Computer Security

Chapter 2: Cryptographic Tools

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Outline

- Confidentiality with Symmetric Encryption
- Message Authentication and Hash Function
- Public-Key Encryption
- Digital Signatures and Key Management
- Random and Pseudorandom Numbers

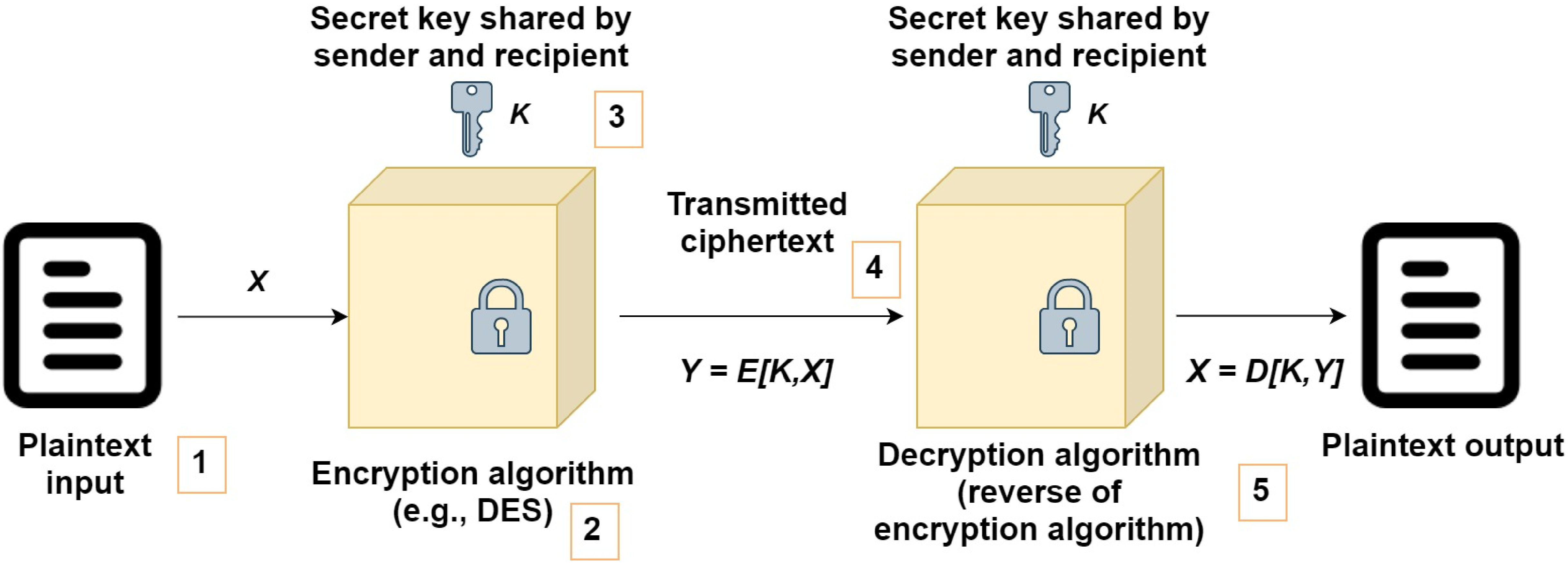
Confidentiality with Symmetric Encryption

- Symmetric encryption
  - □ Providing confidentiality for transmitted or stored data
  - □ Conventional encryption or single-key encryption

- Two requirements for its secure use
  - □ A strong encryption algorithm
    - Opponent: Unable to decrypt ciphertext or discover the key, (given pairs of ciphertexts and plaintexts, as well as the algorithm)
  - □ Secure key distribution and maintenance

Simplified Model of Symmetric Encryption

- Five major components


Secret key shared by sender and recipient
K
3
Secret key shared by sender and recipient
K
X
Transmitted ciphertext
4
Y = E[K,X]
X = D[K,Y]
Plaintext input
1
Encryption algorithm (e.g., DES)
2
Decryption algorithm (reverse of encryption algorithm)
5
Plaintext output

Attacking Symmetric Encryption

Cryptanalytic Attacks

- Exploit
  - □ Nature of the algorithm
  - □ General characteristics of the plaintext
  - □ Sample plaintext-ciphertext pairs
- Deduce a specific plaintext or the key

Brute-Force Attacks

- Exploit
  - □ Knowledge about the expected plaintext
- Try all possible keys on some ciphertexts
  - □ Until an intelligible translation into plaintext is obtained
  - □ On average half of all possible keys must be tried to achieve success

Data Encryption Standard (DES)

- Adopted in 1977 by the NIST (FIPS PUB 46)
  - Most widely used encryption scheme: aka Data Encryption Algorithm (DEA)
  - 64-bit plaintext blocks and a 56-bit key ➔ 64-bit ciphertext blocks

- Security concerns
  - Algorithm: characteristics may be exploited?
    - Most-studied encryption algo: numerous attempts to find weakness, but no fatal one yet
  - Key length: too short
    - 56 bits ➔ $2^{56} = 7.2 \times 10^{16}$ possible keys (Inadequate for today's processor speed)

<u>FIPS (Federal Information Processing Standard)</u>: describes document processing, encryption algorithms and other technology standards for use within non-military government agencies and by government contractors and vendors who work with the agencies.

Brute-Force Attacks against DES

- On average, half the key space has to be searched
  - □ One DES encryption per micro second ➔ more than 1000 years (3.6 x 10^{16} keys)
- In July 1998, EFF broke a DES encryption
  - □ DES cracker: less than \$250,000, less than three days
    - ■ http://cs-exhibitions.uni-klu.ac.at/index.php?id=263
- Encryption speeds advance
  - □ Seagate Technology [SEAG08]
    - ■ Multicore computers (2008): 10^9 per second
  - □ EE Times [AROR12]
    - ■ Contemporary supercomputer (2012): 10^{13} per second ➔ break DES within 1 hour

DES cracker circuit board: key discovery in 56 hours

<u>EFF (Electronic Frontier Foundation):</u> the leading nonprofit organization defending civil liberties in the digital world

Triple DES (3DES)

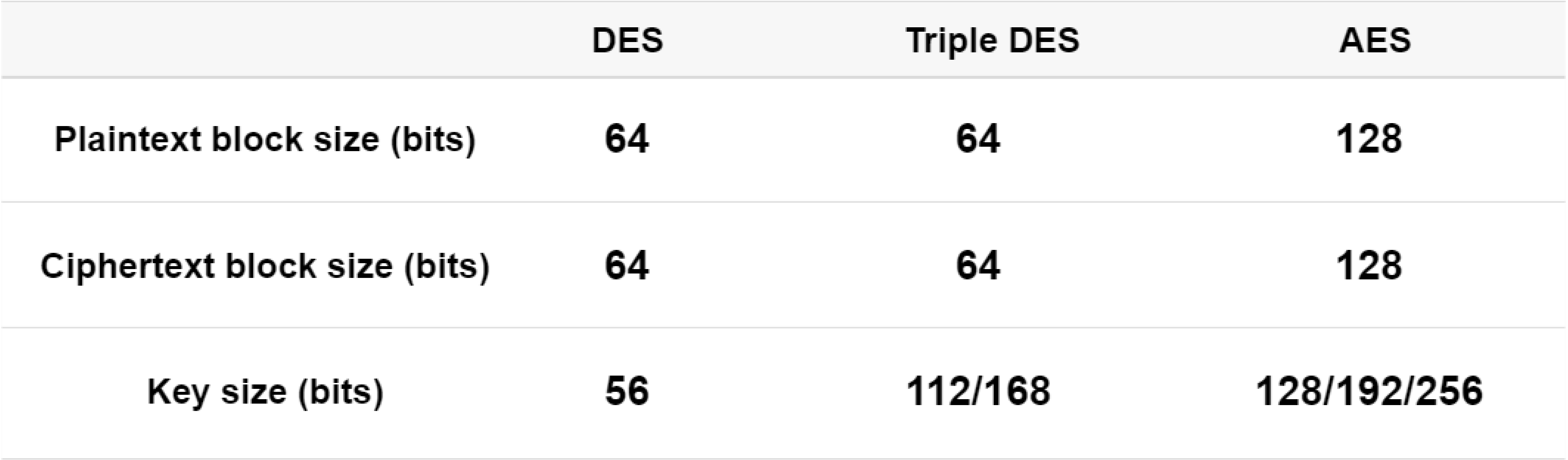
- Part of the DES in 1999: FIPS PUB 46-3
  - Repeat basic DES algorithm 3 times using either 2 or 3 unique keys
  - A key size of 112 or 168 bits
- Two attractions
  - 168-bit key length: overcomes brute-force attack of DES
  - Underlying encryption algorithm is the same as in DES
- Two drawbacks
  - Sluggish algorithm/software: not efficient software code and three times as DES
  - Uses a 64-bit block size: not efficient and not secure

Advanced Encryption Standard (AES)

- AES: now widely available in commercial products
  - □ A replacement for 3DES
  - □ 3DES was not reasonable for long term use
- NIST called for proposals for a new AES in 1997
  - □ Security strength: equal to or better than 3DES
  - □ Significantly improved efficiency
  - □ Symmetric block cipher
  - □ 128-bit data and 128/192/256 bit keys
- Selected Rijndael Algorithm in Nov. 2001: published as FIPS 197

