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# Computer Networks

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*Material with thanks to James F. Kurose,  Mosharaf Chowdhury, and other colleagues.*

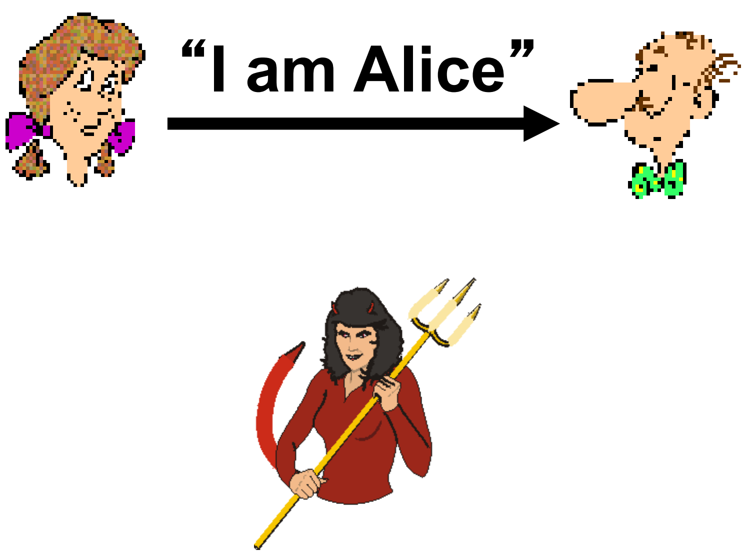
# Chapter 5. Network Security

- Network Attacks
- Cryptographic Technologies
- Authentication
- Message Integrity
- Key Distribution
- Security in Different Network Layers
- Firewalls

# 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**

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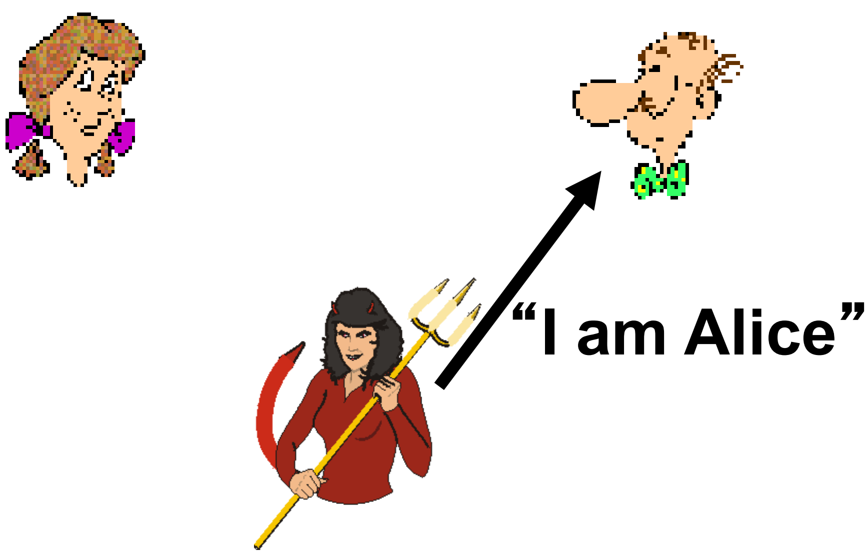



