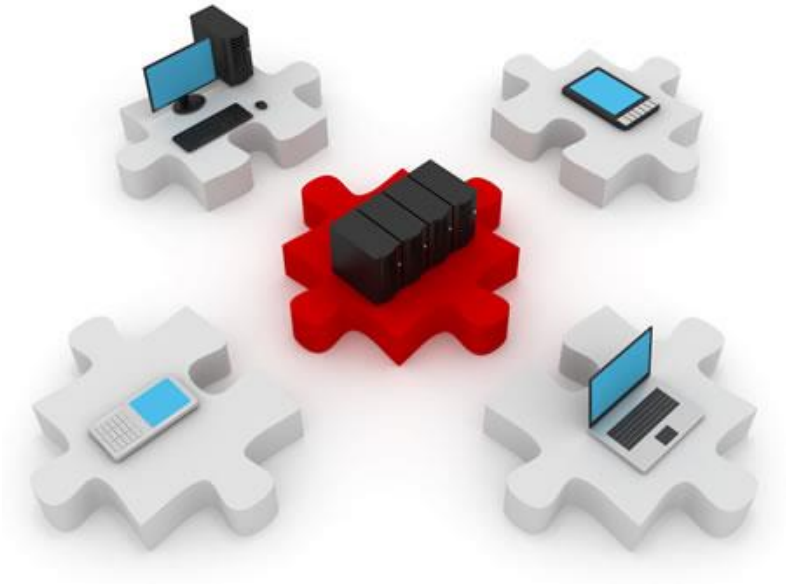


Cryptography

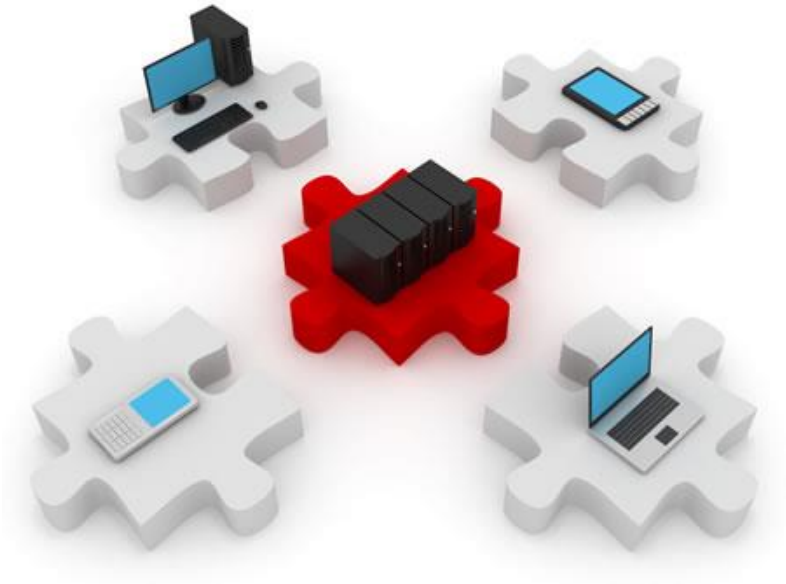
December 3, 2013

Overview

- Principles of security
- Encryption algorithms
- Key exchanges
- Hashing algorithms
- Authentication algorithms

Security concepts

Confidentiality	Keeping data secret
Integrity	Testing whether data has been tampered with
Authentication	Checking whether an entity is who it claims to be



CONFIDENTIALITY

Confidentiality Overview

- Keeping data secret from eavesdroppers
- Data must be retrievable

- Broken when the attacker becomes able to decrypt encrypted content

Caesar	DES
Monoalphabetic Substitution	3DES
Vigenere	AES
OTP	RSA

Confidentiality – Key Concepts

- Plaintext
  - The text before it is encrypted; the input of the encryption algorithm
- Ciphertext
  - The text after it was encrypted; the output of the encryption algorithm

- Key
  - A second input, usually secret, used to customize the encryption algorithm
- Key space
  - The set of data from which keys may be selected
  - A larger set of keys leads to an increase in the duration of brute force attempts

Caesar cipher

Caesar	Class	Classical Monoalphabetic substitution Symmetrical
	Date invented	1st century BC
	Prerequisites	Both parties must know the secret key

- One of the earliest known uses of encryption
- Used by Julius Caesar during military campaigns

Caesar cipher – Algorithm

Plaintext

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

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

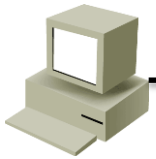
Ciphertext

Monoalphabetic substitution table:

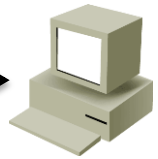
A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V

ALICE → WHEYA

Key = 4



WHEYA



WHEYA → ALICE

Key = 4

Alice

Bob

Caesar cipher – Conclusion

The key

Key space: $26 \cong 2^5$

Key format: Number or letter

Weaknesses:

Brute force attacks (low key space)

Frequency analysis

Known plaintext attacks

Keys must be preshared

Verdict: **Do not use**

Substitution cipher

Substitution cipher	Class	Classical Monoalphabetic substitution Symmetric
	Date invented	Specific types in use during 1st century BC
	Prerequisites	Both parties must know the secret key

- One letter (or byte) is substituted for another letter (or byte), according to a permutation
- Caesar cipher is a specific type of substitution cipher
- Many ancient ciphers were variants of the simple substitution cipher

Substitution cipher – Algorithm

- The key is a permutation
- Example #1: Key = {2, 3, 4, 5, 6, 1}

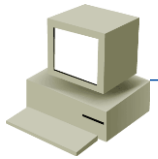
A	B	C	D	E	F
B	C	D	E	F	A

- Example #2: Key = {1, 6, 4, 3, 2, 5}

A	B	C	D	E	F
A	F	D	C	B	E

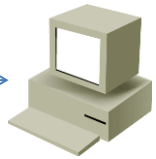
BEEF → FBBE

Key = {1, 6, 4, 3, 2, 5}



Alice

FBBE



Bob

FBBE → BEEF

Key = {1, 6, 4, 3, 2, 5}

Substitution cipher – Conclusion

The key

Key space: $P_{26} \cong 2^{88}$

Key format: Permutation

Weaknesses:

Frequency analysis

Known plaintext attacks

Keys must be preshared

Verdict: **Do not use**

Vigenere cipher

Vigenere	Class	Classical Polyalphabetic substitution Symmetric
	Date invented	16th century
	Prerequisites	Both parties must know the secret key

- Composed of 26 inverted Caesar ciphers
- Difficulty in breaking it at the time gave it the nickname *The unbreakable cipher*

Vigenere cipher – Algorithm

Key:
SCR
Plaintext:
Hello world
Ciphertext:
???

HELLOWORLD
SCRSCRSCRS
ZECDQNG . . .

	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
A	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
B	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	A
C	C	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
D	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	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	D
F	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E
G	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F
H	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G
I	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H
J	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	E	F	G	H
K	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	E	F	G	H	I
L	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	E	F	G	H	I	J
M	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	E	F	G	H	I	J	K
N	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M
O	O	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N
P	P	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Q	Q	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
R	R	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
S	S	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
T	T	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
U	U	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
V	V	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
W	W	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
X	X	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W
Y	Y	Z	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Z	Z	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

Vigenere cipher – Conclusion

The key

- Key space: Infinite
- Key format: Letter sequence

Weaknesses:

- Brute force (due to bad key choices)
- Frequency analysis
- Known plaintext attacks
- Keys must be preshared

Verdict: **Do not use**

One time pad

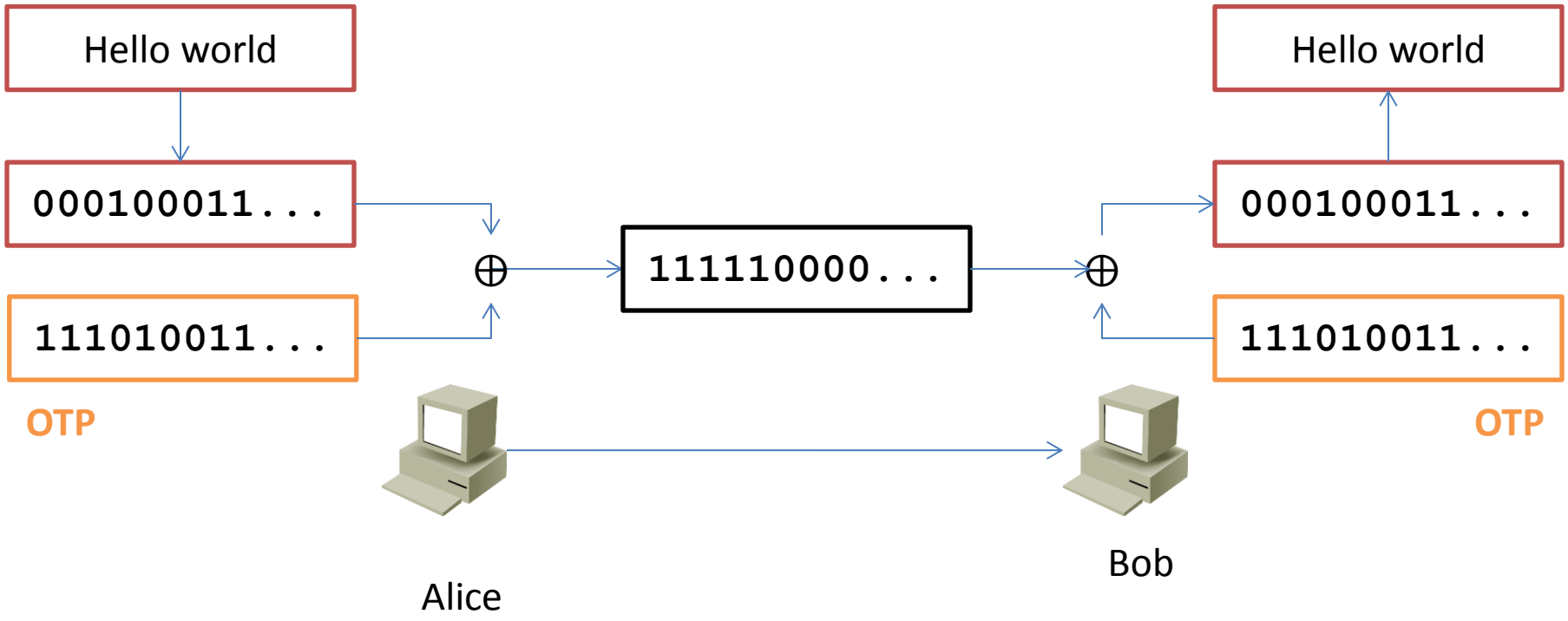
OTP	Class	Classical Symmetric
	Date invented	1882/1917
	Prerequisites	Both parties must know the secret key

