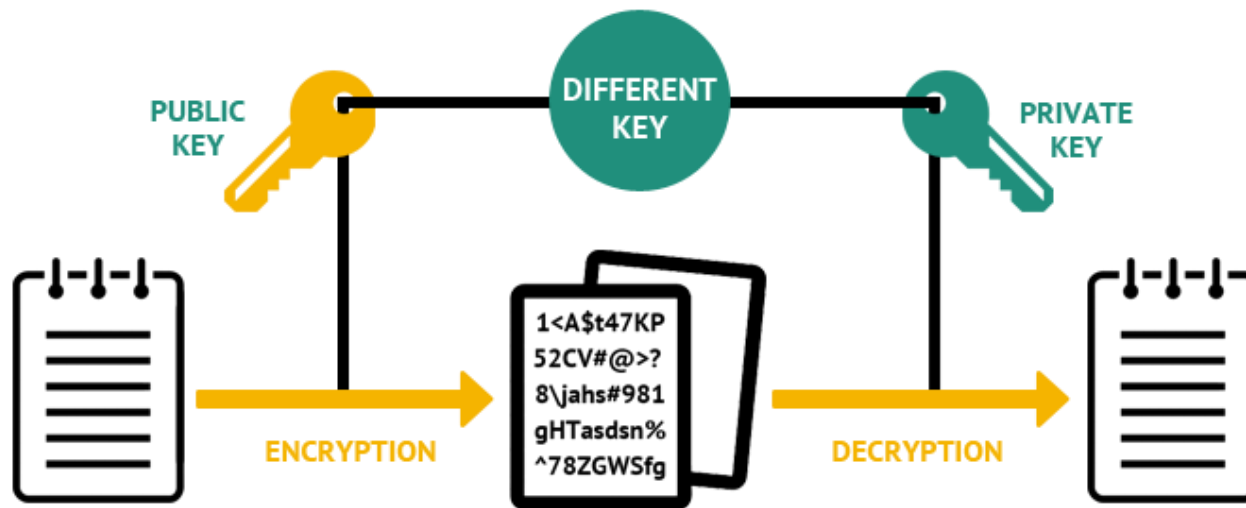
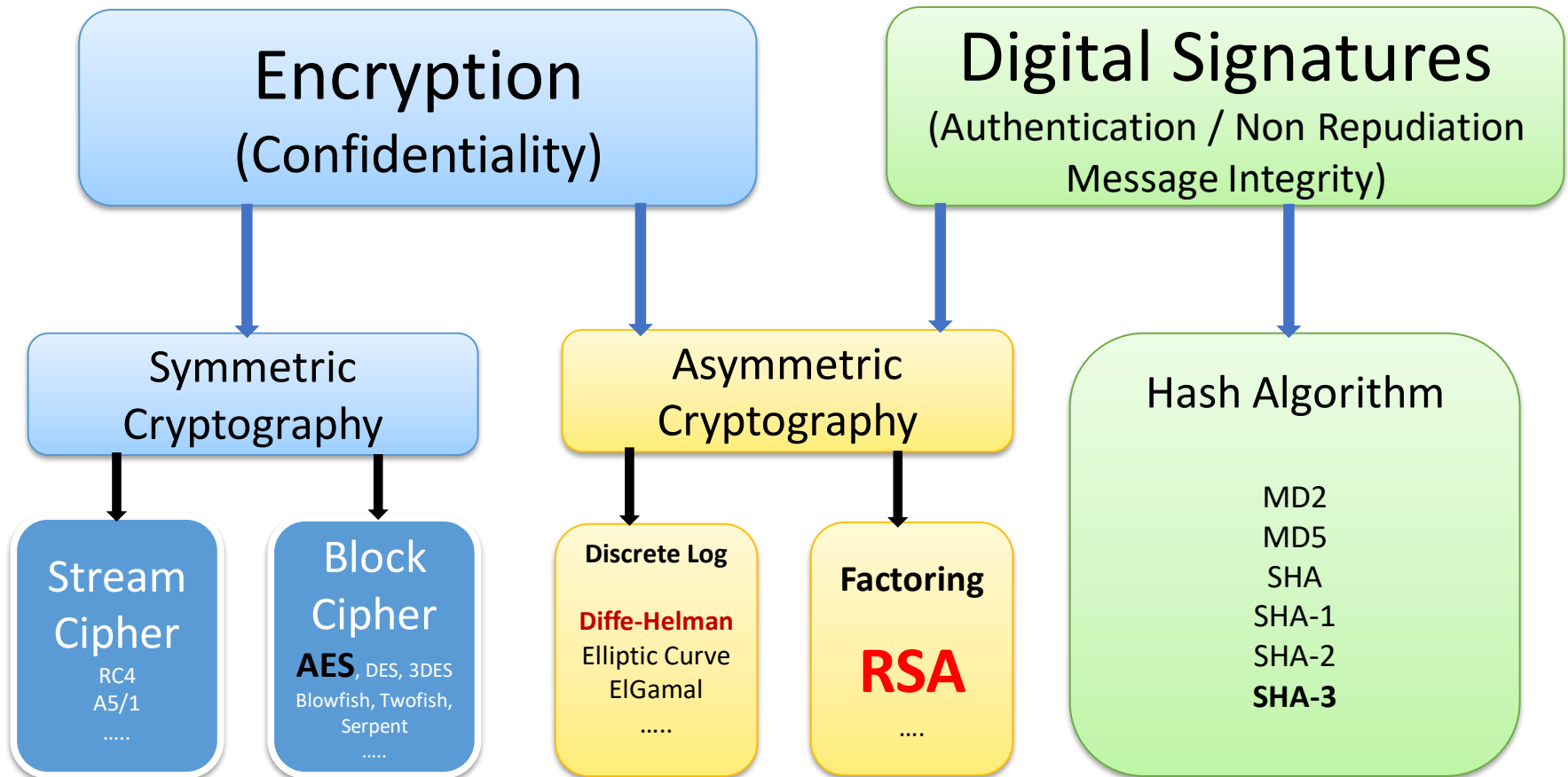


