Network Security

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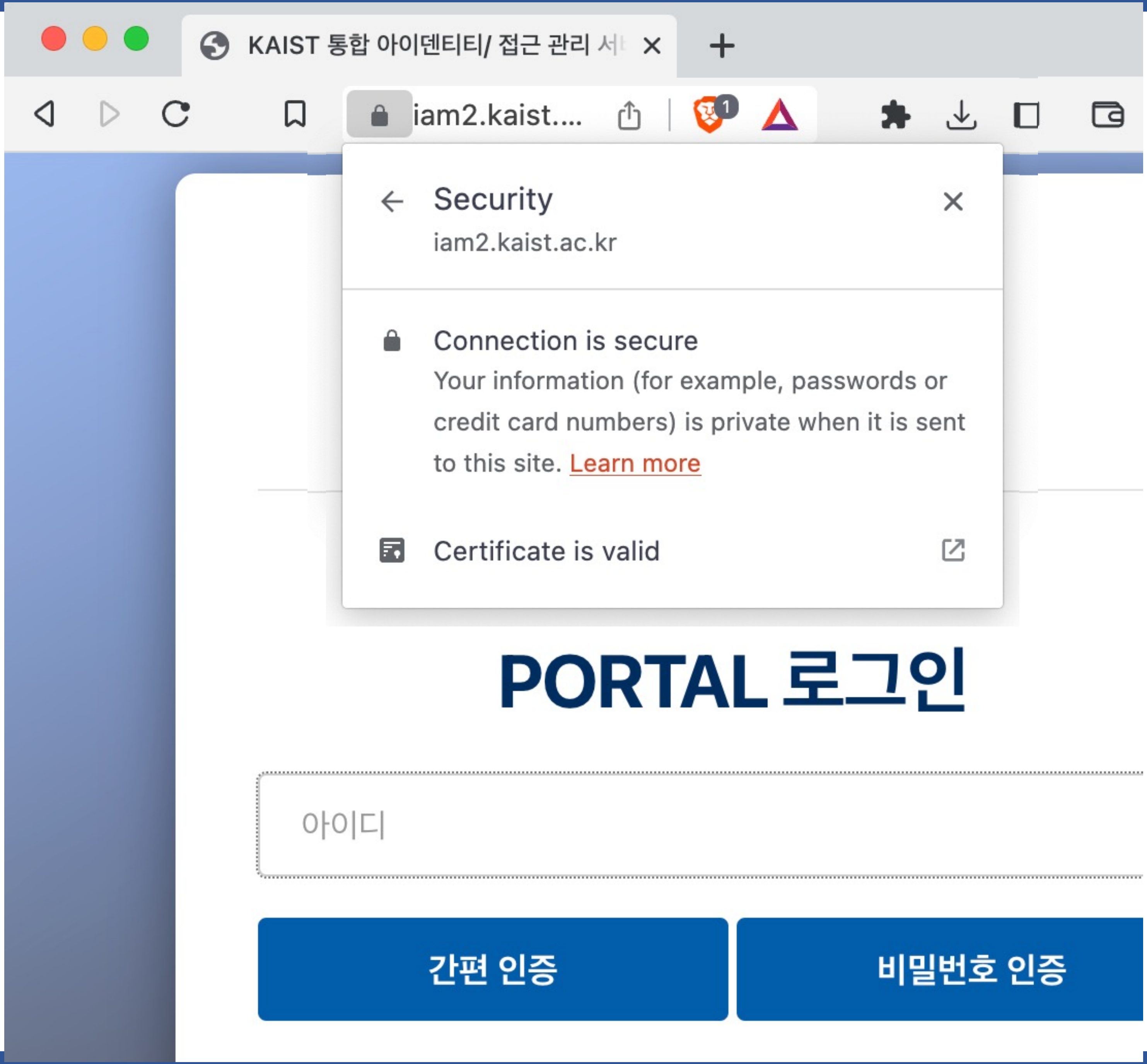
Chapter 8 outline

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

Chapter goals:

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

What is network security?

기밀성

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

전송자와 의도한 수신자만 이해 가능 (암호화)

- sender encrypts message
- receiver decrypts message

authentication: sender, receiver want to confirm identity of each other → identity 확인으로 정체 인증

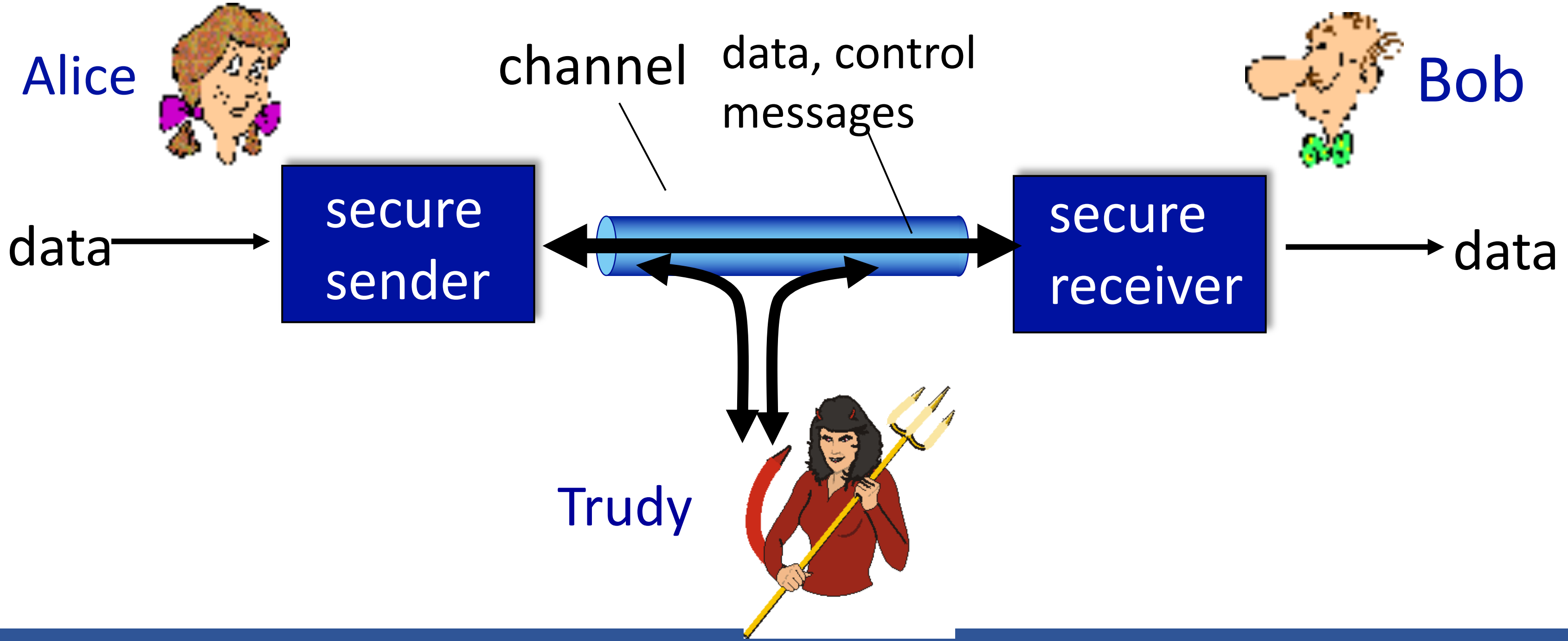
무결성

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

access and availability: services must be accessible and available to users → 사용 편리

Friends and enemies: Alice, Bob, Trudy

- well-known in network security world
- Bob, Alice (lovers!) want to communicate “securely”
- Trudy (intruder) may intercept, delete, add messages



Friends and enemies: Alice, Bob, Trudy

Who might Bob and Alice be?