- Shannon proved that the OTP leaks no information about the plaintext message
- The key must be as long as the message
- If the key is used more than once , OTP security is broken

One time pad – Algorithm

Modular addition (XOR, ⊕)

⊕	0	1
0	0	1
1	1	0



One time pad – Conclusion

The key

Key space: 2^{length}

Key format: Bit sequence

Weaknesses:

Broken by chosen plaintext attacks

Keys must be preshared

Keys are as long as the message

Keys must only be used once

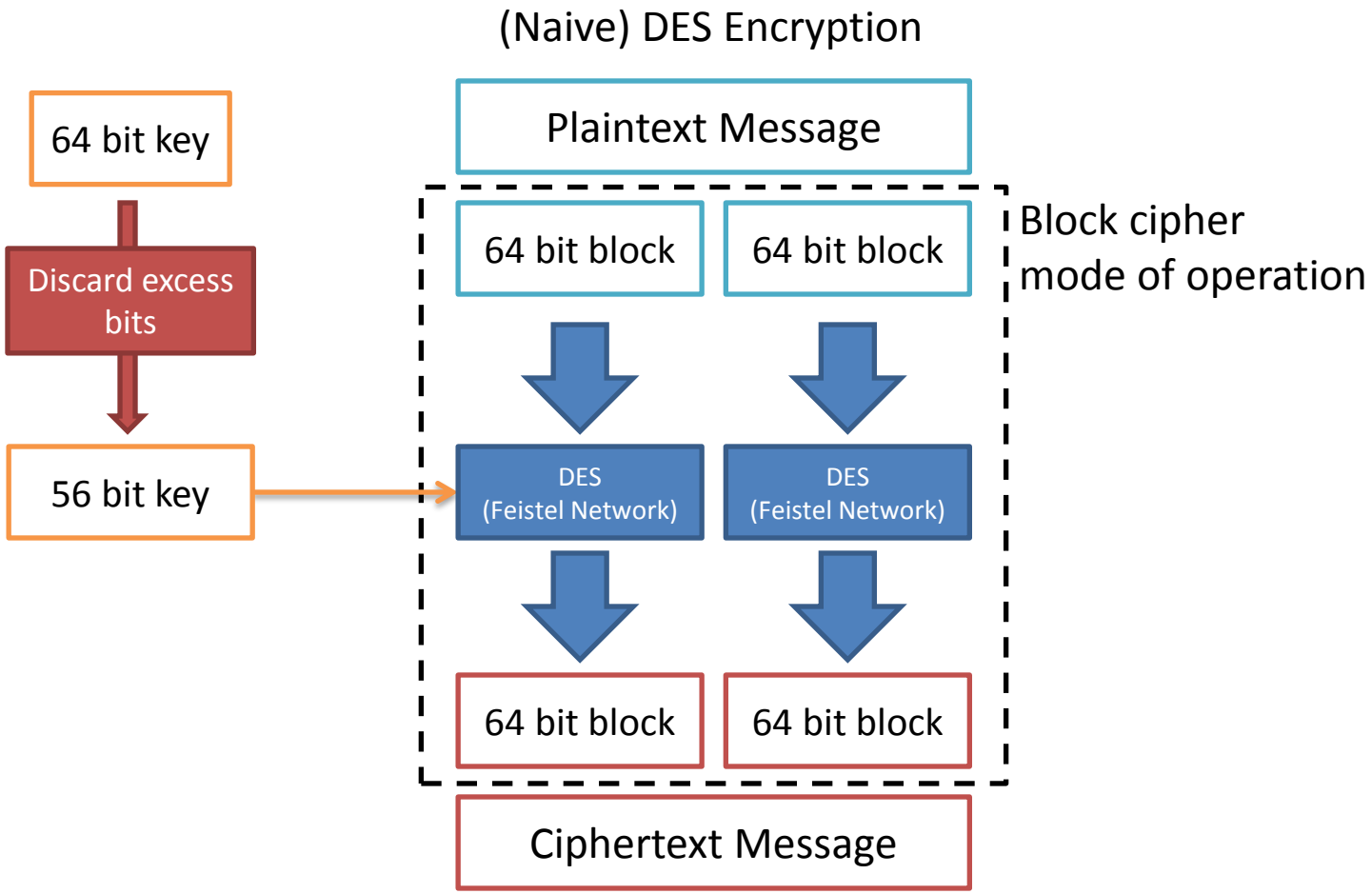
Verdict: **Use with care**

DES

DES	Class	Modern Symmetric
	Date published	1977
	Prerequisites	Both parties must know the secret key

- Data Encryption Standard
- The first US federal standard for encryption algorithms
- Extensively studied since the 1970s
- Advances in computing power rendered it obsolete

DES – Algorithm



DES – Conclusion

The key

Key space: 2^{56} (approx.)

Key format: Bit sequence

Weaknesses:

Brute force feasible with current processors

Keys must be preshared

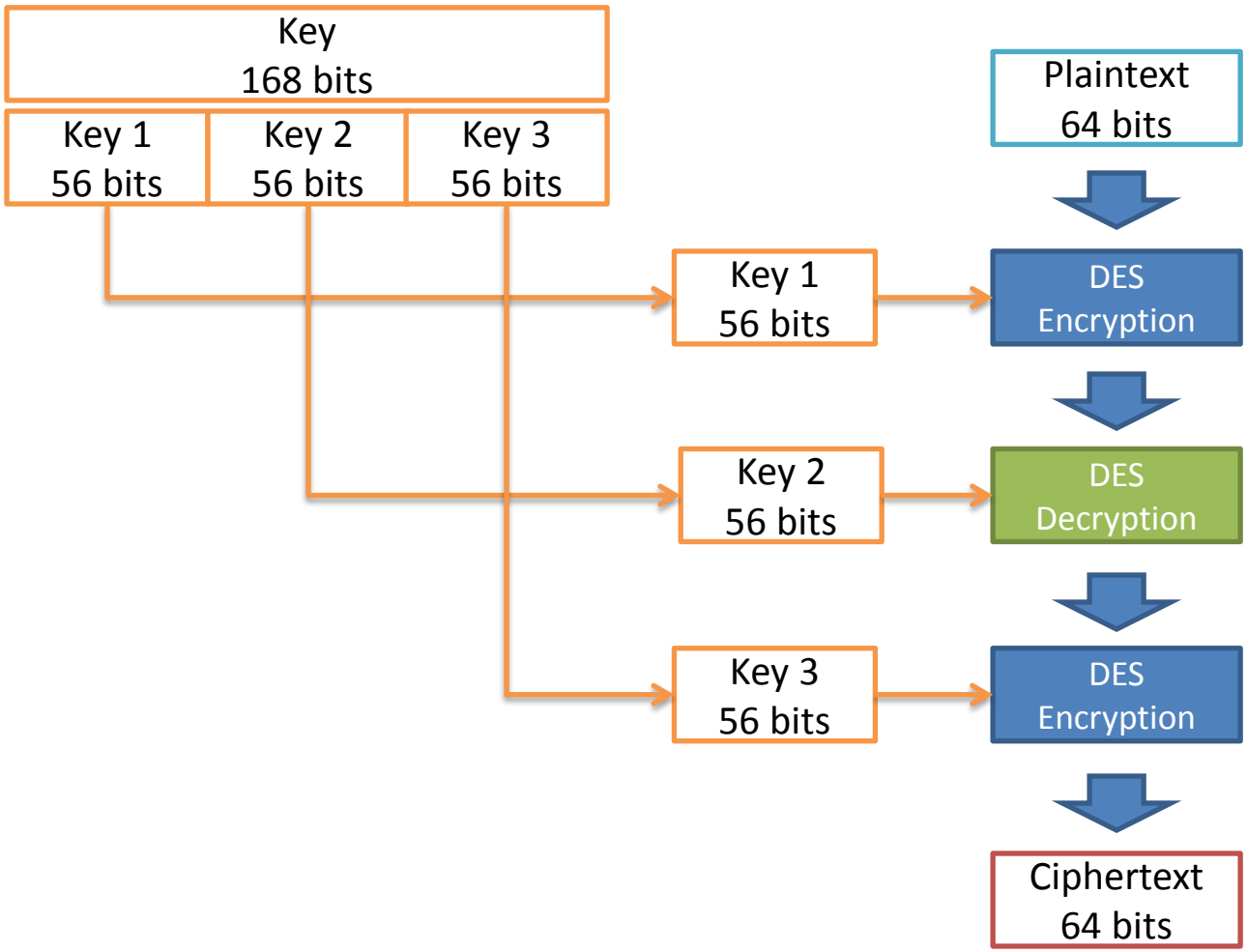
Verdict: **Do not use**

3DES

3DES	Class	Modern Symmetric
	Date published	1998
	Prerequisites	Both parties must know the secret key

