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# Asymmetric Cryptography (Public Key Cryptography)

## Mathematical Foundations

### Fundamental Theorem of Arithmetic and Euler's Totient Function

Asymmetric cryptography relies on solid mathematical foundations from number theory. Two concepts are essential:

**Fundamental Theorem of Arithmetic:** Every positive integer greater than 1 can be written uniquely (up to order) as a product of prime powers:

$$n = p_1^{e_1} \cdot p_2^{e_2} \cdot p_3^{e_3} \cdots p_m^{e_m}$$

**Euler's Totient Function**  $\phi(n)$ : Number of positive integers smaller than  $n$  that are coprime with  $n$ .

To compute  $\phi(n)$ :

$$\phi(n) = \prod_{i=1}^m p_i^{e_i} \cdot \left(1 - \frac{1}{p_i}\right)$$

**Important special case:** If  $n = p \cdot q$  with  $p$  and  $q$  prime, then:

$$\phi(n) = (p-1)(q-1)$$

#### Original Text

### Mathematical Foundations

**Fundamental Theorem of Arithmetic:** Every positive integer  $n$  can be written uniquely (up to order) as a product of powers of distinct prime numbers  $p_i$ :

$$n = p_1^{e_1} \cdot p_2^{e_2} \cdot p_3^{e_3} \cdots p_m^{e_m}$$

**Euler's Totient Function:** Let  $n \in \mathbb{Z}^+$ , the **Euler's totient function**  $\phi(n)$  is equal to the number of positive integers smaller than  $n$  that are **relatively prime** to  $n$ .

**Calculation of Euler's totient function:** According to the fundamental theorem of arithmetic, every integer  $n > 1$  can be written as:

$$n = \prod_{i=1}^m p_i^{e_i}$$

then  $\phi(n)$  is calculated as:

$$\phi(n) = \prod_{i=1}^m (p_i^{e_i} - p_i^{e_i-1})$$

In particular, if  $n = p \cdot q$  with  $p$  and  $q$  prime, then:

$$\phi(n) = (p-1)(q-1)$$

### Quick Revision

- **Unique decomposition:** every integer = product of prime numbers
- $\phi(n)$ : counts integers  $< n$  coprime with  $n$
- **Key for RSA:** if  $n = pq$  (primes) then  $\phi(n) = (p-1)(q-1)$

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## Euler's Theorem and Fermat's Little Theorem

These theorems are at the heart of RSA and other asymmetric algorithms.

**Euler's Theorem:** If  $n \in \mathbb{Z}^+$  and  $a \in \mathbb{Z}$  with  $\gcd(a, n) = 1$ , then:

$$a^{\phi(n)} \equiv 1 \pmod{n}$$

**Fermat's Little Theorem** (special case if  $n = p$  prime): If  $a \in \mathbb{Z}$  and  $p$  prime does not divide  $a$ :

$$a^{p-1} \equiv 1 \pmod{p}$$

### Important applications:

1. **Exponent reduction:** If  $n$  is a product of distinct primes and  $r \equiv s \pmod{\phi(n)}$ , then:

$$a^r \equiv a^s \pmod{n}$$

2. **Calculation of inverses:**  $a^{\phi(n)-1}$  is the inverse of  $a$  modulo  $n$ . In particular, if  $p$  is prime,  $a^{p-2}$  is the inverse of  $a$  modulo  $p$ .

## Original Text

### Mathematical Foundations (II)

**Euler's Theorem:** Let  $n \in \mathbb{Z}^+$  and  $a \in \mathbb{Z}$  with  $\gcd(a, n) = 1$ , then we have:

$$a^{\phi(n)} \equiv 1 \pmod{n}$$

**Fermat's Little Theorem** (special case of Euler's theorem if  $n$  is prime): Let  $a \in \mathbb{Z}$  and  $p$  a prime number such that  $p$  does not divide  $a$ , then we have:

$$a^{p-1} \equiv 1 \pmod{p}$$

Note that since  $p$  is prime, we have  $\phi(p) = p - 1$ .

**Exponent reduction mod  $\phi(n)$ :** If  $n$  is the product of distinct primes and  $r, s \in \mathbb{Z}$  such that  $r \equiv s \pmod{\phi(n)}$  then  $\forall a \in \mathbb{Z}$ :

$$a^r \equiv a^s \pmod{n}$$

**Application of Euler's Theorem to inverse calculation:** From Euler's theorem, we have that:

$$a \cdot a^{\phi(n)-1} \equiv 1 \pmod{n}$$

which means that  $a^{\phi(n)-1}$  is the **inverse of  $a$  modulo  $n$** . In particular,  $a^{p-2}$  is the inverse of  $a$  modulo  $n$  if  $p$  is prime.

## Quick Revision

- **Euler's Theorem:**  $a^{\phi(n)} \equiv 1 \pmod{n}$
- **Fermat:** special case if  $p$  prime:  $a^{p-1} \equiv 1 \pmod{p}$
- **Modular inverse:**  $a^{-1} \equiv a^{\phi(n)-1} \pmod{n}$
- **Base of RSA:** enables encryption/decryption with exponents

---

## Multiplicative Groups and Generators

**Multiplicative group  $\mathbb{Z}_n^*$ :** Set of elements of  $\mathbb{Z}_n$  coprime with  $n$ :

$$\mathbb{Z}_n^* = \{a \in \mathbb{Z}_n \mid \gcd(a, n) = 1\}$$

If  $n$  is prime:  $\mathbb{Z}_n^* = \{1, 2, \dots, n-1\}$

**Order of an element:** Smallest positive integer  $t$  such that  $a^t \equiv 1 \pmod{n}$

**Generator:** An element  $\alpha$  is a generator of  $\mathbb{Z}_n^*$  if its order is  $\phi(n)$ . Then  $\mathbb{Z}_n^*$  is said to be **cyclic**.