**in a network,**
**Bob can not "see"**
**Alice, so Trudy simply**
**declares**
**herself to be Alice**

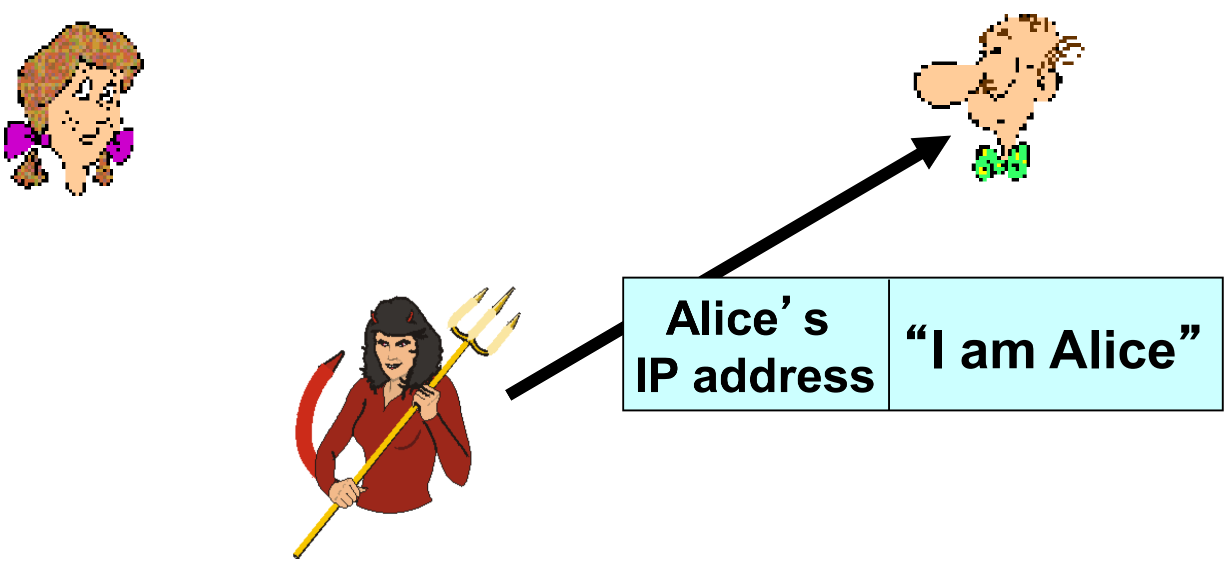
# Authentication: another try

***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**

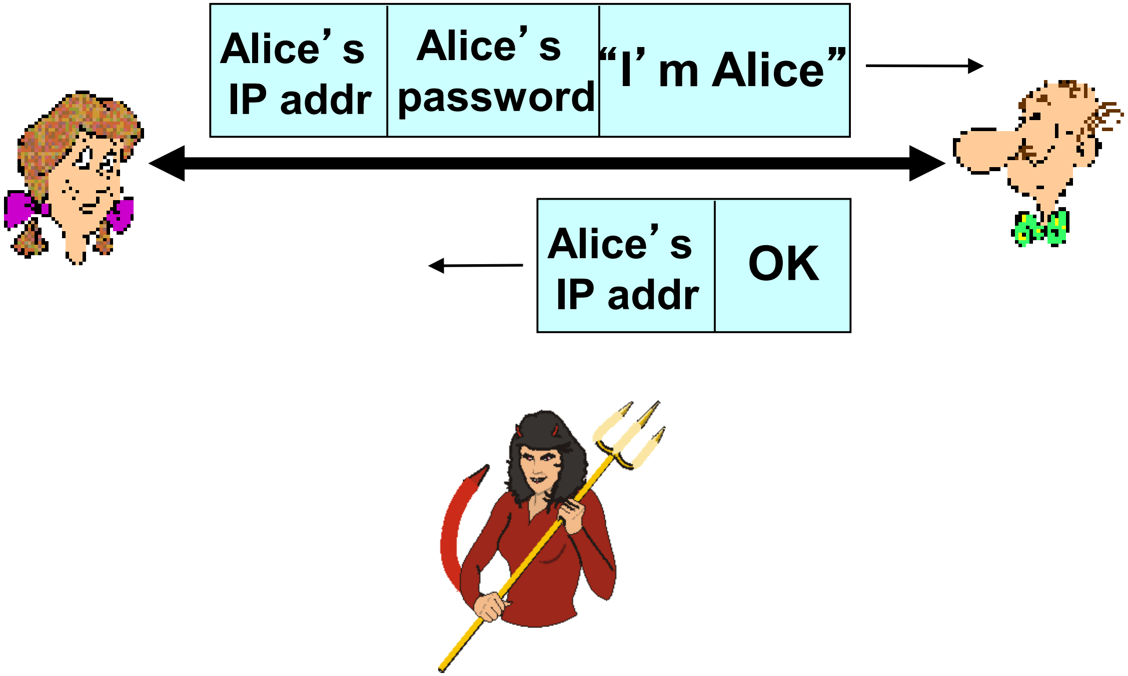



**Trudy can create a packet "spoofing" Alice's address**

# 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:*

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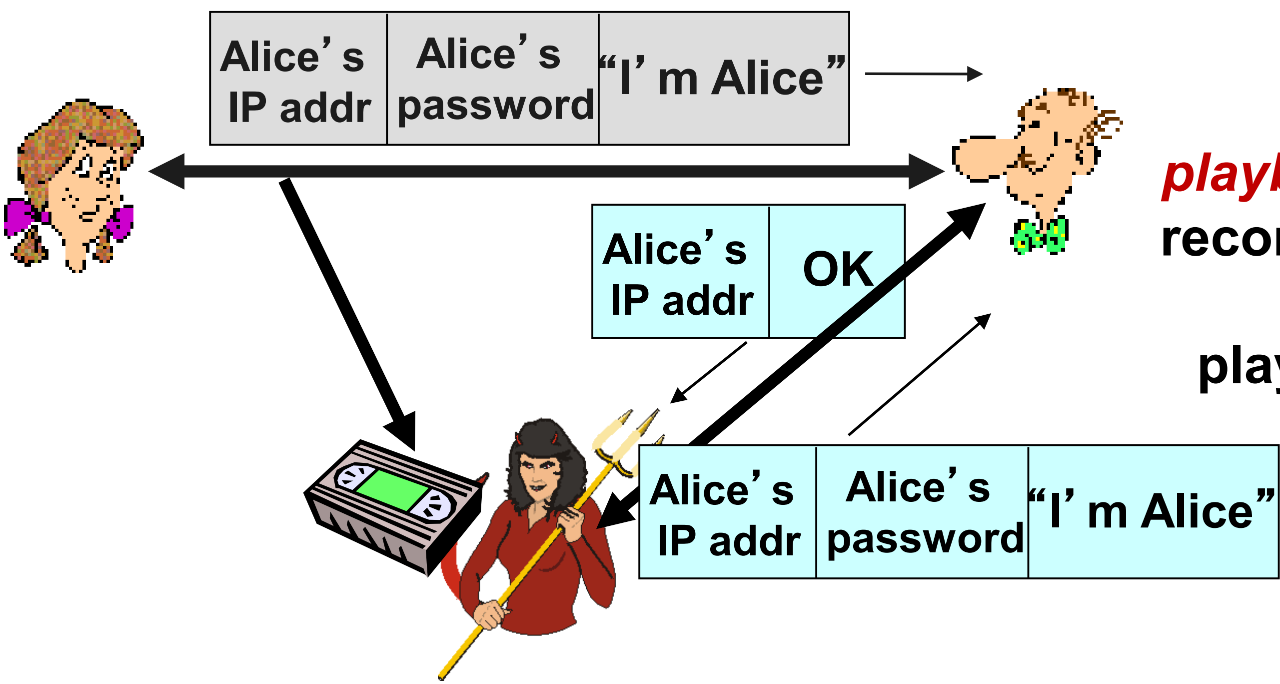
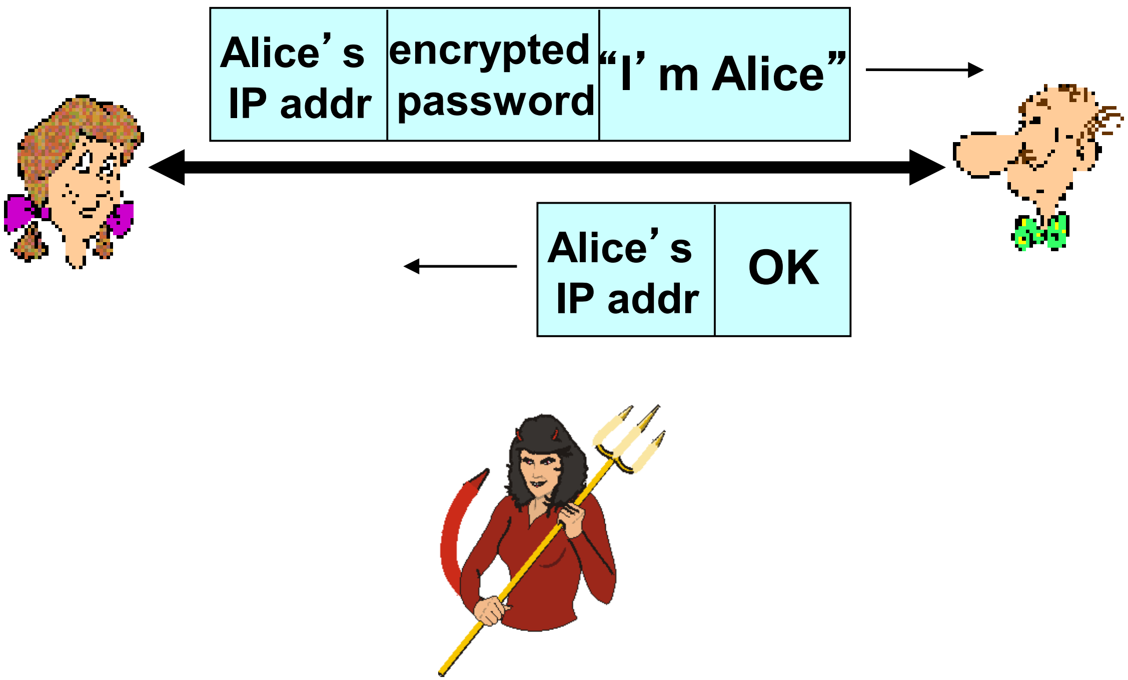