Asymmetric Cryptography

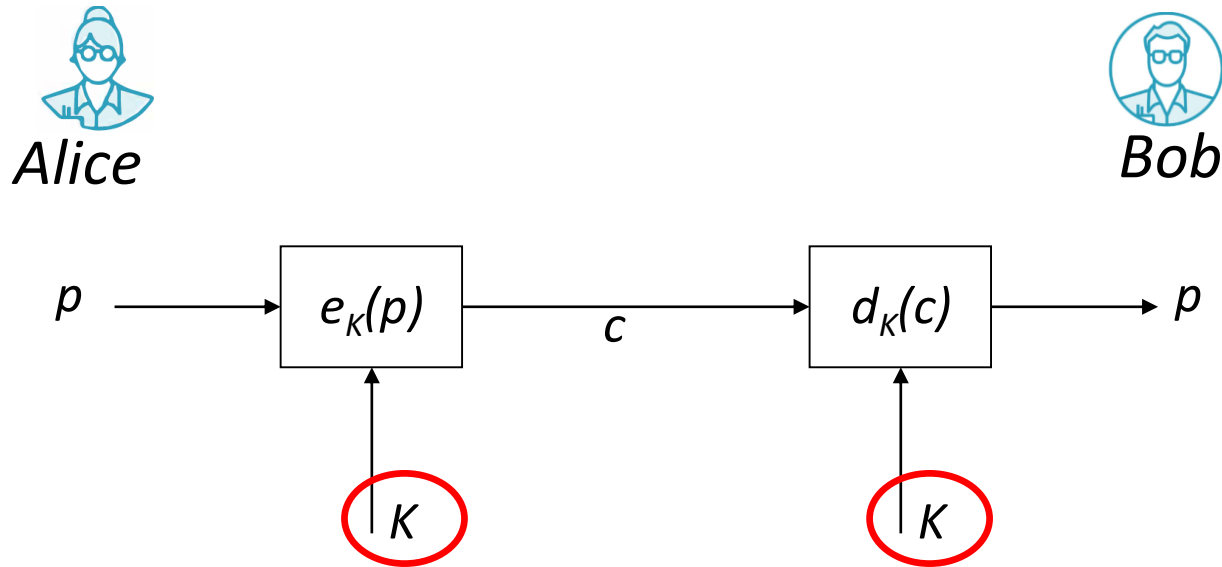




Current Cryptographic Standards



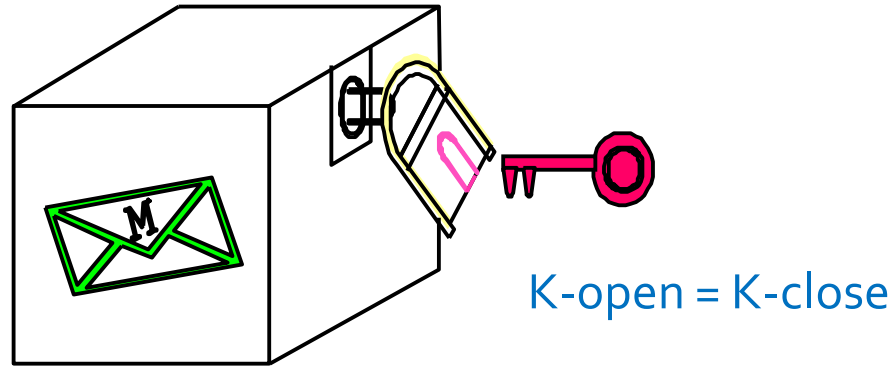
Cryptography revisited



Two properties of symmetric (secret-key) crypto-systems:

- The **same secret key K** is used for encryption and decryption
- Encryption and Decryption are very similar (or even identical) functions

Symmetric Cryptography: Analogy



Safe with a strong lock, only Alice and Bob have a copy of the key

- Alice encrypts → locks message in the safe with her key
- Bob decrypts → uses his copy of the key to open the safe

- Open and close using **shared secret keys**
- Secret key agreement required !