- … well, *real-life* Bobs and Alices!
- Web browser/server for electronic transactions (e.g., on-line purchases)
- on-line banking client/server
- DNS servers
- BGP routers exchanging routing table updates
- other examples?

There are bad guys (and girls) out there!

Q: What can a "bad guy" do?

A: A lot! (recall section 1.6)

도청

- eavesdrop: intercept messages
- actively insert messages into connection

사칭

- 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

DoS

- denial of service: prevent service from being used by others (e.g., by overloading resources)

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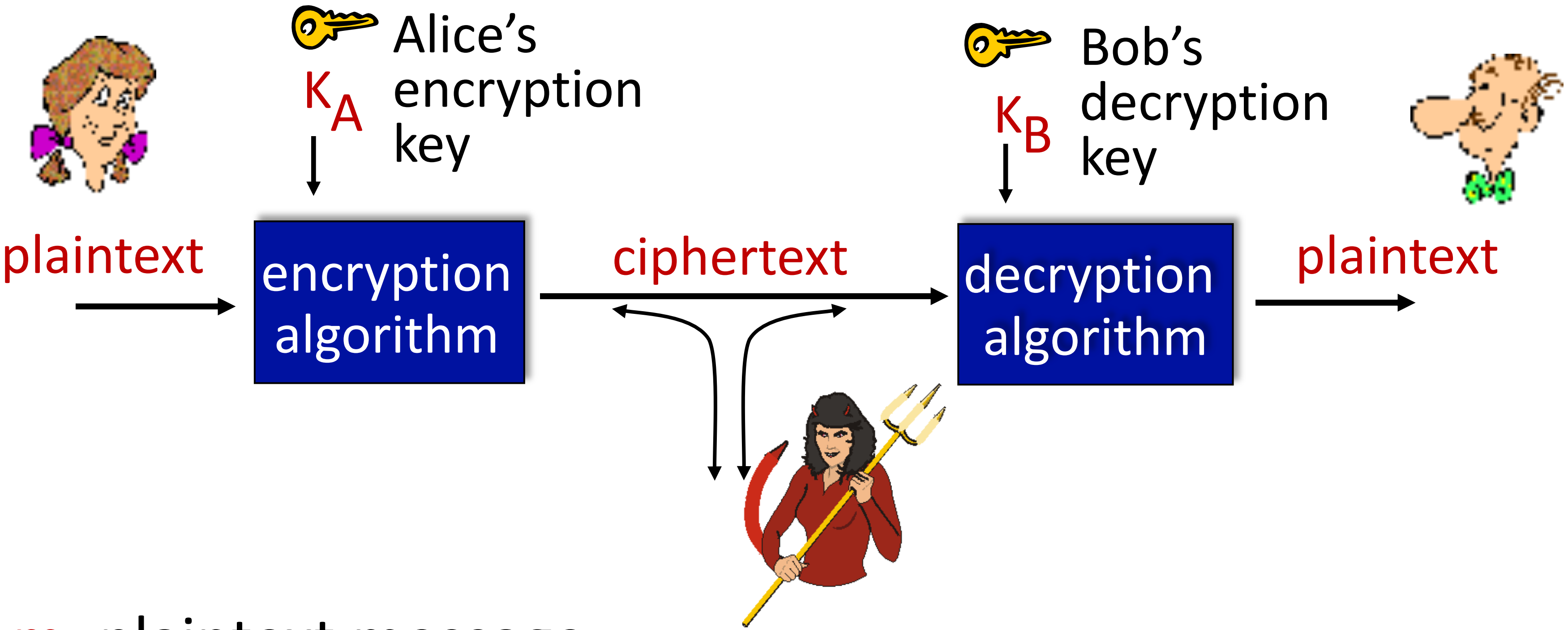
The language of cryptography



m: plaintext message

$K_A(m)$: ciphertext, encrypted with key K_A

$m = K_B(K_A(m))$

Breaking an encryption scheme

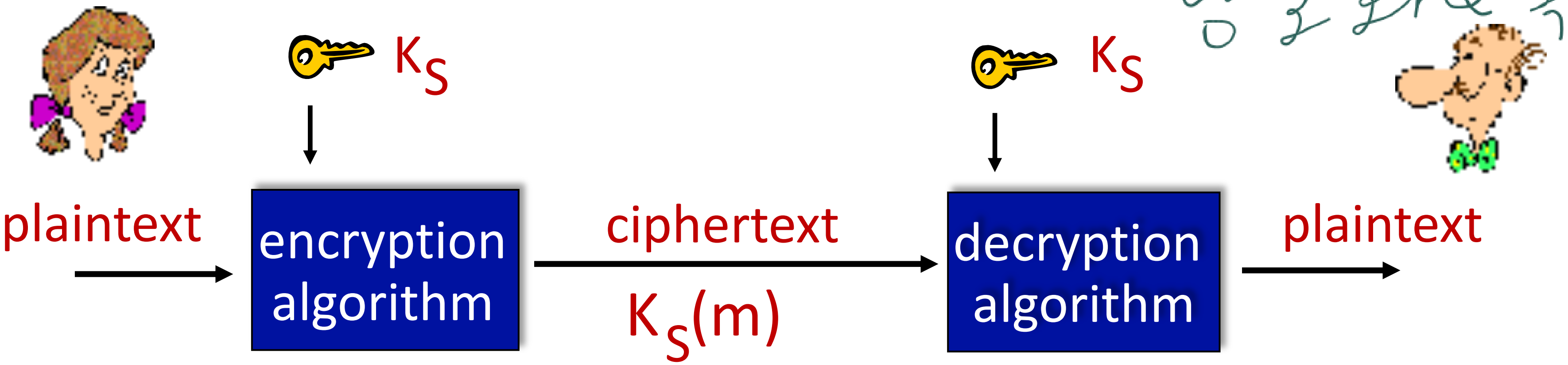
- **cipher-text only attack:** Trudy has ciphertext she can analyze → 암호문에만 접근 가능
- **two approaches:**
  - brute force: search through all keys → 무차별 대입
  - statistical analysis

알고 있는 plaintext와 암호문을 비교해 암호화 알고리즘 분석

- **known-plaintext attack:** Trudy has plaintext corresponding to ciphertext
  - *e.g.*, in monoalphabetic → 알파벳 치환 cipher, Trudy determines pairings for a,l,i,c,e,b,o,
- **chosen-plaintext attack:** Trudy can get ciphertext for chosen plaintext