*playback attack:* Trudy records Alice's packet and later plays it back to Bob

# Authentication: yet another try

*Protocol ap3.1:*

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

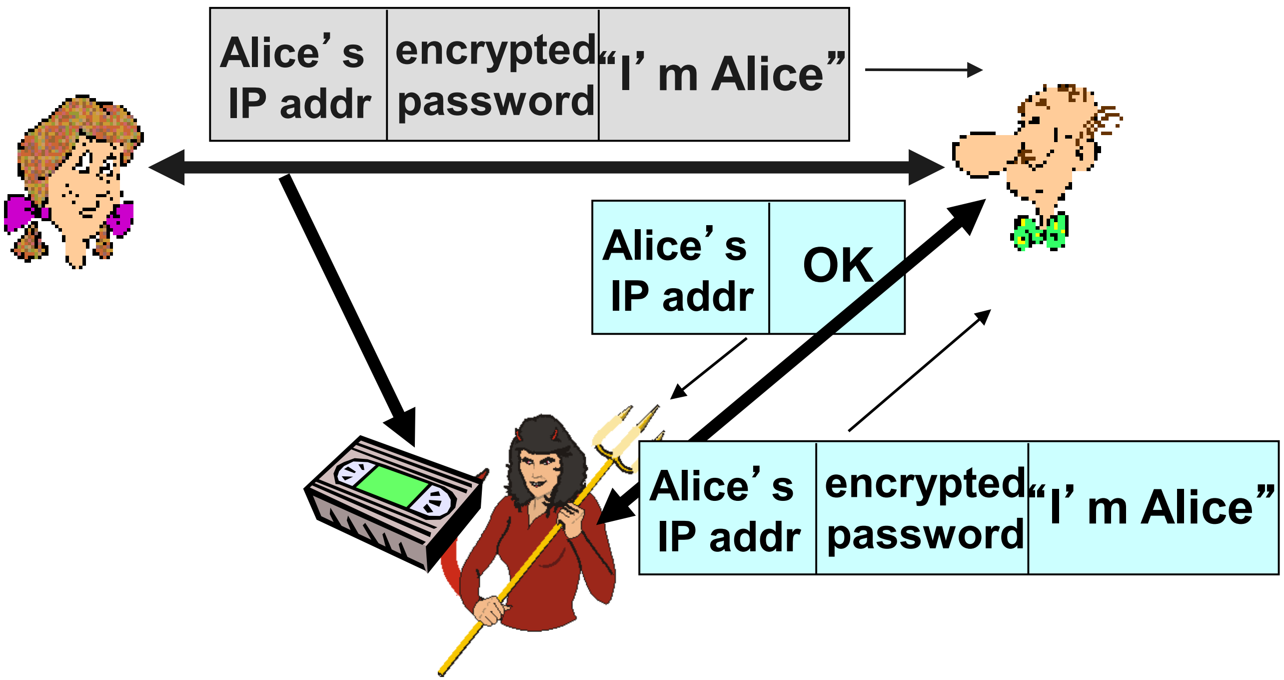



**Failure scenario??**

# Authentication: yet another try

*Protocol ap3.1:*

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



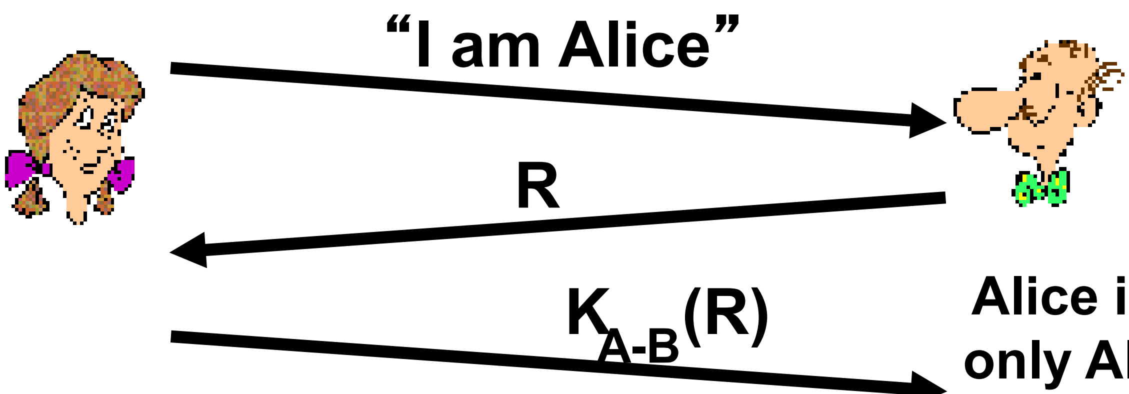

**record and playback *still* works!**

# 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!**

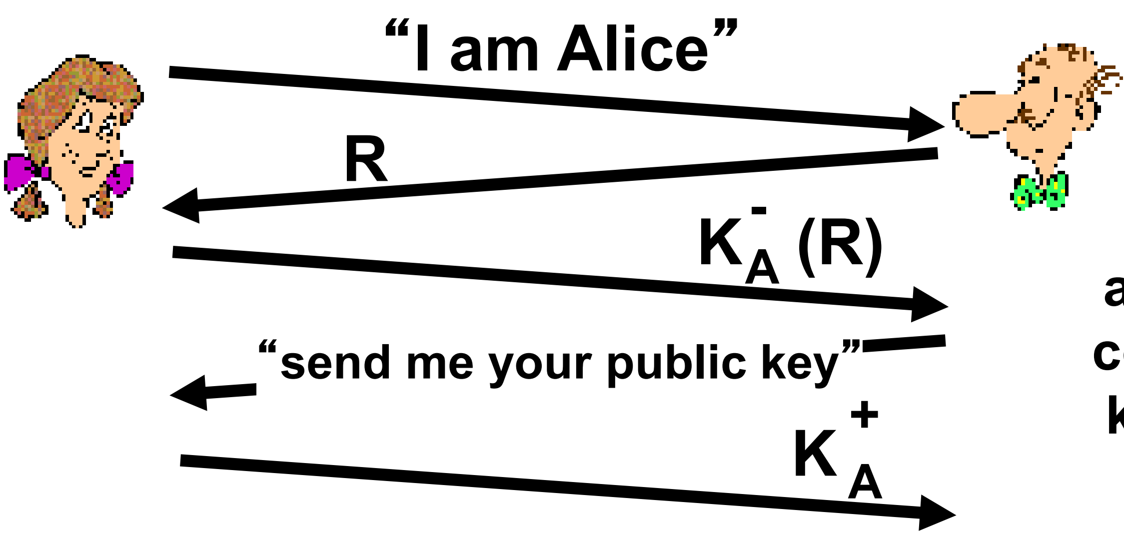
**Failures, drawbacks?**

# 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

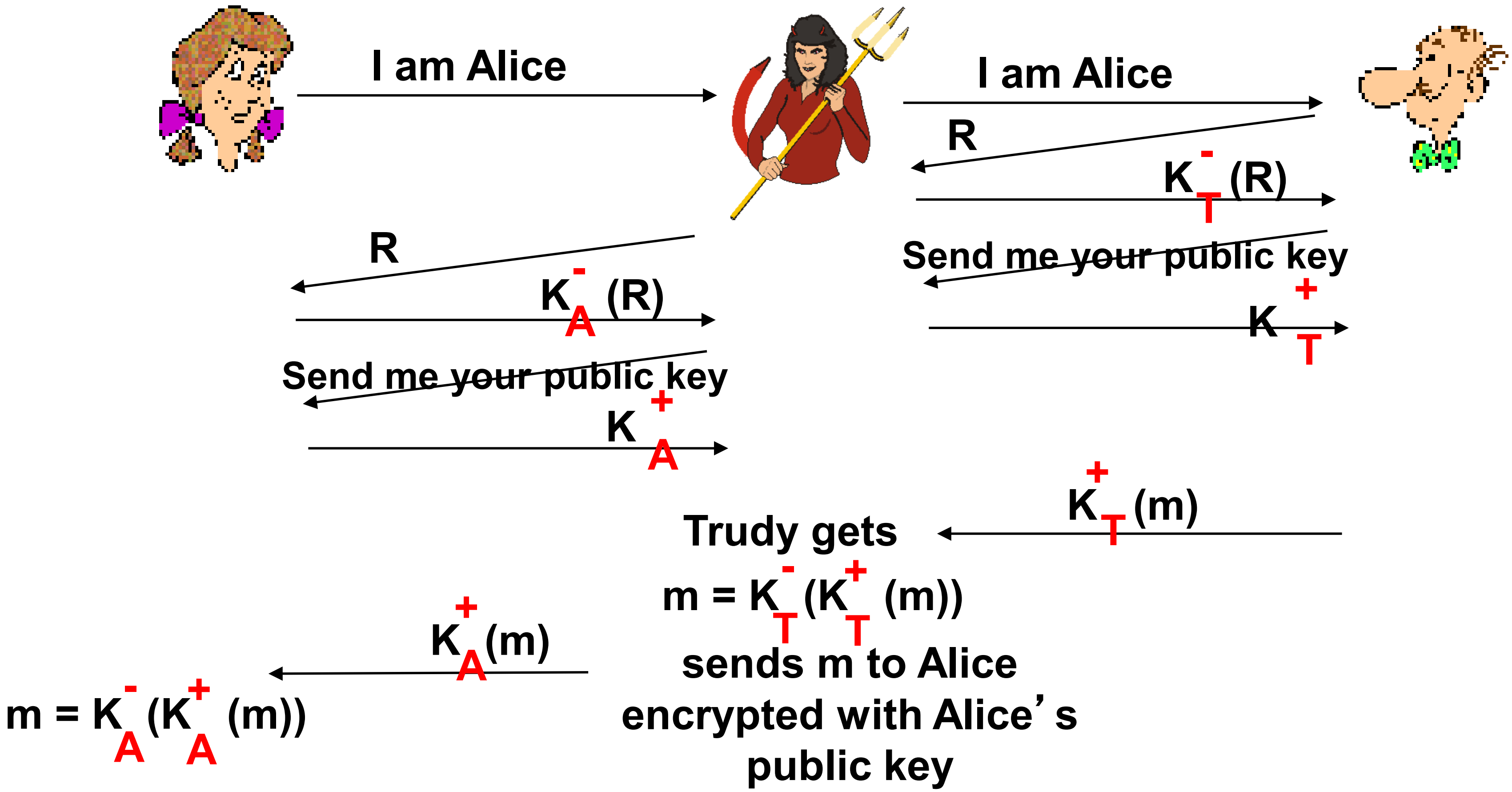
$$K_A^+(K_A^-(R)) = R$$

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

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

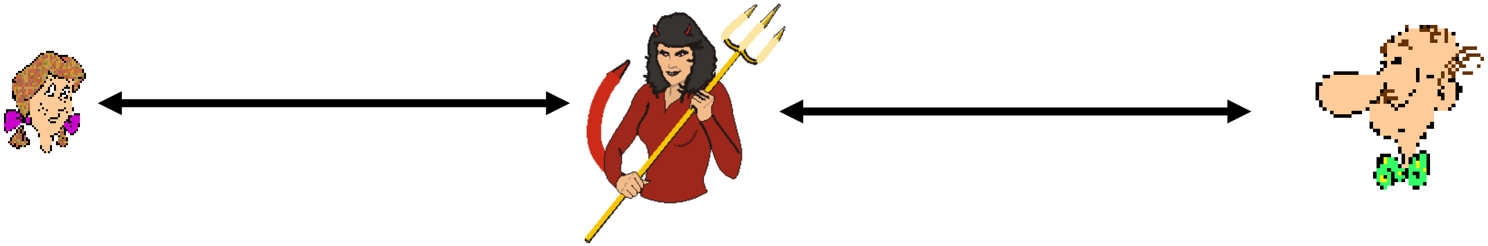
# ap5.0: security hole

*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!

# Message Integrity and Authentication

- Receiving msgs from Alice, Bob wants to ensure:
  - Message originally came from Alice
  - Message not changed since sent by Alice

- Security handling
  - Source impersonation / spoofing
  - Message injection / modification
  - Message re-sequencing / replaying

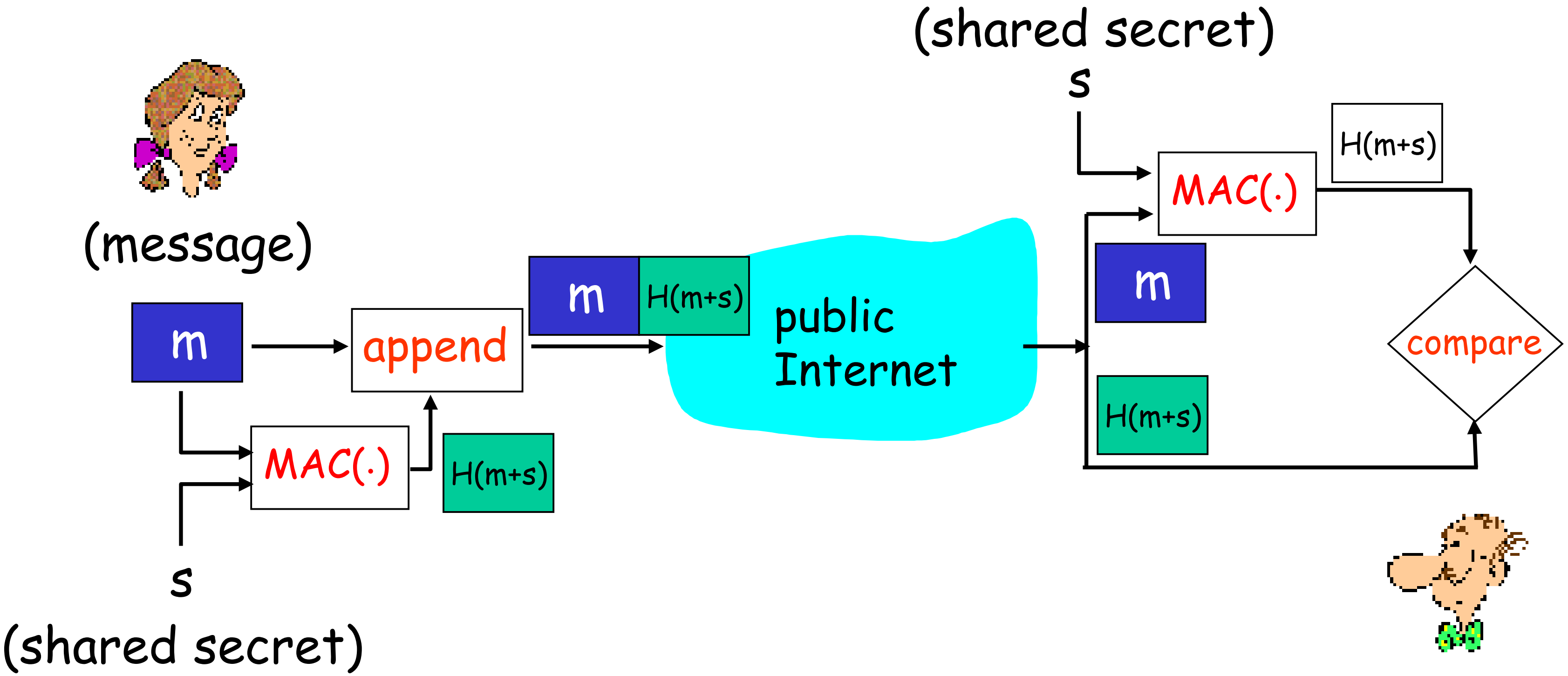
# Authentication Functions

- Creating an authenticator which may involve functions of
  - Sender / Message Text
  - Time Stamp / Sequence Number / Random Value
  - Secret Keys

- The sender computes and sends the authenticator as part of the regular message

- The recipient compares the received authenticator with the expected authenticator

# Message Authentication Code



# Authentication by MAC

- *MAC* is a fixed-size code that is appended to the message
  - Typical sizes of *MAC* range from 64 to 256 bits
- Message can be sent in the clear without encryption
- *MAC* is a function of the message and a secret key
  - Can assure msg not altered, and from alleged sender
- *MAC* should not be reversible, decryption is not needed
- The strength of the *MAC* depends on the function and on the secrecy of the key

# Authentication Methods

- Authentication by Crypto
  - Using `crypto` functions of the text and secret keys
  - CBC-MAC

- Authentication by Hash
  - Using hash functions and involving secret keys in the computations
  - MD5, 128 bit MAC, (RFC 1321)
  - SHA-1, 160 bit MAC, (NIST, FIPS PUB 180-1)

# Requirements of MAC Functions

- Operability
  - Work on any input length
  - Produce output of fixed size
  - Should be easy to compute

- Security
  - One-way – given value Y, it is hard to find content X such that $Y = MAC(X)$
  - Weak Collision Resistance – given content $X_1$ it is hard to find another content $X_2$ such that $MAC(X_1) = MAC(X_2)$
  - Strong Collision Resistance – it is hard to find any two different contents $X_1$ and $X_2$ such that $MAC(X_1) = MAC(X_2)$

# CBC-MAC Authentication

- Cipher block chaining message authentication code
- Divide message $M$ into $L$ blocks of size $n$ bits each