- Block algorithm, based on three iterations of DES
- Multiple keying options
  - Option 1: all keys are independent
  - Option 2: $K_1 = K_3$; K_1, K_2 independent
  - Option 3: $K_1 = K_2 = K_3$

3DES – Algorithm (keying option 1)



3DES – Conclusion

The key

Key space: 2^{168}

Best known attack: 2^{112}

Key format: Bit sequence

Weaknesses:

Keys must be preshared

Slower than other safe options

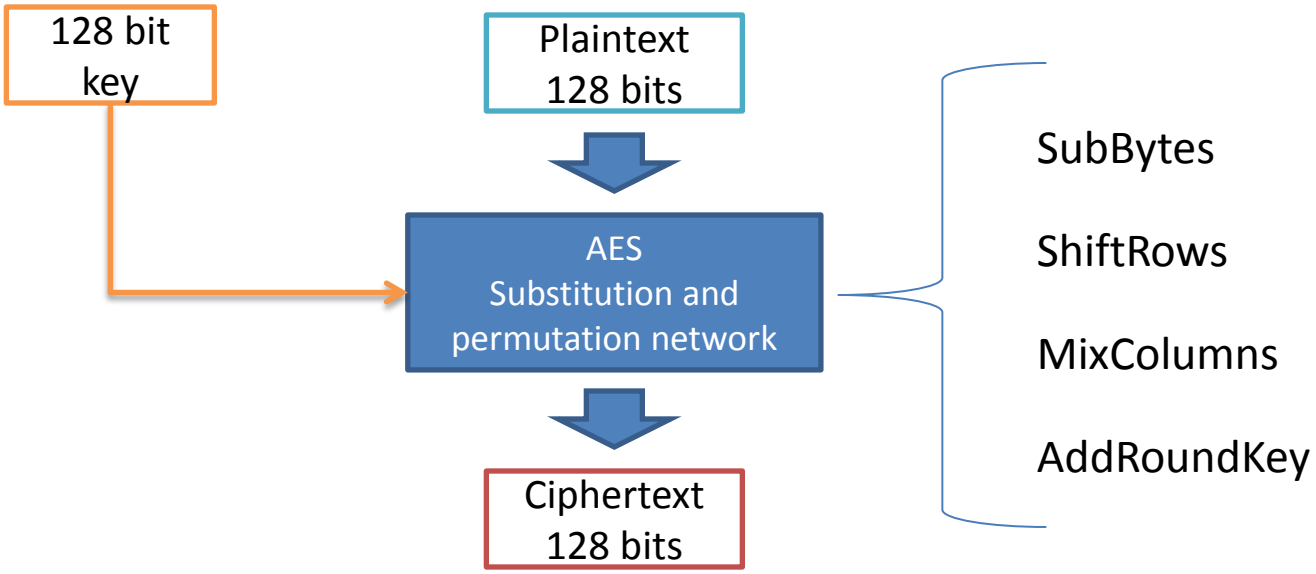
Verdict: **Safe to use**

AES

AES	Class	Modern Symmetric
	Date published	1998
	Prerequisites	Both parties must know the secret key

- AES is the 128 bit block version of the Rijndael Cipher
- Very fast
- Hardware support
- AES-128, AES-192 and AES-256 refer to key sizes, and not block sizes

AES – Algorithm



AES – Conclusion

The key

Key space: 2^{128}, 2^{192}, 2^{256}

Best known attacks: $2^{126.1}$, $2^{189.7}$, $2^{254.4}$

Key format: Bit sequence

Weaknesses:

Keys must be preshared

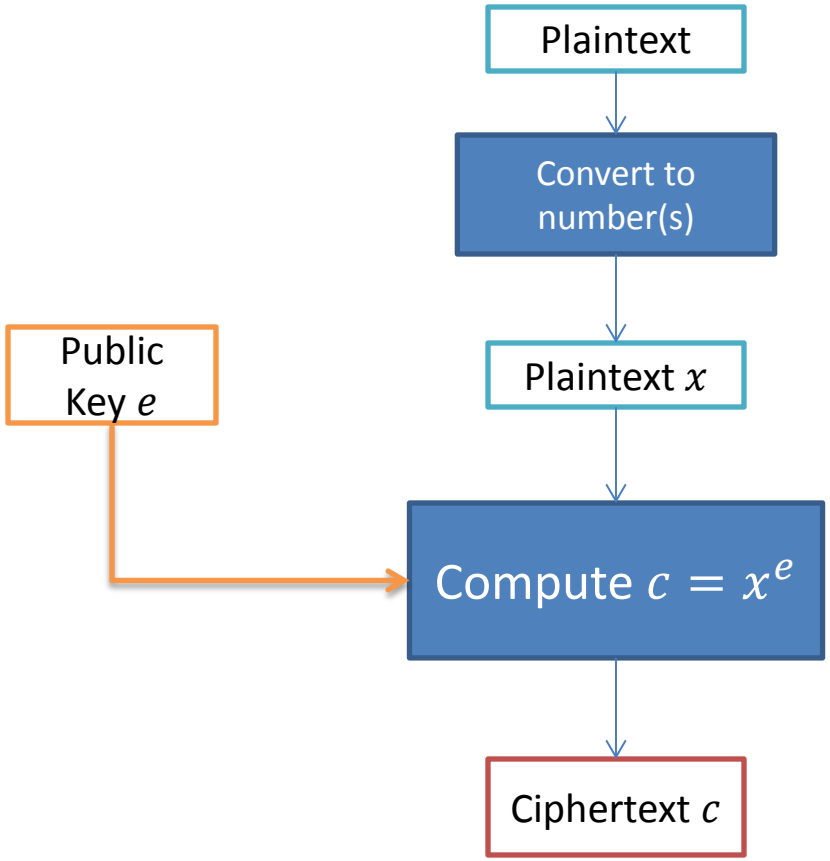
Verdict: **Safe to use**

RSA Encryption

RSA	Class	Modern Asymmetric
	Date published	1977
	Prerequisites	Receiving party must know the **public** key

- The algorithm uses a key pair:
  - The public key (PubKey, or e); this is free to share
  - The private key (PrivKey, or d); this must be kept secret by the owner
- The important property is that $(x^e)^d = \left(x^d\right)^e = x$ (inside an algebraic structure with certain properties)

RSA Encryption – Algorithm



Why isn't the private key used for encryption?

RSA Encryption – Conclusion

The key

Key **size**: 2^{1024} to 2^{4096}, or larger

Best known brute forced key: 2^{768}

Key format: Large numbers, key pair

Weaknesses:

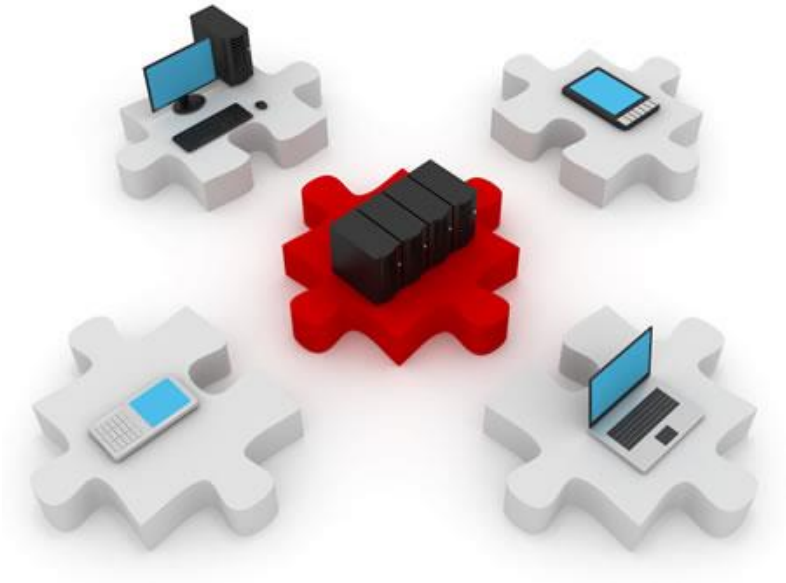
Very slow

Verdict: **Use sparingly**

Confidentiality – Conclusion

- Problems left to solve:
  - Key distribution
  - Message integrity

- Possible attacks:
  - Brute force
  - Cryptananalysis
    - Frequency analysis
    - Known plaintext/ciphertext cryptanalysis attacks
    - Chosen plaintext/ciphertext cryptanalysis attacks



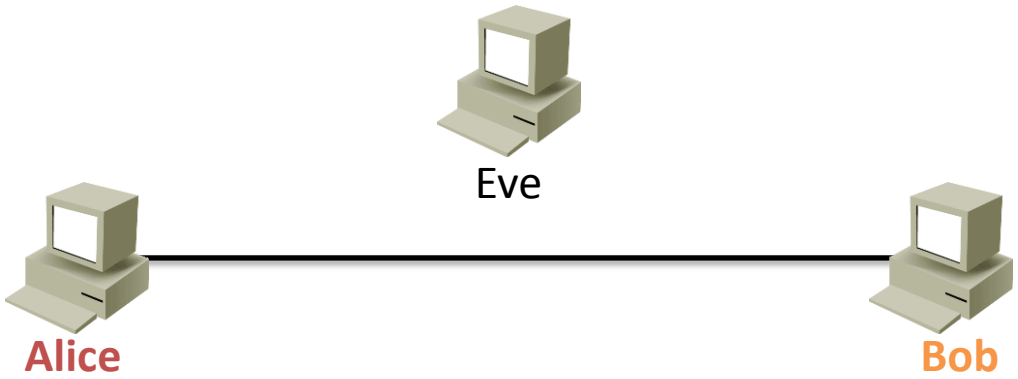
SECURE KEY EXCHANGES

Diffie Hellman

DH	Class	Key exchange algorithm
	Date published	1976
	Prerequisites	Authentication