**Properties of generators:**

1.  $\mathbb{Z}_n^*$  has a generator iff  $n = 2, 4, p^k$  or  $2p^k$  (with  $p$  prime,  $p \neq 2$  and  $k \geq 1$ )
2. If  $p$  is prime,  $\mathbb{Z}_p^*$  always has a generator
3. If  $\alpha$  is a generator, all elements can be written as:  $\mathbb{Z}_n^* = \{\alpha^i \bmod n \mid 0 \leq i < \phi(n)\}$
4. The number of generators is  $\phi(\phi(n))$

**Generator test**

- $\alpha$  is a generator of  $\mathbb{Z}_n^*$  iff for every prime  $p$  dividing  $\phi(n)$ ,  $\alpha^{\phi(n)/p} \not\equiv 1 \pmod{n}$
- if  $n = 2p + 1$  is a “safe prime” with  $p$  prime:  $\alpha$  is a generator iff  $\alpha^2 \not\equiv 1 \pmod{n}$  and  $\alpha^p \not\equiv 1 \pmod{n}$

**i** Original Text

### Mathematical Foundations (III)

**Definition:** The **multiplicative group of  $\mathbb{Z}_n$** , denoted  $\mathbb{Z}_n^*$  is:

$$\mathbb{Z}_n^* = \{a \in \mathbb{Z}_n \mid \gcd(a, n) = 1\}$$

In particular, if  $n$  is prime:  $\mathbb{Z}_n^* = \{a \mid 1 \leq a \leq n - 1\}$

The **number of elements or order** of the multiplicative group  $\mathbb{Z}_n^*$  is  $\phi(n)$  (by definition of  $\phi$ ).

**Definition:** Let  $a \in \mathbb{Z}_n$ , the **order of  $a$**  is the smallest positive integer  $t$  for which:

$$a^t \equiv 1 \pmod{n}$$

**Definition:** Let  $\alpha \in \mathbb{Z}_n^*$ , if the order of  $\alpha$  is  $\phi(n)$ , then  $\alpha$  is a **generator of  $\mathbb{Z}_n^*$** . When a group  $\mathbb{Z}_n^*$  has a generator, it is said to be **cyclic**.

**Properties of generators:**

- $\mathbb{Z}_n^*$  has a generator iff  $n = 2, 4, p^k$  or  $2p^k$ , with  $p$  prime,  $p \neq 2$  and  $k \geq 1$ . In particular, if  $p$  is prime,  $\mathbb{Z}_p^*$  has a generator.
- If  $\alpha$  is a generator of  $\mathbb{Z}_n^*$ , then all elements of  $\mathbb{Z}_n^*$  can be written as:

$$\mathbb{Z}_n^* = \{\alpha^i \bmod n \mid 0 \leq i \leq \phi(n) - 1\}$$

- The number of generators of  $\mathbb{Z}_n^*$  is  $\phi(\phi(n))$ .

- $\alpha$  is a generator of  $\mathbb{Z}_n^*$  iff for every prime  $p$  dividing  $\phi(n)$ , we have:

$$\alpha^{\phi(n)/p} \not\equiv 1 \pmod{n}$$

In particular if  $n$  is a prime of the form  $n = 2p + 1$  with  $p$  prime (such  $n$  is called a **safe prime**),  $\alpha$  is a generator of  $\mathbb{Z}_n^*$  iff  $\alpha^2 \not\equiv 1 \pmod{n}$  and  $\alpha^p \not\equiv 1 \pmod{n}$ .

### 💡 Quick Revision

- $\mathbb{Z}_n^*$ : elements coprime with  $n$ , cardinality =  $\phi(n)$
- **Generator**: element of order  $\phi(n)$  (generates the entire group)
- **Crucial for DH and ElGamal**: security based on discrete logarithm in cyclic group
- **Safe prime**:  $n = 2p + 1$  with  $p$  and  $n$  prime

## Fast Exponentiation

Efficient computation of  $a^k \bmod n$  in polynomial time, essential for all asymmetric algorithms.

**Principle**: Use the binary representation of the exponent  $k$ .

**Example**: Computation of  $2^{644} \bmod 645$

1. Binary representation:  $(644)_{10} = (1010000100)_2$
2. Compute successive powers of 2 modulo 645:
  - $2^1 \bmod 645$
  - $2^2 \bmod 645$
  - $2^4 \bmod 645$
  - $2^8 \bmod 645$
  - ...
  - $2^{512} \bmod 645$
3. Combine according to bits set to 1:  $2^{644} = 2^{512} \cdot 2^{128} \cdot 2^4$

**Complexity**:  $O(\log^3 n)$  - very efficient!

**Application**: Computation of the inverse using Euler's theorem in polynomial time.

Alternative: **Extended Euclidean algorithm** to find  $x$  such that  $ax \equiv 1 \pmod{n}$  by solving  $ax - kn = 1 = \gcd(a, n)$ . Complexity also  $O(\log^3 n)$ .

## Original Text

### Fast Exponentiation

**Fast exponentiation:** Using the binary representation of a number, we can compute powers very efficiently.

**Example:** computation of  $2^{644} \bmod 645$

$$(644)_{10} = (1010000100)_2$$

Now, we compute the exponents corresponding to the powers of 2, namely:

$$2^1 \bmod 645, \quad 2^2 \bmod 645, \quad 2^4 \bmod 645, \quad \dots, \quad 2^{512} \bmod 645$$

From the binary representation, we compute:

$$2^{644} = 2^{512+128+4} = 2^{512} \cdot 2^{128} \cdot 2^4 = 160 \cdot 153 \cdot 6 \bmod 645$$

**The complexity of this algorithm** fast exponentiation is  $O(\log^3 n)$ .

By relying on **Euler's theorem**, the computation of the **inverse of a number** in such a group is therefore performed in polynomial time.

**The extended Euclidean algorithm** can also be used to find an  $x$  such that:

$$ax \equiv 1 \pmod{n}$$

since this congruence can be written as:  $ax - 1 = kn$  and therefore:

$$ax - kn = 1 = \gcd(a, n)$$

The complexity of this algorithm is also  $O(\log^3 n)$ .

## Quick Revision

- **Idea:** binary representation of the exponent
- **Complexity:**  $O(\log^3 n)$  - polynomial!
- **Essential:** makes RSA, ElGamal, DH practical
- **Alternative:** extended Euclidean algorithm for inverses

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## Chinese Remainder Theorem (CRT)

The CRT allows solving systems of simultaneous congruences, with important applications in cryptography.