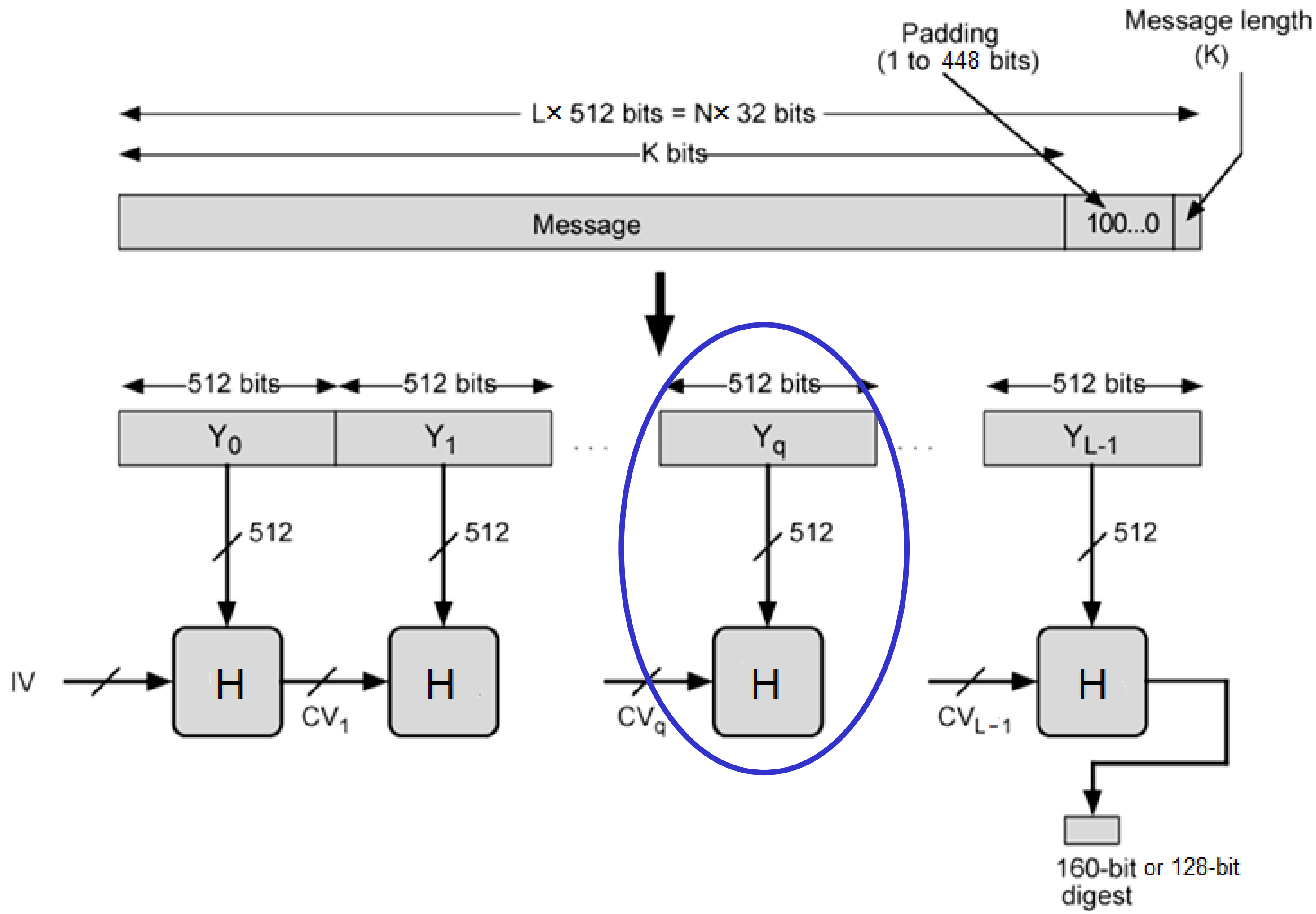
  $M = M_1, M_2, \ldots, M_L$

- Let $K$ be a secret key of the encryption algorithm $E$

- Let $C_0 = IV$ be a random block of $n'$ bits
- Compute $C_i = E_K(M_i + C_{i-1})$ for $i = 1, 2, \ldots, L$
  - $CBC\text{-}MAC_K(M) = C_L$

- Let $MAC_K(M) = (C_0, C_L) = (IV, CBC\text{-}MAC_K(M))$
  - i.e. the first and last blocks of *CBC* encryption

# Common Structure for MD5 and SHA-1



# Common Steps

- Input message less than $2^{64}$ bits
  - Processed in 512 bit blocks
- Appends padding bits
  - Message Length congruent to 448(mod 512)
- Adds length field
  - Original message length is written in last 64 bits

# MD5 Processing

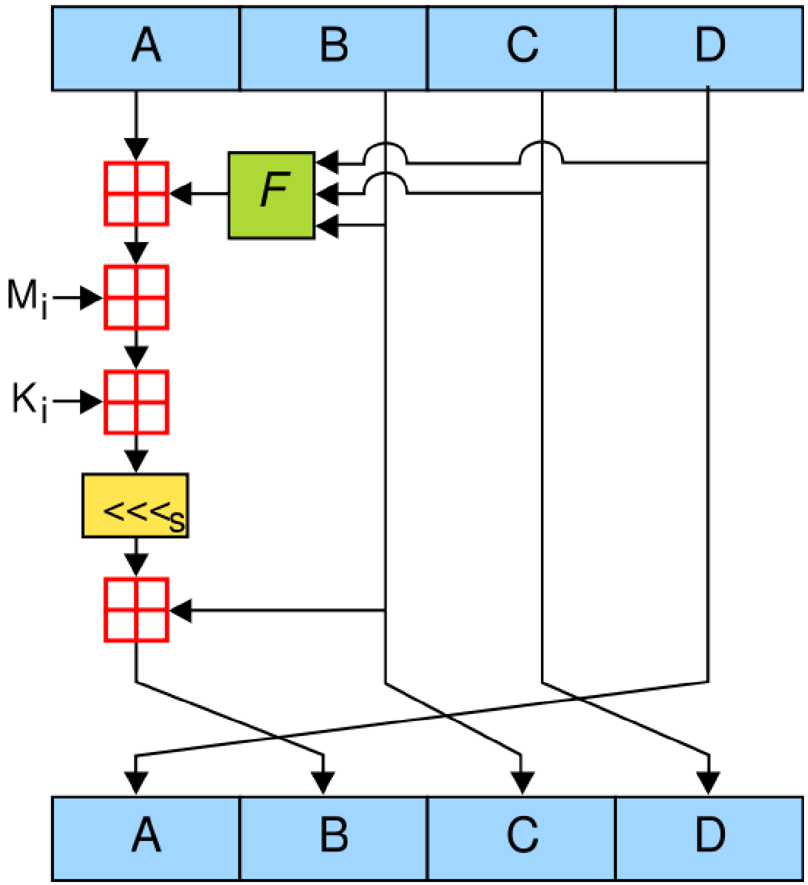
- Uses 4-word state buffer A, B, C, D to compute the message digest
  - Initial value: 01234567, 89abcdef, fedcba98, 76543210
  - Total 128 bits
- Process message in 16-word blocks
  - $M_0$, $M_1$, … $M_{15}$
- Processing of a msg block consists of 4 similar stages
  - Each with a different function F
- Each stage is composed of 16 similar operations
  - Using F, modular +, and left rotation

# One MD5 Operation

- A different F is used for each stage

$$F_1(X,Y,Z) = (X \wedge Y) \vee (\neg X \wedge Z)$$
$$F_2(X,Y,Z) = (X \wedge Z) \vee (Y \wedge \neg Z)$$
$$F_3(X,Y,Z) = X \oplus Y \oplus Z$$
$$F_4(X,Y,Z) = Y \oplus (X \vee \neg Z)$$

- $M_i$ is a 32-bit word of msg
- $K_i$ is a 32-bit generated constant

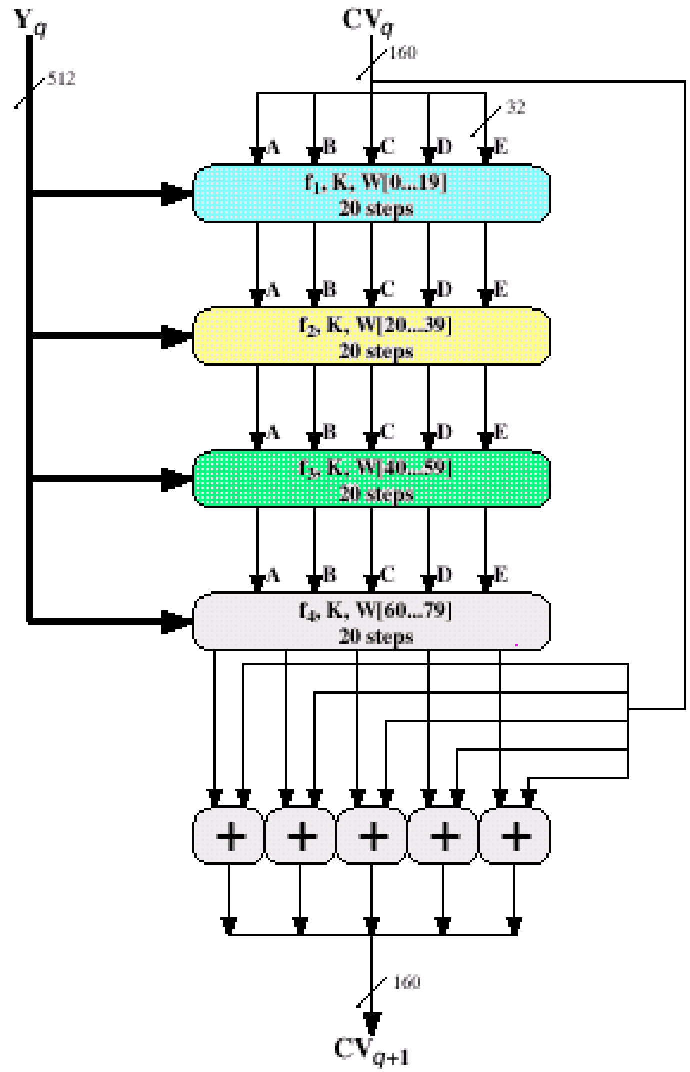


# SHA-1 Processing

- Uses 5 word state buffer $A$, $B$, $C$, $D$, $E$ to compute the message digest
  - Value 67452301, efcdab89, 98badcfe, 10325476, c3d2e1f0
  - Total 160 bits
- Process message in 16-word chunks
  - $M_0, M_1, \ldots M_{15}$
- Processing of a msg block consists of 4 similar stages
  - Each with a different function F
- Each stage is composed of 20 similar operations

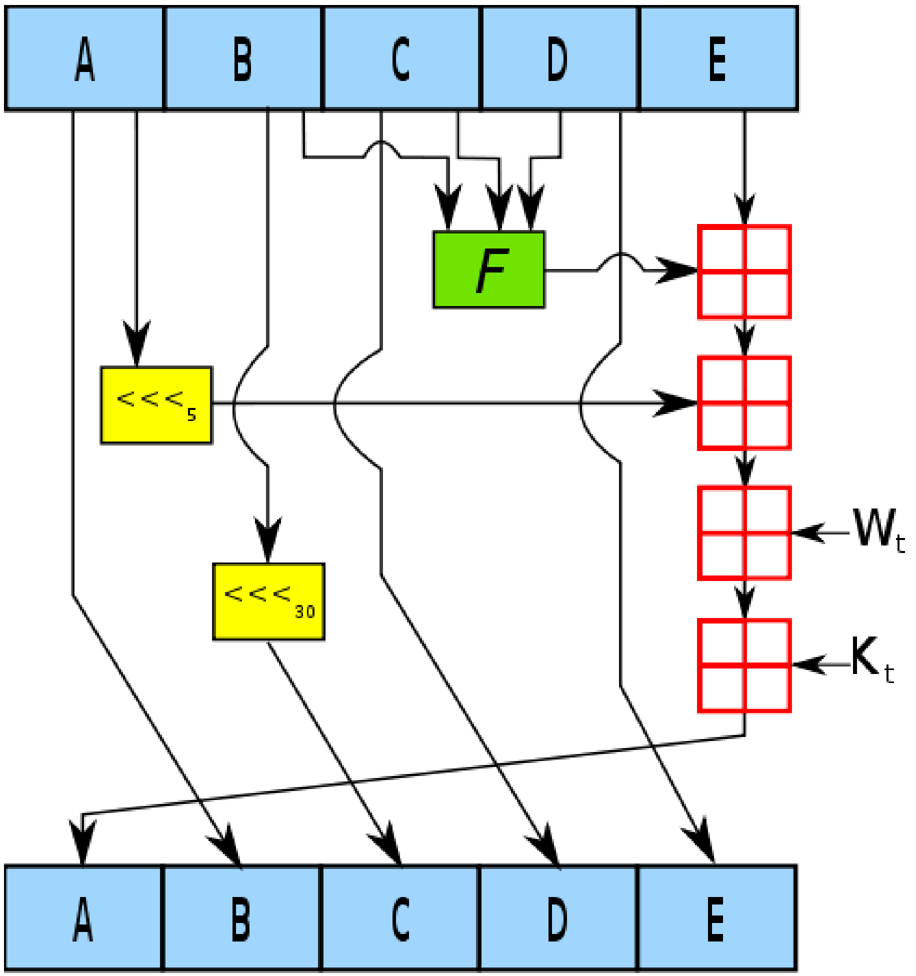
# SHA for a Single Chunk

- $M_0, M_1, \ldots, M_{15}$ : 16 words of input chunk
- For t = 0 to 15, $W_t = M_t$
- For t = 16 to 79, $W_t = S^1(W_{t-16} \oplus W_{t-14} \oplus W_{t-8} \oplus W_{t-3})$
- $F_1, F_2, F_3, F_4$ : 4 different elementary functions
- K : distinct set of constants for each $F_i$