Symmetric Block Encryption Algorithms

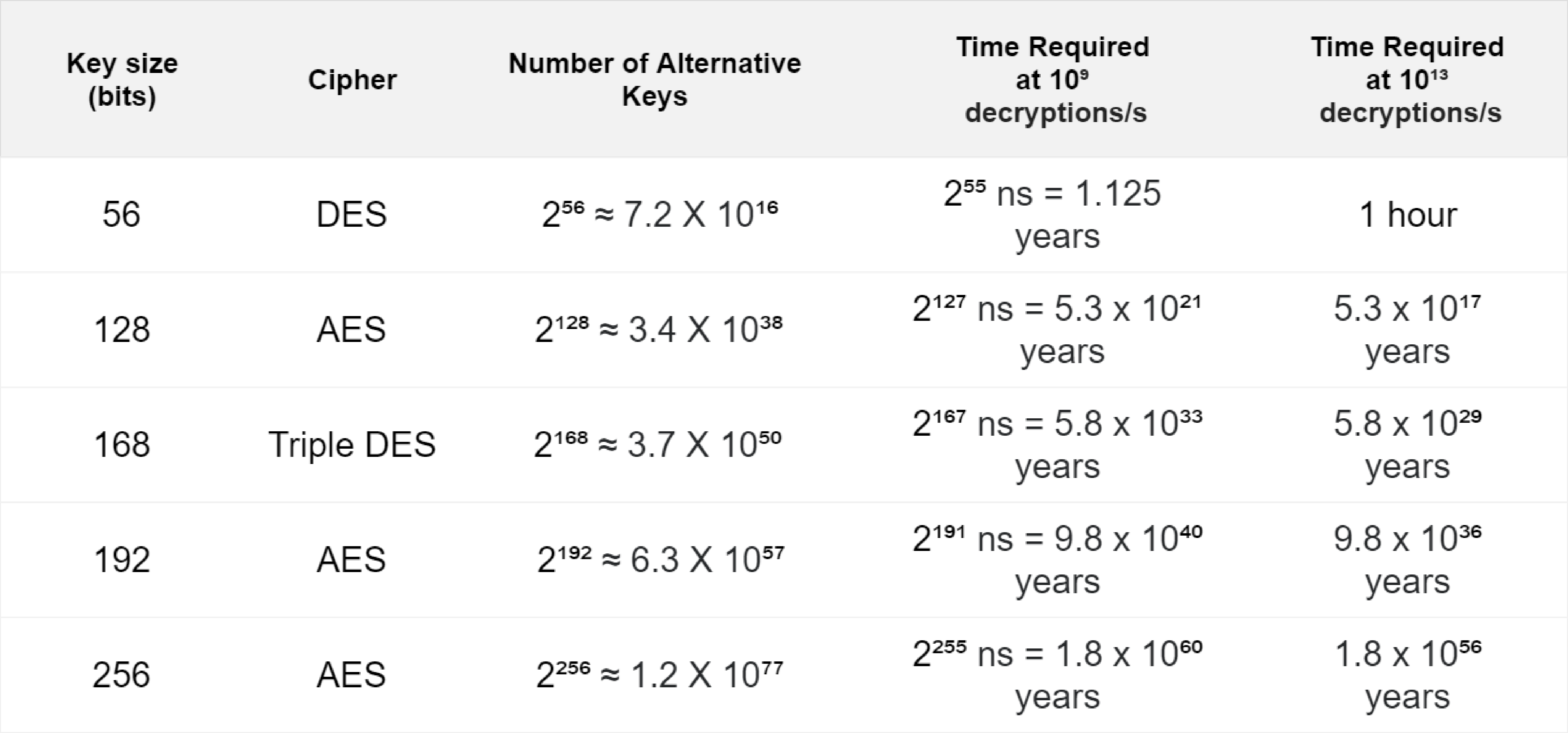
- Block ciphers: most commonly used symmetric encryption
  - □ Fixed-size blocks of plaintext ➔ blocks of ciphertext of equal size



	DES	Triple DES	AES
Plaintext block size (bits)	64	64	128
Ciphertext block size (bits)	64	64	128
Key size (bits)	56	112/168	128/192/256

DES = Data Encryption Standatd
AES = Advanced Encryption Standatd

Average Time Required for Exhaustive Key Search

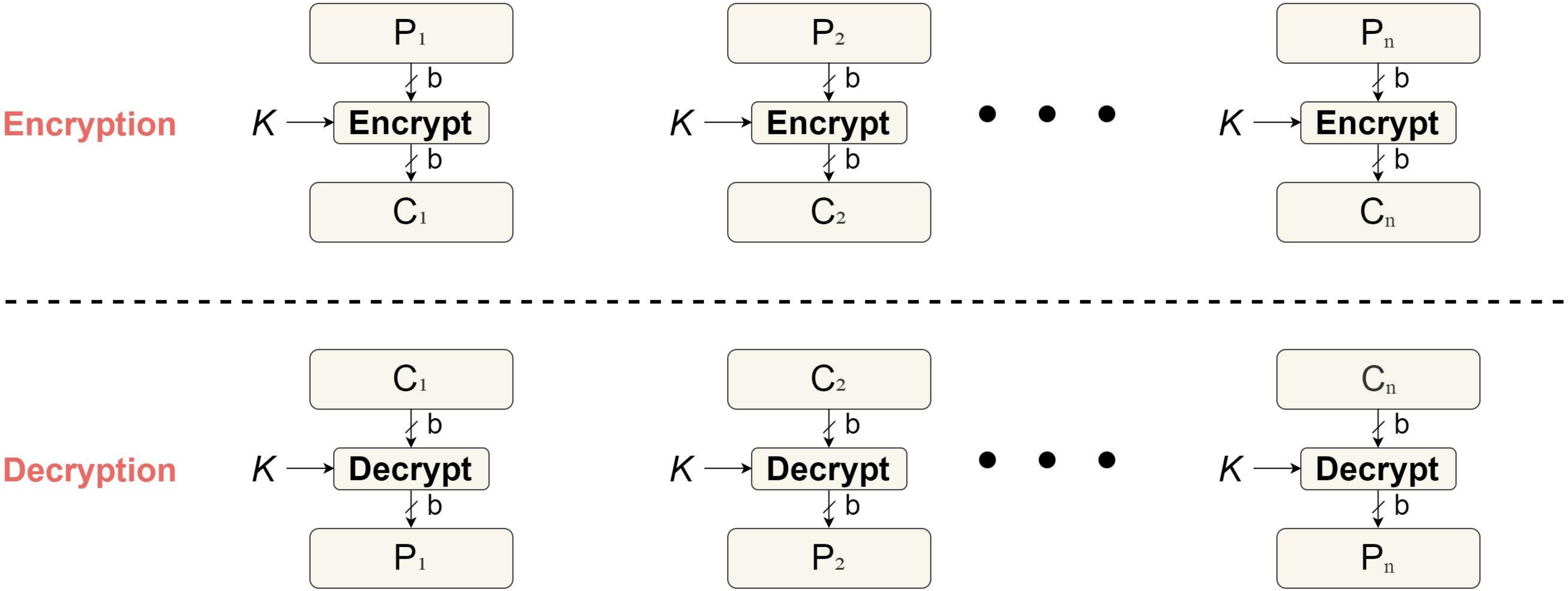


Key size (bits)	Cipher	Number of Alternative Keys	Time Required at 10^9 decryptions/s	Time Required at 10^{13} decryptions/s
56	DES	$2^{56} \approx 7.2 \text{ X } 10^{16}$	2^{55} ns = 1.125 years	1 hour
128	AES	$2^{128} \approx 3.4 \text{ X } 10^{38}$	2^{127} ns = 5.3×10^{21} years	5.3×10^{17} years
168	Triple DES	$2^{168} \approx 3.7 \text{ X } 10^{50}$	2^{167} ns = 5.8×10^{33} years	5.8×10^{29} years
192	AES	$2^{192} \approx 6.3 \text{ X } 10^{57}$	2^{191} ns = 9.8×10^{40} years	9.8×10^{36} years
256	AES	$2^{256} \approx 1.2 \text{ X } 10^{77}$	2^{255} ns = 1.8×10^{60} years	1.8×10^{56} years

Practical Security Issues

- How to apply the symmetric encryption to a unit of data larger than a single 64-bit or 128-bit block?
  - e.g., E-mail messages, network packets, and database records
- Simplest approach: electronic codebook (ECB)
  - Multiple block encryption
  - Each block of plaintext is encrypted using the same key
- Issue: Cryptanalysts may exploit regularities in the plaintext

