



UNIVERSITA' DEGLI STUDI DI PARMA
Dipartimento di Ingegneria dell'Informazione

Public Key (asymmetric) Cryptography

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Public Key Cryptography

Public-Key Cryptography

- Sometimes also referred to as asymmetric cryptography (or two-key cryptography)
- Probably most significant advance in the 3000 year history of cryptography
- Public invention due to Whitfield Diffie & Martin Hellman in 1975
 - at least that's the first published record
 - known earlier in classified community (e.g. NSA?)
- Uses clever application of number theoretic concepts
- Complements rather than replaces private key crypto

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Public Key Cryptography

Public-Key Cryptography

- With symmetric/secret-key cryptography
 - you need a secure method of telling your partner the key
 - you need a separate key for everyone you might communicate with
- Instead, with public-key cryptography, keys are not shared
- Uses two keys:
 - a public-key, which may be known by anybody, and can be used to encrypt messages, and verify signatures
 - a private-key, known only to the recipient, used to decrypt messages, and sign (create) signatures
- Is asymmetric because
 - those who encrypt messages or verify signatures cannot decrypt messages or create signatures

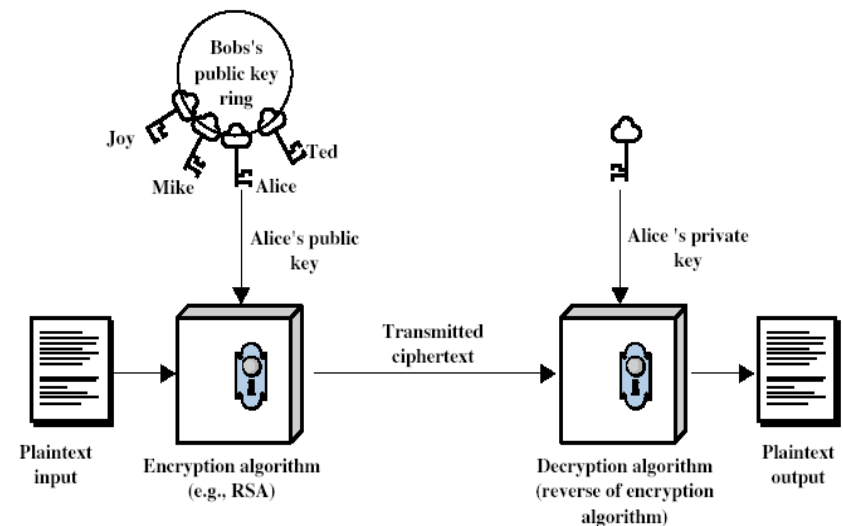
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Public Key Cryptography

Public-Key Cryptography



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Public-Key Characteristics

- Public-Key algorithms rely on two keys with the characteristics that it is:
 - **computationally infeasible to find decryption key knowing only algorithm & encryption key**
 - **computationally easy to en/decrypt messages when the relevant (en/decrypt) key is known**
 - **either of the two related keys can be used for encryption, with the other used for decryption (in some schemes)**
- Public-Key algorithms rely on mathematic functions rather than on permutations and substitutions

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Public-Key Characteristics

- Public key cryptography can do anything secret key cryptography can do, but..
- The known public-key cryptographic algorithms are orders of magnitude slower than the best known secret key cryptographic algorithms
 - **security of public-key algorithms still relies on key size (as for secret-key algorithms)**
 - **are usually only used for things secret key cryptography can't do (or can't do in a suitable way)**
- Often it is mixed with secret key technology
 - **e.g. public key cryptography might be used in the beginning of communication for authentication and to establish a temporary shared secret key used to encrypt the conversation**

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Why Public-Key Cryptography?

- Can be used to:
 - key distribution – **secure communications without having to trust a KDC with your key (key exchange)**
 - digital signatures –**verify a message is come intact from the claimed sender (authentication)**
 - encryption/decryption - **secrecy of the communication (confidentiality)**
- Some algorithms are suitable for all uses, others are specific to one
- Note that public-key cryptography simplifies but not eliminates the problem of trusted systems and key management