원하는 평문에 대한 암호문 획득 가능 ⇒ data↑

Symmetric key cryptography → 같은 키로 암호화 & 복호화



symmetric key crypto: Bob and Alice share same (symmetric) key: K

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

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

Simple encryption scheme

→ 다른 문자로 치환하여 암호화

substitution cipher: substituting one thing for another

- monoalphabetic cipher: substitute one letter for another

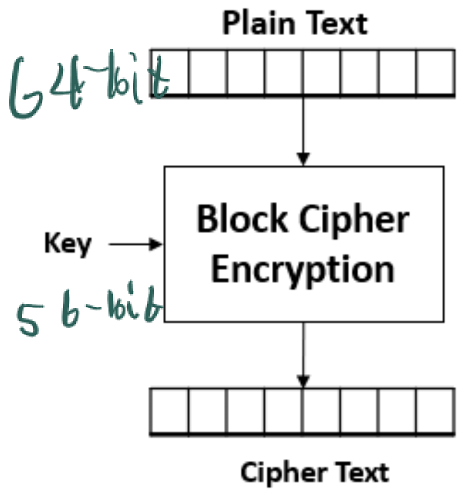
```
plaintext:   abcdefghijklmnopqrstuvwxyz

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

Symmetric key crypto: DES



DES: Data Encryption Standard

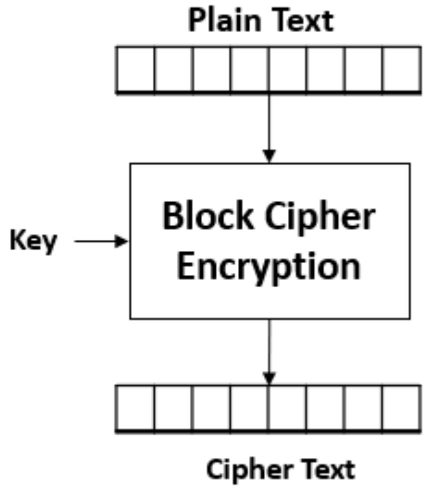
- US encryption standard [NIST 1993]
- 56-bit symmetric key, 64-bit plaintext input
- block cipher with cipher block chaining
- how secure is DES?
  - DES Challenge: 56-bit-key-encrypted phrase decrypted (brute force) in less than a day → 무차별 대입으로 하루도 지나지 않아 해독
  - no known good analytic attack
- making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

AES: Advanced Encryption Standard

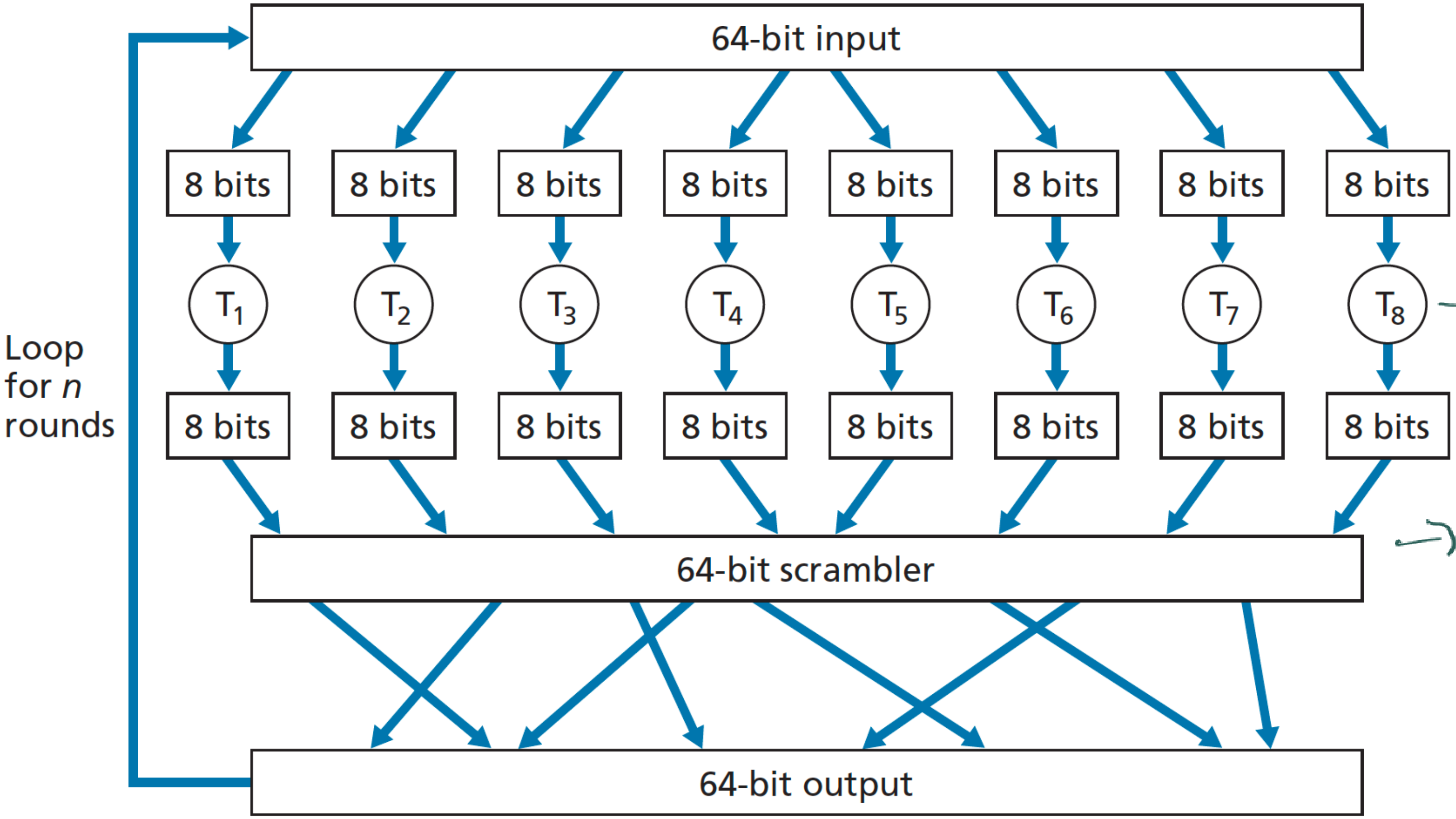
- symmetric-key NIST standard, replaced DES (Nov 2001)
- processes data in 128 bit blocks
- 128, 192, or 256 bit keys > bit↑
- brute force decryption (try each key) taking 1 sec on DES, takes 149 trillion years for AES

↳ 365·24·60·60sec

bit 수 증가로 경우의 수를 늘려 brute force 방지



Block Ciphers

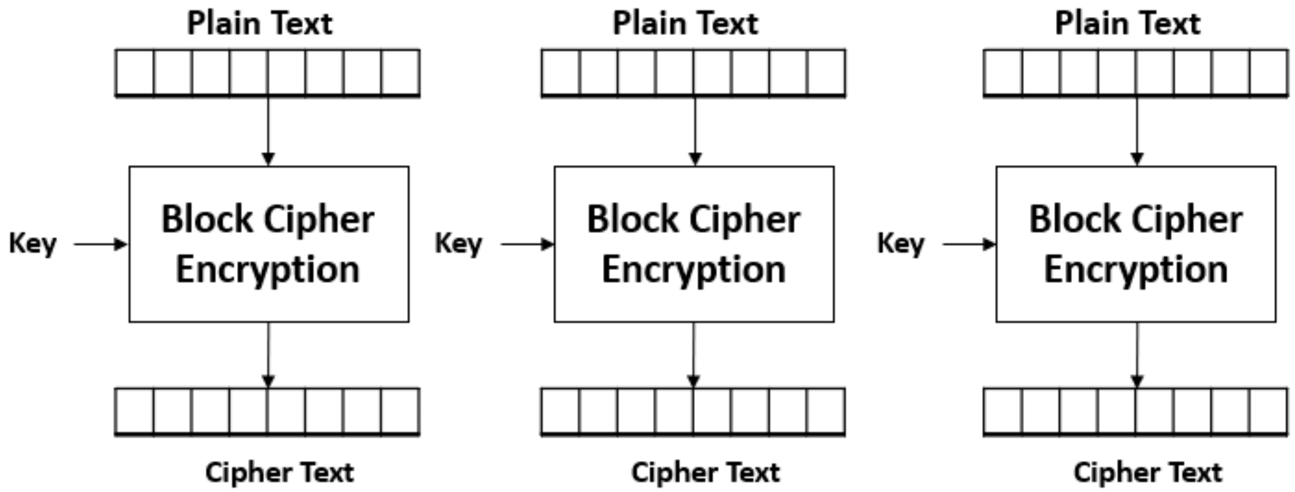


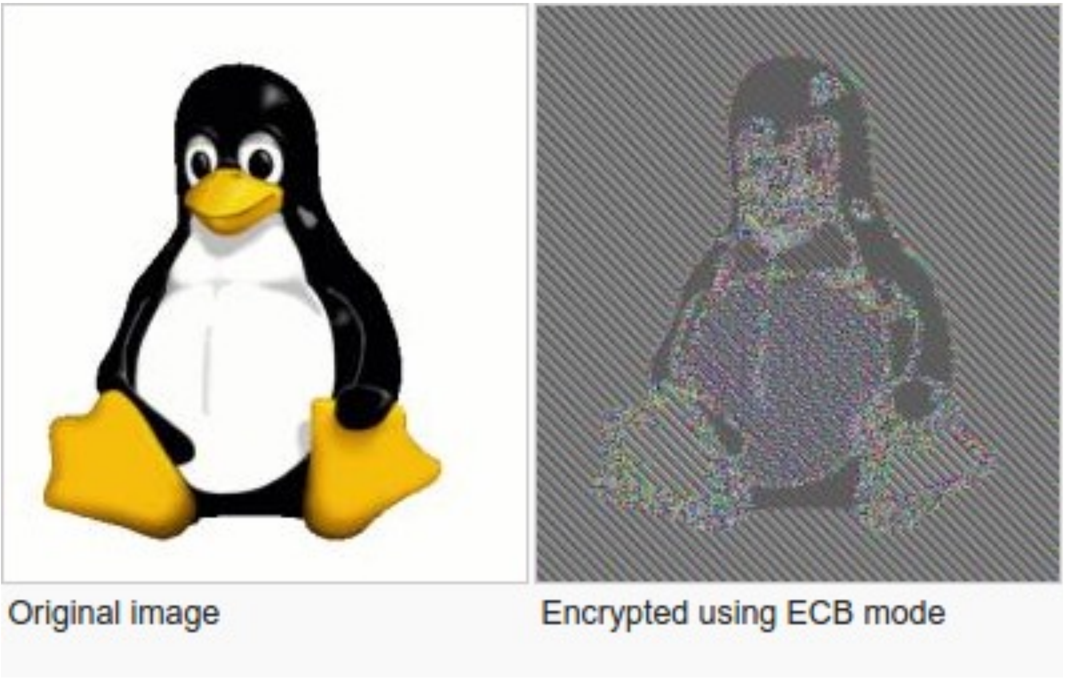
→ chunk 분리

→ 암호화

→ chunks 순서 섞기

Using Block Ciphers for Encryption



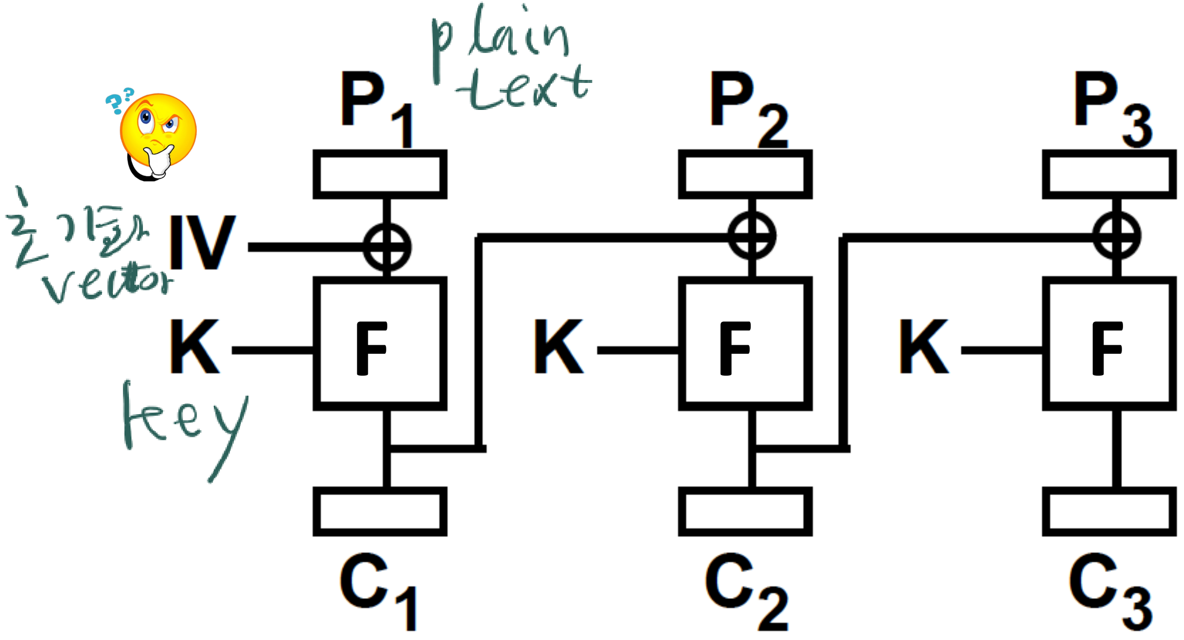