Illustration of the ECB Mode

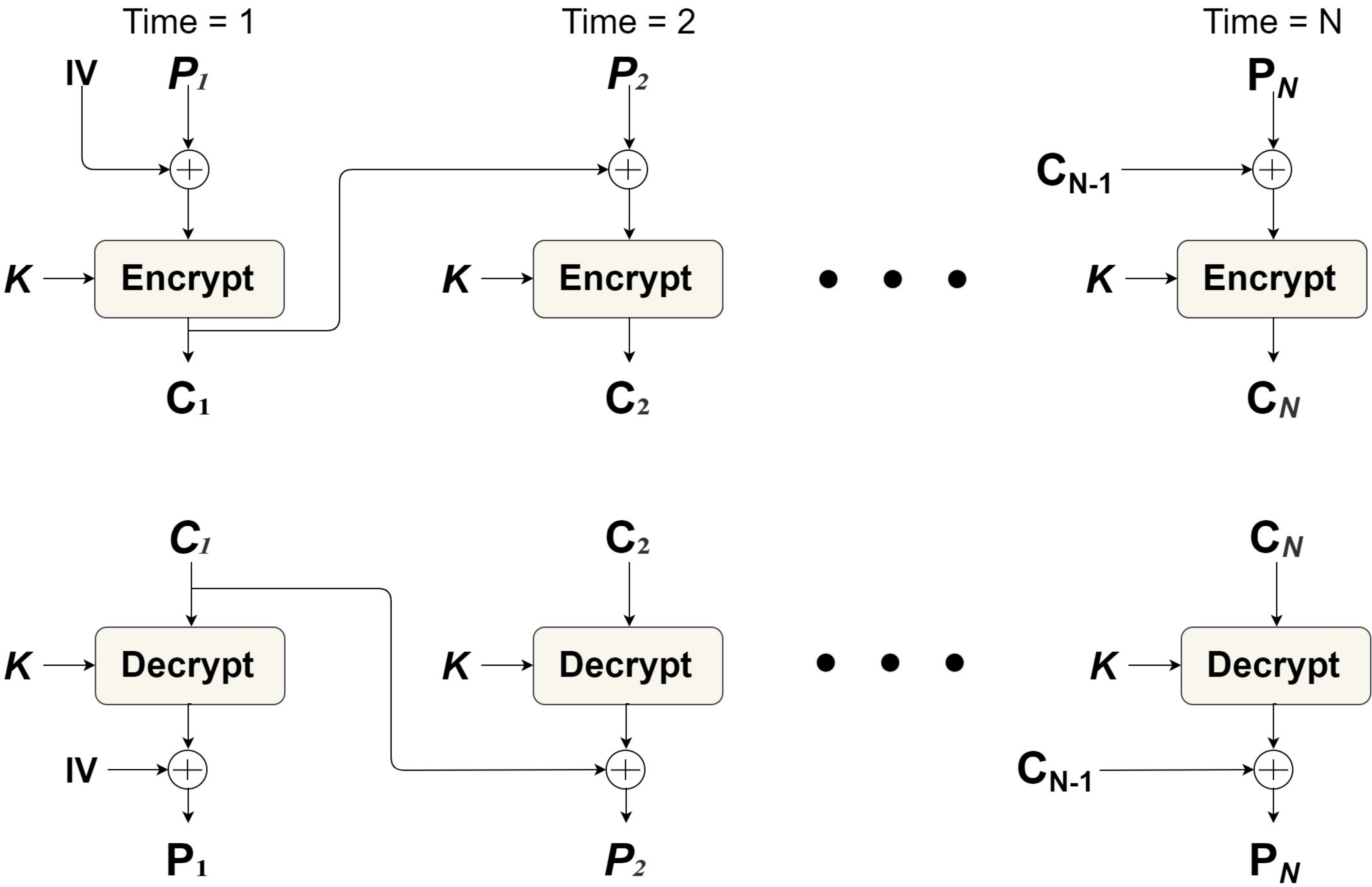


How to address the ECB issue (regularities)?

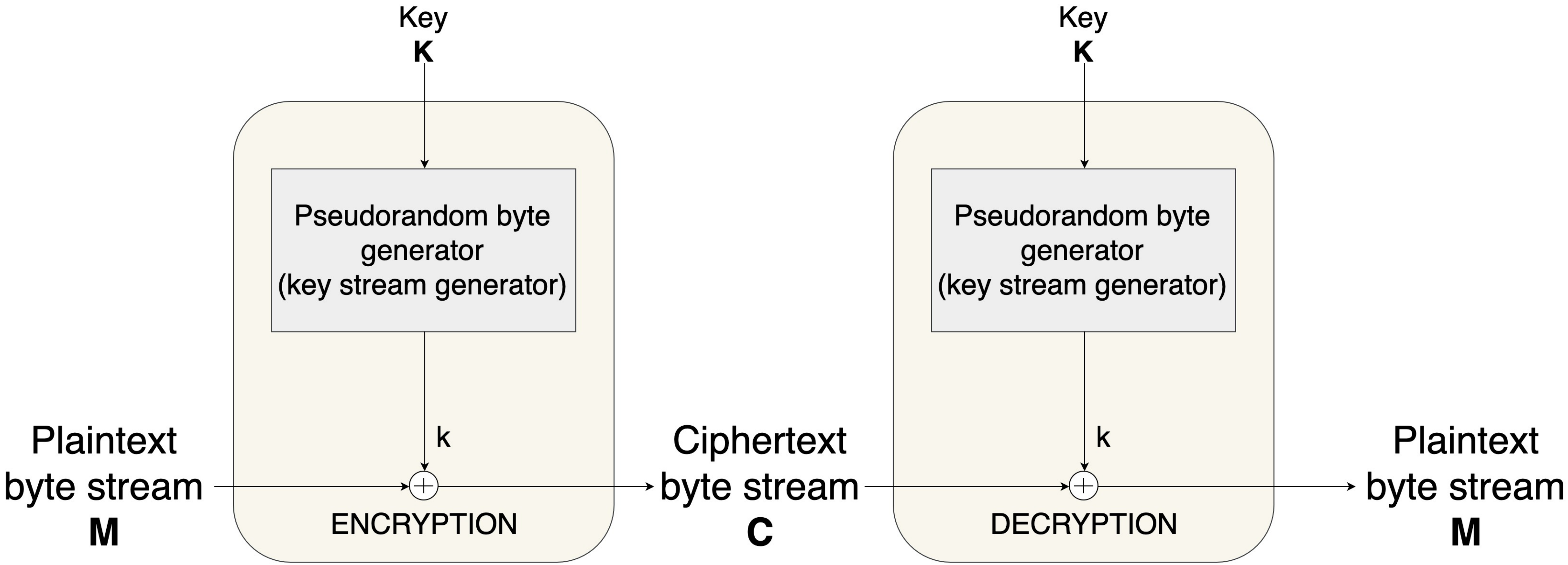
Modes of Operation

Cipher Block Chaining (CBC) Mode

- Five modes of operation defined by NIST
  - ECB, CBC, etc.
- CBC can overcome the weakness of ECB



The Other Cipher Method: Stream Cipher



Block & Stream Ciphers

Block Cipher

- Processing one block at a time
- Each input block → an output block
- Pro: Can reuse keys
  - More common
- Apps: file transfer, e-mail, and database

Stream Cipher

- Processing input elements continuously
- One element at a time
  - Typically: one byte; one bit or larger units are also allowed
- Pro: almost always faster (XOR) and use far less code
- Apps: data stream over a communication channel or a browser/Web link

The keystream must not be reused!!

Consider: $(\mathrm{A} \oplus \mathrm{K}) \oplus (\mathrm{B} \oplus \mathrm{K}) = \mathrm{A} \oplus \mathrm{B}$

Message Authentication and Hash Functions

- Message (data) authentication
  - Communicating parties can verify that received/stored messages are authentic
  - Against falsification of data and transactions
- Two major aspects to verify
  - Message contents: not altered
  - Message source: authentic
- Another aspect
  - Message timeliness/sequence: not artificially delayed or replayed

Can We Use Symmetric Encryption?

- Authentic source
  - Only the sender and the receiver share the key
- No altered contents
  - An error-detection code
- Proper message timeliness
  - A sequence number or a timestamp

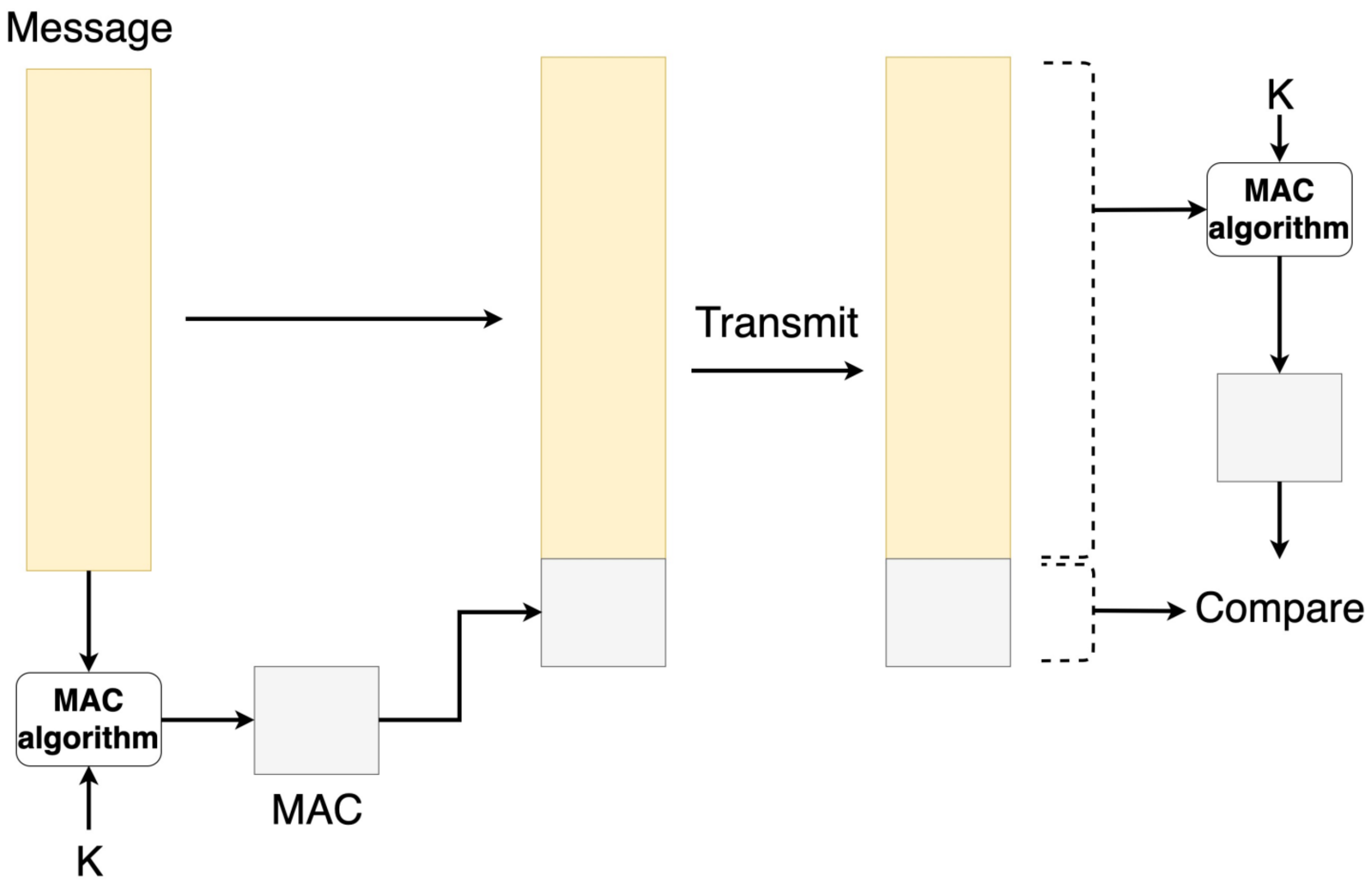
It seems proper, but it is not a suitable tool for data authentication. Why?