Symmetric Cryptography: Analogy



Alice

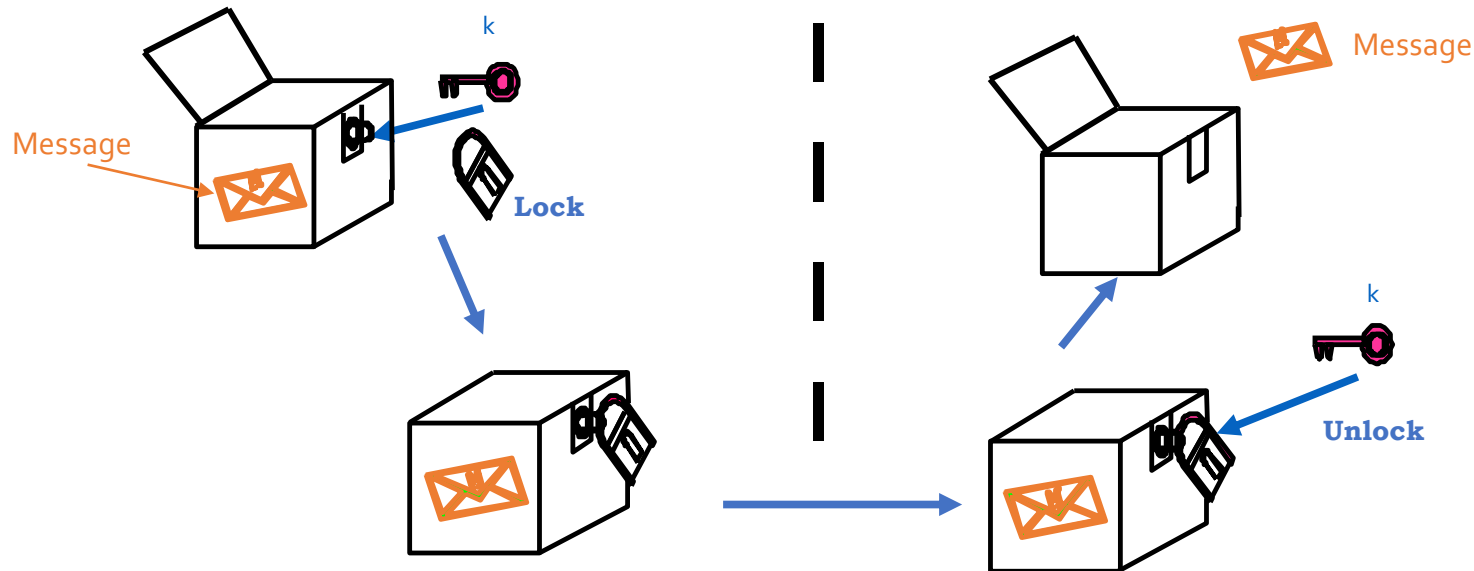


Bob

Shared Key = k

Secret key agreement

Shared Key = k

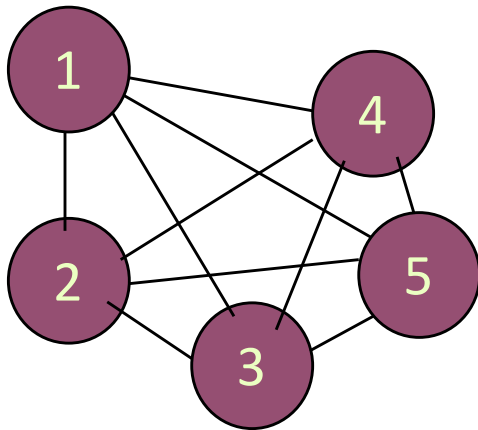


Symmetric Cryptography Shortcomings

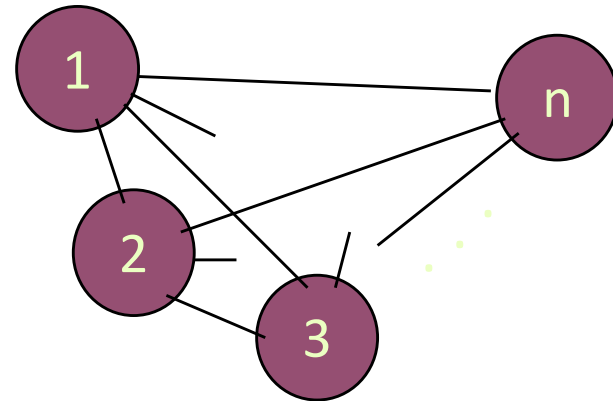
- Key distribution problem: The secret key must be **exchanged securely**
 - Establish a shared key with each entity we want to communicate with
- Number of keys: In a network, each pair of users requires an individual key
 - n users in the network require $\frac{n \cdot (n - 1)}{2}$ keys, each user stores $(n-1)$ keys
- No support for message **integrity**: verifying that a message comes intact from the sender
- No support for “**non-repudiation**”
 - **Example**: Alice can claim that she never ordered a TV on-line from Bob (he could have fabricated her order)

Symmetric Cryptography Shortcomings

Question: How many secret-keys needed to be exchanged in order to set up a system of n-users?



10 key-exchanges for 5 users



$\frac{n(n-1)}{2}$ keys for n users

For 10 000 users we need 50 million key-exchanges !