We should use a “secure” ***mode of encryption*** when utilizing block ciphers

Cipher Block Chaining (CBC)

- $C_j = F_K(P_j \oplus C_{j-1})$
- $P_j = F^{-1}_K(C_j) \oplus C_{j-1}$
- C_0 = IV called

  initialization vector



- Idea 1: chaining ciphertext with plaintext
- Idea 2: additional input IV to make encryption probabilistic

↳ 암호화에 random성 부여

What happens if we ignore IV?

- What about IV == 0?
  - This happens frequently (by software engineers with no security education)
  - Not a ***probabilistic*** encryption!

↳ 확률에 의한 변조 X

- In principle, a random IV is chosen each time

매번 random한 IV 선택

Public Key Cryptography

symmetric key crypto:

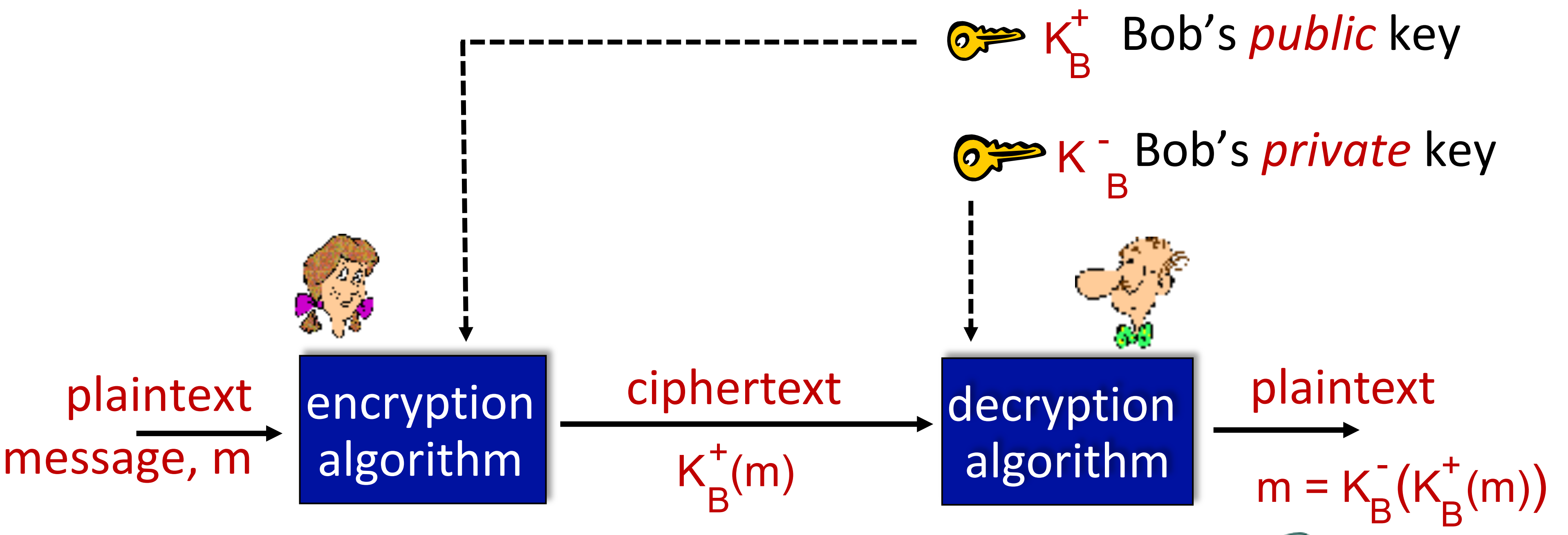
- requires sender, receiver know shared secret key 같은 키 공유
- Q: how to agree on key in first place (particularly if never "met")? (암호화/복호화키 동일)

ㄴ) 처음에 공유할 방법은?

public key crypto

- *radically* different approach [Diffie-Hellman76, RSA78]
- sender, receiver do *not* share secret key
- *public* encryption key known to *all* → 공개 키는 모두가 안다
- *private* decryption key known only to receiver → 비밀키는 수신자만

Public Key Cryptography



Wow - public key cryptography revolutionized 2000-year-old (previously only symmetric key) cryptography!

- similar ideas emerged at roughly same time, independently in US and UK (classified)

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

소인수분해 사용

Notion of public-key cryptography

- Diffie and Hellman introduced the notion of *public-key crypto*
  - a party generates a ***pair*** of keys (***K***$^{+}$, ***K***$^{-}$):
    - ***K***$^{+}$: public key. widely disseminated