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Public-key Cryptography

- Note
 - **All secret key algorithms do the same thing: they take a block and encrypt it in a reversible way; there are chaining method to convert block ciphers into message ciphers**
 - **All the hash algorithms do the same thing: they take a message and perform an irreversible transformation on it**
 - **Instead, public key algorithms look very different**
 - in how they perform their function
 - in what functions they perform
- Example of public key algorithms:
 - **RSA, which does encryption and digital signature**
 - **El Gamal and DSS, which do digital signature but not encryption**
 - **Diffie-Hellman, which allows establishment of a shared secret**
 - **zero knowledge proof systems, which only do authentication**
- They all have in common: a private and a public quantities associated with a principal

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Security of Public Key Schemes

- Like private key schemes brute force **exhaustive search** attack is always theoretically possible
- But keys used are too large (>512bits)
- A crucial feature is that the private key is difficult to determine from the public key
- Security relies on a **large enough** difference in difficulty between **easy** (en/decrypt) and **hard** (cryptanalyse) problems
- More generally the **hard** problem is known, its just made too hard to do in practise
 - requires the use of very large numbers
 - hence is slow compared to private key schemes

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Rivest, Shamir, and Adleman (RSA)

Rivest, Shamir, and Adleman



- by Rivest, Shamir & Adleman of MIT in 1977
- best known & widely used public-key scheme
- Based on exponentiation in a finite (Galois) field over integers modulo n
 - nb. exponentiation takes $O((\log n)^3)$ operations (easy)
- uses large integers (eg. 1024 bits)
- security due to cost of factoring large numbers
 - nb. factorization takes $O(e^{\log n \log \log n})$ operations (hard)
- The key length is variable
 - long keys for enhanced security, or a short keys for efficiency
- The plaintext block size (the chunk to be encrypted) is also variable
 - The plaintext block size must be smaller than the key length
 - The ciphertext block will be the length of the key
- RSA is much slower to compute than popular secret key algorithms like DES and IDEA

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Some Arithmetic

- Relatively prime** - means that two values do not share any common factors other than 1
 - eg. 8 & 15 are relatively prime since factors of 8 are 1,2,4,8 and of 15 are 1,3,5,15 and 1 is the only common factor
- totient function** - $\phi(n)$ - (based on the words total and quotient)
The function tells how many numbers less than n are relatively prime to n ; a.k.a. Euler's totient function
 - to compute $\phi(n)$ need to count number of elements to be excluded
 - e.g. $\phi(8) = |1,3,5,7| = 4$
 - in general need prime factorization, but
 - theo: If n is prime, the all integers less than n (that is: 1, 2, ..., $n-1$) are relatively prime to n . Therefore $\phi(p) = p - 1$
 - e.g. $\phi(37) = 36$
 - theo: If n is the product of two primes (p and q) then there are $(p-1)(q-1)$ numbers relatively prime to that quantity, that is $\phi(n) = \phi(p \cdot q) = (p-1)(q-1)$
 - e.g. $\phi(21) = (3-1) \times (7-1) = 2 \times 6 = 12$

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Some Arithmetic \mathbb{Z}_n

- $a \bmod n = r_a \mid a = q_a \cdot n + r_a$
- $a \equiv b \pmod n$ means that $(a \bmod n) = (b \bmod n)$
 - i.e. $a - b = k \cdot n$
- properties:
 - $a \text{ op } b \bmod n \equiv (a \bmod n) \text{ op } (b \bmod n) = (a \text{ op } b) \bmod n$
 - with op = +, -, *
- Some definitions in arithmetic modulo n
 - complete set of residues is: $0..n-1$
 - reduced set of residues is those numbers (residues) which are relatively prime to n
 - eg for $n=10$, complete set of residues is $\{0,1,2,3,4,5,6,7,8,9\}$
 - reduced set of residues is $\{1,3,7,9\}$
 - number of elements in reduced set of residues is the Euler Totient Function $\phi(n)$

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Some Arithmetic \mathbb{Z}_n

- **Multiplicative inverse** - the multiplicative inverse of a number x is the number we multiply x by to get 1. With real numbers this is just $1/x$ (for all but one case, guess which one that is) For our application we want to find:
 - The multiplicative inverse of $m \bmod n$
 - $u \mid u \cdot m = 1 \bmod n$
 - this means what we want to find a number u so that $u \cdot m = 1 \bmod n$
 - or we can say that $u \cdot m$ differs from 1 by a multiple of n, or $u \cdot m + v \cdot n = 1$
 - Euclid's algorithm can be used to solve this knotty problem. It only works if m and n are relatively prime

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Multiplicative Inverse Example