- The problem:
  - Internet traffic requires encryption
  - Asymmetric encryption algorithms may share public keys freely, but they are too slow during encryption/decryption
  - Symmetric encryption algorithms require preshared keys

Diffie Hellman – Algorithm



Generate a

g

Generate b

g^a

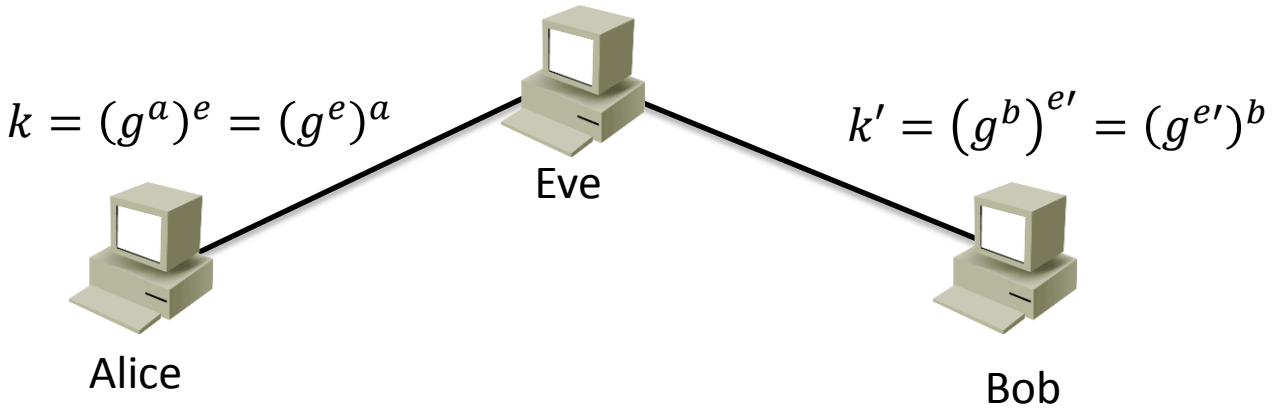
g^b

Compute
$k = (g^b)^a$

Compute
$k = (g^a)^b$

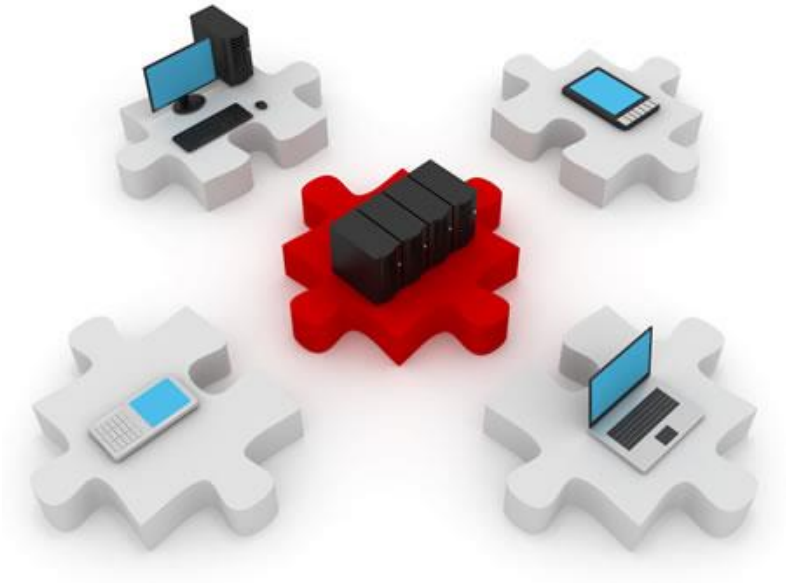
Eve
Know $g, g^a, g^b, k = ???$

Diffie Hellman – Conclusion



Weakness:

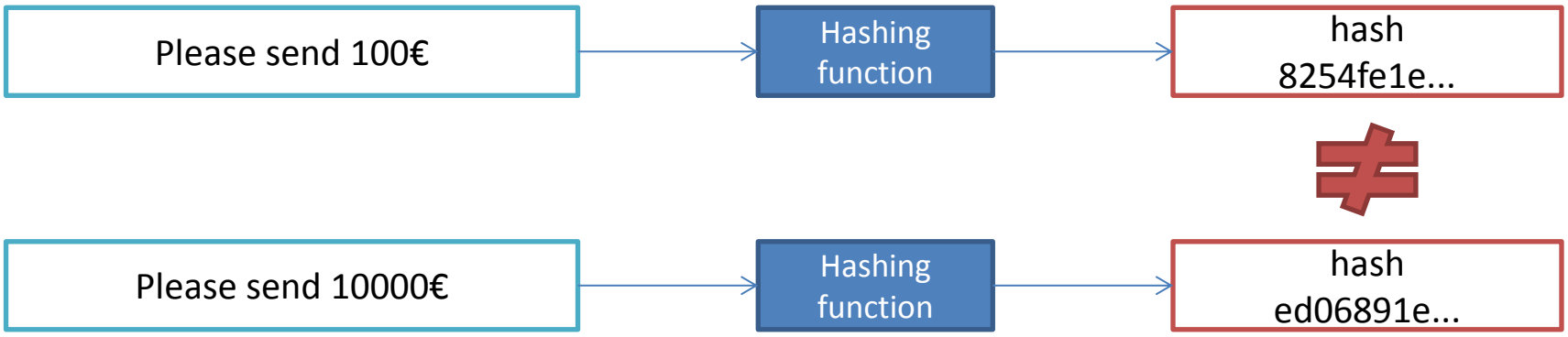
MITM attacks



INTEGRITY

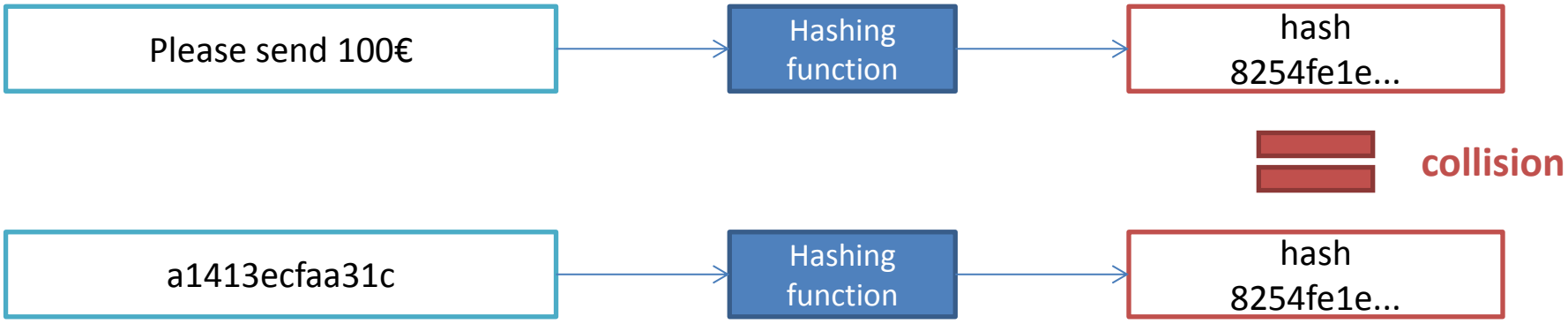
Integrity – Overview

- Integrity algorithms detect whether a message (or file) has been tampered with
- Hash functions output a fixed length summary of the message
- Good hash functions output very different results when small changes are performed on the input message



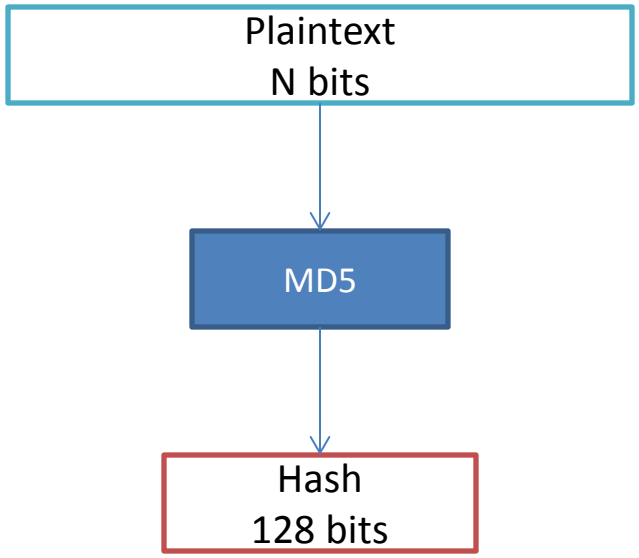
Integrity – Overview

- A hash function is not invertible
  - multiple messages may yield the same hash
  - a hash is considered broken when two such messages are discovered
    - this is called a **hash collision**, and it means the hash has been broken



