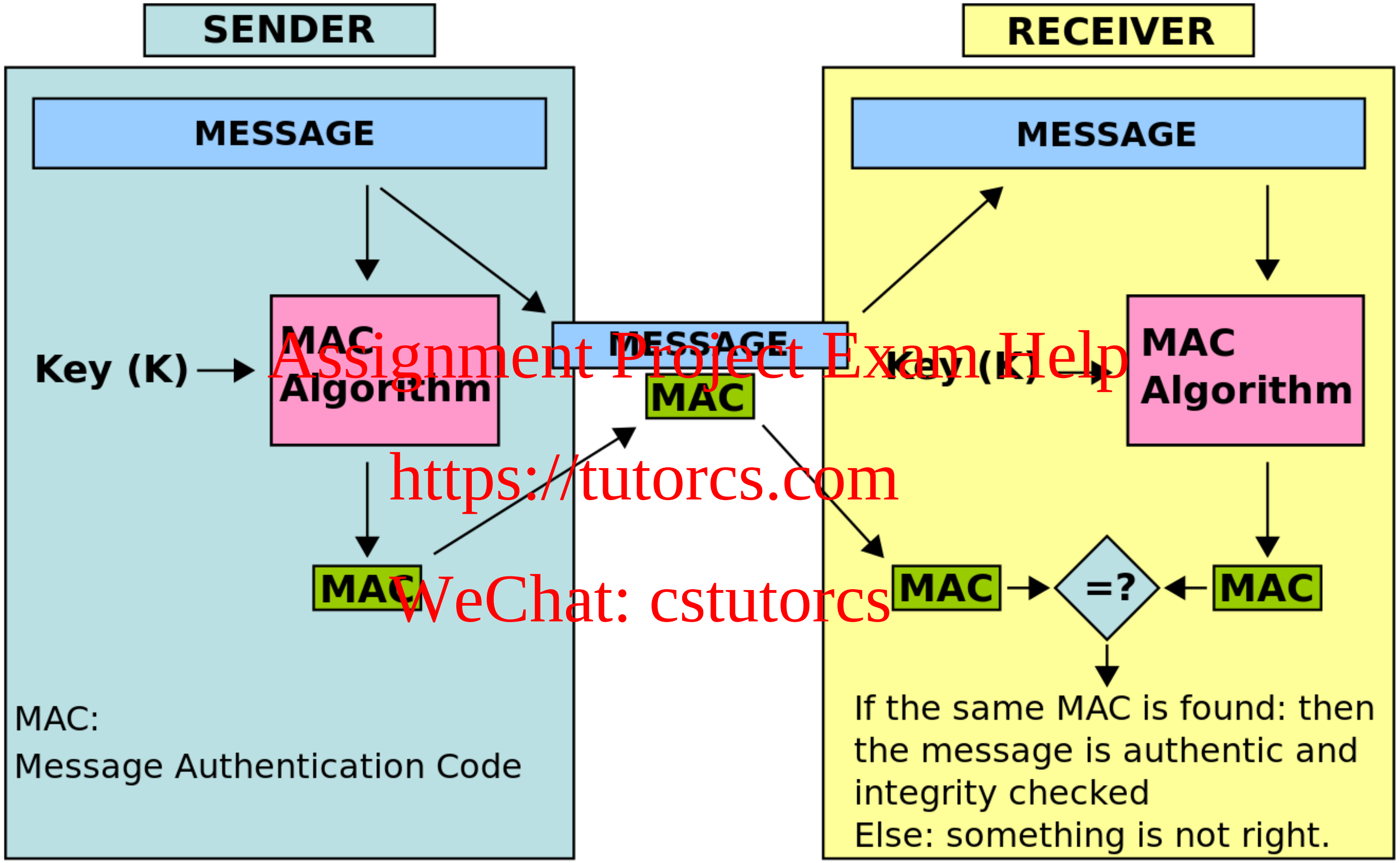
Digital signature = signed message digest

Bob sends digitally signed message:

Alice verifies signature, integrity of digitally signed message:



Message Authentication Code (MAC)



Digital signatures use asymmetric key crypto

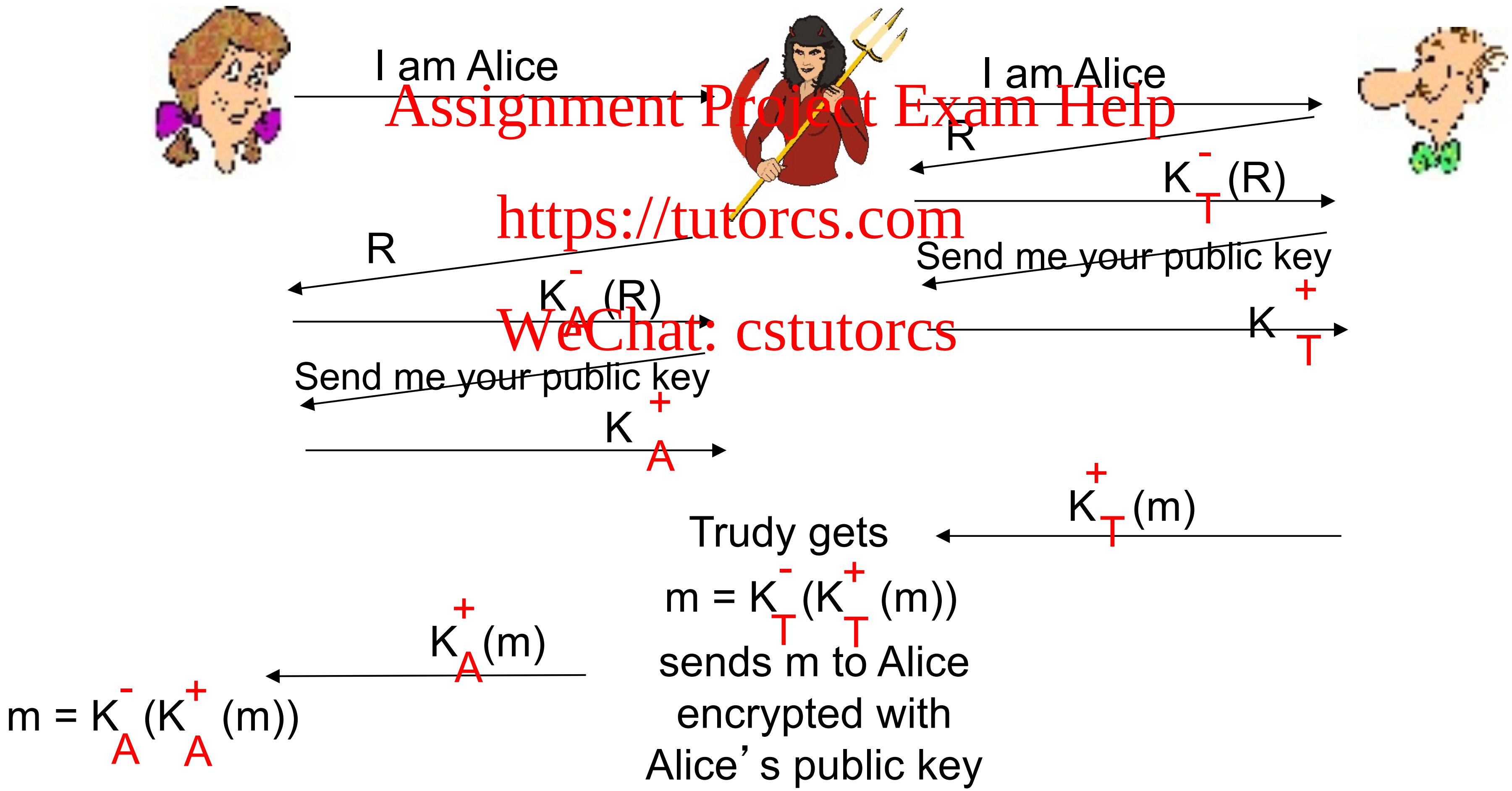
MAC allows a way to sign a message but using symmetric key