- Find the inverse of 797 mod 1047?
- That is, find u such that $u \cdot 797 = 1 \bmod 1047$, or $u \cdot 797 + v \cdot 1047 = 1$
- Using Euclid's algorithm
 - we get $u = -490$ and $v = 373$
 - That is: $-490 \cdot 797 + 373 \cdot 1047 = 1$
 - So $(u \cdot m)$ is $-490 \cdot 797 = -390530$
 - The multiplicative inverse (u) is -490
 - $-390530 \bmod 1047 = 1 \bmod 1047$

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Fermat's Theorem

- $a^{p-1} \bmod p = 1$
 - where p is prime, and
 - a is not divisible by p
 - i.e. the greatest common divisor $\gcd(a, p) = 1$

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Euler's Theorem

- A generalisation of Fermat's Theorem
- $a^{\phi(n)} \bmod n = 1$
 - where $\gcd(a, n) = 1$
- eg.
 - $a=3; n=10; \phi(10)=4;$
 - hence $3^4 = 81 = 1 \bmod 10$
 - $a=2; n=11; \phi(11)=10;$
 - hence $2^{10} = 1024 = 1 \bmod 11$

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Euler's Theorem - Corollary

- a Corollary from Euler's Theorem
- $a^{k\phi(n)+1} \bmod n = a$

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RSA Algorithm

- First, you need to generate a public key and a corresponding private key. The scheme is:
 - Choose two large primes p and q (probably around 512 bits each).
 - Multiply them together (result is 1024 bits), and call the result n . The factors p and q will remain secret. (You won't tell anybody, and it's practically impossible to factor numbers that large.)
 - To generate your public key, choose a number e that is relatively prime (that is, it does not share any common factors other than 1) to $\phi(n)$. Since you know p and q , you know $\phi(n)$ -- it's $(p-1)(q-1)$. Your public key is $\langle e, n \rangle$
 - To generate your private key, find the number d that is the multiplicative inverse of $e \bmod \phi(n)$. $\langle d, n \rangle$ is your private key.
 - To encrypt a message m ($< n$), someone using your public key should compute ciphertext $c = m^e \bmod n$
 - Only you will be able to decrypt c , using your private key to compute $m = c^d \bmod n$

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RSA Key Setup

- each user generates a public/private key pair by:
 - selecting two large primes at random - p, q
 - computing their system modulus $N = p \cdot q$
 - note $\phi(N) = (p-1)(q-1)$
 - selecting at random the encryption key e
 - where $1 < e < \phi(N), \gcd(e, \phi(N)) = 1$
 - solve following equation to find decryption key d
 - $e \cdot d = 1 \bmod \phi(N)$ and $0 < d < N$
 - publish their public encryption key: $KU = \{e, N\}$
 - keep secret private decryption key: $KR = \{d, p, q\}$

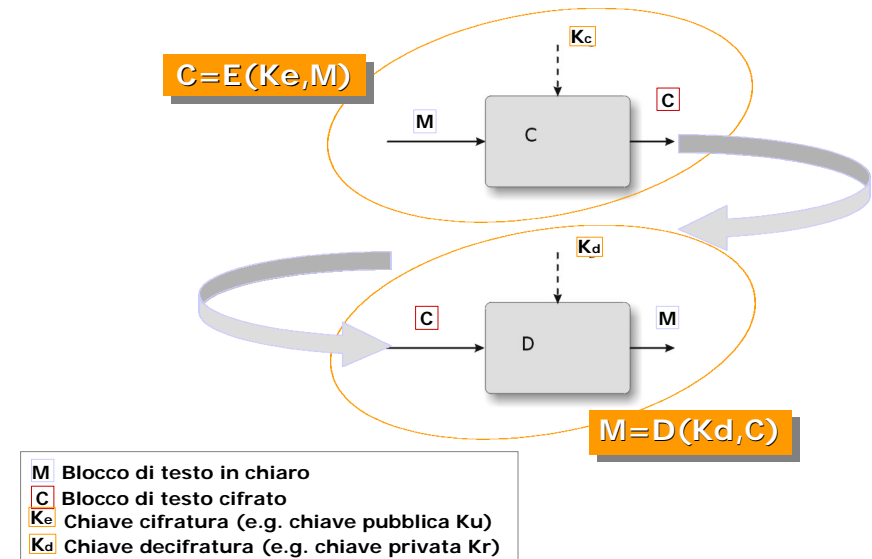
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RSA Use