    - ***K***$^{-}$: private key. kept secretly

private-key crypto

Alice
key

Bob
key

- ***key*** can be used for **encryption/decryption** or **MAC/verification**
- *symmetric* key or *private* key
- assumption: **only** two parties shares ***key***

public-key crypto

Alice
K_A^-

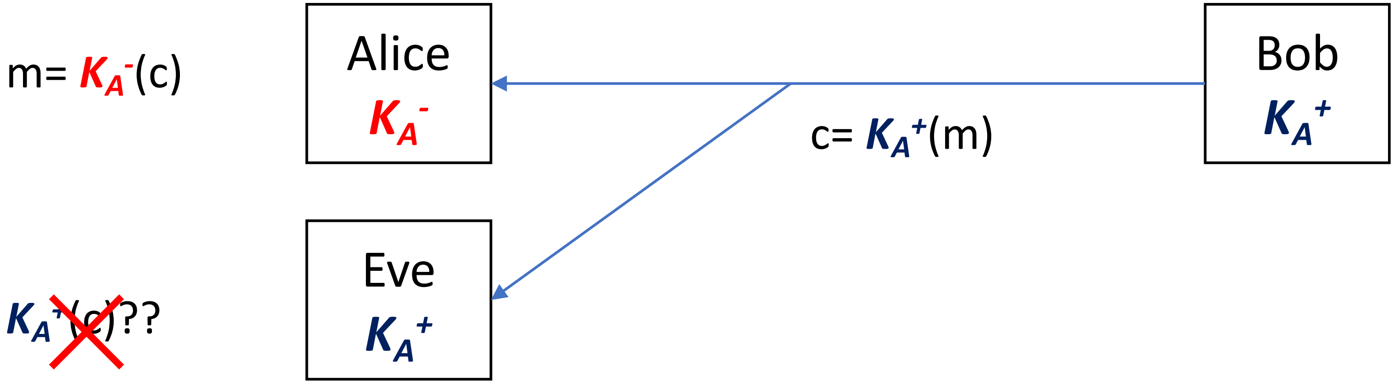
K_A^+

Bob
K_A^+

K_A^+

- K_A^+ for **encryption** and K_A^- for **decryption** or K_A^- for **signature** and K_A^+ for **verification**
- *asymmetric* key or *public* key
- assumption: K_A^+ is disseminated via **authenticated channel**

Public-key encryption



K_A^+ 를 가진 누구나 암호화 가능

- anyone with K_A^+ can encrypt message
  - assume that intended parties receive K_A^+ via *authenticated channels* (what if there's no such channel? We'll learn PKI)
- only the one with K_A^- can decrypt message

→ K_A^- 는 수신자만 지님, K_A^- 로만 복호화 가능

  - cannot decrypt with K_A^+ (Eve may encrypt but can't decrypt)
- Receiver (Alice) generates (K_A^+, K_A^-) and sends K_A^+ to Bob
  - or publicize her K_A^+ (e.g., her webpage, central database)

RSA: Creating public/private key pair

1. choose two large prime numbers *p, q.* (e.g., 1024 bits each)

매우 큰 소수 매우 큰 소수 → $\phi(n)$

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"). → 공통인 소인수 X

4. choose d such that $ed-1$ is exactly divisible by z. (in other words: $ed \bmod z = 1$).

$e \cdot d = z \cdot k + 1$

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

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.

encrypt:	bit pattern	m	m^e	$c = m^e \bmod n$
	0000l000	12	24832	17
decrypt:	c	c^d		$m = c^d \bmod n$