Requires a shared secret key

Examples: UMAC-VMAC, SipHash, Poly1305-AES

Recall: ap5.0 security hole

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

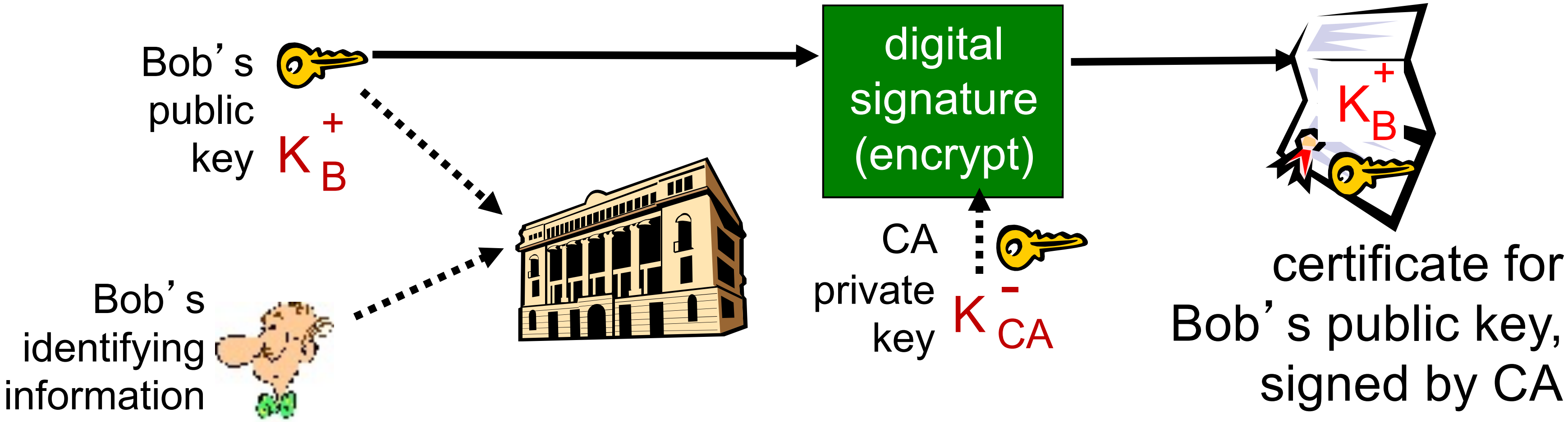


Public-key certification

- 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

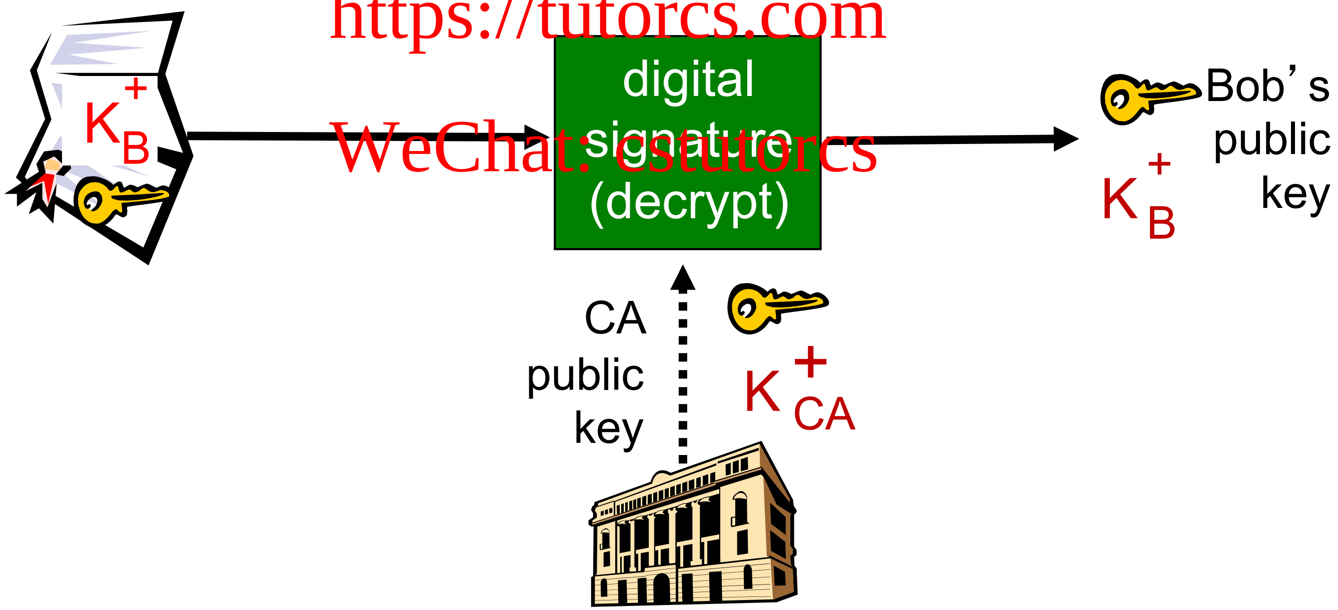
Certification authorities

- *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"