- to encrypt a message M the sender:
 - obtains public key of recipient $K_U = \{e, N\}$
 - computes: $C = M^e \bmod N$, where $0 < M < N$
- to decrypt the ciphertext C the owner:
 - uses their private key $K_R = \{d, p, q\}$
 - computes: $M = C^d \bmod N$
- note that the message M must be smaller than the modulus N (block if needed)

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RSA



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Why RSA Works

- because of Euler's Theorem:
 - $a^{\phi(n)} \bmod N = 1$
 - where $\gcd(a, N) = 1$
- in RSA have:
 - $N = p \cdot q$
 - $\phi(N) = (p-1)(q-1)$
 - carefully chosen e & d to be inverses mod $\phi(N)$
 - hence $e \cdot d = 1 + k \cdot \phi(N)$ for some k
- hence :

$$C^d = (M^e)^d = M^{1+k\phi(N)} = M^1 \cdot (M^{\phi(N)})^k = M^1 \cdot (1)^k = M^1 = M \bmod N$$

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RSA Example

- Select primes: $p=17$ & $q=11$
- Compute $n = p \cdot q = 17 \times 11 = 187$
- Compute $\phi(n) = (p-1)(q-1) = 16 \times 10 = 160$
- Select $e : \gcd(e, 160) = 1$; choose $e=7$
- Determine $d : d \cdot e = 1 \bmod 160$ and $d < 160$ Value is $d=23$ since $23 \times 7 = 161 = 10 \times 160 + 1$
- Publish public key $K_U = \{7, 187\}$
- Keep secret private key $K_R = \{23, 187\} = \{23, 17, 11\}$

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RSA Example (cont)

RSA encryption/decryption:

- given message $M = 88$ (nb. $88 < 187$)
- encryption:
 $C = 88^7 \bmod 187 = 11$
- decryption:
 $M = 11^{23} \bmod 187 = 88$

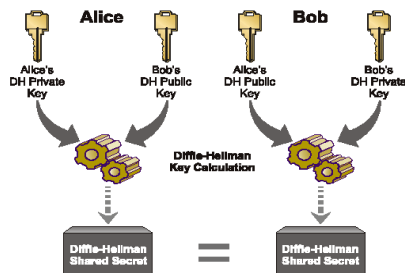
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RSA Security

- three approaches to attacking RSA:
 - **brute force key search** (infeasible given size of numbers)
 - **mathematical attacks** (based on difficulty of computing $\phi(N)$, by factoring modulus N)
 - **timing attacks** (on running of decryption)

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Diffie-Hellman



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Diffie-Hellman

- First public-key type scheme proposed
- by Diffie & Hellman in 1976 along with the exposition of public key concepts
 - **note:** now know that James Ellis (UK CESG) secretly proposed the concept in 1970
 - **predates RSA**
 - **Less general than RSA:** it does neither encryption nor signature
- is a practical method for public exchange of a secret key
 - **allows two individuals to agree on a shared secret (key)**
 - **It is actually used for key establishment**
- used in a number of commercial products

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Diffie-Hellman Setup

- all users agree on global parameters:
 - large prime integer or polynomial p
 - a g primitive root mod p
- each user (eg. A) generates their key
 - chooses a secret key (number): $x_A < p$
 - compute their public key: $y_A = g^{x_A} \bmod p$
- each user makes public that key y_A

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Diffie-Hellman Key Exchange

- shared session key for users A & B is K_{AB} :

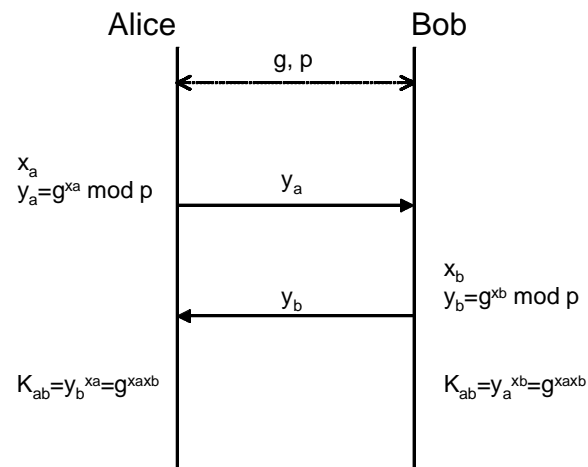
$$K_{AB} = g^{x_A \cdot x_B} \bmod p$$

$$= y_A^{x_B} \bmod p \quad (\text{which B can compute})$$

$$= y_B^{x_A} \bmod p \quad (\text{which A can compute})$$
- K_{AB} is used as session key in private-key encryption scheme between Alice and Bob
- attacker must solve discrete log