Message Digest 5

MD5	Class	Hashing algorithm
	Date published	1992
	Hash length	128 bit

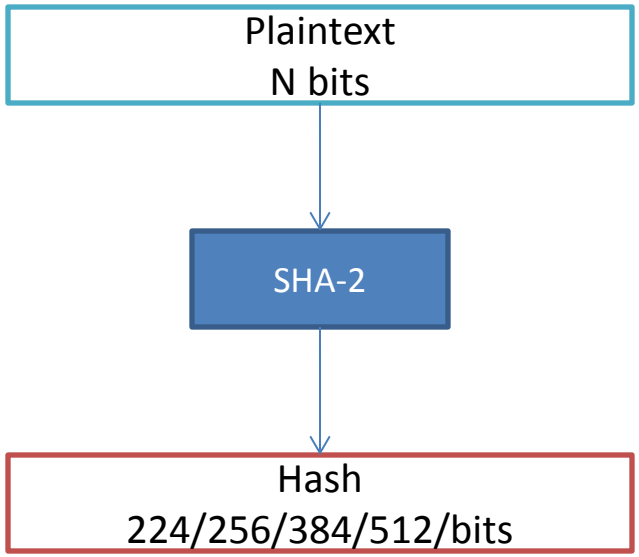


- MD5 is not collision resistant
- Collisions for file checksums have already been generated

Verdict: **Strongly discouraged**

SHA-1/2/3

SHA	Class	Hashing algorithm
	Date published	1995 (SHA-1), 2001 (SHA-2), 2012 (SHA-3)
	Hash length	128 bit



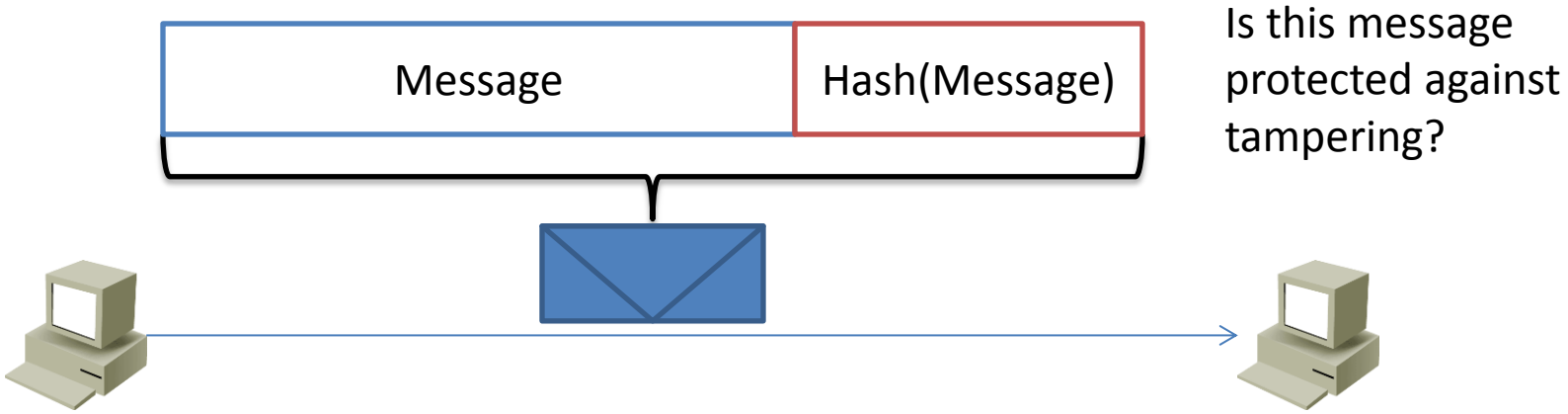
- SHA-1 is now considered broken, but still used by many implementations
- SHA-2 is a federal standard since 2001
- SHA-3 uses a different algorithm to SHA-1 and SHA-2

Verdict for SHA-1: **Strongly discouraged**

Verdict for SHA-2: **Safe for use**

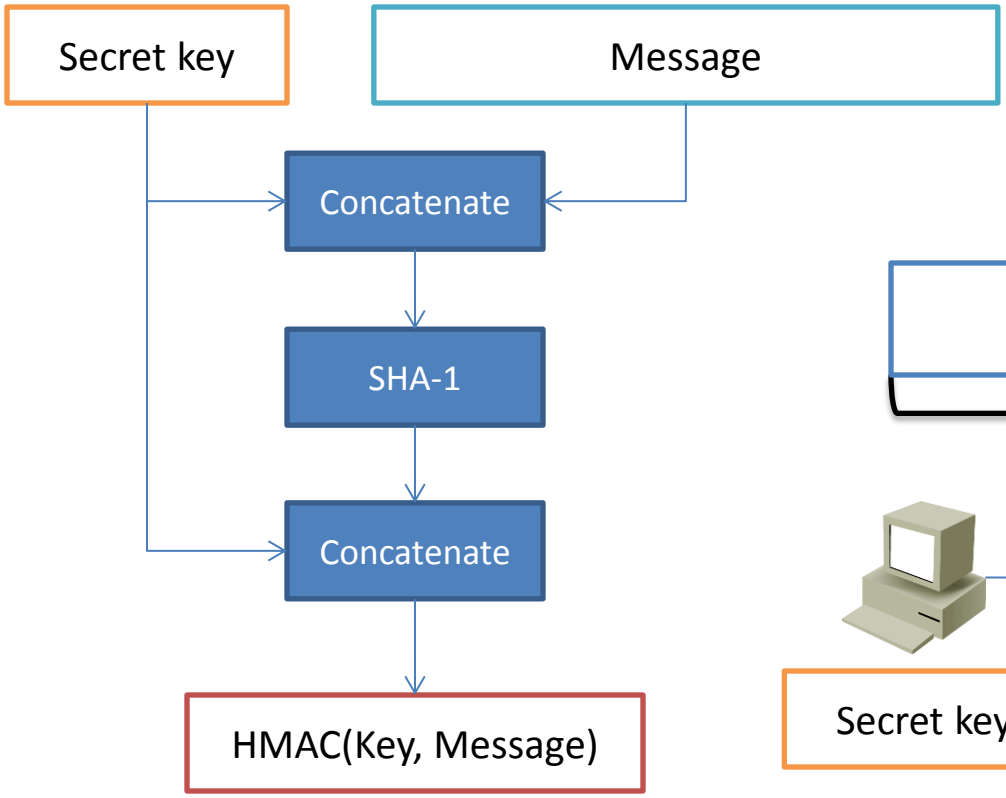
MD5 and SHA use cases

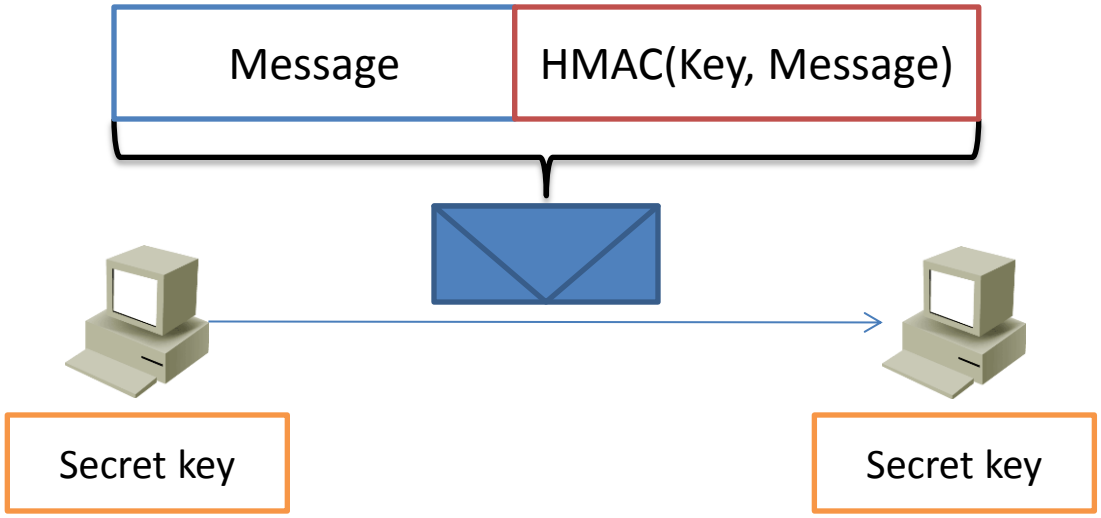
- File checksums
  - For programs, packages, spreadsheets
- Certificate fingerprints (for HTTPS, more on that later)
- Password storage (Linux /etc/shadow)
- Distributed version control (Git, Mercurial)
- Network protocols with protection against message tampering