Public-Key system **drops out** the secret key-agreement completely


Idea behind Asymmetric Cryptography



New Idea:

Use the “good old mailbox” principle:

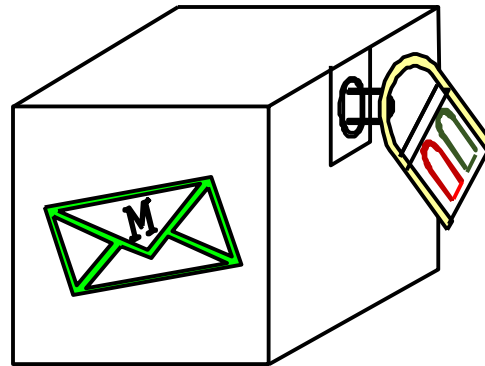
Everyone can drop a letter

But: Only the owner has the correct key  to open the box





Asymmetric Cryptography: Analogy

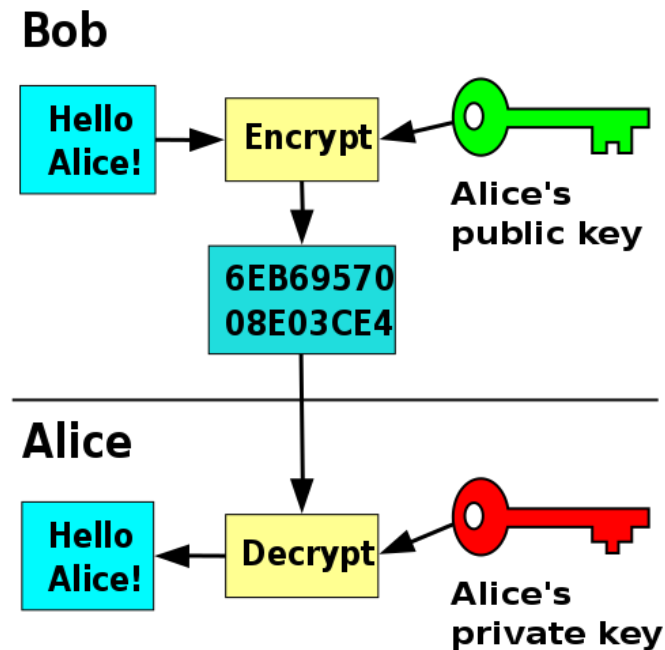


K-lock (public)

K-unlock (private)

- Lock and Unlock with different keys!!
- No Secret Key Agreement required

Asymmetric Cryptography



→ **Key Exchange Problem** solved

→ Anyone can encrypt messages using the **public key**, but only the holder of the **paired private key** can decrypt. Security depends on the secrecy of the private key.

→ During the key generation, a key pair K_{pub} and K_{pr} is computed

Public Key Cryptography Applications

The asymmetric cryptography (e.g., RSA) is mainly used for:

- **Key Exchange** without a pre-shared secret (key)
- **Digital Signatures** to provide message integrity and non-repudiation

Rarely used for:

- **Encryption** because it is computationally very intensive (1000 times slower than symmetric Algorithms!)