Message Authentication w/o Encryption

- Message authentication: a separate function from message encryption
  - □ e.g., a broadcast message to many destinations, not able to decrypt all incoming messages, wasteful of processor resources
- How? an auth. tag is generated and appended to each message
  - □ Message Authentication Code (MAC)
  - □ One-Way Hash Function

MAC

- Use a secret key to generate a small block of data
- Assumption: two communicating parties share the secret key
- MAC algorithms: NIST recommends DES
  - □ MAC: last 16- or 32-bit code of the encrypted message



What are the drawbacks?

MAC (Cont.)

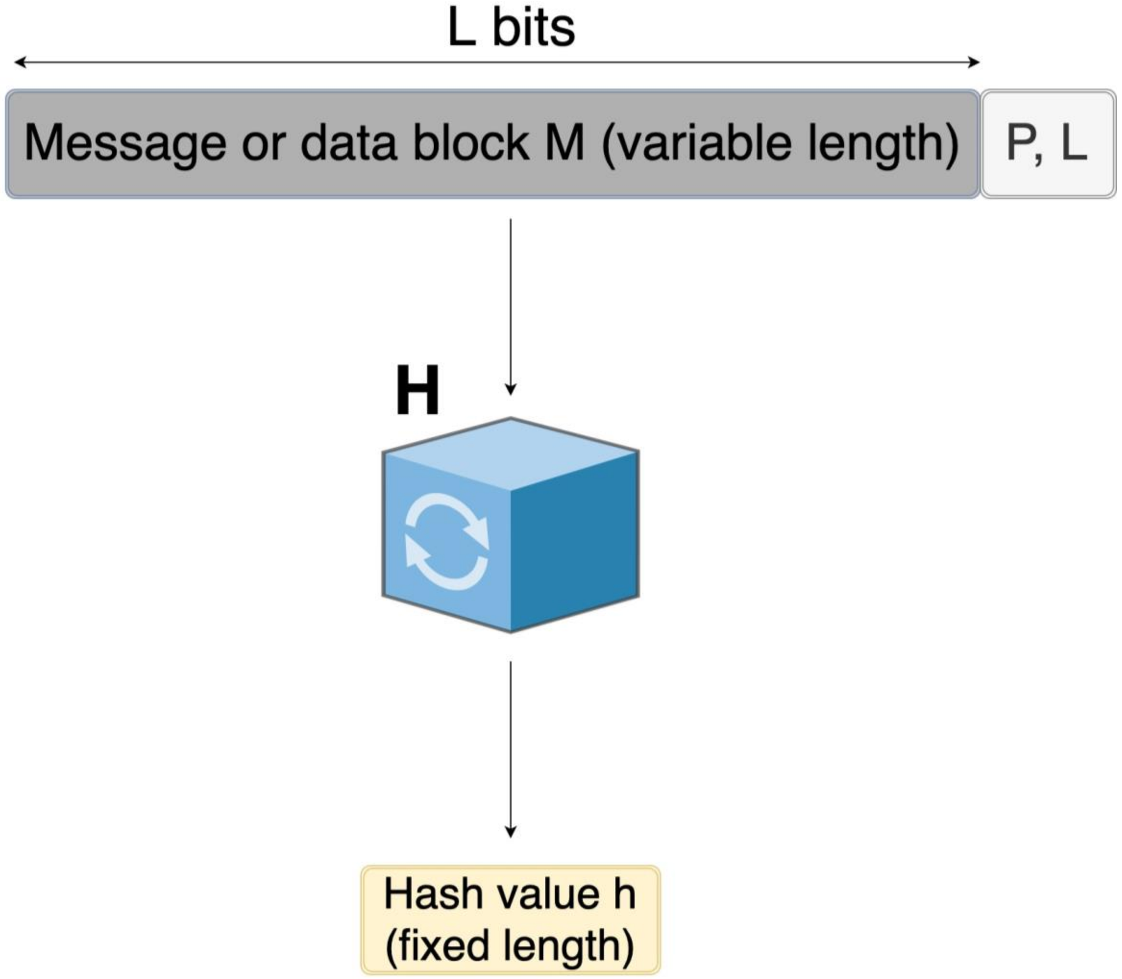
- Drawbacks
  - □ Encryption software is quite slow
  - □ Encryption hardware costs are non-negligible
  - □ Encryption hardware is optimized toward large data sizes

Does message authentication really need encryption of the message?

- No. Why?
  - □ Authentication need not be reversible
  - □ Only need a way to generate a tag which can verify messages

One-way Hash Function

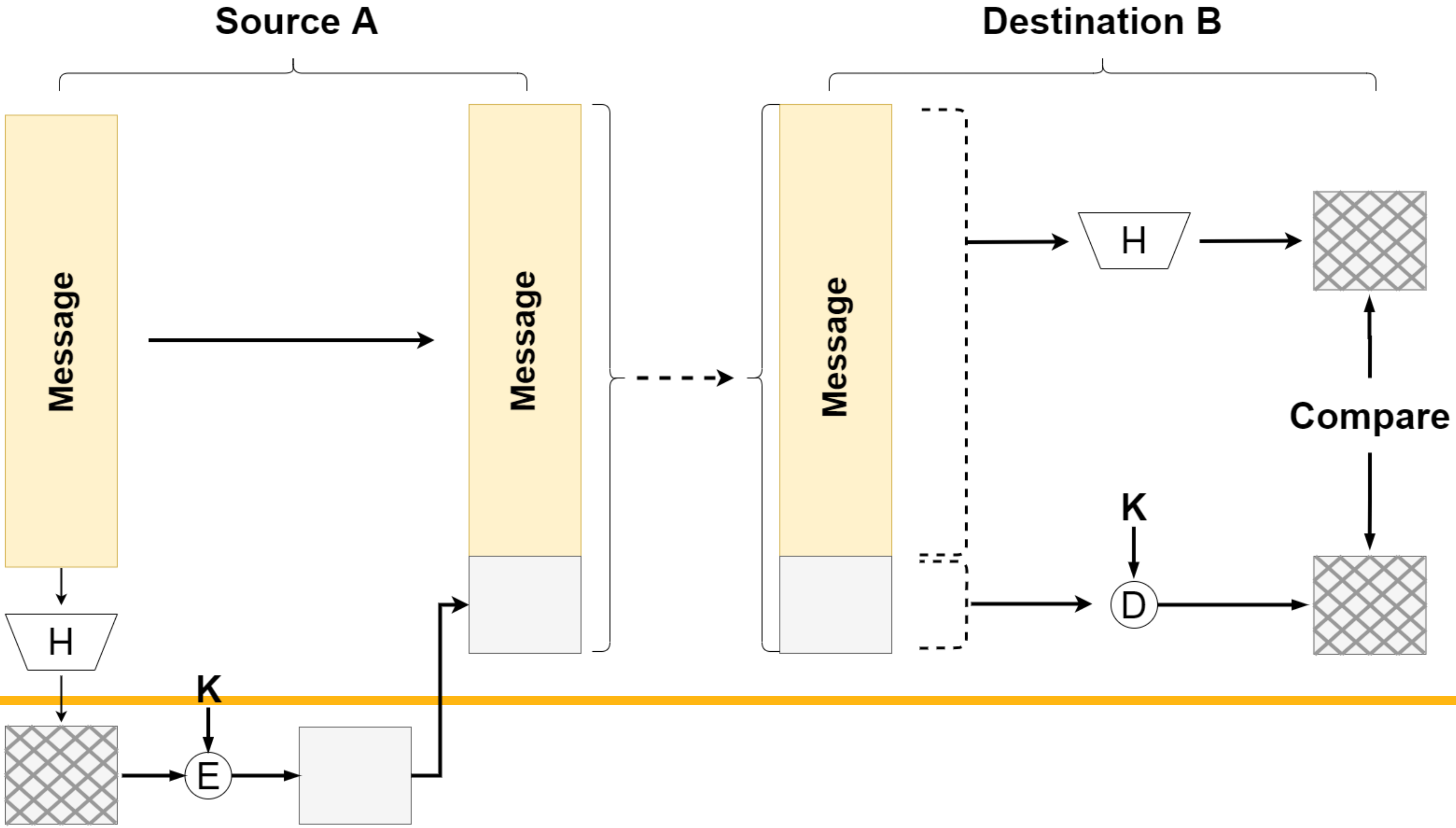
- A variable-size message M ➔ Tag: a fixed-size message digest H(M)
- Unlike MAC
  - □ does not take a secret key as input