**Theorem:** Let  $n_1, n_2, \dots, n_t \in \mathbb{Z}^+$  pairwise coprime ( $\gcd(n_i, n_j) = 1$  if  $i \neq j$ ) and  $a_1, a_2, \dots, a_t \in \mathbb{Z}$ . Then the system:

$$\begin{cases} x \equiv a_1 \pmod{n_1} \\ x \equiv a_2 \pmod{n_2} \\ \vdots \\ x \equiv a_t \pmod{n_t} \end{cases}$$

has a unique solution  $x \bmod N$  with  $N := n_1 \cdot n_2 \cdots n_t$ .

**Gauss's algorithm** (1801) to compute  $x$ :

$$x = \sum_{i=1}^t a_i N_i M_i \bmod N$$

with:

- $N_i = N/n_i$
- $M_i = N_i^{-1} \bmod n_i$  (modular inverse)

**Complexity:**  $O(\log^3 n)$  - polynomial!

**Cryptographic applications:**

1. Acceleration of RSA computations (use  $p$  and  $q$  separately)
2. Secret sharing (secret sharing schemes)
3. Certain attacks on RSA (if small exponent and multiple messages)

#### Original Text

##### **Chinese Remainder Theorem**

The **Chinese Remainder Theorem** (3rd century!) allows solving linear systems of simultaneous congruences. It solves problems raised in ancient Chinese puzzles. It was, for example, about finding a number that produces a remainder of 1 when divided by 3, of 2 when divided by 5 and of 3 when divided by 7... It was also used to calculate the exact moment of alignment of several celestial bodies having different orbits (and therefore periods).

**Chinese Remainder Theorem:** Let  $n_1, n_2, \dots, n_t \in \mathbb{Z}^+$  be pairwise coprime (i.e.,  $\gcd(n_i, n_j) = 1, \forall i \neq j$ ) and  $a_1, a_2, \dots, a_t \in \mathbb{Z}$ . Then, the system of congruences:



$$\begin{cases} x \equiv a_1 \pmod{n_1} \\ x \equiv a_2 \pmod{n_2} \\ \vdots \\ x \equiv a_t \pmod{n_t} \end{cases}$$

has a unique solution  $x \pmod{N := n_1 n_2 \cdots n_t}$

**Gauss's algorithm** (1801) for the computation of  $x$ :

$$x = \sum_{i=1}^t a_i N_i M_i \pmod{N}$$

with  $N_i = N/n_i$  and  $M_i = N_i^{-1} \pmod{n_i}$ .

The **complexity** of this algorithm is  $O(\log^3 n)$ .

It is therefore possible in **polynomial time** to go from congruences mod  $n_i$  to congruences mod  $N$ !

### 💡 Quick Revision

- **Solves:** systems of congruences with pairwise coprime moduli
- **Unique solution:** modulo product of moduli
- **Complexity:**  $O(\log^3 n)$  (polynomial)
- **Crypto usage:** RSA optimization, attacks if small exponent

## Basic Problems and Complexity

### Classification of Hard Problems

The security of asymmetric cryptography relies on mathematical problems reputed to be hard:

**Generic problems:**

1. **Factorization (FACTP):** Given  $n$ , find its factorization into prime numbers
  - Base of **RSA** and **Rabin**
2. **Discrete Logarithms (DLP):** Given prime  $p$ , a generator  $\alpha \in \mathbb{Z}_p^*$  and  $\beta \in \mathbb{Z}_p^*$ , find  $x$  such that:

$$\alpha^x \equiv \beta \pmod{p}$$

- Base of **ElGamal** and **Diffie-Hellman**

3. **Square Root modulo composite (SQROOTP)**: Given composite  $n$  and a quadratic residue  $a$ , find  $\sqrt{a} \bmod n$ 
  - Base of **Rabin**

**Specific problems:**

1. **RSA Problem (RSAP)**: Given  $n = pq$ ,  $e$  with  $\gcd(e, \phi(n)) = 1$  and  $c$ , find  $m$  such that  $m^e \equiv c \pmod{n}$
2. **Diffie-Hellman Problem (DHP)**: Given prime  $p$ , generator  $\alpha$ ,  $\alpha^a \bmod p$  and  $\alpha^b \bmod p$ , find  $\alpha^{ab} \bmod p$

**Proven equivalences:**

- **DHP** **DLP** (equivalent under certain conditions)
- **RSAP** **FACTP** (proven equivalent for the generic case)
- **SQROOTP** **FACTP**

**i** Original Text

### Basic Problems

**Main generic problems:**

- **Factorization (FACTP)**: Given a positive integer  $n$ , find its factorization into prime numbers.
- **Discrete Logarithms (DLP)**: Given a prime number  $p$ , a generator  $\alpha \in \mathbb{Z}_p^*$  and an element  $\beta \in \mathbb{Z}_p^*$ , find the integer  $x$ ,  $0 \leq x \leq p-2$ , such that:  $\alpha^x \equiv \beta \pmod{p}$ .
- **Square Root in  $\mathbb{Z}_n$  if  $n$  is composite (SQROOTP)**: Given a composite integer  $n$  and a quadratic residue  $a$ , find the square root of  $a \bmod n$ .

**Specific problems** (proper to an encryption system):

- **RSA (RSAP)**: Given a positive integer  $n = pq$ , a positive integer  $e$  with  $\gcd(e, (p-1)(q-1)) = 1$  and an integer  $c$ , find an integer  $m$  with  $m^e \equiv c \pmod{n}$ .
- **Diffie-Hellman (DHP)**: Given a prime number  $p$ , a generator  $\alpha \in \mathbb{Z}_p^*$  and the elements  $\alpha^a \bmod p$  and  $\alpha^b \bmod p$ , find  $\alpha^{ab} \bmod p$ .