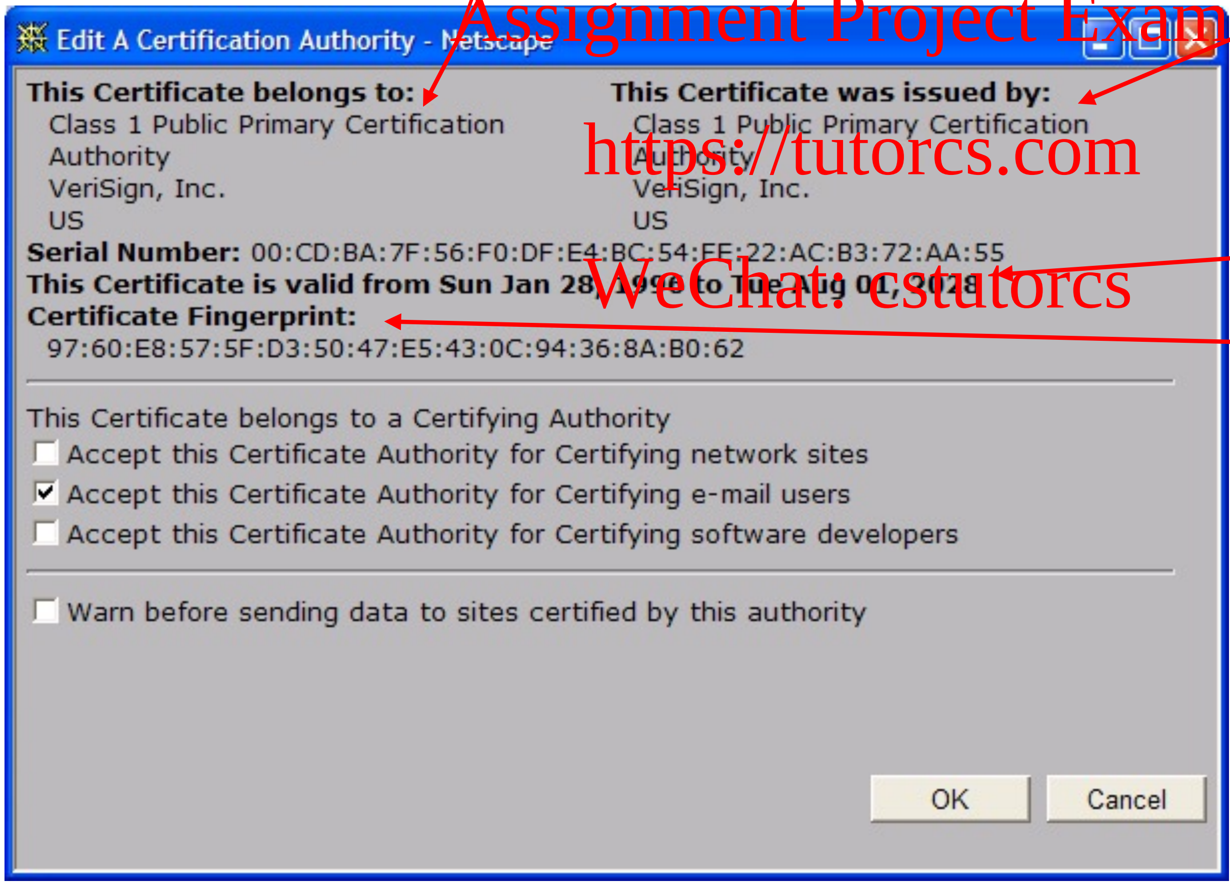
Certification authorities

- 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



A certificate contains:

- Serial number (unique to issuer)
- info about certificate owner, including algorithm and key value itself (not shown)



- info about certificate issuer
- valid dates
- digital signature by issuer

Certificates: summary

- Primary standard X.509 (RFC 2459)
- Certificate contains:
  - Issuer name
  - Entity name, address, domain name, etc.
  - Entity's public key
  - Digital signature (signed with issuer's private key)
- Public-Key Infrastructure (PKI)
  - Certificates and certification authorities
  - Often considered "heavy"

Quiz

- Suppose Bob wants to send Alice a digital signature for the message *m*. To create the digital signature

a) Bob applies a hash function to *m* and encrypts the result with his private key

b) Bob applies a hash function to *m* and encrypts the result with Alice's public key

c) Bob encrypts *m* with his private key and then applies a hash function to the result

d) Bob applies a hash function to *m* and encrypts the result with his public key

Answer: A

Quiz

- Suppose a CA creates Bob's certificate, which binds Bob's public key to Bob. This certificate is signed with

Answer: C

a) Bob's private key

b) Bob's public key
c) The CA's private key
d) The CA's public key
e) Donald Trump's key