	17	481968572106750915091411825223071697		12

Why does RSA work?

- must show that $c^d \bmod n = m$, where $c = m^e \bmod n$
- fact: for any x and y: $x^y \bmod n = x^{(y \bmod z)} \bmod n$
  - where $n = pq$ and $z = (p-1)(q-1)$

오일러 정리

- thus,

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

n이 충분히 클때

RSA: another important property

The following property will be *very* useful later:

$$\underbrace{K_B^-(K_B^+(m))}_{\text{use public key first, followed by private key}} = m = \underbrace{K_B^+(K_B^-(m))}_{\text{use private key first, followed by public key}}$$

result is the same!

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

follows directly from modular arithmetic:

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

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

소인수분해는 소수의 크기가 커질수록
계산이 어려워진다

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 session key K_S
- once both have K_S, they use symmetric key cryptography

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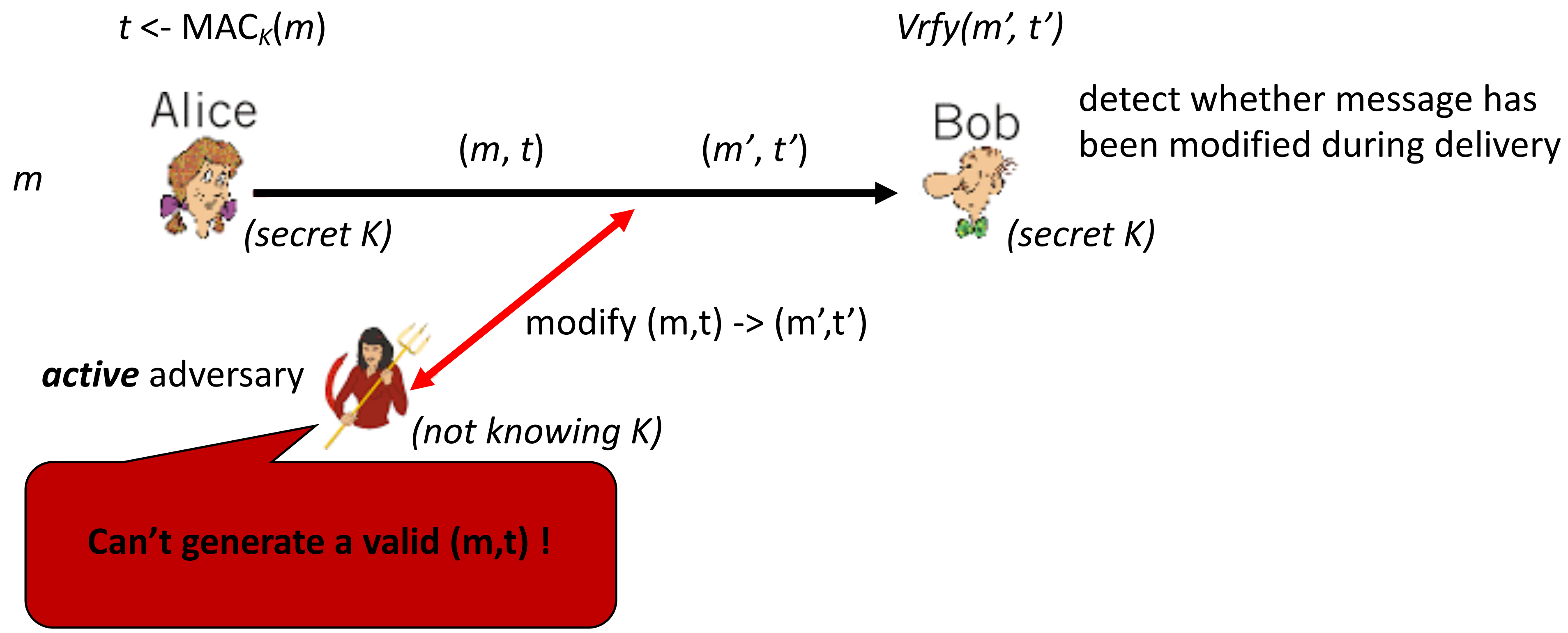
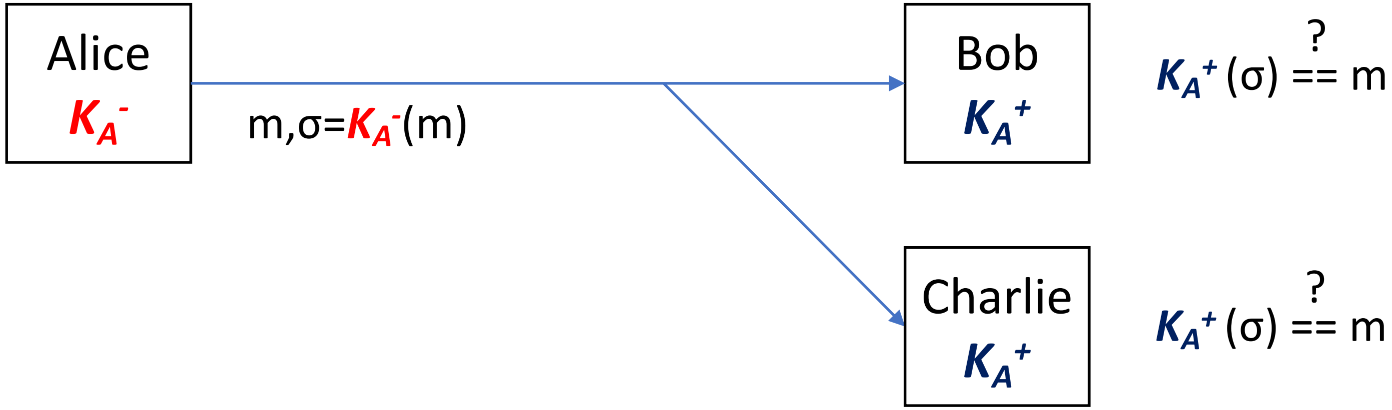
Message integrity (in symmetric key setting)

Message Authentication Code



Digital signature

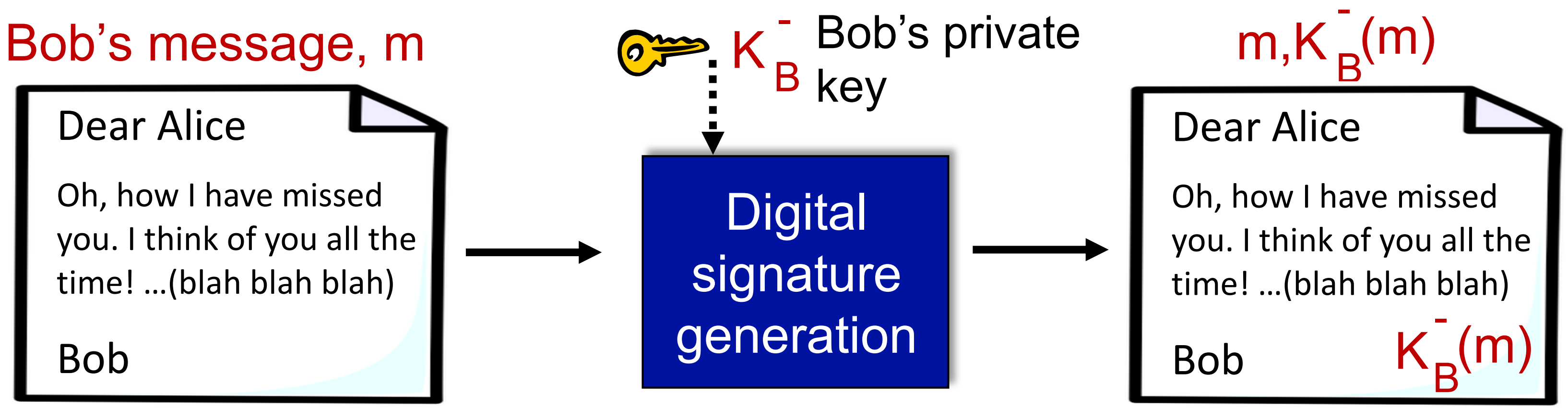


- only the one with K_A^- can generates signature σ for message m
- anyone with K_A^+ can verify the signature
  - assume that intended parties receive K_A^+ via *authenticated channels*
- **non-repudiation**: signed document becomes proof that Alice indeed signed the document

Digital signatures

cryptographic technique analogous to hand-written signatures:

- sender (Bob) digitally signs document: he is document owner/creator.
- *verifiable, nonforgeable:* recipient (Alice) can prove to someone that Bob, and no one else (including Alice), must have signed document
- simple digital signature for message m:
  - Bob signs m 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:

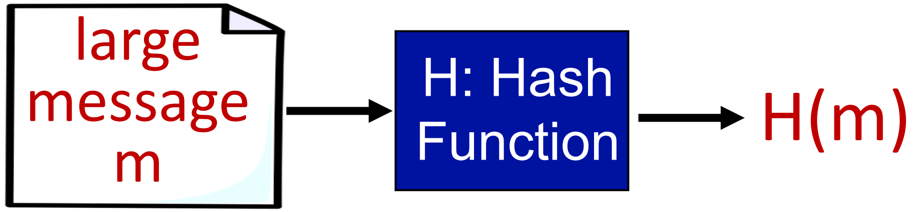
✓ Alice can take m, and signature $K_B^-(m)$ to court and prove that Bob signed m

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)*



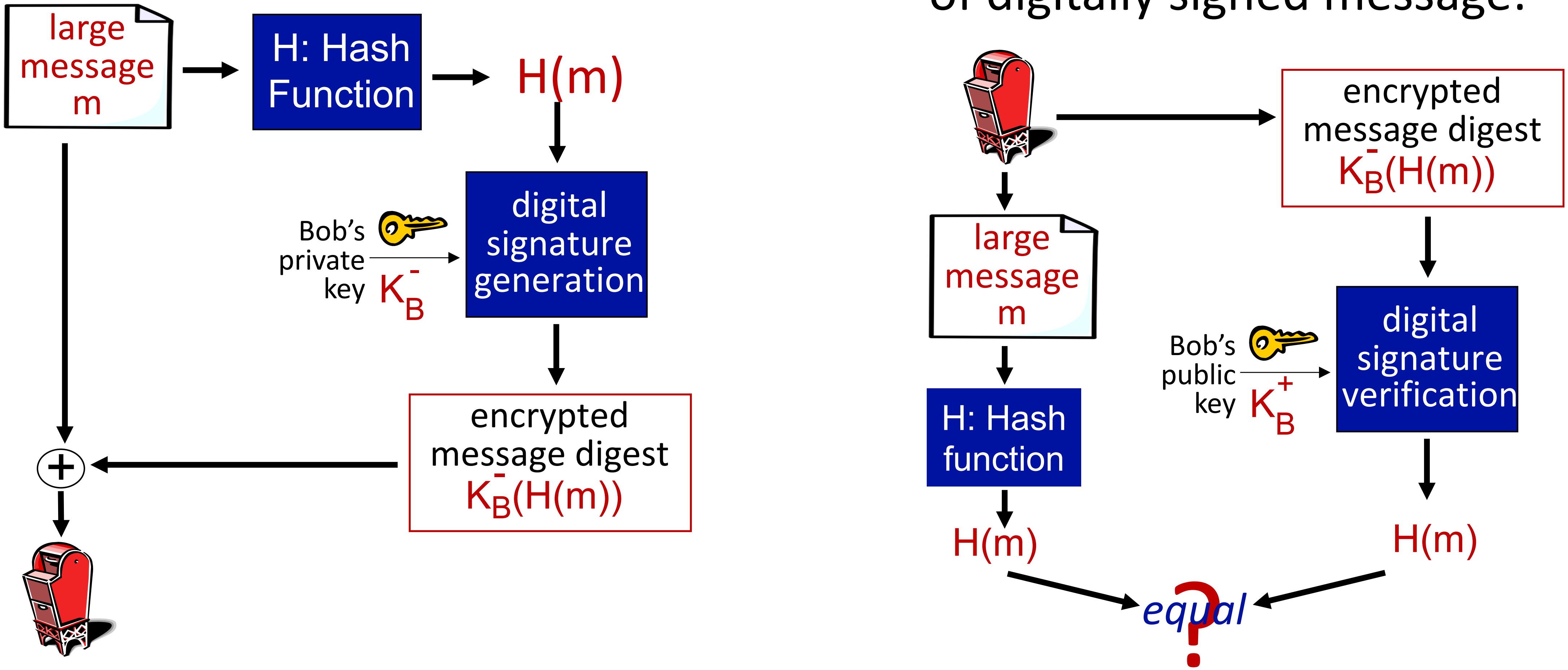
“Cryptographic” (or secure) hash function properties:

- produces fixed-size msg digest (fingerprint)
- given message *x*, computationally infeasible to find *x’=/=x* such that *H(x)=H(x’)*
- given message digest *y*, computationally infeasible to find *x* such that *y = H(x)*

Digital signature = signed message digest

Bob sends digitally signed message:

Alice verifies signature, integrity of digitally signed message:



Hash function algorithms

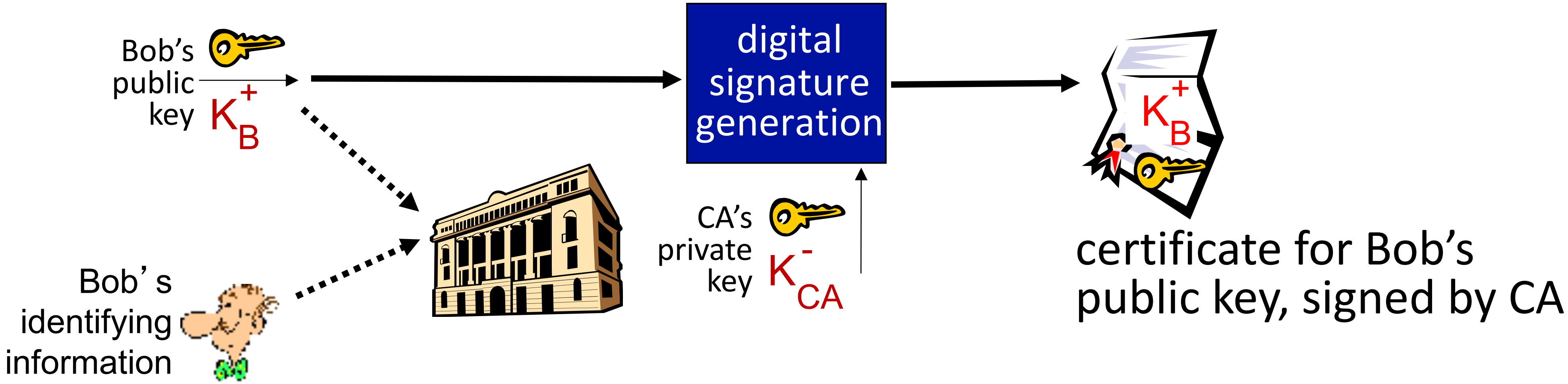
- MD5 hash function widely used (RFC 1321)
  - computes 128-bit message digest in 4-step process.
  - arbitrary 128-bit string x, appears difficult to construct msg m whose MD5 hash is equal to x
- But now SHA-1, SHA-2, SHA-3 are used in newer systems
  - US standard [NIST, FIPS PUB 180-1]
  - 160-bit, 256-bit, … message digest

Need for certified public keys

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

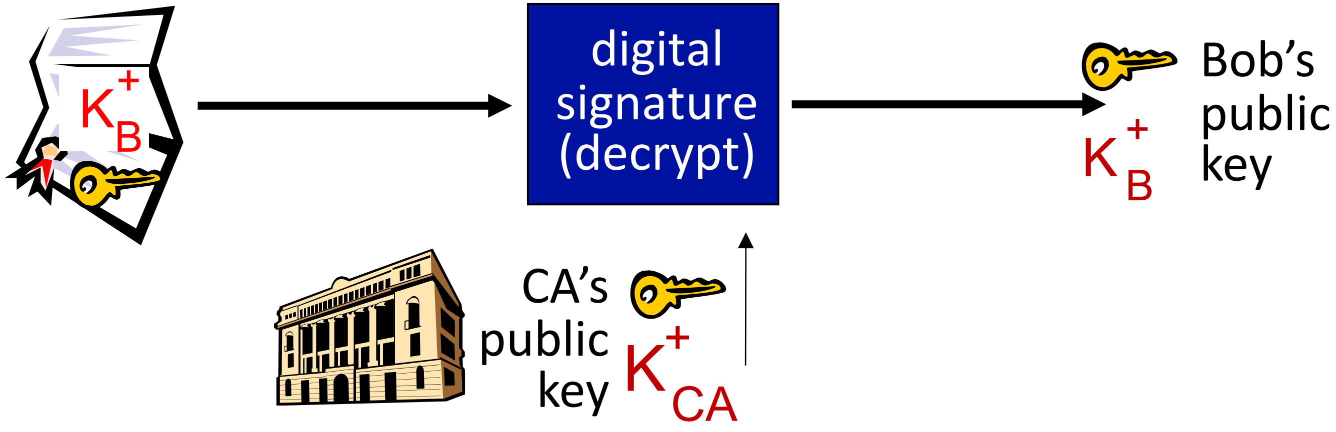
Public key Certification Authorities (CA)

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