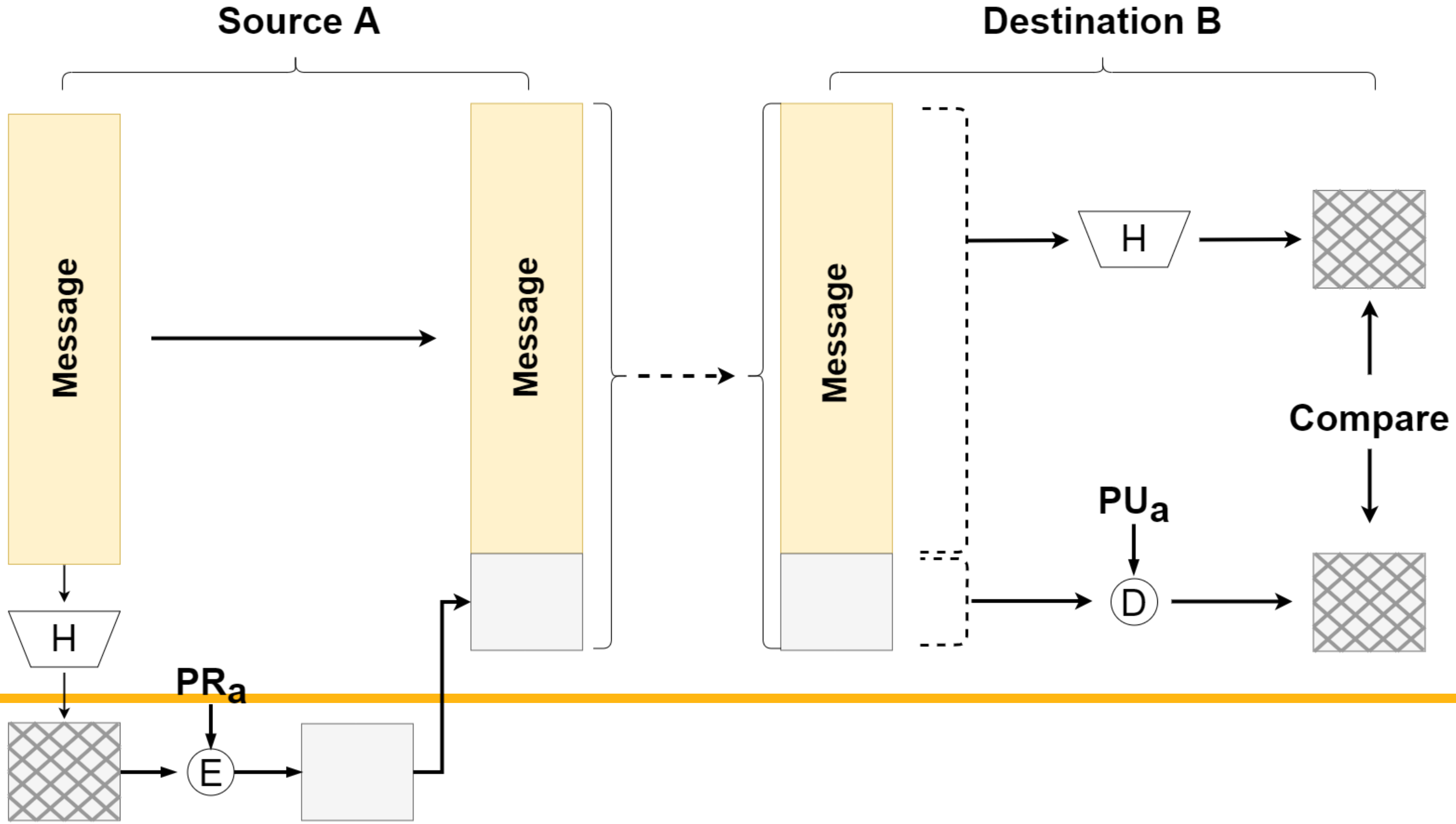
P, L = padding plus length field

The hash value ensures only unaltered contents.
How about authentic source?

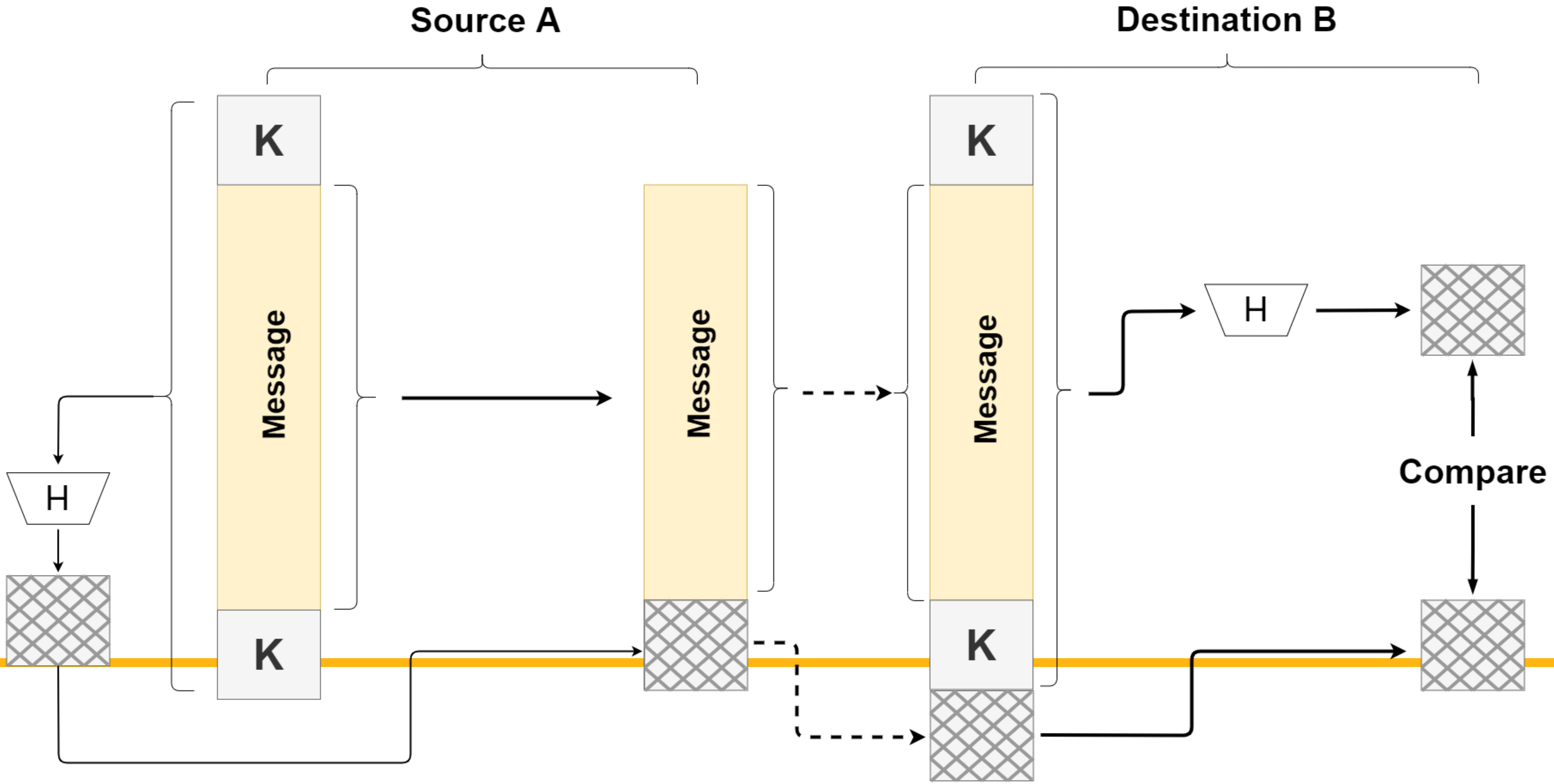
Hash Function w/ Symmetric Encryption



Hash Function w/ Public-key Encryption



Hash Function w/o Encryption: Keyed Hash MAC



Secure Hash Functions

- A hash function H must have the following properties
  - H can be applied to a block of data of any size
  - H produces a fixed-length output
  - $H(x)$ is relatively easy to compute for any given x
    - Making both hardware and software implementations practical
  - One-way (pre-image resistant)
    - For any given code h, it is computationally infeasible to find x such that $H(x) = h$
  - Second pre-image (weak collision) resistant
    - For any given block x, it is computationally infeasible to find $y \neq x$ with $H(y) = H(x)$
  - Collision (strong collision) resistant
    - It is computationally infeasible to find any pair (x, y) such that $H(x) = H(y)$

Security of Hash Functions

- Two attack approaches
  - □ Cryptanalysis: exploits logical weaknesses in algorithms ➔ algorithm dependent
  - □ Brute-force ➔ solely on the length of the hash code

- Security strength against brute-force attacks
  - □ Preimage resistant: 2^n
  - □ Second preimage resistant: 2^n
  - □ Collision resistant: $2^{n/2}$
    - ■ Based on that a birthday attack on a message digest of size n produces a collision
    - ■ 128-bit MD5 [VANO94]: 24 days
    - ■ 160-bit SHA: > 4000 years

Security of Hash Functions (Cont.)

- Most widely used hash algorithm: Secure Hash Algorithm (SHA)
  - □ Developed by NIST, and published in FIPS 180, 1993
  - □ SHA-1 160-bit (1995)
  - □ SHA-256, SHA-384, SHA-512 (2002)
- Applications of hash functions
  - □ Message authentication
  - □ Digital signatures (later in this Chapter)
  - □ Passwords (Chapter 3)
  - □ Intrusion detection (Chapter 8)