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Network Security: roadmap

8.1 What is network security?

8.2 Principles of cryptography

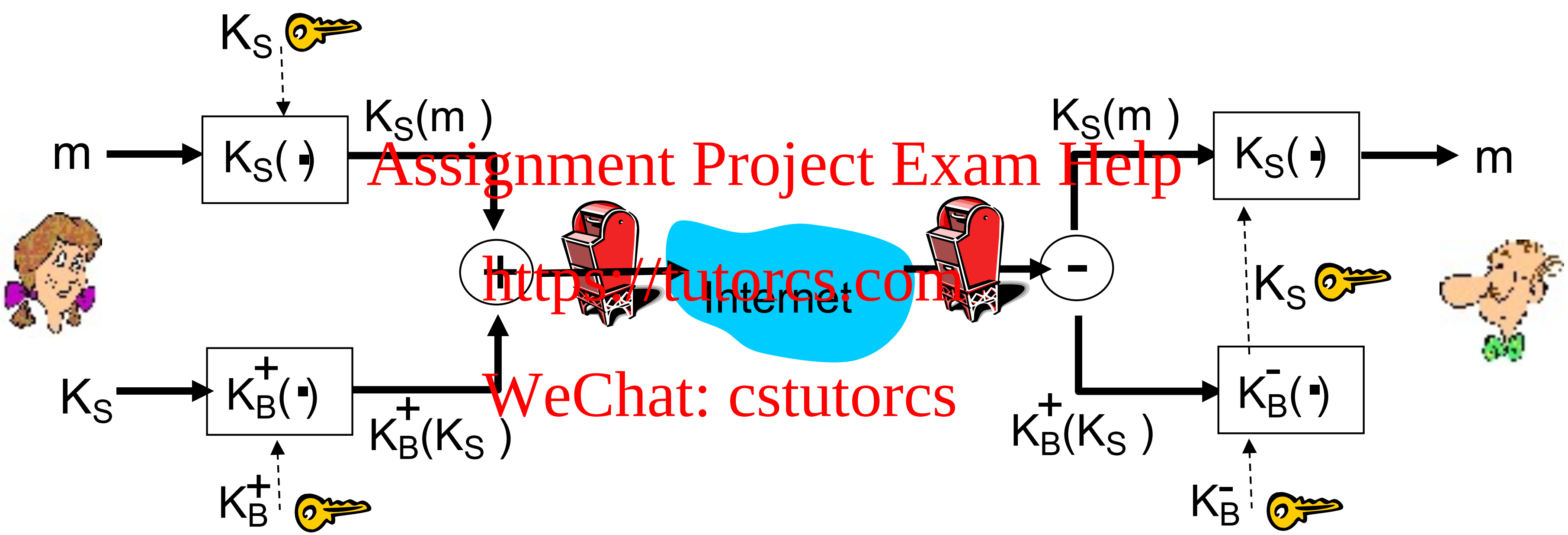
8.3 Message integrity

8.4 Authentication

8.5 Securing e-mail

Secure e-mail