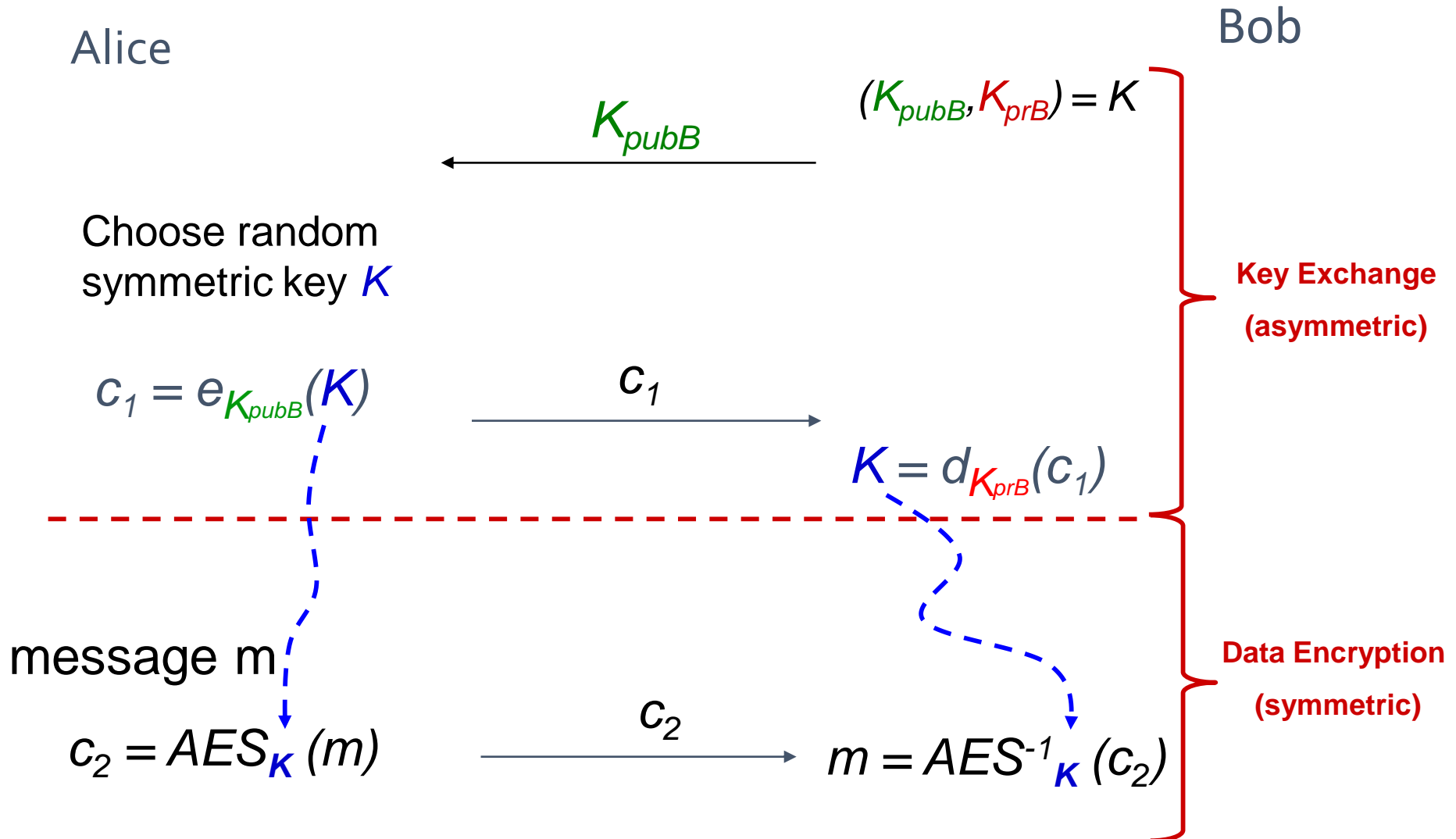
Hybrid Crypto System

In practice, **hybrid system** is used incorporating both asymmetric and symmetric algorithms:

1. **Key exchange** and **digital signatures** are performed with (slow) **asymmetric** algorithms
2. **Encryption** of data is done using (fast) symmetric ciphers, e.g., **block ciphers** or **stream ciphers**

Hybrid Crypto System – Example

Example: Hybrid protocol with AES as the symmetric cipher

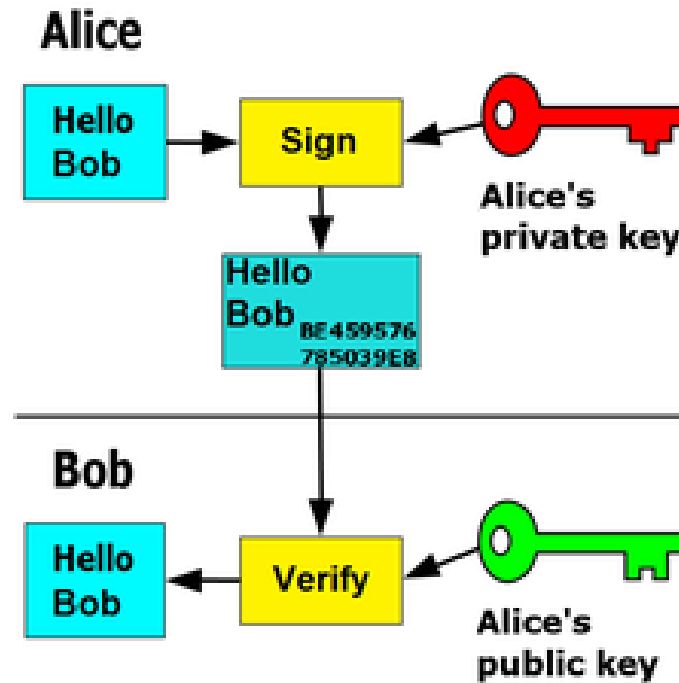


Key Exchange with Public Key Crypto

- Alice creates a secret key, encrypts it with Bob's public key and sends it off
- Bob decrypts the message with his private key
- Use shared key for further communication
- This is how many applications work
- Could encrypt/decrypt using public key cryptography but it is slow