**Proven results:**

- **DHP** **DLP** (Equivalent under certain conditions)
- **RSAP** **FACTP** (Proven equivalent for the generic problem)
- **SQROOTP** **FACTP**

### 💡 Quick Revision

- **FACTP**: factor  $n \rightarrow$  base of RSA/Rabin
- **DLP**: find discrete logarithm  $\rightarrow$  base ElGamal/DH
- **SQROOTP**: square root mod composite  $\rightarrow$  Rabin
- **Equivalences**: breaking = solving the base problem

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## Factorization Techniques

The security of RSA depends on the difficulty of factoring large numbers.

**Exponential time methods:**  $O(\exp(c \cdot \ln(n)))$

- Trial Division (successive division)
- Sieve of Eratosthenes (2nd century BC)
- Fermat's Method (~1650)
- Pollard's  $\rho$  Method (1975)
- Pollard's  $p - 1$  Method (1974)

**Sub-exponential time methods:**  $O(\exp(c \cdot (\ln(n))^{1/3}))$

- Continued Fractions (1975)
- **Quadratic Sieve (1981)** - very effective in practice
- **Number Field Sieve - NFS (1990)** - currently the fastest
- General Number Field Sieve - GNFS (2006)

**Polynomial time methods:**

- **Shor's Algorithm** (1994):  $O(\log^c n)$  on **quantum computer**

**Current records (2020):**

- Largest number factored: **RSA-829** (250 digits, 829 bits)
- Computation time: 2700 core-years (Intel Xeon Gold 6130 CPUs)
- Method: General Number Field Sieve

**Implications:**

- RSA keys  $< 1024$  bits: **vulnerable**
- RSA keys 1024 bits: **limits** (states with significant resources)
- Recommendation: **2048 bits minimum** (3072-4096 for long term)

## Original Text

### Classical Factoring Techniques and New Developments

**Exponential time:**  $O(\exp(c \cdot \ln(n)))$

- Trial Division
- Eratosthenes' Sieve (II B.C.)
- Fermat's Difference of Squares Method (~1650)
- Square Form Factorization (1971)
- Pollard's p-1 method (1974)
- Pollard's Rho Method (1975)

**Sub-exponential time:**  $O(\exp(c \cdot (\ln(n))^{1/3}))$

- Continued Fractions (1975)
- **Quadratic Sieve (1981)**
- **Number Field Sieve - NFS (1990)**
- **General Number Field Sieve - GNFS (2006)**

**Polynomial time:**

- **Shor's Algorithm in a Quantum Computer (1994):**  $O(\log^c n)$

**Recent developments:**

- Bernstein's specific NFS computer to factor a 1536-bit number would take the same time as a 512-bit computation on a conventional machine
- **Largest factorization to date (2020):** RSA-829 (250-digit number) using NFS
- Total computation time: **2700 core-years** (Intel Xeon Gold 6130 CPUs at 2.1GHz)

**Factorization on quantum computer:**

- Significant problems (errors, dispersion, etc.)
- 2001: 7-qubit computer (IBM Almaden)
- Feasibility of a computer with millions of qubits... ?

## Quick Revision

- **Sub-exponential:** NFS currently the fastest
- **Record 2020:** RSA-829 (829 bits) in 2700 core-years
- **Recommendation:** keys 2048 bits for RSA
- **Future threat:** quantum computers (Shor)

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## The RSA Algorithm

### RSA Operation (Encryption/Decryption)

RSA (Rivest-Shamir-Adleman, 1978) is the most used asymmetric algorithm.

#### Key generation:

1. Choose two **large** prime numbers  $p$  and  $q$  ( 1024 bits each)
2. Compute  $n := p \cdot q$  and  $\phi(n) = (p - 1)(q - 1)$
3. Choose encryption exponent  $e$  with:
  - $1 < e < \phi(n)$
  - $\gcd(e, \phi(n)) = 1$
4. Compute decryption exponent  $d$  such that:

$$e \cdot d \equiv 1 \pmod{\phi(n)}$$

(using extended Euclidean algorithm or fast exponentiation)

#### Resulting keys:

- **Public** key:  $(n, e)$
- **Private** key:  $d$  (keep  $p$  and  $q$  secret too!)

#### Encryption (by Bob, to Alice):

1. Obtain authentic public key  $(n, e)$  of Alice
2. Transform plaintext into integers  $m_i \in [0, n - 1]$
3. Compute ciphertexts:  $c_i := m_i^e \bmod n$
4. Send the  $c_i$  to Alice

#### Decryption (by Alice):

- Use private key  $d$  to compute:

$$m_i = c_i^d \bmod n$$

#### Proof of operation:

$$c^d \equiv (m^e)^d \equiv m^{ed} \pmod{n}$$

Since  $ed \equiv 1 \pmod{\phi(n)}$ , there exists  $k$  such that  $ed = 1 + k\phi(n)$ , therefore:

$$c^d \equiv m^{1+k\phi(n)} \equiv m \cdot (m^{\phi(n)})^k \equiv m \cdot 1^k \equiv m \pmod{n}$$

(by Euler's theorem)

## Original Text

### RSA Encryption/Decryption Procedure and Proof

#### Key generation:

- Each entity (A) creates a key pair (public and private) as follows:
  - A chooses the size of the modulus  $n$  (e.g.,  $\text{size}(n) = 1024$  or  $\text{size}(n) = 2048$ ).
  - A generates two prime numbers  $p$  and  $q$  of large size ( $n/2$ ).
  - A computes  $n := pq$  and  $\phi(n) = (p-1)(q-1)$ .
  - A generates the encryption exponent  $e$ , with  $1 < e < \phi(n)$  such that  $\gcd(e, \phi(n)) = 1$ .
  - A computes the decryption exponent  $d$ , such that:  $ed \equiv 1 \pmod{\phi(n)}$  using the extended Euclidean algorithm or fast exponentiation.
- The pair  $(n, e)$  is A's **public** key;  $d$  is A's **private** key.

#### Encryption:

- Entity B obtains  $(n, e)$ , the **authentic** public key of A.
- B transforms its plaintext into a series of integers  $m_i$ , such that  $m_i \in [0, n-1] \forall i$ .
- B computes the ciphertext  $c_i := m_i^e \bmod n$ ,  $\forall i$  using fast exponentiation.
- B sends to A all the ciphertexts  $c_i$ .