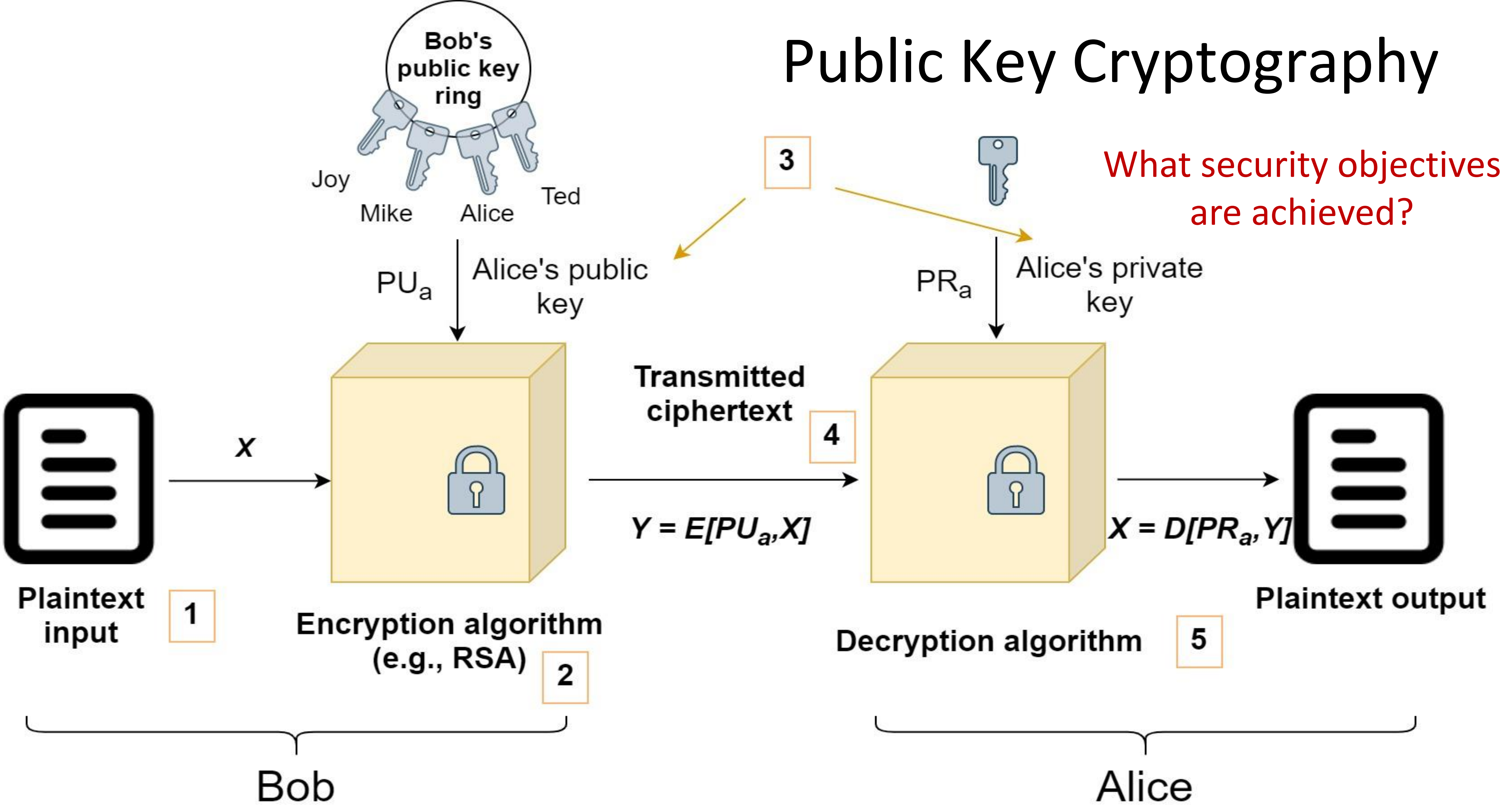
Public-Key Encryption

- Public-key cryptography
  - Proposed by Diffie and Hellman in 1976
  - Asymmetric algorithm
    - Two separate keys: public and private keys
  - Based on mathematical functions
    - Different from symmetric algorithms: simple operations on bit patterns

- Three common *misconceptions* for public-key encryption
  - More secure than symmetric ones
  - A general-purpose technique that has made symmetric ones obsolete
  - Key distribution is trivial

Public Key Cryptography

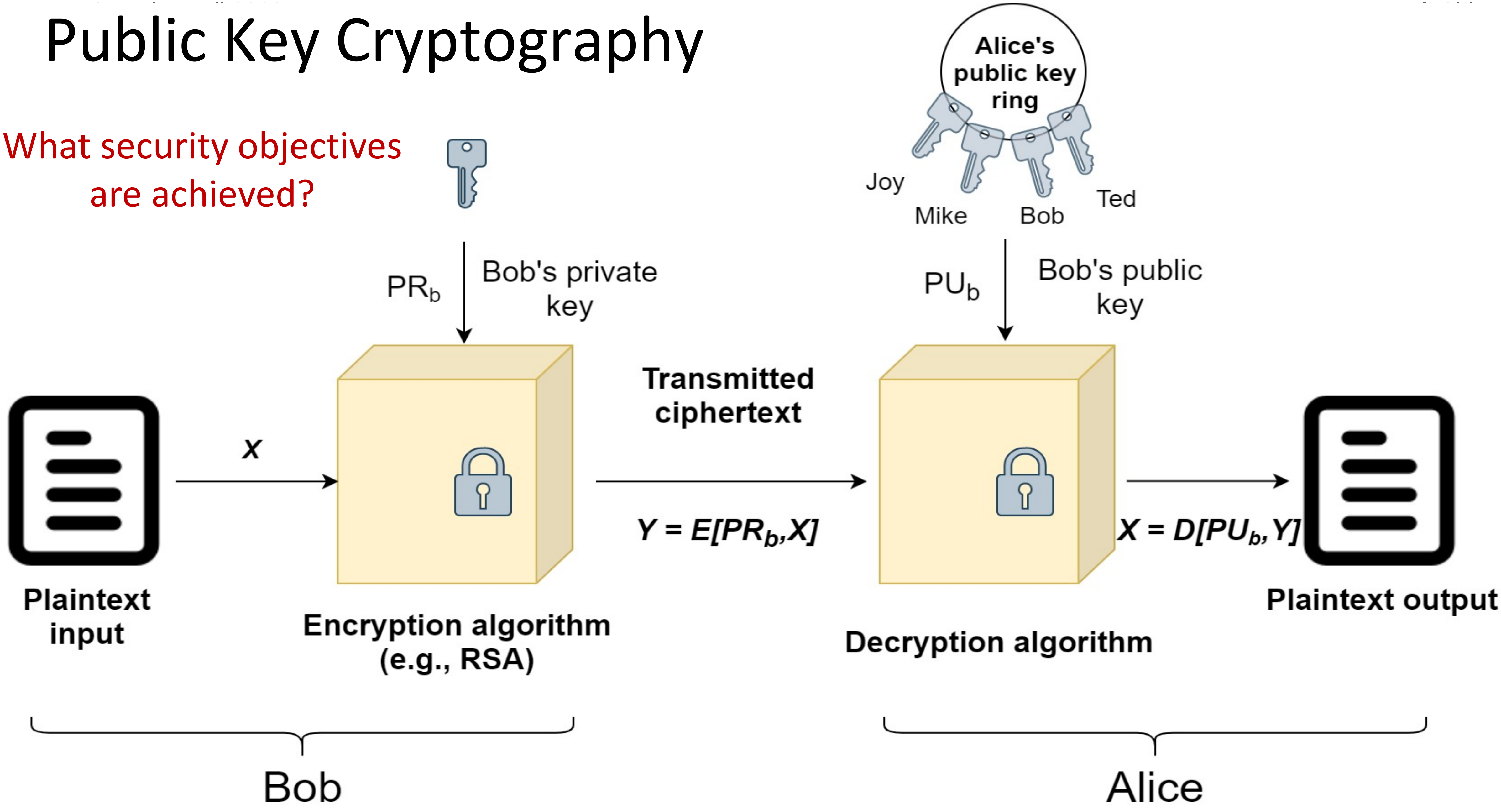
What security objectives are achieved?



(a) Encryption with public key

Public Key Cryptography

What security objectives are achieved?

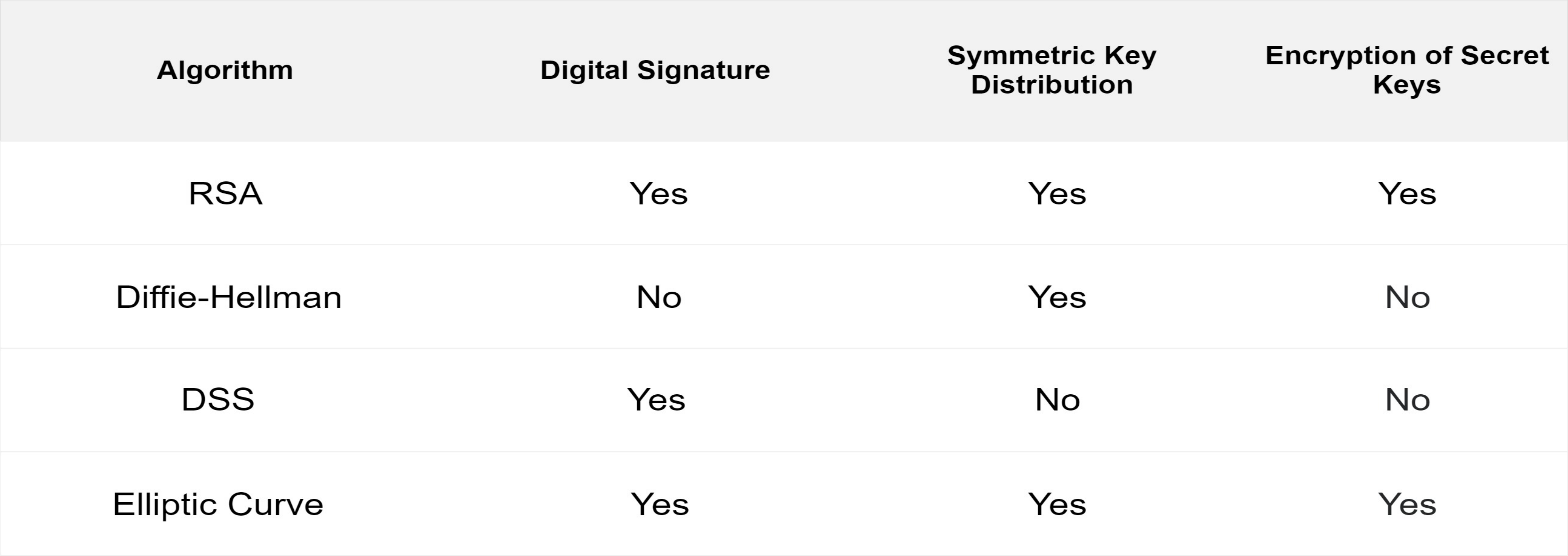


(b) Encryption with pribate key

Requirements for Public-Key Cryptosystems

- Computationally easy
  - Create key pairs
  - for sender knowing public key to encrypt messages
  - for receiver knowing private key to decrypt ciphertext
- Computationally infeasible for opponent knowing public key
  - Determine private key
  - Recover original message, which is encrypted by public key
- Either of private and public keys can be used for encryption