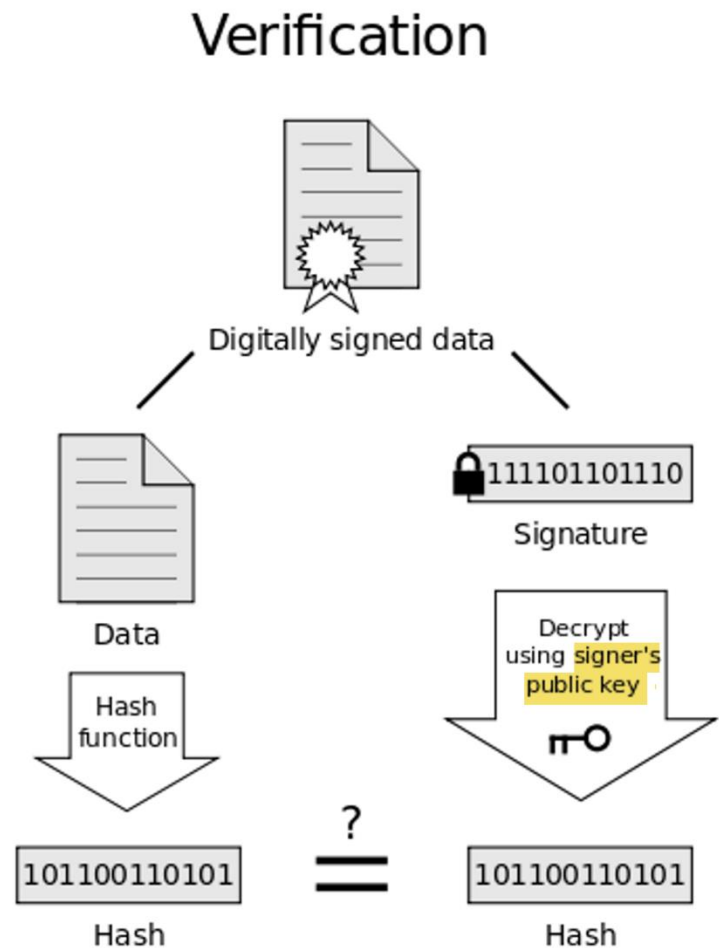
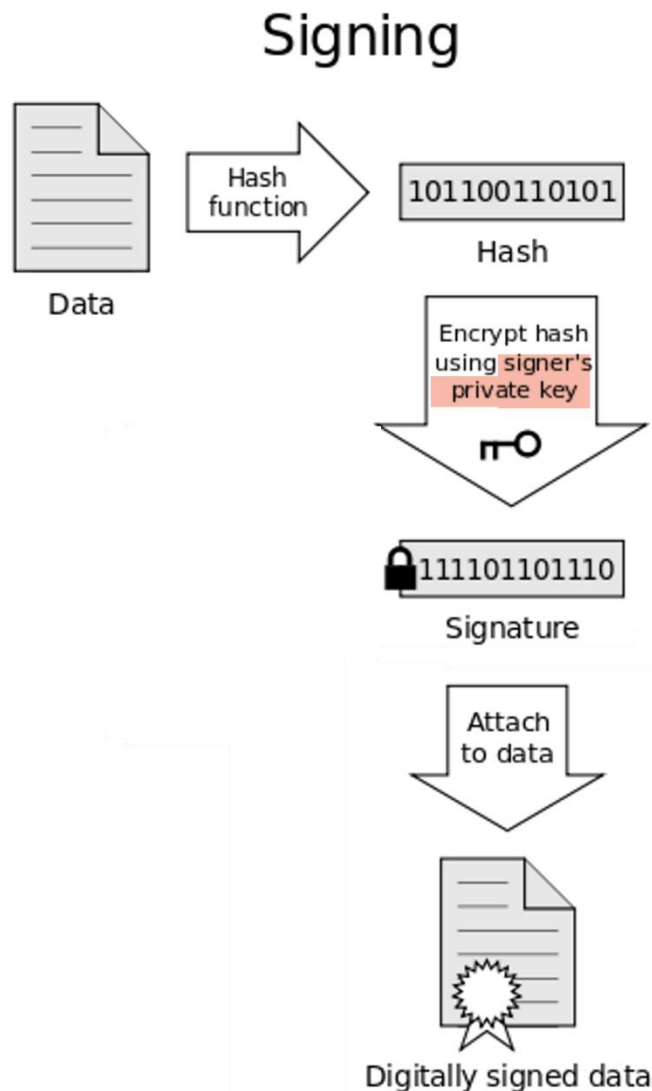


Digital Signatures



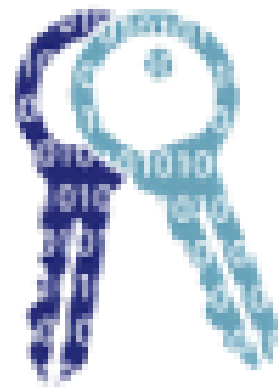
1. Alice signs a message with her private key
2. Bob can verify that Alice sent the message (i.e., **non-repudiation**) and that the message has not been modified (i.e., **integrity**)

Public-Key Signature Process

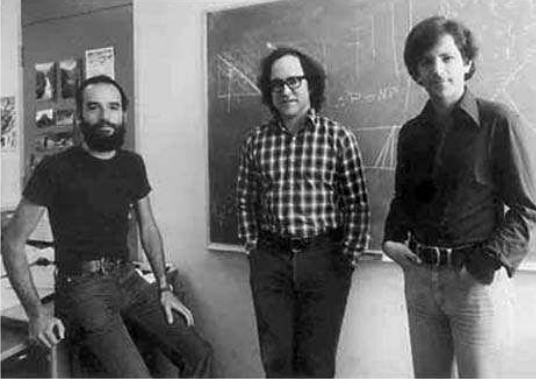


If the hashes are equal, the signature is valid.