#### Decryption:

- A uses its private key to compute the plaintexts  $m_i = c_i^d \bmod n$ .

**Proof:** Let  $m$  be the plaintext and  $c$  the ciphertext with  $c := m^e \bmod n$ , we need to prove:  $m \stackrel{!}{=} c^d \bmod n$

Substituting  $c$  by its value we obtain:

$$c^d \bmod n = m^{ed} \bmod n \quad (*)$$

but, we know that:

$$ed \equiv 1 \pmod{\phi(n)}$$

and therefore by definition of congruences, there exists an integer  $k$  with:

$$ed - 1 = k\phi(n)$$

substituting in (\*):

$$c^d \equiv m^{k\phi(n)+1} \equiv m^{k\phi(n)} \cdot m \pmod{n}$$

If  $\gcd(m, n) = 1$ , we have by **Euler's theorem**:

$$m^{\phi(n)} \equiv 1 \pmod{n}$$

therefore:

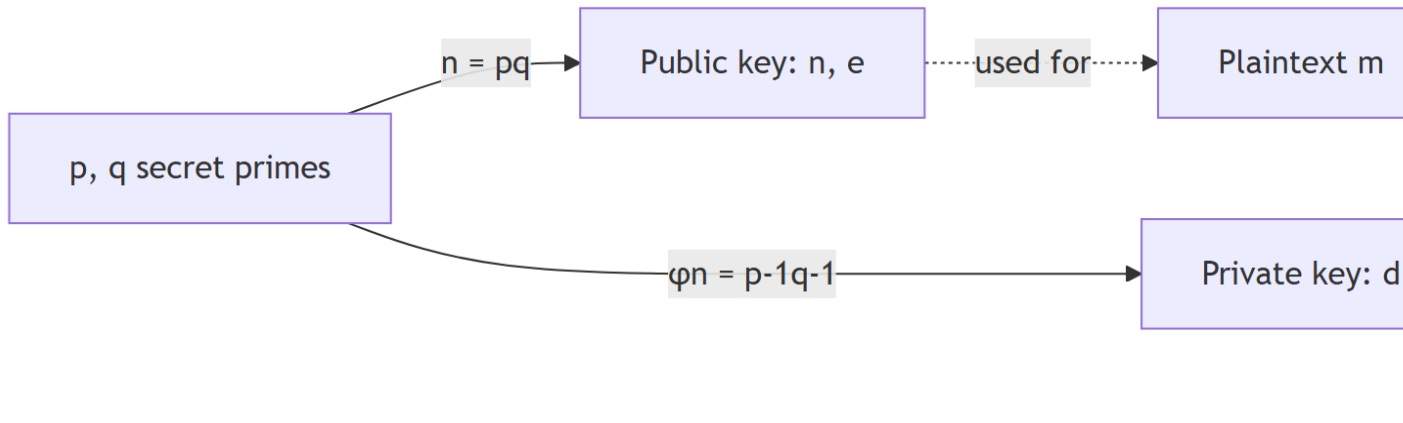
$$c^d \equiv (m^{\phi(n)})^k \cdot m \equiv m \pmod{n}$$

Q.E.D. !

If  $\gcd(m, n) \neq 1$ ,  $m$  is necessarily a multiple of  $p$  or  $q$  (very unlikely case...), we can show by doing the calculations mod  $p$  and mod  $q$  that the congruence remains true.

### 💡 Quick Revision

- **Public key:**  $(n, e)$  with  $n = pq$
- **Private key:**  $d$  such that  $ed \equiv 1 \pmod{\phi(n)}$
- **Encryption:**  $c = m^e \pmod{n}$
- **Decryption:**  $m = c^d \pmod{n}$
- **Security:** based on difficulty of factoring  $n$



## RSA Security

Equivalence RSA problem    **Factorization:**

- Finding  $d$     factoring  $n$  (proven equivalent)
- Decrypting without  $d$  is **not proven** as hard as factoring, but...
- No method faster than factoring is known

### Factorization complexity:

- Fastest methods:  $O(\exp(c \cdot (\ln(n))^{1/3}))$  (sub-exponential)
- Computationally impossible for  $n \geq 1024$  bits
- **Current recommendation:** 2048 bits minimum (3072-4096 for long-term security)

### Choice of exponents:

- **Encryption exponent  $e$ :**
  - Often **small** for speed:  $e = 3, 17, 65537$  (common)
  - Caution: if  $e$  too small AND  $m < n^{1/e}$ , attack possible ( $e$ -th root in  $\mathbb{Z}$ )
  - Solution: **randomization** (padding) of the message
- **Decryption exponent  $d$ :**
  - Must be **large**: at least half the size of  $n$
  - If  $d$  small: vulnerable to Wiener's attack

### Performance consequence:

- **Fast encryption** ( $e$  small)
- **Slow decryption** ( $d$  large)

#### Original Text

#### **RSA: Security**

The **RSAP** problem of finding  $m$  from  $c$  is not proven to be as hard as factorization but...:

- We can prove that if we find  $d$  we can easily compute  $p$  and  $q$ . This is equivalent to saying that **factoring  $n$  and finding  $d$  require equivalent computational effort**.
- We know that the fastest methods for factoring have a **sub-exponential complexity**  $O(\exp(c \cdot (\ln(n))^{1/3}))$ . The problem therefore remains **computationally impossible** for modulus  $\geq 1048$  bits (2048 bits is a frequent choice for long-term security...).
- To improve encryption speed, we tend to choose **relatively small exponents  $e$**  (typically:  $e := 3$ ,  $e := 17$  and  $e := 19$ ). However, it has been proven that computing an  $i$ -th root (with small  $i$ ) modulo a composite  $n$  can be significantly easier than factoring  $n$ . On the other hand, in 2008 it was proven that the generic RSA problem is equivalent to factorization.
- The **decryption exponent  $d$  must imperatively be large** (at least half the size



of  $n$ ) to guarantee the system's security.

- Consequently, **encryption is normally significantly faster than decryption** since the exponents used are much smaller!