Keyed Hashing

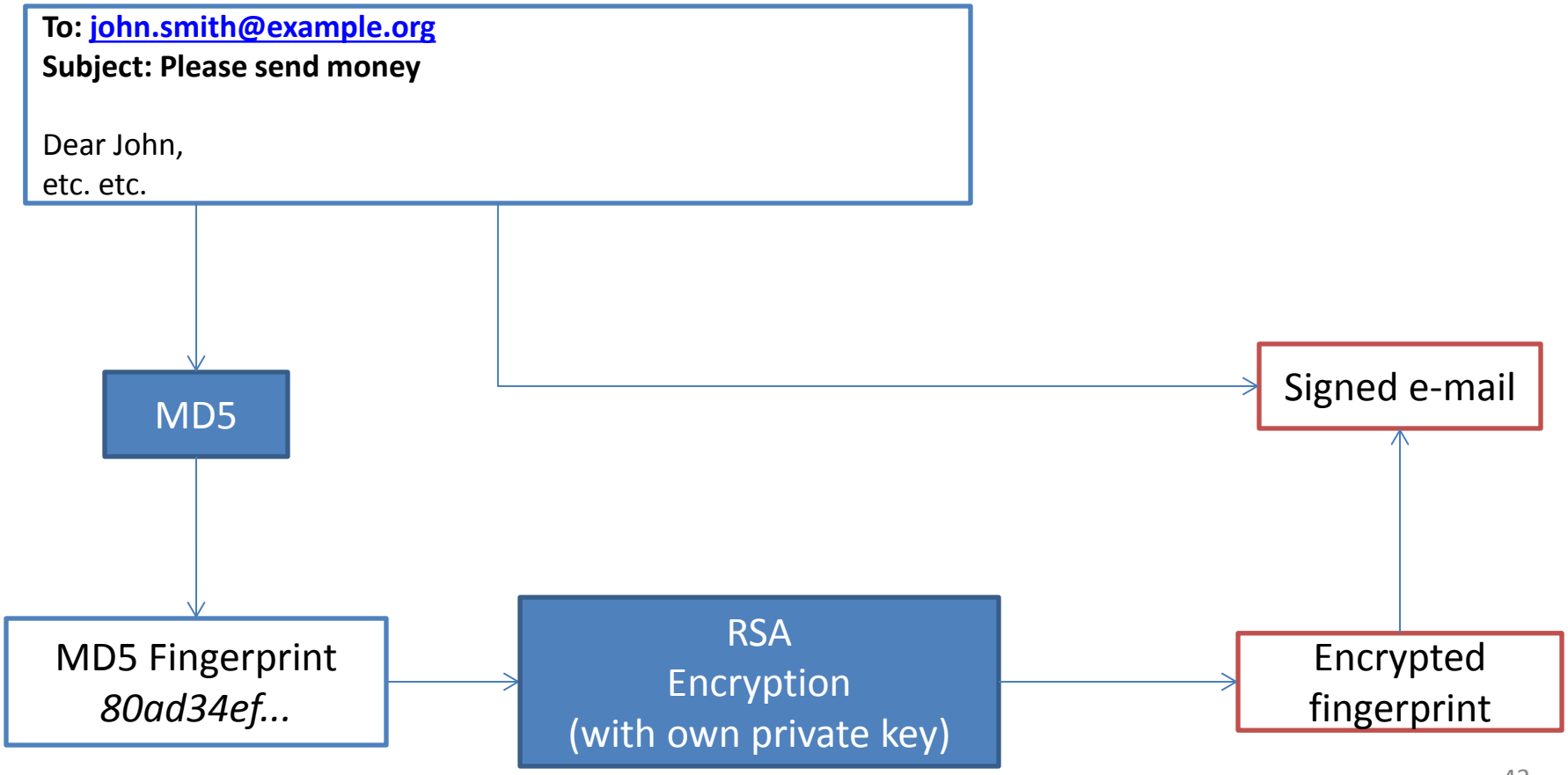
- Same as hashing, but a **pre-shared** key is also hashed along with the message
- Also known as HMAC (Hash-based Message Authentication Code)

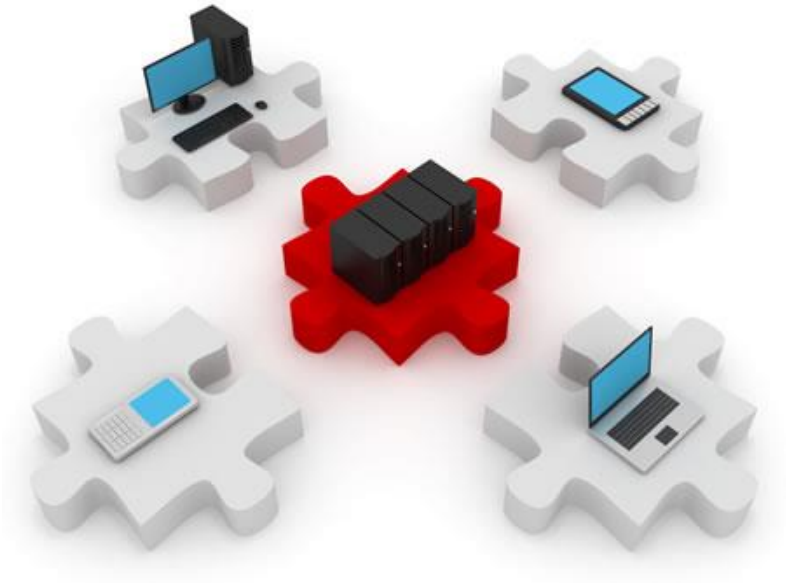




RSA Signing

- The RSA private key can also be used for encryption
  - The advantage is that anyone can decrypt, thus proving that the data was actually encrypted by the sender
  - Also provides **non-repudiation**