RSA



RSA Cryptosystem



Rivest



Shamir



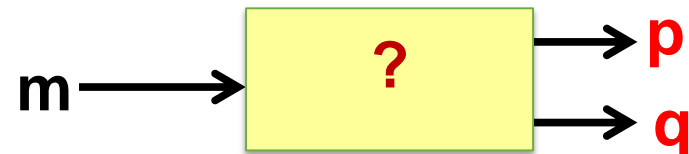
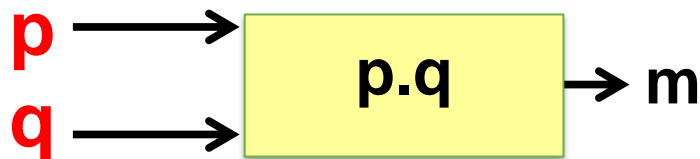
Adleman

- Developed by Rivest, Shamir, and Adleman in 1977
- Until now, RSA is the most widely use asymmetric cryptosystem although Elliptic Curve cryptography (ECC) becomes increasingly popular
- RSA is mainly used for two applications: Key exchange & Digital signatures

RSA One-way Function (Lock)

Asymmetric schemes are based on a “**one-way function**” $f()$:

- Computing $y = f(x)$ is computationally easy
- Computing the inverse $x = f^{-1}(y)$ is computationally infeasible
- One way functions are based on **mathematically hard problems**
- RSA security relies on the difficulty of **factoring** large integers
 - Multiplying two primes is easy (e.g., $1889 \times 3547 = 6,700,283$)
 - Given a composite integer n , find its prime factors is mathematically hard!
(e.g., It is hard to find Prime_1 and Prime_2 such that $\text{Prime}_1 \times \text{Prime}_2 = 6,700,283$)



Factorization
Problem (RSA Lock)

Encryption and Decryption

- Encryption and decryption are simply exponentiations

Definition

Given the public key $(n, e) = k_{pub}$ and the private key $d = k_{pr}$ we write

$$c = e_{k_{pub}}(m) = m^e \bmod n$$

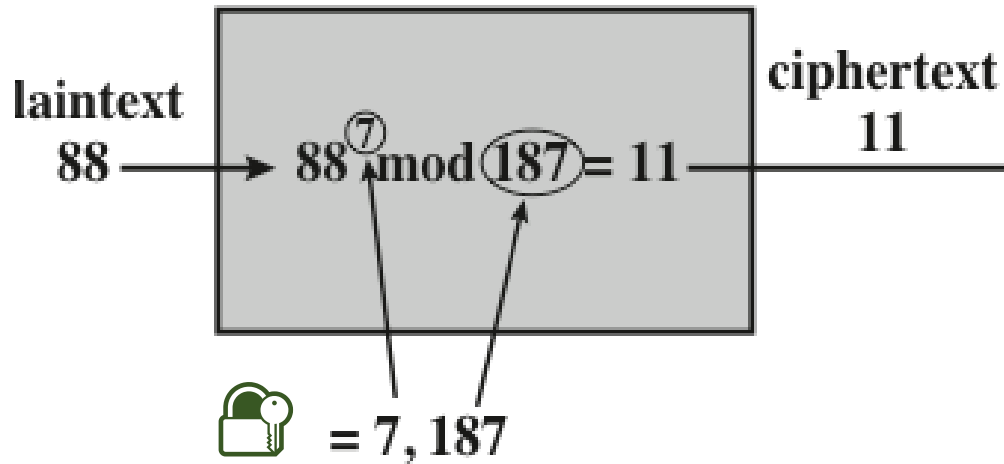
$$m = d_{k_{pr}}(c) = c^d \bmod n$$

$e_{k_{pub}}()$ is the encryption operation and $d_{k_{pr}}()$ is the decryption operation.

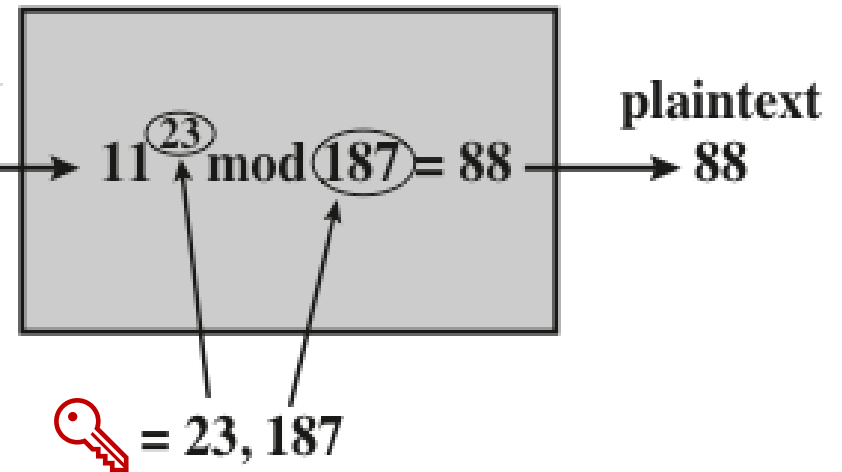
- In practice d and n are very long integer numbers (≥ 1024 bits)
- The security of the scheme relies on the fact that it is hard to derive the private key d given the public-key (n, e)