# One SHA Operation

- F is a nonlinear function that varies
- $W_t$ is the expanded message word of step t
- $K_t$ is the constant of step t

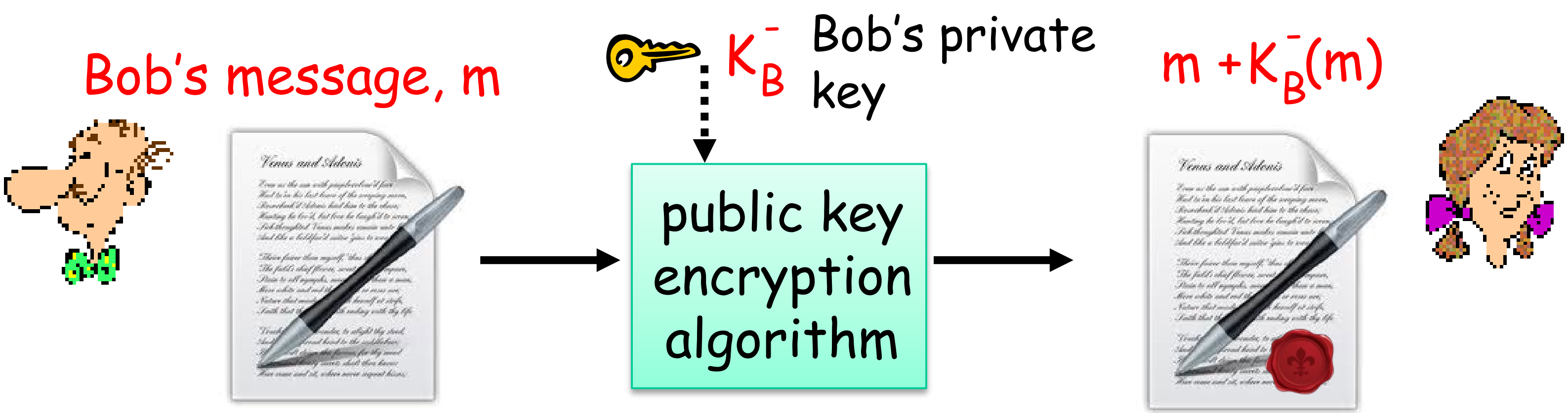


# Breaking MD5 & SHA-1

- 2004年，山东大学数学系王小云首次展示MD5产生碰撞的高效算法。
- 2005年2月，王小云提出SHA-1产生碰撞的算法，其复杂度从$O(2^{80})$降为$O(2^{69})$，同年8月，该复杂度进一步降为$O(2^{63})$。
- 但是，产生碰撞并不等于可以随意产生所需要的内容，更不能随意篡改内容并通过哈希校验，所以MD5和SHA-1至今仍被广泛使用。

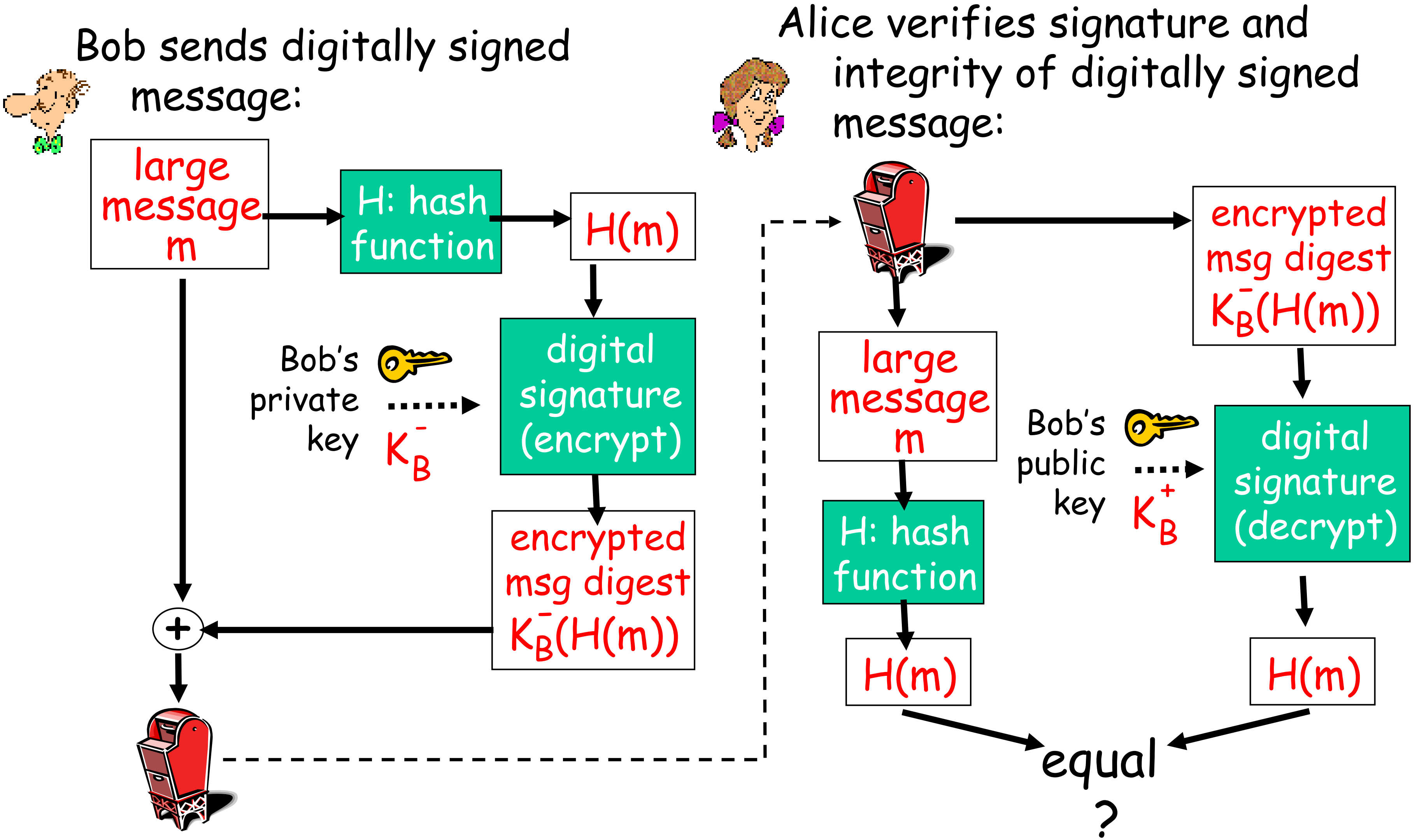
# Digital Signature

- Sender (Bob) digitally signs document, making him document owner/creator
- Recipient (Alice) can prove to someone that Bob, and no one else, must have made the document




- Bob's private key is essential

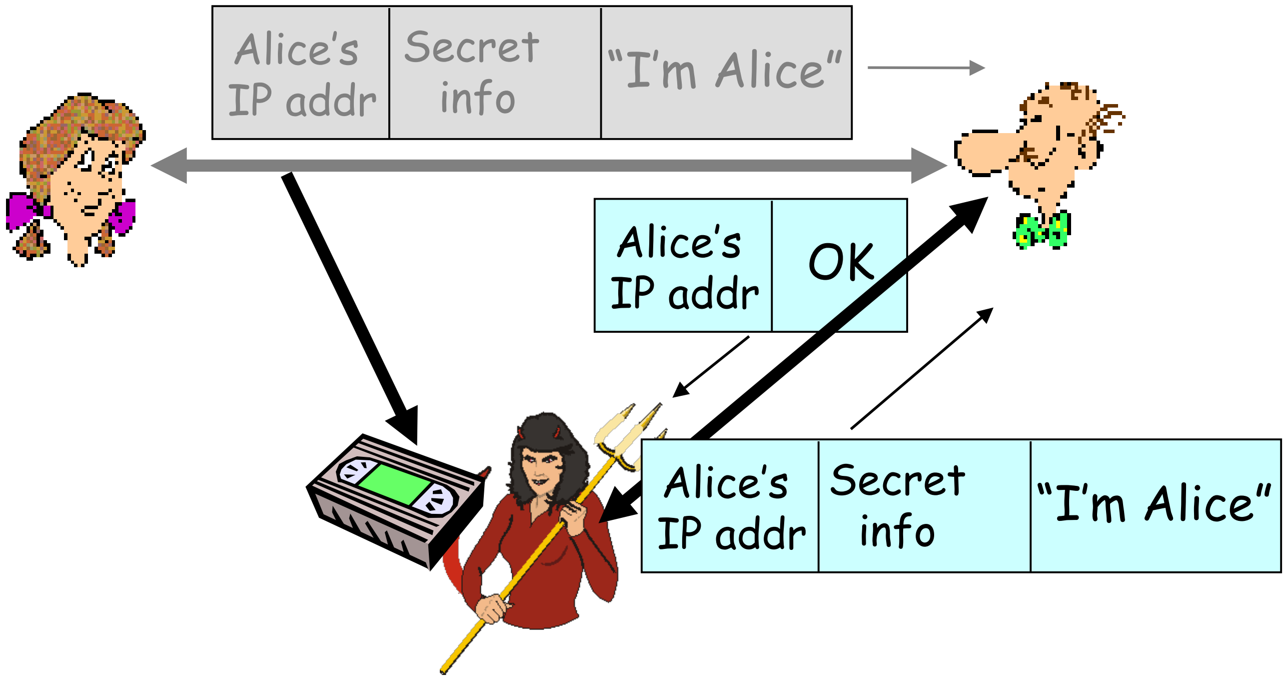
# Digital Signature is Signed MAC



# Key Distribution

- Problem
  - How can Alice and Bob share the common secret key
  - How does Alice know Bob’s public key does be Bob’s public key
- Solution
  - Diffie-Hellman Key Exchange
  - Trusted certification authority (CA)
  - Certificate for public key