Public key Certification Authorities (CA)

- when Alice wants Bob's public key:
  - gets Bob's certificate (Bob or elsewhere)
  - apply CA's public key to Bob's certificate, get Bob's public key



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Transport-layer security (TLS)

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

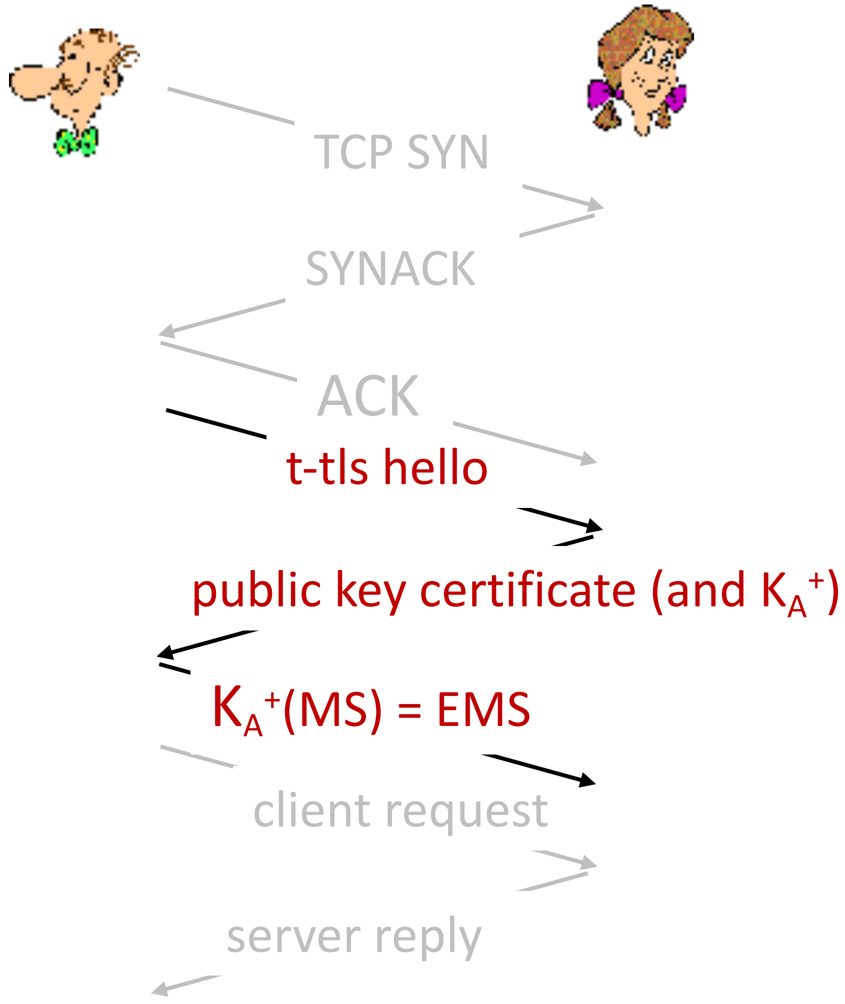
all techniques we have studied!

- history:
  - early research, implementation: secure network programming, secure sockets
  - secure socket layer (SSL) deprecated [2015]
  - TLS 1.3: RFC 8846 [2018]

Transport-layer security: what's needed?

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

t-tls: initial handshake



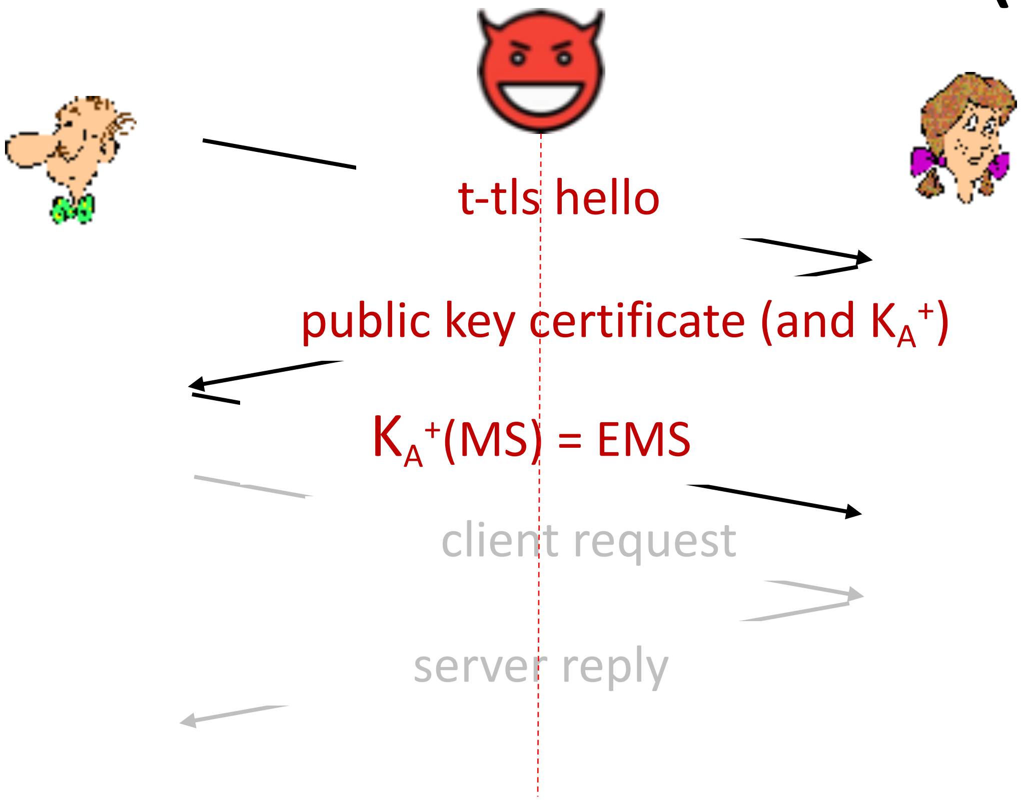
t-tls handshake phase:

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

t-tls: cryptographic keys

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

Man-in-the-Middle (MITM) Attacks



- Can Mallory obtain encryption and authentication keys?

t-tls: encrypting data

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

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

t-tls: encrypting data (more)

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

t-tls: connection close

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

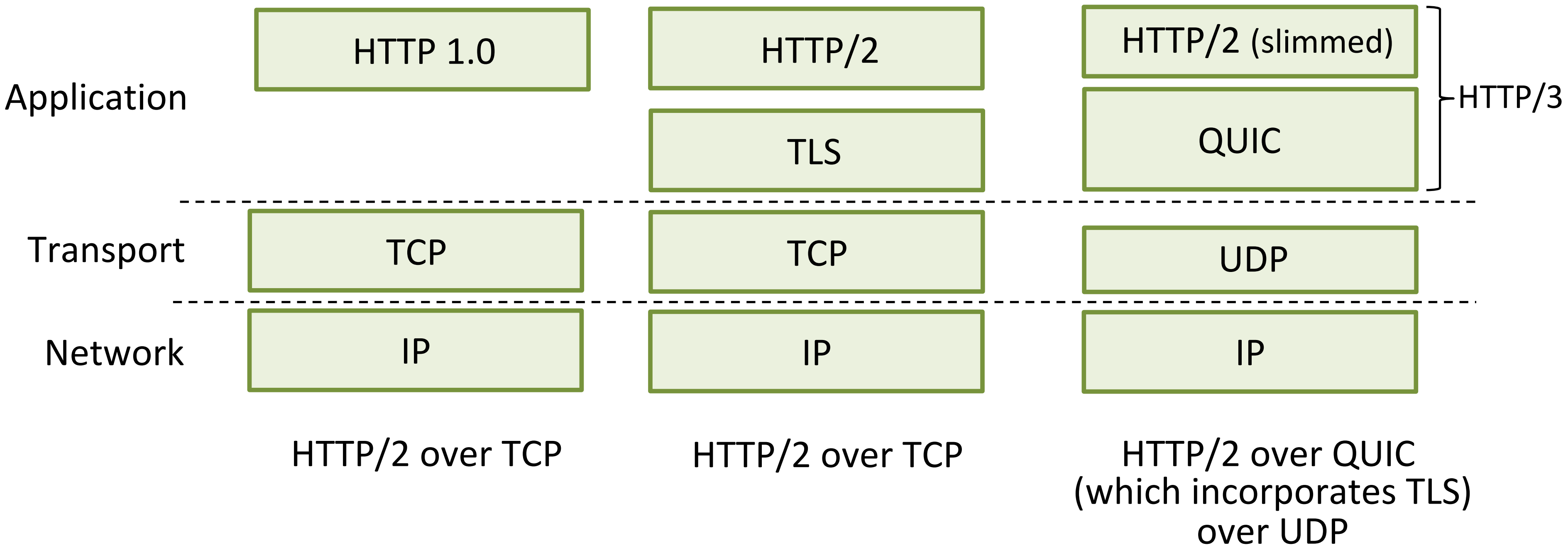
K_c(

length	*type*	*data*	*MAC*

)

Transport-layer security (TLS)

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



Next…

- *Chapter 8.6 Securing TCP Connections: TLS*
- *Chapter 8.7 Network-Layer Security: IPsec and Virtual Private Networks*