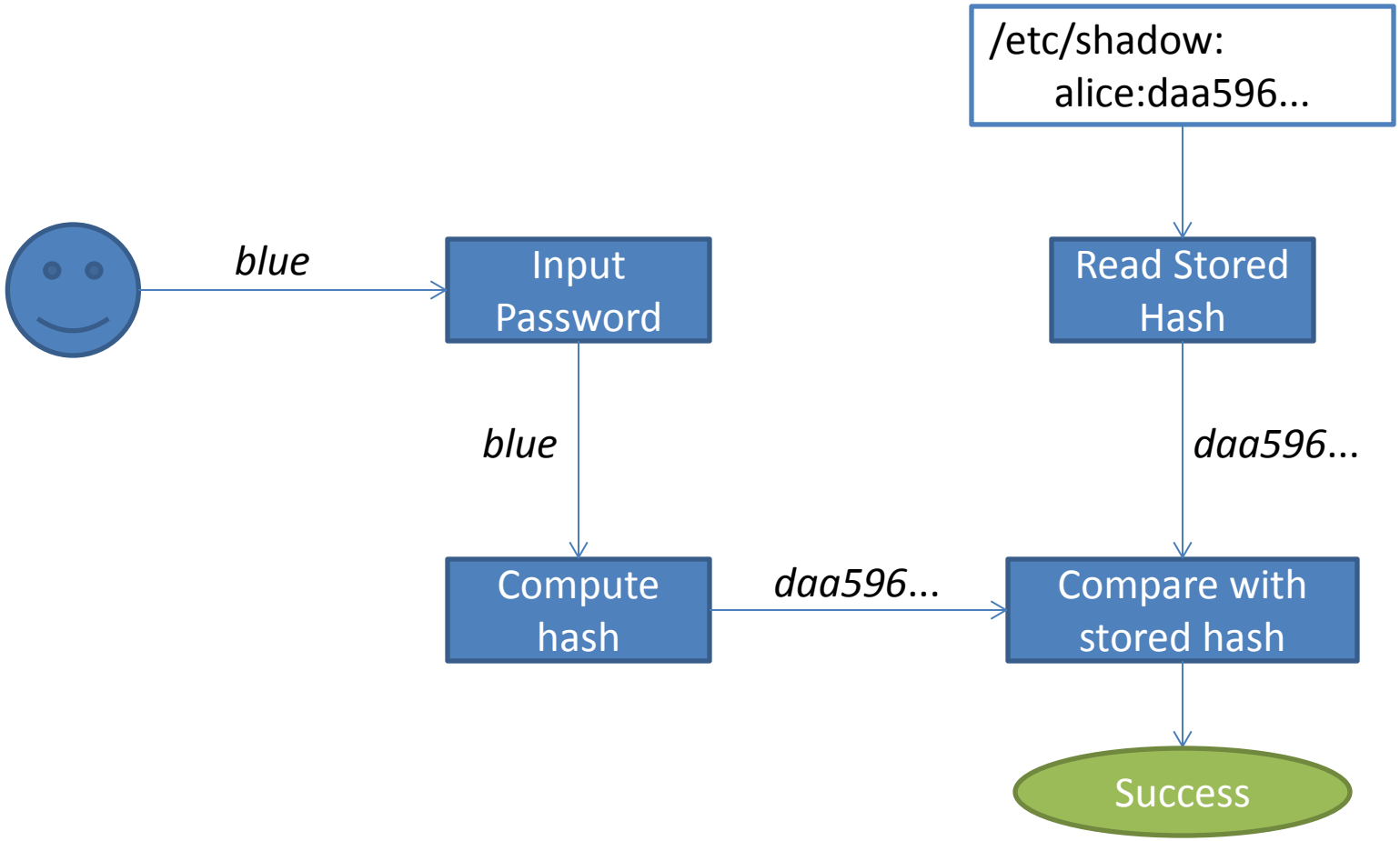




AUTHENTICATION

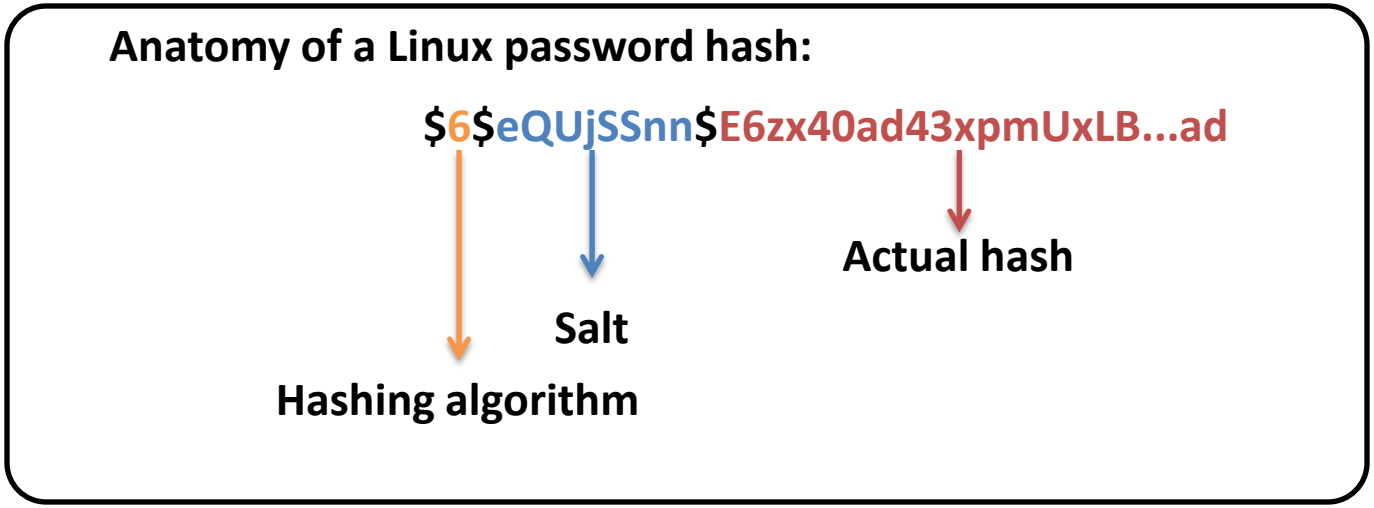
Password based authentication

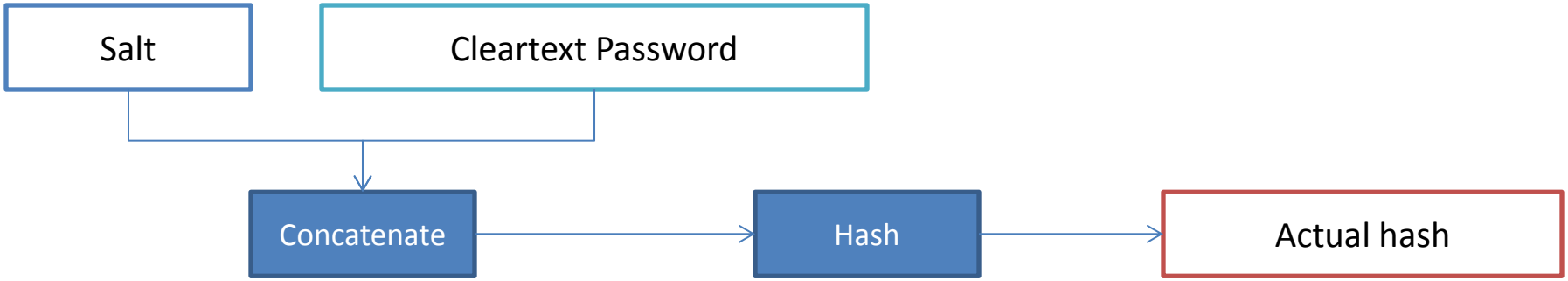
- Storing passwords in clear is not recommended
  - Any breach immediately compromises user accounts



Password based authentication

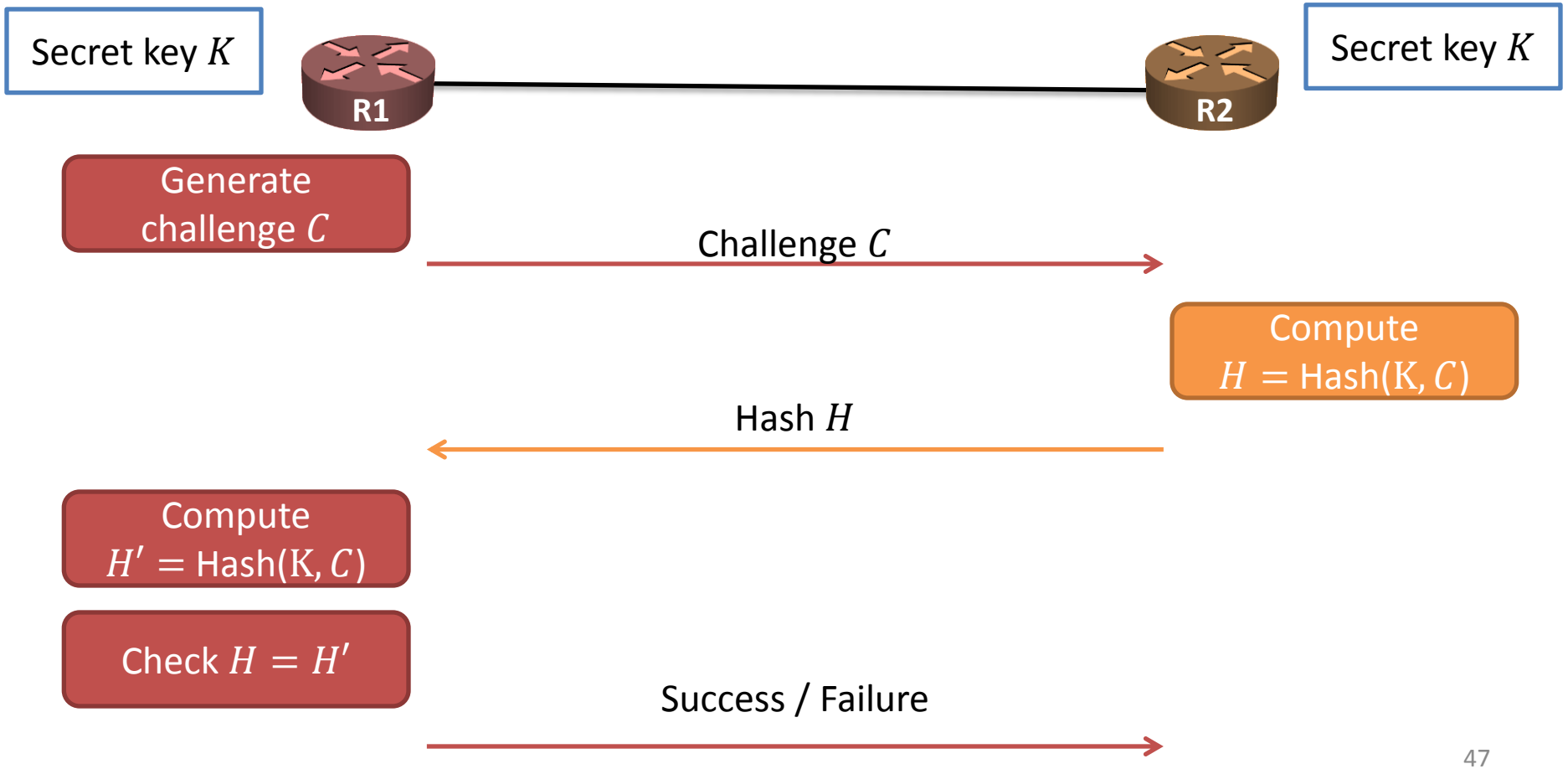
- Everything is better with salt
  - The same password will produce different hashes due to different salts
  - Prebuilt hash libraries for common passwords are useless





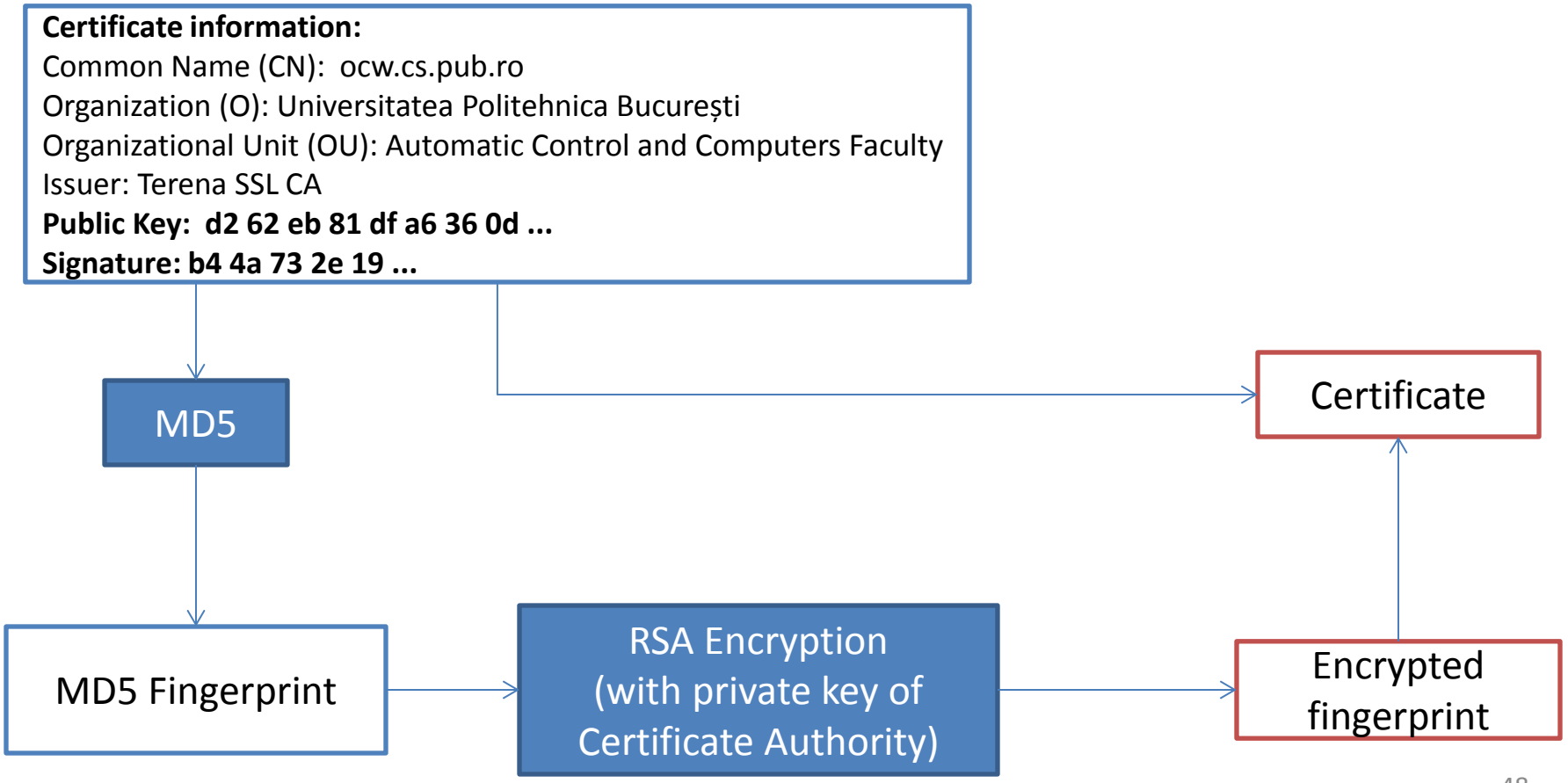
Challenge based authentication

- Solves the problem of authenticating endpoints when a secret key is pre-shared, without transmitting the key over the wire