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

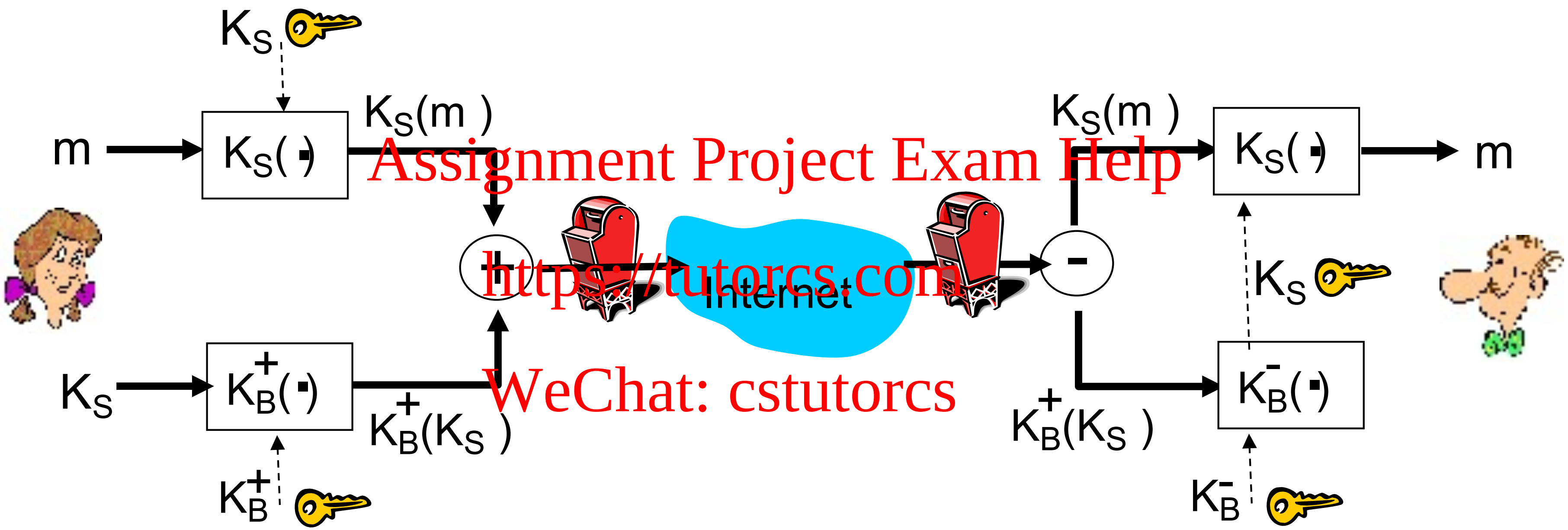


Alice:

- generates random *symmetric* session key, K_S
- encrypts message with K_S (for efficiency)
- also encrypts K_S with Bob's public key
- sends both $K_S(m)$ and $K_B^+(K_S)$ to Bob