Encryption Algorithms and Applications



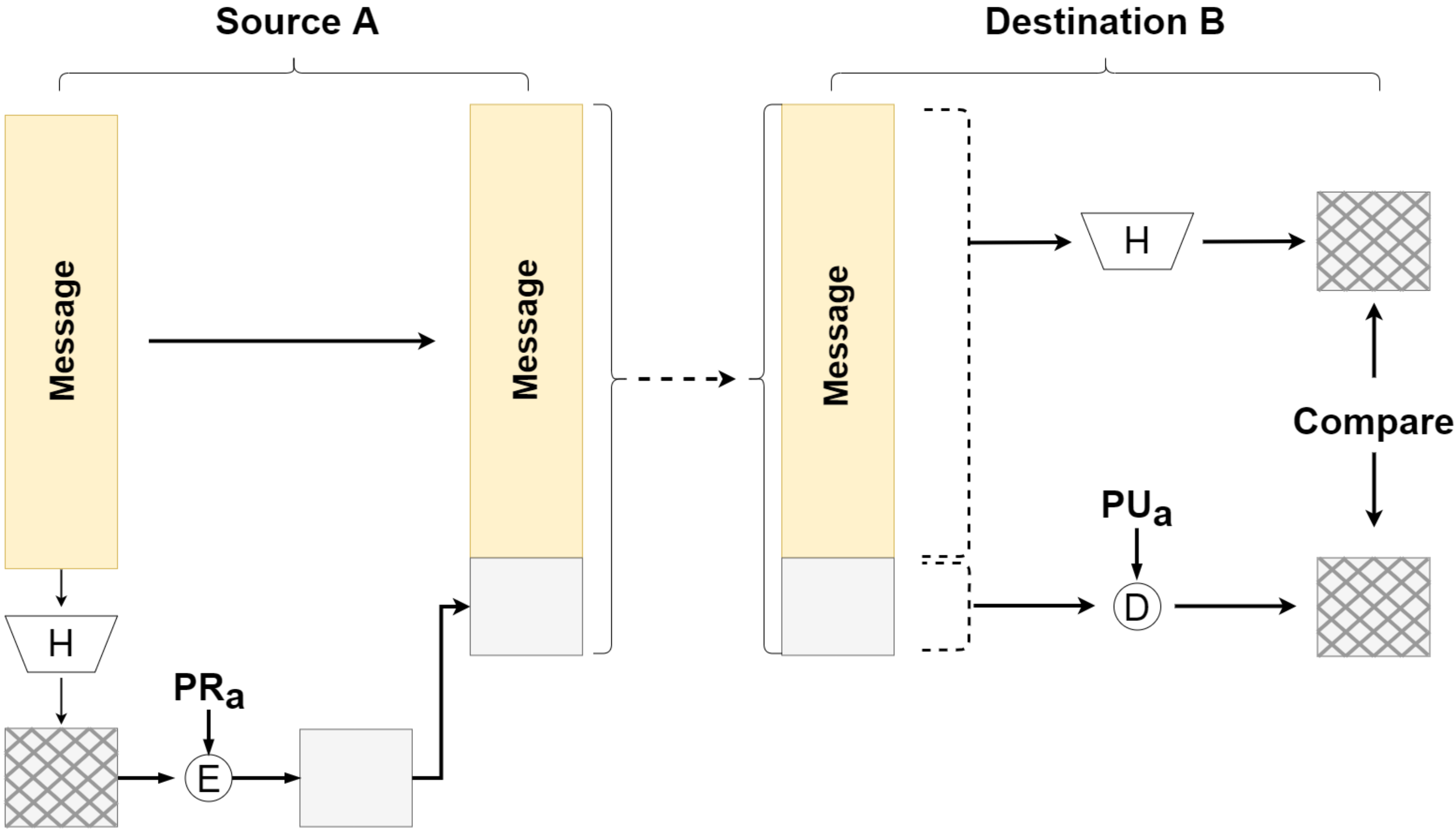
Algorithm	Digital Signature	Symmetric Key Distribution	Encryption of Secret Keys
RSA	Yes	Yes	Yes
Diffie-Hellman	No	Yes	No
DSS	Yes	No	No
Elliptic Curve	Yes	Yes	Yes

Digital Signatures and Key Management

- Digital signatures
- Public-key certificates: secure distribution of public keys
- Symmetric key exchange using public-key encryption
- Digital envelopes: distribution of secret keys

Digital Signatures

- Encrypts hash code with private key
- What security objectives can be achieved?
- Do they provide confidentiality?



Public-Key Certificates

- Public key distribution
  - □ Any person can release his or her public key
  - □ But anyone can forge such a public announcement
- Solution: public-key certificate
  - □ Certificate: a public key + a user ID of the key owner
  - □ The whole block signed by a trusted third party, CA (Certificate Authority)
    - ■ CA has to be trusted by the user community (e.g., government)
  - □ Certificate also includes CA information and validity period
- X.509 standard: universally accepted certificates
  - □ Used in most network security apps: IPSec, TLS, SSH, S/MIME

Survey of CAs

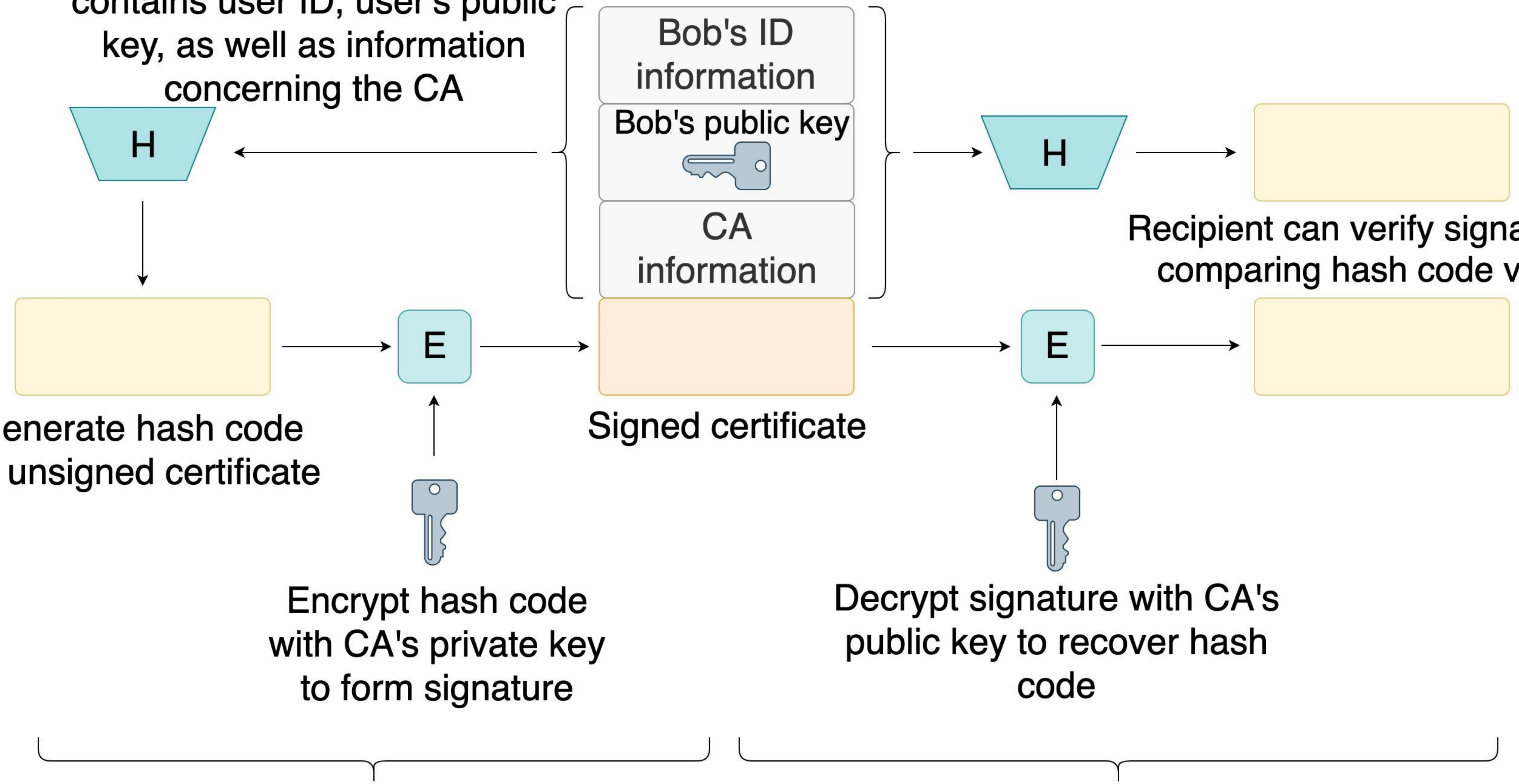
2017

Rank	Issuer	Usage	Market share
1	Comodo	16.7%	38.4%
2	IdenTrust	13.9%	32.0%
3	Symantec	5.6%	12.9%
4	GoDaddy	3.3%	7.5%
5	GlobalSign	1.9%	4.5%
6	DigiCert	1.0%	2.2%
7	Certum	0.3%	0.7%
8	Entrust	0.2%	0.4%
9	Secom	0.1%	0.3%
10	Actalis	0.1%	0.3%
11	Trustwave	0.1%	0.2%
12	Let's Encrypt	0.1%	0.2%

2018

Rank	Issuer	Usage	Market share
1	IdenTrust	20.4%	39.7%
2	Comodo	17.9%	34.9%
3	DigiCert	6.3%	12.3%
4	GoDaddy	3.7%	7.2%
5	GlobalSign	1.8%	3.5%
6	Certum	0.4%	0.7%
7	Actalis	0.2%	0.3%
8	Entrust	0.2%	0.3%
9	Secom	0.1%	0.3%
10	Let's Encrypt	0.1%	0.2%
11	Trustwave	0.1%	0.1%
12	WISeKey Group	< 0.1%	0.1%