#### 💡 Quick Revision

- **Security:** based on difficulty of FACTP (factorization)
- **Recommended size:**  $n \geq 2048$  bits
- **Small  $e$ :** fast encryption (3, 17, 65537)
- **Large  $d$ :** at least  $\text{size}(n)/2$
- **Separate keys:** encryption    signature

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## Attacks on RSA

### Attack on small exponent with same message

If the same message  $m$  is sent to 3 recipients with  $e = 3$ :

- $c_1 \equiv m^3 \pmod{n_1}$
- $c_2 \equiv m^3 \pmod{n_2}$
- $c_3 \equiv m^3 \pmod{n_3}$

The **Chinese Remainder Theorem** gives a unique solution  $x \pmod{n_1 n_2 n_3}$  such that:

$$x \equiv c_1 \pmod{n_1}, \quad x \equiv c_2 \pmod{n_2}, \quad x \equiv c_3 \pmod{n_3}$$

If  $m^3 < n_1 n_2 n_3$  (often true), then  $x = m^3$  in  $\mathbb{Z}$  and we can compute  $m$  by simply taking the integer cube root!

**Protection:** always randomize the message before encryption (OAEP padding)

### Attack if message small

If  $m < n^{1/e}$ , then  $m^e < n$ , so  $c = m^e$  (in  $\mathbb{Z}$ , not modulo). We can directly compute the  $e$ -th root!

**Protection:** padding mandatory

## Multiplicative property

$$E(m_1) \cdot E(m_2) \equiv (m_1 \cdot m_2)^e \equiv E(m_1 \cdot m_2) \pmod{n}$$

Allows chosen-ciphertext attacks and blind signatures.

## General attack

The most effective method remains **factoring**  $n$  (if parameters well chosen and implementation correct).

### Original Text

#### RSA: Attacks

When we want to encrypt the **same message for a group of correspondents**, it is advisable to introduce variations (**randomization**) before encryption to avoid the following attack:

Assume we compute ciphertexts  $c_1, c_2, c_3$  from the same plaintext  $m$  and the same exponent  $e := 3$  addressed to three entities with modulus:  $n_1, n_2, n_3$ .

The **Chinese Remainder Theorem** tells us that there exists a solution  $x \pmod{n_1 n_2 n_3}$ , such that:

$$x \equiv c_1 \pmod{n_1}, \quad x \equiv c_2 \pmod{n_2}, \quad x \equiv c_3 \pmod{n_3}$$

But if  $m$  does not change for the three encryptions, we have that  $x = m^3 \pmod{n_1 n_2 n_3}$  and, moreover:  $m^3 < n_1 n_2 n_3$ . We can, therefore, find  $m$  by computing the **integer cube root** of  $m^3$ , knowing that for this calculation there exist efficient algorithms!

More generally, if  $m < n^{1/e}$ , we can apply fast algorithms (in  $\mathbb{Z}$ ) to compute the  $e$ -th roots of  $m^e$ . It is therefore advisable to perform **“randomization” of  $m$  before encrypting!**

**The multiplicative property of RSA:**  $(m_1 m_2)^e \equiv m_1^e \cdot m_2^e \equiv c_1 \cdot c_2 \pmod{n}$

gives rise to **dangerous vulnerabilities** (see blind signatures).

Assuming parameters are correctly chosen and the implementation has no flaws, **the most effective method to “break” the generic RSA algorithm remains factoring  $n$ .**

### Quick Revision

- **Same message, small  $e$ :** CRT allows extracting  $m$ !
- **Message too small:**  $m < n^{1/e} \rightarrow$  direct root
- **Multiplicative property:**  $E(m_1) \cdot E(m_2) = E(m_1 m_2)$
- **Protection:** always padding/randomization (OAEP)

## The ElGamal Algorithm

Asymmetric system (1985) based on the **discrete logarithm problem (DLP)**.

**Keys:**

- Choose prime  $p$ , generator  $\alpha \in \mathbb{Z}_p^*$ , secret  $a$
- Compute  $y = \alpha^a \bmod p$
- **Public:**  $(p, \alpha, y)$  | **Private:**  $a$

**Encryption:** For message  $m$ , choose unique random  $k$

- $\gamma = \alpha^k \bmod p$
- $\delta = m \cdot y^k \bmod p$
- Send  $(\gamma, \delta)$

**Decryption:**  $m = \delta \cdot \gamma^{-a} \bmod p$

**i** Original Text

### ElGamal Encryption/Decryption Procedure

#### Key generation

Each entity (A) creates a key pair (public and private) as follows:

- A generates a prime number  $p$  ( $\text{len}(p) = 1024$  bits) and a **generator**  $\alpha$  of the multiplicative group  $\mathbb{Z}_p^*$
- A generates a random number  $a$ , such that  $1 \leq a \leq p-2$  and computes  $y := \alpha^a \bmod p$
- The **public key** of A is  $(p, \alpha, y)$ , the **private key** of A is  $a$

#### Encryption

- Entity B obtains  $(p, \alpha, \alpha^a \bmod p)$ , the authentic public key of A
- B transforms its plaintext into a series of integers  $m_i$ , such that  $m_i \in [0, p-1] \forall i$
- For each message  $m_i$ :
  - B generates a **unique** random number  $k$ , such that  $1 \leq k \leq p-2$
  - B computes  $\gamma := \alpha^k \bmod p$  and  $\delta := m_i \cdot (\alpha^a)^k \bmod p$  and sends the ciphertext  $c := (\gamma, \delta)$

#### Decryption

- A uses its private key  $a$  to compute  $\gamma^{p-1-a} \bmod p$  (note that:  $\gamma^{p-1-a} \equiv \gamma^{-a} \equiv \alpha^{-ak} \bmod p$ )
- A retrieves the plaintext by computing:  $\delta \cdot \gamma^{-ak} \bmod p$