Secure e-mail

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

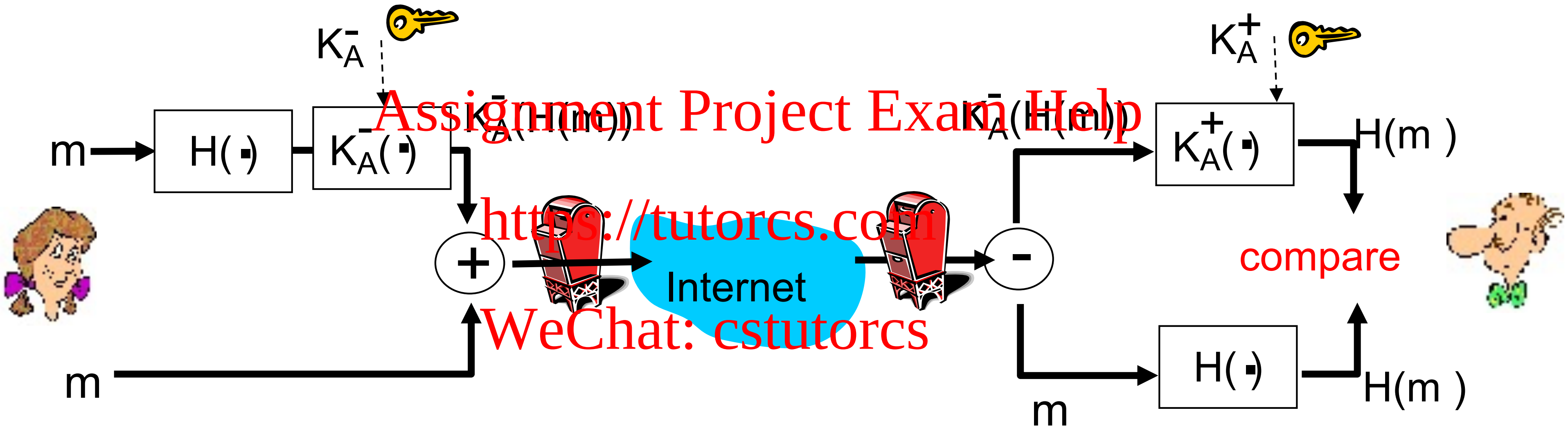


Bob:

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

Secure e-mail (continued)