Reference: Surveys from w3techs.com



Unsigned certificate: contains user ID, user's public key, as well as information concerning the CA

Generate hash code of unsigned certificate

Encrypt hash code with CA's private key to form signature

Signed certificate

Decrypt signature with CA's public key to recover hash code

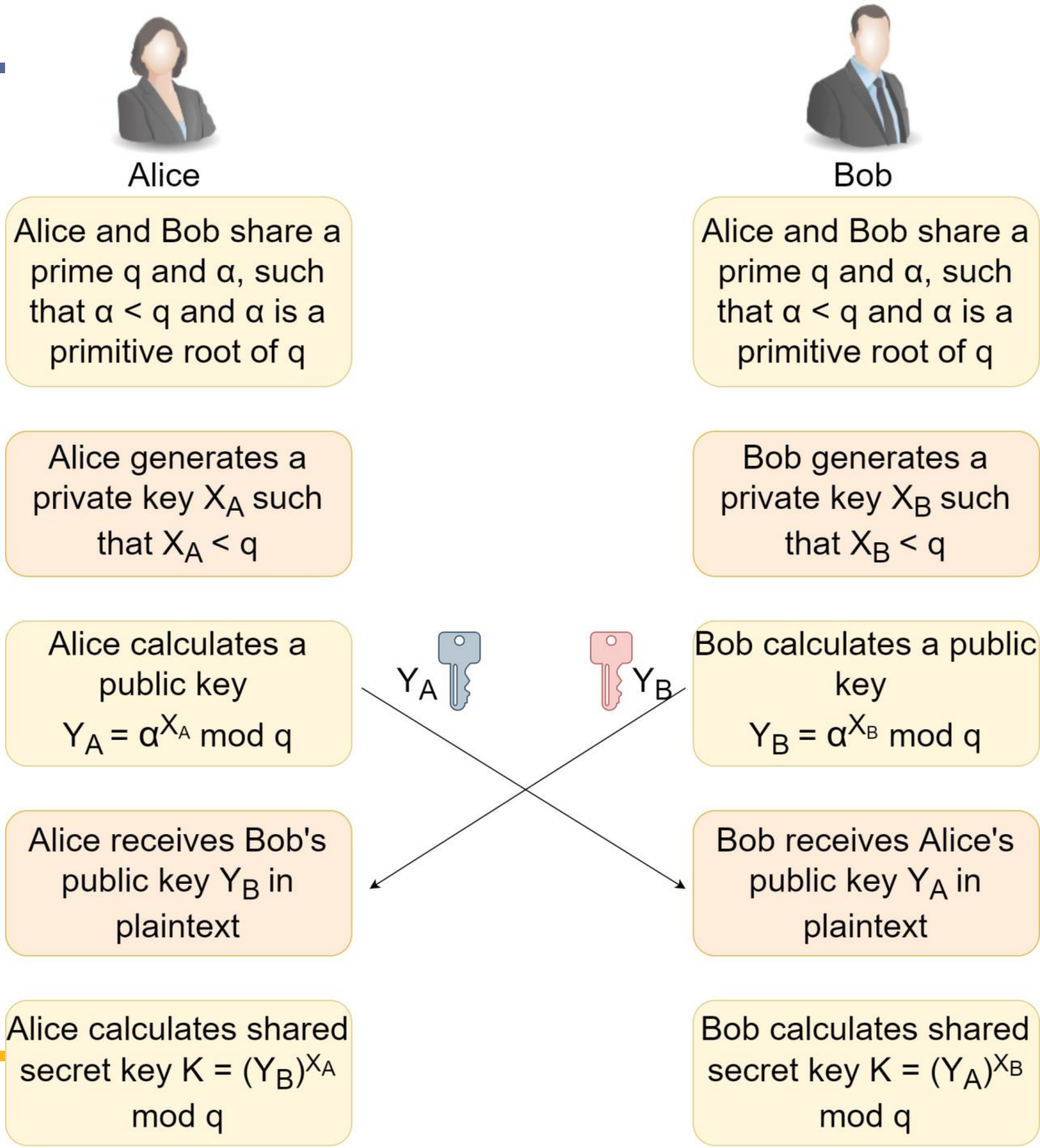
Recipient can verify signature by comparing hash code values

Create signed digital certificate

Use certificate to verify Bob's public key

Symmetric Key Exchange

- Diffie-Hellman key exchange
  - □ Major drawback: no authentication of two communicating partners
  - □ Many variations proposed to overcome this problem



Alice and Bob share a prime q and α, such that α < q and α is a primitive root of q

Alice and Bob share a prime q and α, such that α < q and α is a primitive root of q

Alice generates a private key X_A such that $X_A < q$

Bob generates a private key X_B such that $X_B < q$

Alice calculates a public key $Y_A = \alpha^{X_A} \bmod q$

Bob calculates a public key $Y_B = \alpha^{X_B} \bmod q$

Alice receives Bob's public key Y_B in plaintext

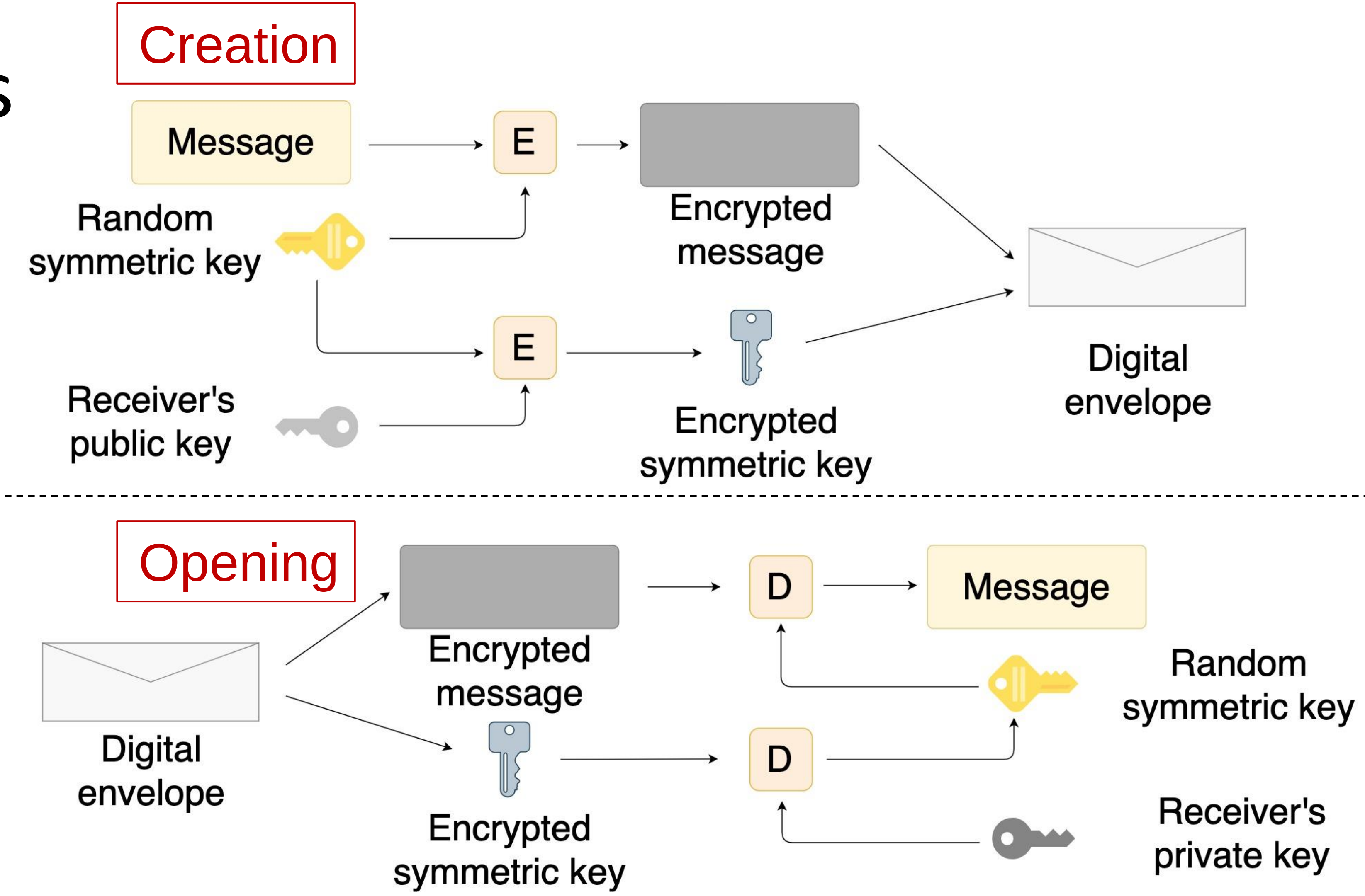
Bob receives Alice's public key Y_A in plaintext

Alice calculates shared secret key $K = (Y_B)^{X_A} \bmod q$

Bob calculates shared secret key $K = (Y_A)^{X_B} \bmod q$

Digital Envelopes

- Protect a message without having the same secret key between sender/receiver
  - □ Equate to the same thing as a sealed envelope containing a letter
- Can also be used to deliver a symmetric key only



Random Numbers

- Used for generation of
  - Keys for public-key algorithms, stream keys for symmetric stream cipher, symmetric keys, etc.

- Two distinct requirements
  - Randomness
    - Uniform distribution: frequency of each number should be roughly the same
    - Independence: no one value can be inferred from the others
  - Unpredictability
    - Not so much that the sequence of numbers be statistically random
    - But, the successive members of the sequence are unpredictable

Random vs. Pseudorandom

- Pseudorandom: its use is widely accepted
  - Apps typically use deterministic algorithms
  - Sequences: not statistically random, but can satisfy statistical randomness tests
- Random: true random number generator (TRNG)
  - Use a nondeterministic source to produce randomness
  - Most operate by measuring unpredictable natural processes
    - E.g., radiation, gas discharge, leaky capacitors, thermal noise
  - Increasing provided on modern chips

Questions?