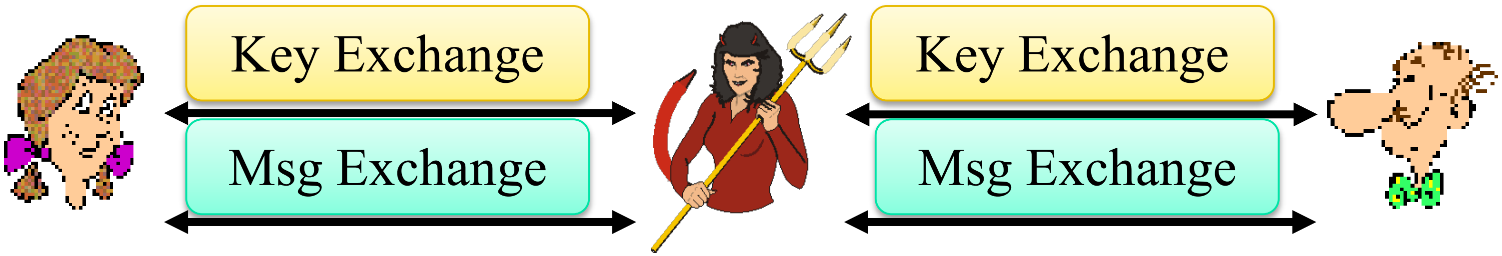
# Attack Key Distribution




- Record and playback
  - Still account for large part of secret holes
  - Needs proper use of timestamp and nonce

**Nonce：不重数**

# Attack Key Distribution




- Middle attack (Man-in-the-middle attack)
  - Trudy poses as Alice (to Bob) and as Bob (to Alice)
- Hard to detect
  - Bob receives everything that Alice sends, and vice versa
  - But Trudy receives all messages as well!

- 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

# Diffie-Hellman Key Exchange

- Diffie-Hellman Key Exchange, 1976
- Diffie, Hellman (Turing Award 2015)

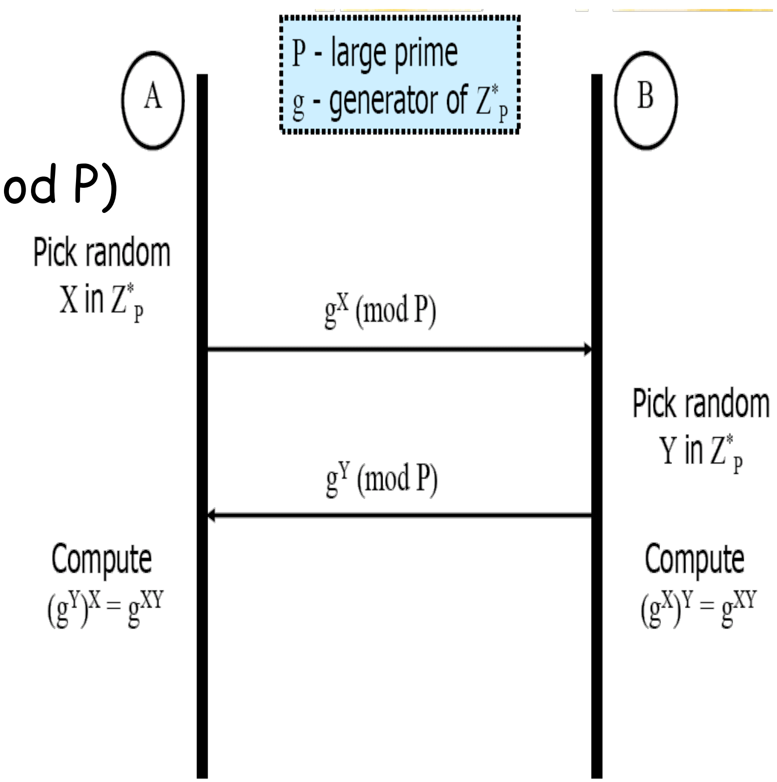
# Diffie-Hellman Key Exchange (1)

- Preliminary
  - Large prime $P$ known to the world
  - Generator $g$ of $Z_p^*$ known to the world
  - $A$ and $B$ do not share any secret value

**$Z_p^* = \{0, 1, 2, \ldots, p-1\}(\bmod\ p)$**

# Diffie-Hellman Key Exchange (2)

- The D-H Protocol
  - A picks at random a number $X \in \{1, 2, \ldots, P-1\}$ and sends to B the value $g^X (\mathrm{mod}\ P)$
  - B picks at random a number $Y \in \{1, 2, \ldots, P-1\}$ and sends to A the value $g^Y (\mathrm{mod}\ P)$
  - A computes $(g^Y)^X\ (\mathrm{mod}\ P) = g^{XY} (\mathrm{mod}\ P)$
  - B computes $(g^X)^Y\ (\mathrm{mod}\ P) = g^{XY} (\mathrm{mod}\ P)$
  - A and B now share the secret value $g^{XY} (\mathrm{mod}\ P)$
- Note:
  - $Z_P^* = \{1 \le a \le P-1: \gcd(a,P)=1\}$
    - Each $[a]$ denote a set $[a] = \{a+k \times P: k \in Z\}$
    - For a prime P, $Z_P^* = \{1, 2, \ldots, P-1\}$
  - Generator $g$ of $Z_P^*$: $g \in Z_P^*$
    - $\forall a \in Z_P^*, \exists k \in Z, a = g^k (\mathrm{mod}\ P)$



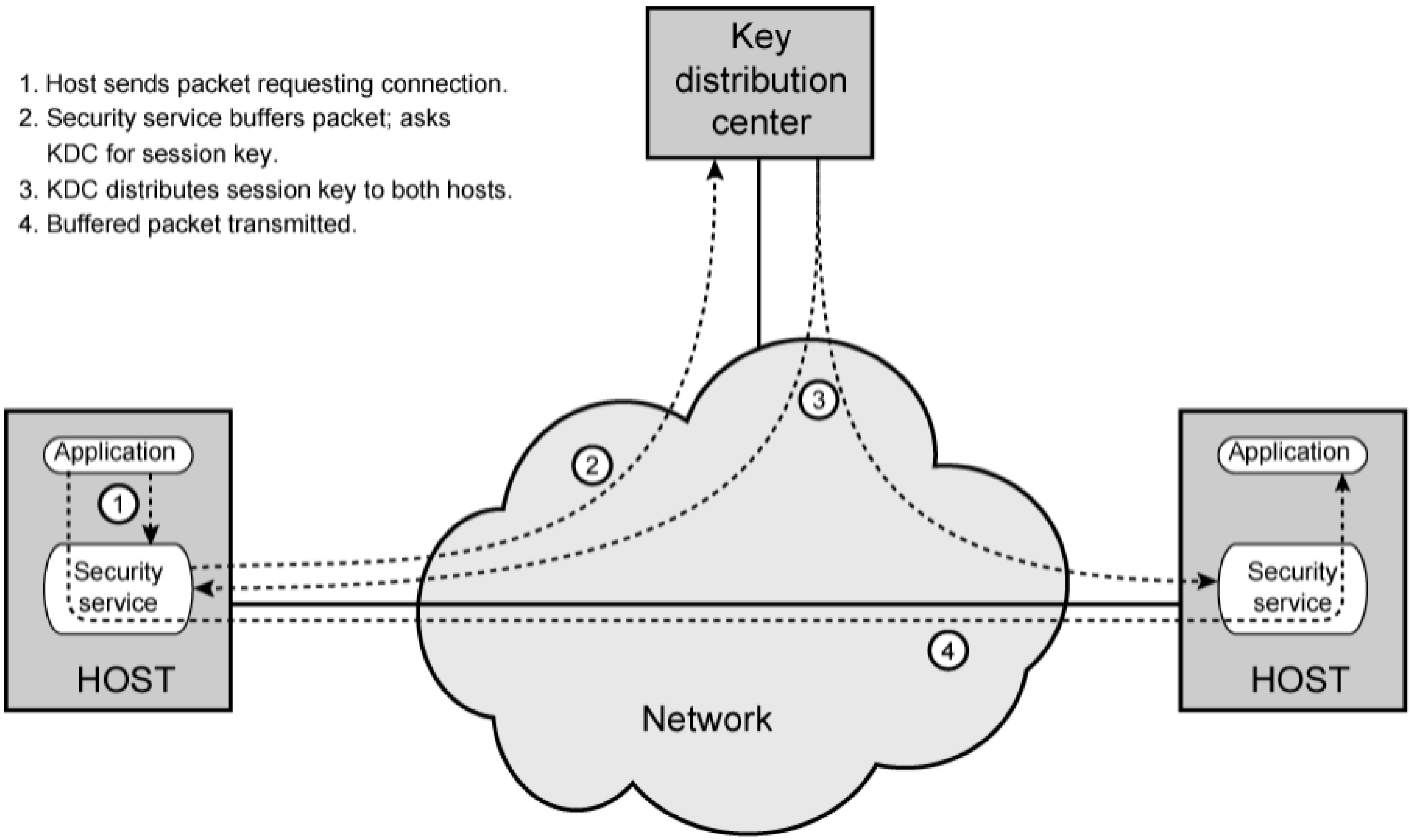
| Alice | |
|---|---|
| knows | doesn't know |
| $p = 23$ | $b = ?$ |
| base $g = 5$ | |
| $a = 6$ | |
| $A = 5^a \bmod 23$ | |
| $A = 5^6 \bmod 23 = 8$ | |
| $B = 19$ | |
| $s = B^a \bmod 23$ | |
| $s = 19^6 \bmod 23 = 2$ | |
| $s = 2$ | |

| Bob | |
|---|---|
| knows | doesn't know |
| $p = 23$ | $a = ?$ |
| base $g = 5$ | |
| $b = 15$ | |
| $B = 5^b \bmod 23$ | |
| $B = 5^{15} \bmod 23 = 19$ | |
| $A = 8$ | |
| $s = A^b \bmod 23$ | |
| $s = 8^{15} \bmod 23 = 2$ | |
| $s = 2$ | |

| Trudy | |
|---|---|
| knows | doesn't know |
| $p = 23$ | $a = ?$ |
| base $g = 5$ | $b = ?$ |
| | $s = ?$ |
| $A = 8$ | |
| $B = 19$ | |
| $s = 19^a \bmod 23 = 8^b \bmod 23$ | |