RSA Example

Encryption



Decryption



RSA Key Generation Algorithm

Output: public key: $k_{pub} = (n, e)$ and private key $k_{pr} = d$

1. Choose two large primes p, q
2. Compute $n = p * q$
3. Compute $\Phi(n) = (p-1) * (q-1)$
4. Select the public exponent e such that $1 < e < \Phi(n)$ and $\gcd(e, \Phi(n)) = 1$ (i.e. e does not share any factor with $\Phi(n)$)
5. Compute the private key d such that $(d * e) \bmod \Phi(n) = 1$
=> Compute d by solving $ex + \phi(n)y = 1$ using **Extended Euclidean Algorithm**
6. **RETURN** $k_{pub} = (n, e), k_{pr} = d$

- d is the **inverse** of $e \bmod \Phi(n)$
- $\gcd(e, \Phi(n)) = 1$ ensures that e has an inverse and, thus, that there is always a private key d
- Φ is called Phi **gcd** is the greatest common divisor

Example: RSA with small numbers

ALICE

Message **$m = 4$**

$$c = m^e = 4^3 \bmod 33 = 31$$

$$c = 31$$

BOB

1. Choose $p = 3$ and $q = 11$
2. Compute $n = p * q = 33$
3. $\Phi(n) = (3-1) * (11-1) = 20$
4. Choose $e = 3$
5. Compute the private key **d** such that **$(d * e) \bmod \Phi(n) = 1$**
 $\Rightarrow d=7$

$$K_{\text{pub}} = (33, 3)$$

$$c^d = 31^7 \bmod 33 = 4$$

Compute **d** using Extended Euclidean Algorithm

- EED calculates **x** and **y** such that $ax + by = \gcd(a, b)$

Now let $a=e$, $b=\phi(n)$, and thus $\gcd(e, \phi(n))=1$

>> We have to solve: $ex + \phi(n)y = 1$

We need to solve $3x + 20y = 1$

1. Euclidean algorithm to compute $\gcd(3, 20)$	2. Back substitution (write 1 as a linear combination of 3 and 20)
$20 = 6(3) + 2$ $3 = 1(2) + 1$	$1 = 3 - 1(2)$ $1 = 3 - 1(20 - 6(3))$ $1 = 7(3) - 1(20) \Rightarrow d = 7$

$$d = x = 7$$

The value of y does not actually matter, since it will get eliminated by modulo $\phi(n)$ regardless of its value \Rightarrow can safely discard it

Asymmetric Key Cryptography – RSA Encryption Algorithm

- Message: $m = 3$
- Choose 2 random, prime numbers: $p = 19, q = 13$
- $n = pq, n = 247$
- Choose a random # to be e (encryption key): $e = 7$
- $\Phi(n) = (p-1)(q-1) = 216$
- Compute d (private key)
 $d * e \bmod \Phi(n) = 1$ (need to solve for d)
 $d = 31$ (using Extended Euclidean Algorithm)
- Public key = $(n, e) = (247, 7)$
- To encrypt: $c = m^e \bmod n \rightarrow c = 3^7 \bmod 247 \rightarrow$
 $c = 211$ (ciphertext)
- To decrypt: $m = c^d \bmod n \rightarrow m = 211^{31} \bmod 247 \rightarrow$
 $m = 3$ (plaintext)

Another example

$$e \cdot d \bmod \varphi(n) = 1$$

$$7 \cdot d \bmod 40 = \textcircled{1}$$

Step 1: Euclidean algorithm

$$40x + 7y = 1$$

$$40 = 5(7) + 5 \leftarrow$$

$$7 = 1(5) + 2 \leftarrow$$

$$5 = 2(2) + 1 \leftarrow$$

Step 2: Back substitution

$$1 = 5 - 2(2)$$

$$1 = 5 - 2(7 - 1(5))$$

$$1 = 3(5) - 2(7)$$

$$1 = 3(40 - 5(7)) - 2(7)$$

$$1 = 3(40) - \textcircled{17}(7)$$

$$p = 11$$

$$q = 5$$

$$n = 55$$

$$\varphi(n) = \underline{40}$$

$$e = 7$$

$$d =$$

Attacks and Countermeasures

- **Brute force key search**

- using exhaustive search for factoring of n in order to obtain $\Phi(n)$
- Can be prevented using a sufficiently large modulus n
- The current factoring record is 664 bits. Thus, it is recommended that n should have a bit length between 1024 and 3072 bits

- Implementation attacks such **Side-channel analysis**

- Exploit physical leakage of RSA implementation (e.g., power consumption, etc.)
- Timing attacks on running of decryption can Infer operand size based on time taken

Summary

- RSA is the most widely used public-key cryptosystem
- RSA is mainly used for key exchange and digital signatures
- RSA relies on the fact that it is hard to factorize n
- Currently 1024-bit cannot be factored, but progress in factorization could bring this into reach within 10-15 years.
 - Hence, RSA with a 2048 or 3076 bit key should be used for long-term security

References

- Asymmetric cryptography Wikipedia pages

https://en.wikipedia.org/wiki/Public-key_cryptography

[https://en.wikipedia.org/wiki/RSA_\(cryptosystem\)](https://en.wikipedia.org/wiki/RSA_(cryptosystem))

- Greatest Common Divisor

<https://www.youtube.com/watch?v=JUzYl1TYMcU>

- Extended Euclidean algorithm

<https://www.youtube.com/watch?v=kYasb426Yjk>