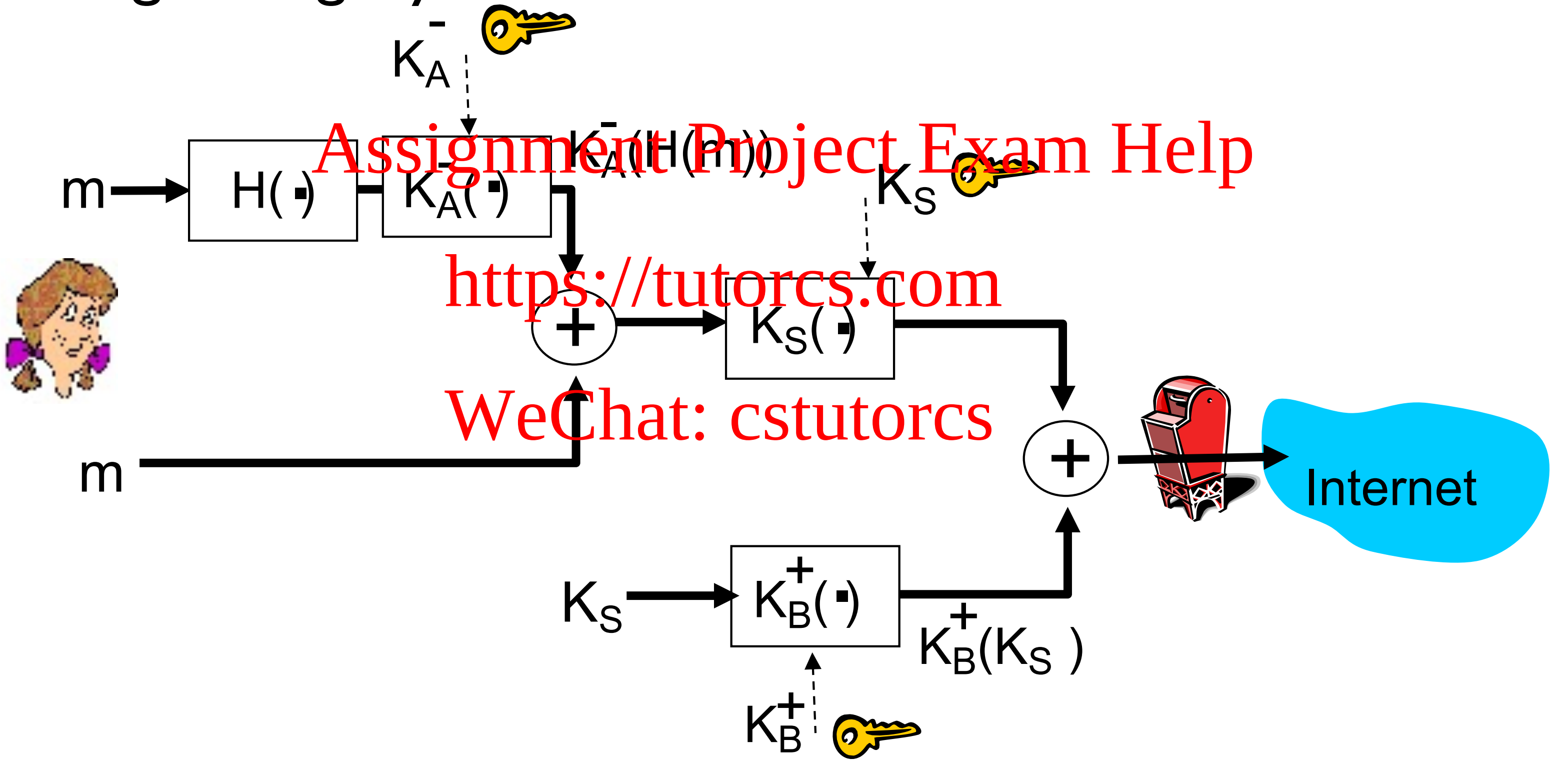
- Alice wants to provide sender authentication, message integrity



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

Secure e-mail (continued)

- Alice wants to provide confidentiality, sender authentication, message integrity.



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

Secure E-mail: PGP

- De-factor standard for email encryption
- On installation PGP creates public, private key pair
  - Public key posted on user's webpage or placed in a public key server
  - Private key protected by password
- Option to digitally sign the message, encrypt the message or both
- MD5 or SHA for message digest
- CAST, triple-DES or DEA for symmetric key encryption
- RSA for public key encryption

Secure E-mail: PGP

```
-----BEGIN PGP SIGNED MESSAGE-----
Hash: SHA1
Bob:
Can I see you tonight?
Passionately yours, Alice
-----BEGIN PGP SIGNATURE-----
Version: PGP for Personal Privacy 5.0
Charset: noconv
yhHJRHhGJGhgg/12EpJ+lo8gE4vB3mqJhFEvZP9t6n7G6m5Gw2
-----END PGP SIGNATURE-----
```

Figure 8.22 ♦ A PGP signed message


```
-----BEGIN PGP MESSAGE-----
Version: PGP for Personal Privacy 5.0
u2R4d+/jKmn8Bc5+hgDsqAewsDfrGdszX68liKm5F6Gc4sDfcXyt
RfdS10juHgbcfDssWe7/K=lKhnMikLo0+1/BvcX4t==Ujk9PbcD4
Thdf2awQfgHbnmKlok8iy6gThlp
-----END PGP MESSAGE
```

Figure 8.23 ♦ A secret PGP message

Network Security: Conclusion

- What is security?
- Symmetric and Asymmetric cryptography
- Encryption
- Authentication
- Message Integrity
  - Digital Signatures
  - MAC
- Secure E-mail
  - Putting it all together