# Trusted Certification Authority

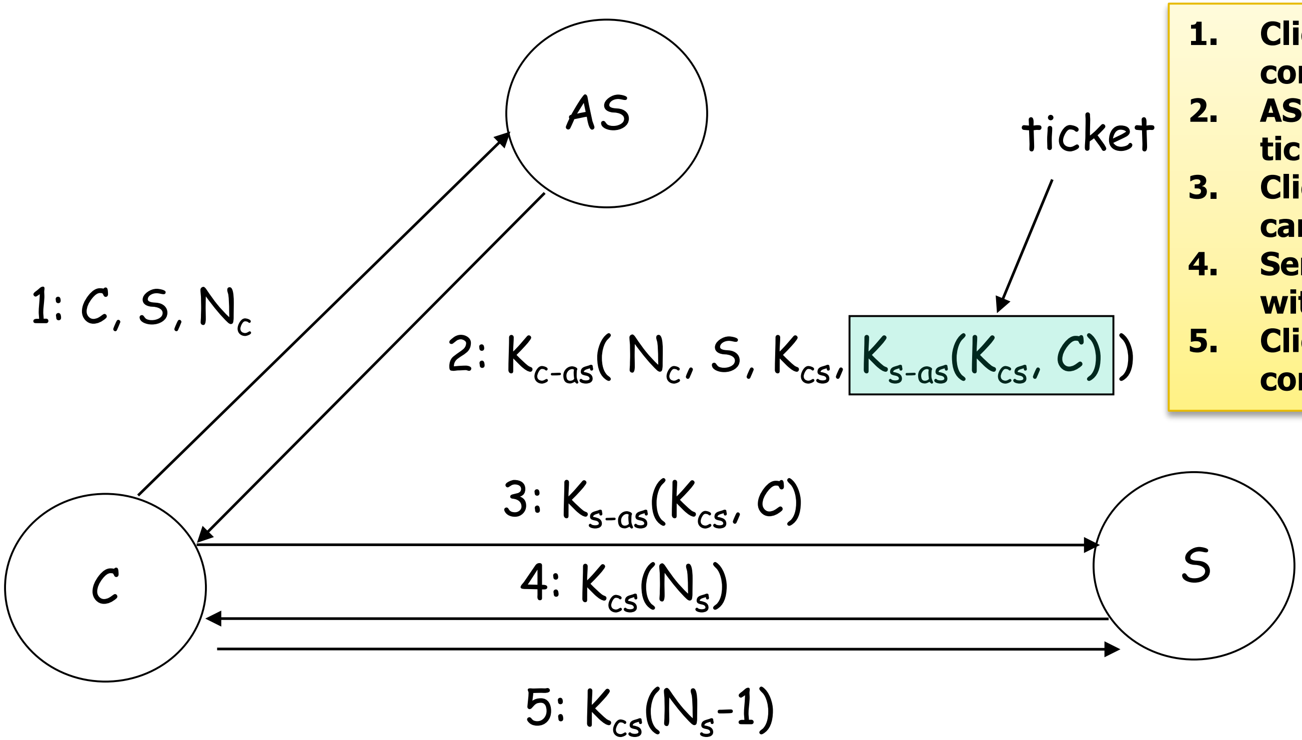
1. Host sends packet requesting connection.
2. Security service buffers packet; asks KDC for session key.
3. KDC distributes session key to both hosts.
4. Buffered packet transmitted.



# Key Distribution via CA

- Session Key
  - Used for duration of one logical connection
  - Destroyed at end of session
- Permanent key
  - Used for distribution of keys
- Key distribution center (CA)
  - Determines validity of sender and receiver
  - Provides one session key for that connection
- Security service module (SSM)
  - Performs end to end encryption
  - Obtains keys for host

# The Needham-Schroder Protocol




1. **Client tells AS that it want to communicate with Server.**
2. **AS generate session key $K_{cs}$ and ticket, then sends back to client**
3. **Client sends ticket to server, server can decrypt using $K_{s\text{-}as}$**
4. **Server send a nonce encrypted with the obtained session key**
5. **Client sends back nonce-1 to show communication OK**

AS: Authentication server (KDC)
C: client
S: server

$K_{x\text{-}as}$: key shared between X and AS, where X is C, or S
$K_{cs}$: session key between client C and server S
$N_x$: Nonce generated by X

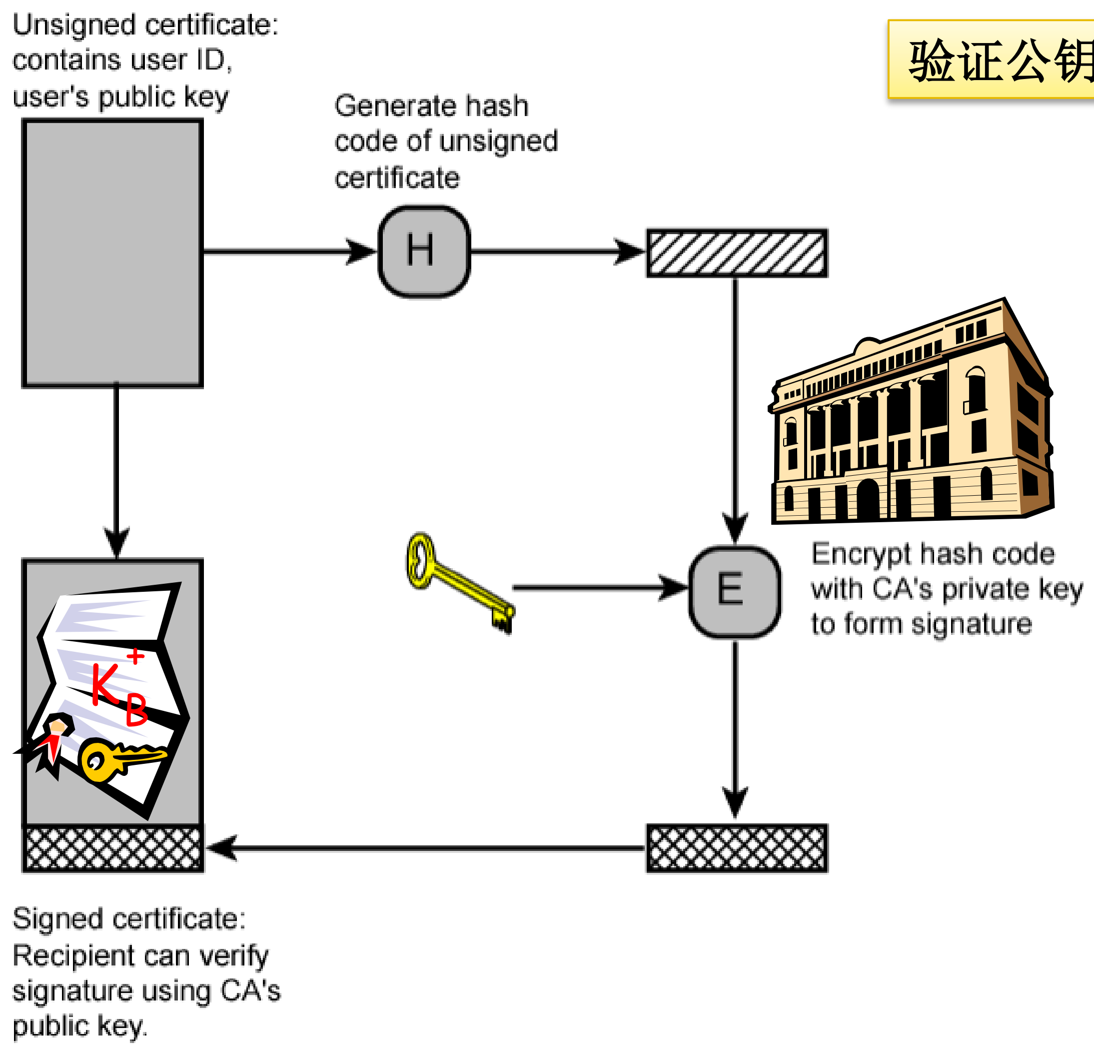
# One-Time Session Key

- Public key not suitable for large blocks of message
- Bob communications with Alice by following steps
  - Prepares a message
  - Encrypts the message using symmetric crypto with a one-time session key
  - Encrypts the session key using Alice's public key
  - Attaches the encrypted session key to the message and sends it to Alice
  - Alice gets the session key using her private key, and decrypts the message

# Public Key Certificate

- Question
  - How to ensure the published public key does be Alice's public key, not from someone else
- Solution: Public key certificate
  - A public key plus User ID of the key owner
  - Above block signed by a trusted CA with a timestamp
- Others cannot substitute Alice's public key with his own
  - Cannot forge the signature of the trusted CA

# Public Key Certificate




验证公钥正确性的过程

# Public Key Certificate

- Serial number (unique to this certificate)
- Info about certificate owner, including algorithms and key value

X509 Public Key Certificate

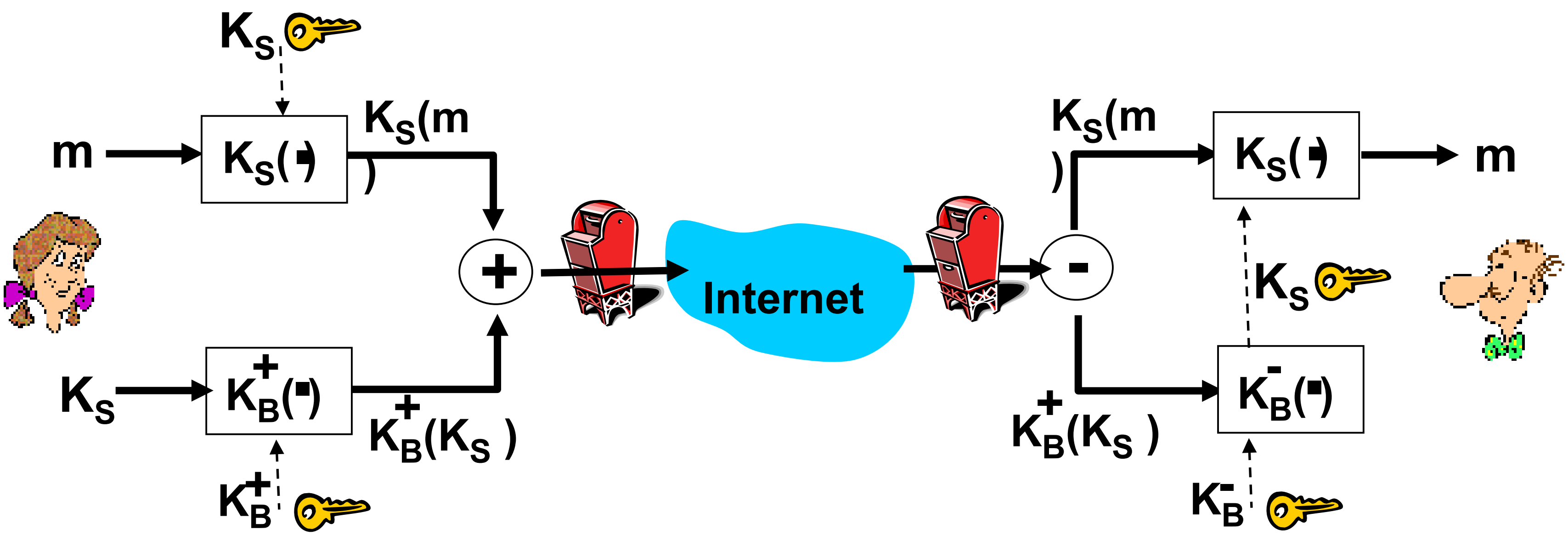
| Field | Value |
|---|---|
| Version | V3 |
| Serial number | 3c 8d 3a 64 ee 18 dd 1b 73 0b... |
| Signature algorithm | sha1RSA |
| Issuer | Thawte SGC CA, Thawte Cons... |
| Valid from | 2. května 2008 18:02:55 |
| Valid to | 2. května 2009 18:02:55 |
| Subject | www.google.com, Google Inc,... |
| Public key | RSA (1024 Bits) |
| Enhanced Key Usage | Server Authentication (1.3.6.... |
| CRL Distribution Points | [1]CRL Distribution Point: Distr... |
| Authority Information Access | [1]Authority Info Access: Acc... |
| Basic Constraints | Subject Type=End Entity, Pat... |
| Thumbprint algorithm | sha1 |
| Thumbprint | 8a aa 9a 71 f0 5c e7 25 8a 35 ... |