### 💡 Quick Revision

**Base:** DLP in  $\mathbb{Z}_p^*$

**Ciphertext:**  $(\alpha^k, m \cdot y^k)$

**Security:**  $k$  must be unique and large

**Disadvantage:** doubles message size

### Essential Remarks

- **Proof:**  $\delta \cdot \gamma^{-a} = m \cdot (\alpha^a)^k \cdot (\alpha^k)^{-a} = m \bmod p$
- **Security:** based on DLP (complexity sub-exponential close to factorization)
- **Exponents:**  $k$  and  $a$  must be large (otherwise vulnerable to baby-step giant-step)
- **Reuse prohibited:** if  $k$  repeated,  $\delta_1/\delta_2 = m_1/m_2$  reveals the messages
- **Major disadvantage:**  $\times 2$  expansion of ciphertext size
- **Generalization:** works on  $GF(2^n)$  or elliptic curves

### i Original Text - Remarks

**Proof** that the scheme works: If  $s \equiv k^{-1}(m_h - ar) \bmod (p-1)$ , we have that:  $m_h \equiv (ar + ks) \bmod (p-1)$  and  $v_2 = \alpha^{H(m)} \bmod p$ . If, as we wish to show  $m_h = H(m)$ , by reducing exponents  $\bmod (p-1)$ , we can rewrite  $v_2$ :  $v_2 \equiv \alpha^{ar+ks} \bmod p$ . On the other hand:  $v_1 = y^r \alpha^{rs} \equiv \alpha^{ar} \alpha^{ks} \equiv \alpha^{ar+ks} \bmod p$ .

The ElGamal procedure is based on the difficulty of computing **discrete logarithms modulo a prime number** (DLP problem) even though it has not been proven to be strictly equivalent to this problem.

The **most efficient algorithms** known have a sub-exponential complexity very close to that of factorization (we often use the same algorithms).

The **chosen exponents** ( $k, a$ ) must be large because there exist efficient algorithms to compute discrete logarithms modulo a prime number when the exponent is small (baby-step giant-step algorithm).

A **disadvantage of ElGamal** is that it multiplies the ciphertext length by 2.

It is **essential** for the security of the procedure that the random number  $k$  is not repeated, otherwise: let  $(\gamma_1, \delta_1)$  and  $(\gamma_2, \delta_2)$  be the two generated ciphertexts, we have that  $\delta_1/\delta_2 = m_1/m_2$  and consequently, it is trivial to recover one plaintext from the other. The ElGamal procedure can be **generalized** to other groups like  $GF(2^n)$  or elliptic curves.

### 💡 Quick Revision - Remarks

**Equivalence:** based on DLP (not proven equivalent)

**$k$  unique:** CRITICAL - otherwise  $m_1/m_2$  revealed

**Key size:** large exponents necessary

**Extensions:**  $GF(2^n)$ , elliptic curves

## Rabin Algorithm

Asymmetric system **equivalent to factorization** (provably secure).

**Keys:**

- Generate two primes  $p, q$  ( 1024 bits total), compute  $n = pq$ 
  - **Public:**  $n$
  - **Private:**  $(p, q)$

**Encryption:**  $c = m^2 \bmod n$

**Decryption:**

- Compute the 4 square roots of  $c \bmod n$  (via roots mod  $p$  and mod  $q$ )
- Identify the correct message by redundancy

### i Original Text

## Rabin Encryption/Decryption Procedure

### Key generation

Each entity (A) creates a key pair (public and private) as follows:

- A generates two random prime numbers  $p$  and  $q$  of large size ( $\text{len}(pq) = 1024$ )
- A computes  $n := pq$
- The **public key** of A is  $n$ , the **private key** of A is  $(p, q)$

### Encryption

- Entity B obtains  $n$ , the authentic public key of A
- B transforms its plaintext into a series of integers  $m_i$ , such that  $m_i \in [0, n - 1] \forall i$
- B computes  $c_i = m_i^2 \bmod n$  for each message  $m_i$
- B sends all the ciphertexts  $c_i$  to A

## Decryption

- A uses its private key  $(p, q)$  to retrieve the **4 solutions** of the equation:  $c_i = x^2 \bmod n$  using **efficient algorithms** to compute square roots mod  $p$  and mod  $q$
- A determines either by an **additional indication** from B, or by **redundancy analysis** which of the 4 messages  $m_1, m_2, m_3, m_4$  is the original plaintext

## 💡 Quick Revision

**Base:** SQROOTP (square root mod composite)

**Advantage:** proven equivalent to factorization

**Problem:** 4 possible solutions, requires redundancy

**Vulnerability:** chosen-ciphertext attack reveals factors

## Essential Remarks

- **Proven security:** SQROOTP = FACTP (only algorithm with proven equivalence)
- **Chosen-ciphertext attack:** if A decrypts  $c = m^2 \bmod n$  chosen by adversary M
  - M receives a root  $m_x$  among 4 possible
  - If  $m \neq m_x \bmod n$  (prob. 0.5), then  $\gcd(m - m_x, n)$  gives a factor of  $n$
- **Solution:** require sufficient redundancy to identify unique solution without ambiguity

## i Original Text - Remarks

The Rabin procedure is based on the **impossibility of finding square roots modulo a composite of unknown factorization** (SQROOTP problem).

The **main interest** of this algorithm lies in the fact that it has been **proven to be equivalent to factorization** (SQROOTP = FACTP). This algorithm therefore belongs to the **provably secure** category for any passive attack.

**Active attacks** can, in some cases, compromise the algorithm's security. More precisely, if we mount the following **chosen ciphertext** attack:

- The attacker M generates an  $m$  and sends to A the ciphertext  $c = m^2 \bmod n$ .
- A responds with a root  $m_x$  among the 4 possible  $m_1, m_2, m_3, m_4$ .
- If  $m \neq m_x \bmod n$  (probability 0.5), M repeats with a new  $m$ .
- Otherwise, A computes  $\gcd(m - m_x, n)$  and thus obtains one of the two factors of  $n$ .

This attack could be **avoided** if the procedure required **sufficient redundancy** in the plaintexts allowing A to identify without ambiguity which of the possible solutions is the

original plaintext. In this case, A would always respond with  $m$  and discard the other solutions that do not have the predefined level of redundancy.