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Diffie-Hellman Key Exchange



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Diffie-Hellman Example

- users Alice & Bob who wish to swap keys:
- agree on prime $p=353$ and $g=3$
- select random secret keys:
 - A chooses $x_A=97$, B chooses $x_B=233$
- compute public keys:
 - $y_A = 3^{97} \bmod 353 = 40$ (Alice)
 - $y_B = 3^{233} \bmod 353 = 248$ (Bob)
- compute shared session key as:
 - $K_{AB} = y_B^{x_A} \bmod 353 = 248^{97} = 160$ (Alice)
 - $K_{AB} = y_A^{x_B} \bmod 353 = 40^{233} = 160$ (Bob)

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Zero Knowledge Proof Systems

- Only do authentication
 - **prove that you know a secret without revealing the secret**
- RSA is a zero knowledge system
- There are zero knowledge systems with much higher performance
- Example (Isomorphic graphs):
 - Alice defines two large (say 500 vertices) isomorphic graphs G_A , G_B
 - G_A and G_B become public, but only Alice knows the mapping
 - to prove her identity to Bob, Alice find a set of isomorphic graphs G_1, G_2, \dots, G_k
 - Bob divides the set into two subset T_A and T_B
 - Alice shows to Bob the mapping between each $G_i \in T_A$ and G_A , and between each $G_j \in T_B$ and G_B

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Security uses of public key cryptography

- Transmitting over an insecure channel
 - each party has a <public key, private key> pair (K_u, K_r)
 - each party encrypts with the public key of the other party

$\text{encrypt } m_A \text{ using } K_{u_B} \xrightarrow{\hspace{1cm}} \text{decrypt } m_A \text{ using } K_{r_B}$
 $\text{decrypt } m_B \text{ using } K_{r_A} \xleftarrow{\hspace{1cm}} \text{encrypt } m_B \text{ using } K_{u_A}$
- Secure storage on insecure media
 - **encrypt with public key, decrypt with private key**
 - useful when you can let third party to encrypt data
- Peer Authentication
 - **public key gives the real benefit**
 - no $n(n-1)/2$ keys are needed

$\text{encrypt } r \text{ using } K_{u_B} \xrightarrow{\hspace{1cm}} \text{decrypt to } r \text{ using } K_{r_B}$
 $\xleftarrow{\hspace{1cm}} r$

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Security uses of public key cryptography

- Data authentication (Digital signature)
 - **based on cryptographic checksum**
- Key establishment
 - e.g. **Diffie-Hellman**
- Note
 - **Public key cryptography has specific algorithm for specific function such as**
 - data encryption
 - MAC/digital signature
 - peer authentication
 - key establishment
- Remarks:
 - RSA encryption with the public key of the peer: encrypt
 - RSA encryption with the own private key: authenticate/sign
 - you can use both to ensure encryption and authentication/signature

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Vantaggio dei sistemi a chiave pubblica

- Ogni utente deve mantenere solo un segreto (la propria chiave privata)
- Le chiavi pubbliche degli altri utenti possono essere mantenuti tramite infrastrutture intermedie sicure (PKI)
- Il numero delle chiavi è proporzionale a N per la comunicazione reciproca tra N utenti

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Digital signature and digital certification