Signature 31 0a 6c a2 9e e9 54 ...

- Info about certificate issuer
- Including valid dates, digital signature by issuer (thumbprint / fingerprint)

# Secure e-mail

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

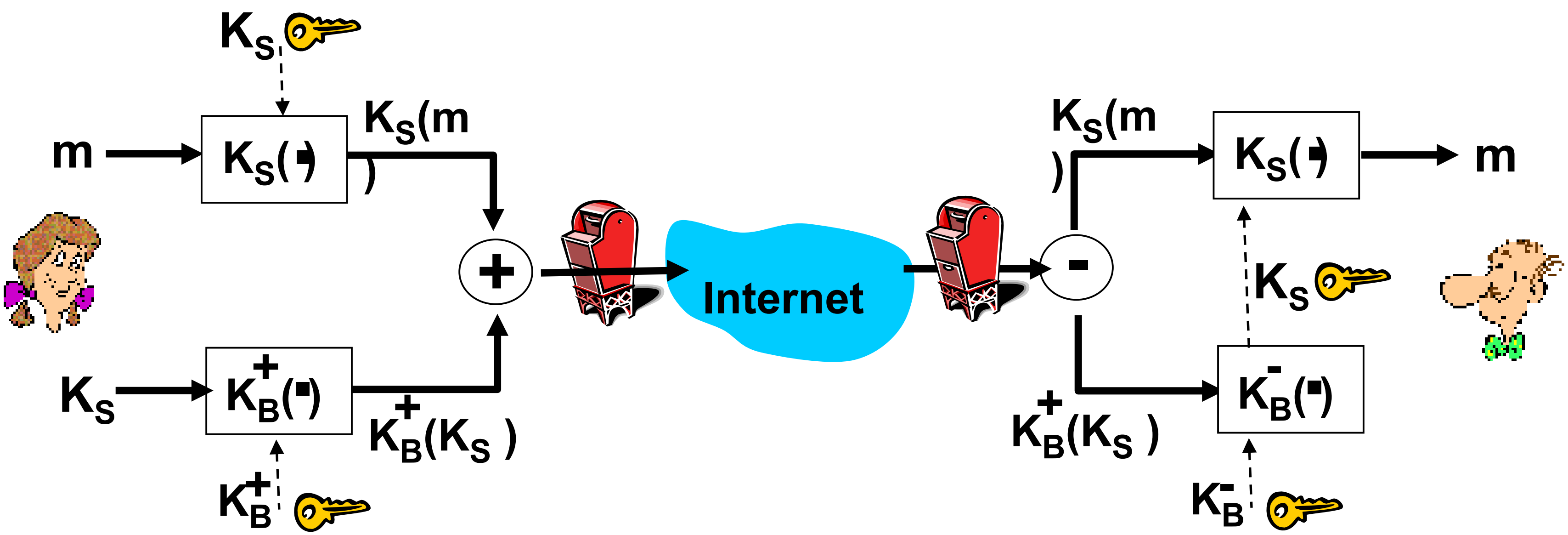



***Alice:***

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

# Secure e-mail

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

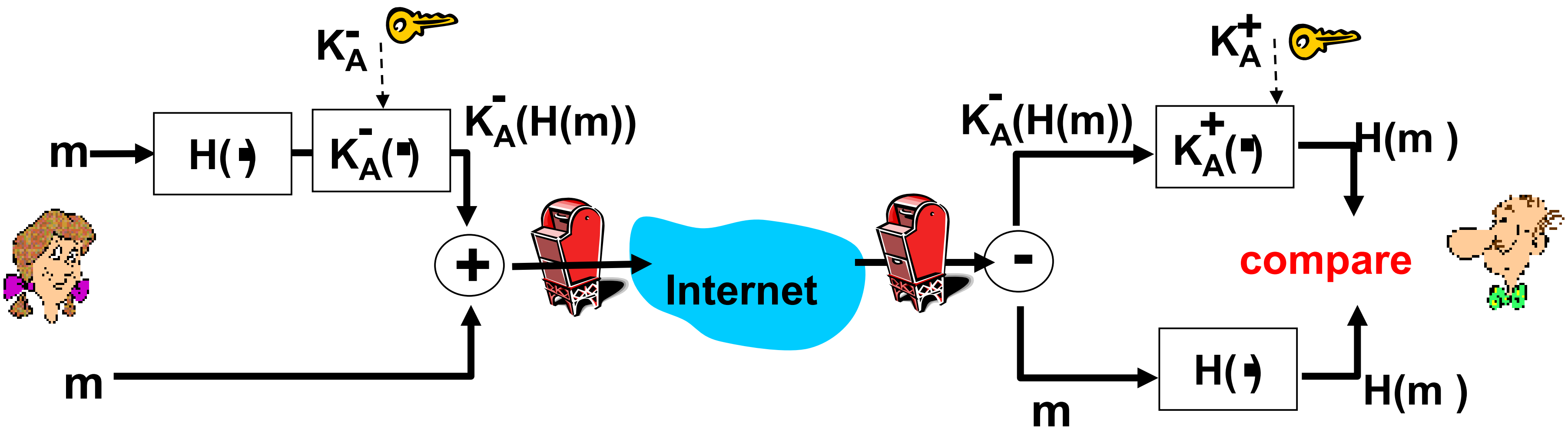



***Bob:***

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

# Secure e-mail (continued)

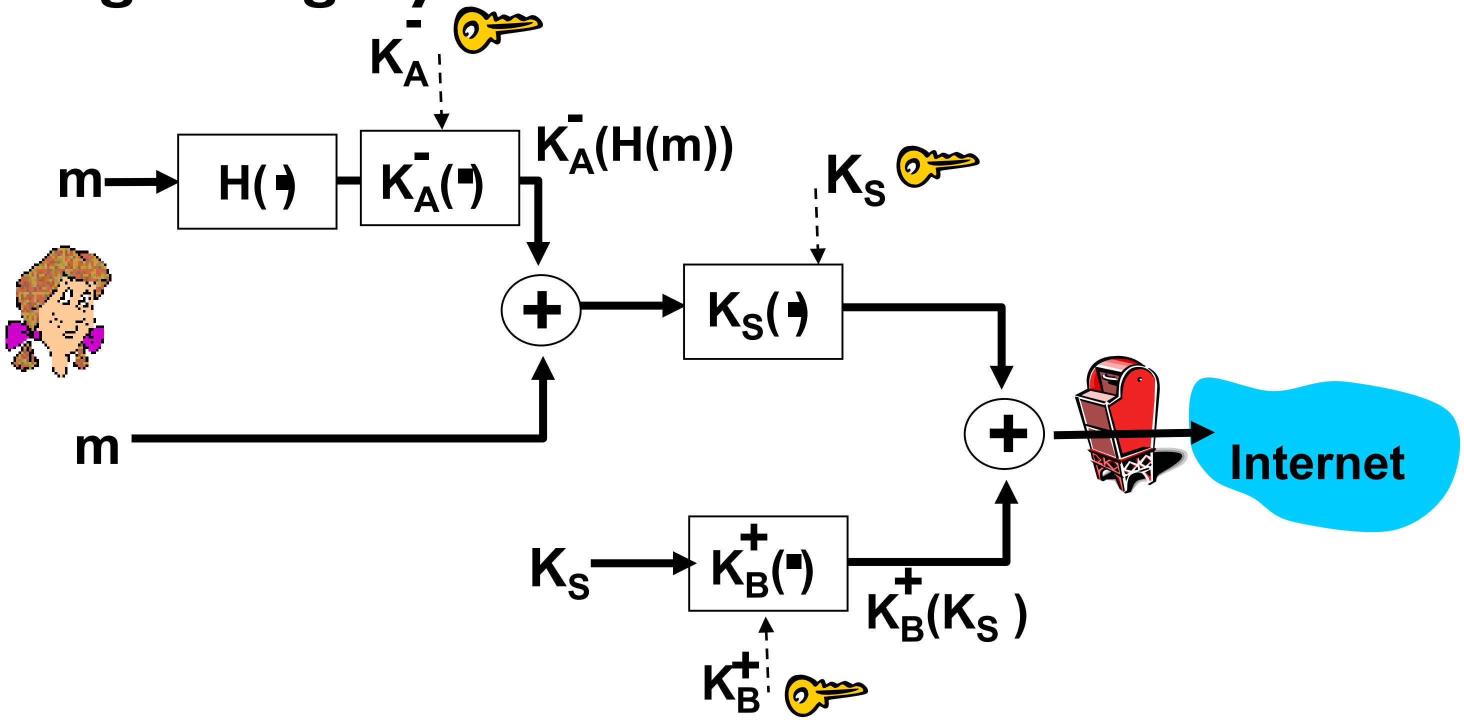
**Alice wants to provide sender authentication message integrity**




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

# Secure e-mail (continued)

**Alice wants to provide secrecy, sender authentication, message integrity.**




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

# Summary

- Authentication
- MAC
  - CBC-MAC
  - MD5
  - SHA-1
- Digital Signature: MAC+Encription
- Key Distribution
  - Diffie-Hellman Key Exchange
  - Trusted certification authority (CA)
  - Certificate for public key

# Homework

- 第八章：R15, P9, P16, P18