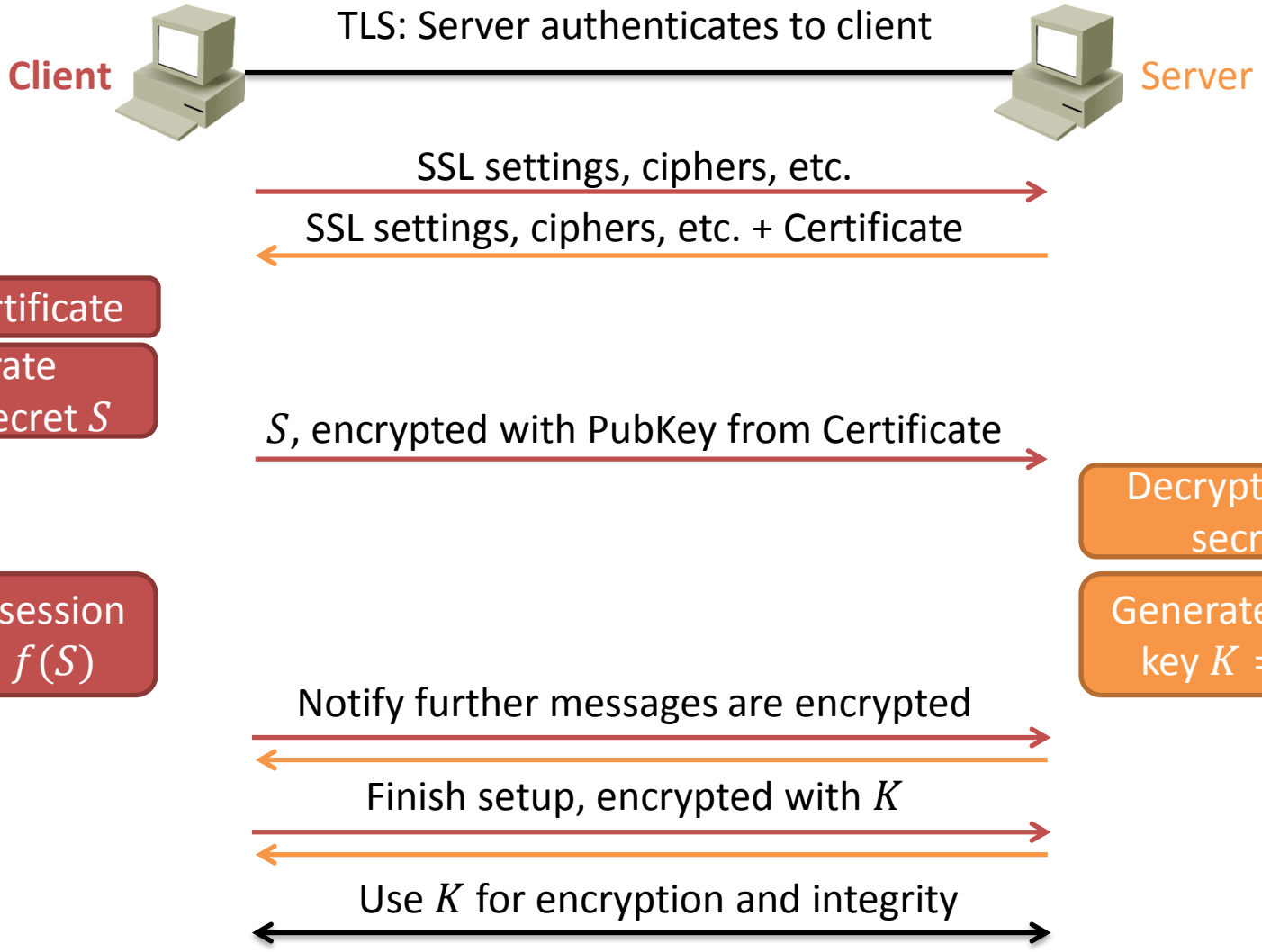
Certificate based authentication

- Certificates contain information about an entity, verified by another trusted entity called a CA (certificate authority)
- Certificates are used to prove that the public key is legit

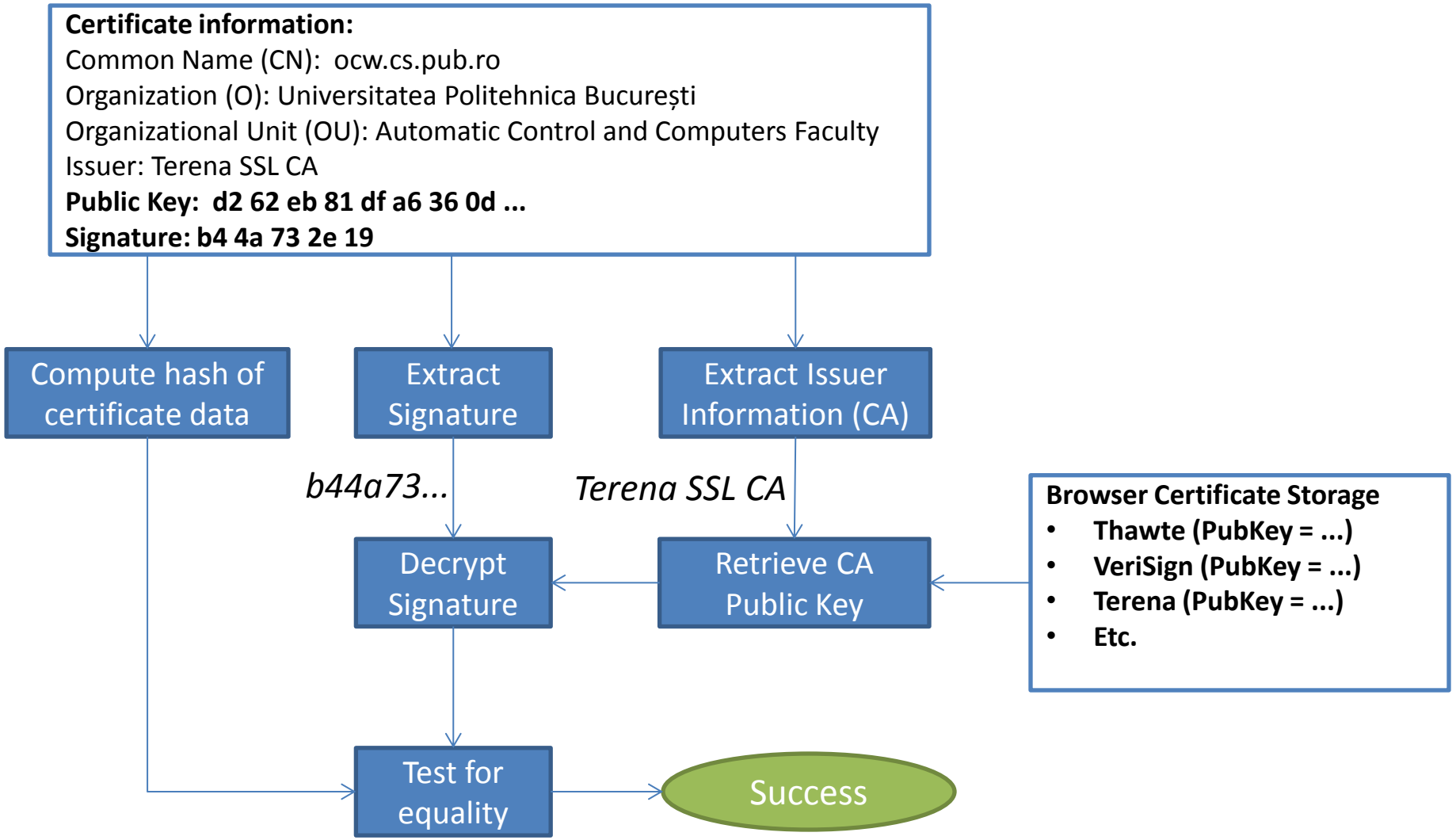


HTTPS/TLS

- HTTPS = HTTP over TLS



TLS: Certificate verification



Food for thought

- Two paranoid users do not trust **any** third party
- How can they establish a secure channel on the Internet, without exchanging prior knowledge? Secure means:
  - Tampering must be detected
  - No third party is able to retrieve private data (even if said party poses as a one of the users, or performs a MITM attack)
  - Covert information or side channels may not be used

Conclusion

- Cryptographic algorithms for:
  - Data confidentiality
  - Data integrity
  - Authentication

- Further reading:
  - The codebreakers, by David Kahn
  - The code book, by Simon Singh
  - Handbook of applied cryptography, by Alfred Menezes
- Other related topics not discussed now: steganography, covert channels, homomorphic encryption, identity-based encryption, elliptic curve cryptography, pairing-based cryptography, Tor network