Digital Signature

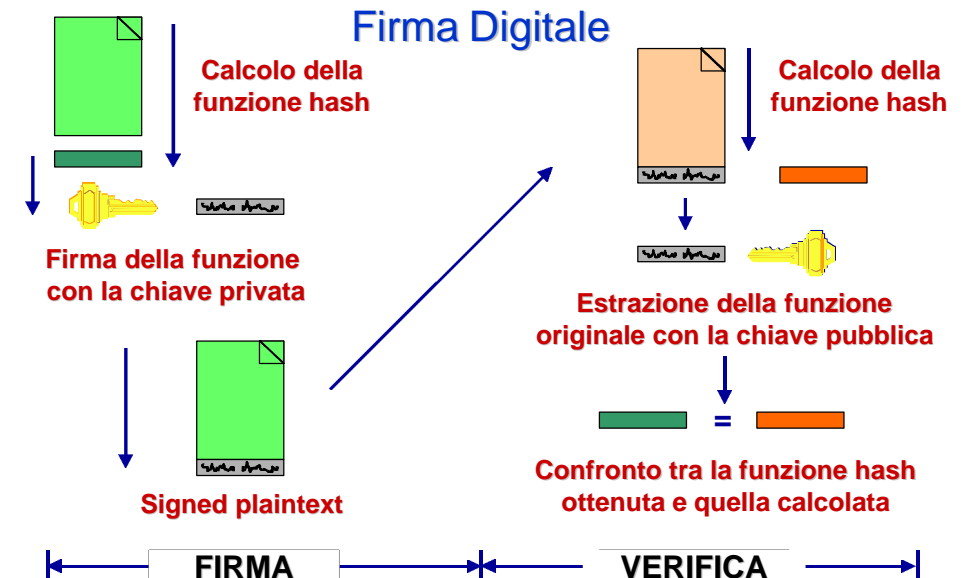
- Digital Signature is an application in which a signer, say "Alice," "signs" a message m in such a way that
 - anyone can "verify" that the message was signed by no one other than Alice, and
 - consequently that the message has not been modified since she signed it
- i.e. the message is a true and correct copy of the original
- The difference between digital signatures and conventional ones is that digital signatures can be mathematically verified
- The typical implementation of digital signature involves a message-digest algorithm and a public-key algorithm for encrypting the message digest (i.e., a message-digest encryption algorithm)

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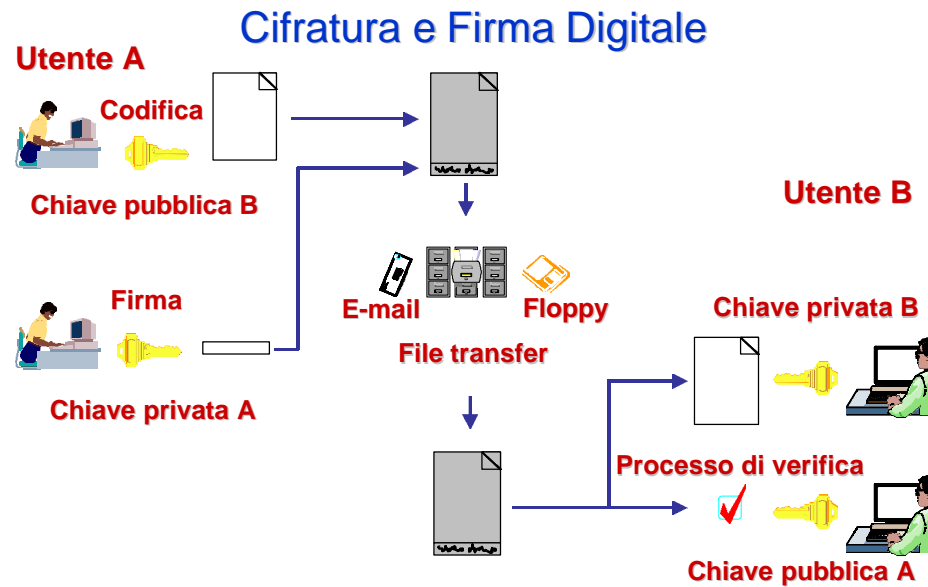
Digital Certification

- Digital certification is an application in which a certification authority "signs" a special message m containing
 - the name of some user, say "Alice," and
 - her public key
 in such a way that anyone can "verify" that the message was signed by no one other than the certification authority and thereby develop trust in Alice's public key
- The typical implementation of digital certification involves a signature algorithm for signing the special message

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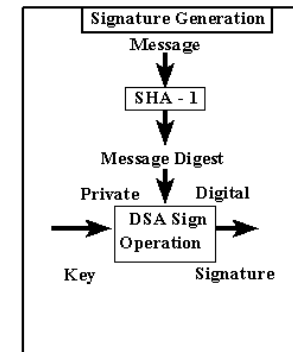


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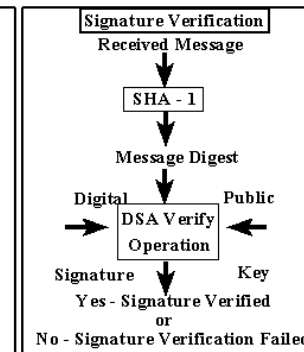
Firma Digitale - DSS/SHS

Digital Signature Standard



Digital Signature Algorithm

Secure Hash Standard



Secure Hash Algorithm