#### 💡 Quick Revision - Remarks

**Unique:** only algorithm proven equivalent to FACTP

**Attack:** chosen-ciphertext gives factors (prob. 0.5)

**Countermeasure:** mandatory redundancy in messages

### Comparison RSA - ElGamal - Rabin

Criterion	RSA	ElGamal	Rabin
<b>Problem</b>	RSAP	DLP	SQROOTP
<b>Security</b>	Equiv. factorization (generic case)	Based on DLP	<b>Proven</b> factorization
<b>Expansion</b>	1:1	<b>1:2</b>	1:1
<b>Decryption</b>	Deterministic	Deterministic	<b>4 solutions</b>
<b>Signature</b>	Yes	Yes	Yes (with precautions)

### Elliptic Curves (Basic Idea)

#### Fundamental Concept

An **elliptic curve**  $E$  is defined by:  $y^2 = x^3 + ax + b$  (with discriminant  $4a^3 + 27b^2 \neq 0$ ).

#### Key operation: Point addition

- Geometrically: draw a line between two points  $P$  and  $Q$ , find the 3rd intersection point, then take its symmetric
- Forms a **commutative group** with point at infinity  $\mathcal{O}$  as identity
- **Scalar multiplication:**  $kP = P + P + \dots + P$  ( $k$  times)

#### Cryptographic advantage:

- The **ECDLP problem**: finding  $k$  such that  $Q = kP$  is very difficult (exponential effort)
- **Shorter keys** for same security as in  $\mathbb{Z}_p^*$

#### Original Text - Definition

An **elliptic curve** is a set of points  $E$  defined by the equation:  $y^2 = x^3 + ax + b$ , with  $x, y, a$  and  $b$  rational numbers, integers or integers modulo  $m$  ( $m > 1$ ). The set  $E$  also contains a “point at infinity” denoted  $\mathcal{O}$ . The point  $\mathcal{O}$  is not on the curve but it is the identity element of  $E$ .

We will choose for our calculations elliptic curves that do not have multiple roots or, in other words, curves where the **discriminant**  $4a^3 + 27b^2 \neq 0$ .

#### Quick Revision - Concept

**Equation:**  $y^2 = x^3 + ax + b$

**Structure:** group with  $\mathcal{O}$

**Operation:** geometric addition

**Hard problem:** ECDLP

### Addition on Elliptic Curves

Let  $P := (x, y) \in E$ , we define  $-P := (x, -y)$  (symmetric with respect to the x-axis). We have  $P + (-P) = \mathcal{O}$ .

For two points  $P, Q \in E$  with  $Q \neq -P$ , we define  $P + Q := R$  where  $-R$  is the 3rd intersection point between the curve and the line passing through  $P$  and  $Q$ .

For **doubling**:  $2P = R$  where  $-R$  is the intersection point of the curve with the tangent to the curve at point  $P$ .

#### Original Text - Addition

Let  $P := (x, y) \in E$ , we define  $-P$  as  $-P := (x, -y)$ . Graphically,  $-P$  is the symmetric point of  $P$  with respect to the x-axis. Note that  $P + (-P) = \mathcal{O}$ .

Let two points  $P, Q \in E$ , such that  $Q \neq -P$ , we define the addition  $P + Q := R$  where  $R \in E$  such that  $-R$  is the 3rd intersection point between the curve and the line passing through  $P$  and  $Q$ .

The set  $E$  with  $\oplus$  defines a **commutative group** for addition.

Let  $P \in E$ , the point  $2P = R$ , such that  $-R$  is the intersection point of the curve with the line tangent to the curve at point  $P$ .



### 💡 Quick Revision - Addition

**Inverse:**  $-P = (x, -y)$

**Addition:** 3rd intersection point + symmetry

**Doubling:** tangent + symmetry

**Property:** commutative group

## ECDLP and Cryptographic Advantages

When the elliptic curve is defined over the field  $\mathbb{Z}_p$  with  $p$  a large prime ( $y^2 \equiv x^3 + ax + b \pmod{p}$ ), the computation of  $k \in \mathbb{Z}_p$  such that  $Q = kP$  with  $(P, Q)$  known is **very difficult** (exponential effort). This problem is the **Elliptic Curve Discrete Logarithm Problem (ECDLP)**.

**Main advantage:** key sizes much smaller for equivalent security.

### i Original Text - ECDLP and Advantages

When the elliptic curve is defined over the field  $\mathbb{Z}_p$  with  $p$  a large prime number ( $y^2 \equiv x^3 + ax + b \pmod{p}$ ), the computation of  $k \in \mathbb{Z}_p$  such that  $Q = kP$  with  $(P, Q)$  known, is very difficult (requires exponential effort). This problem is known as: **Elliptic Curve Discrete Logarithm Problem (ECDLP)**.

The **main advantage** of public cryptography based on elliptic curves is that the size of the numbers used (and therefore, keys) is smaller.

This is due to the **increased complexity** of computations on  $E_p$  (elliptic curve defined over field  $\mathbb{Z}_p$ ) compared to usual fields such as  $\mathbb{Z}_p$  or  $GF(2^m)$ .

The **representation of a plaintext as points** of the curve remains a complex operation. In October 2003, the **US National Security Agency (NSA)** purchased a patent from Certicom for the use of elliptic curve cryptography.

In September 2013 Claus Diem showed that under certain conditions the ECDLP problem could be solved in **sub-exponential time**.

### 💡 Quick Revision - ECDLP

**Problem:** finding  $k$  in  $Q = kP$  (exponential)

**Gain:** keys  $\sim 6-10\times$  shorter

**Limit:** representing messages as points difficult

**NSA:** adopted in 2003

## Key Size Comparison Table

AES (symmetric)	RSA/DH	Elliptic Curves	Ratio
56 bits	512 bits	112 bits	1:4.6
80 bits	1024 bits	160 bits	1:6.4
112 bits	2048 bits	224 bits	1:9.1
128 bits	3072 bits	256 bits	1:12
256 bits	15360 bits	512 bits	1:30

#### **i** Original Text - Table

This table shows the key size ratios compared to RSA for equivalent security.  
*(Table extracted from original document)*

## ElGamal on Elliptic Curves

### Direct Adaptation

Replace operations in  $\mathbb{Z}_p^*$  with operations on  $E_p$

#### Keys:

- Choose curve  $E_p$  and point  $P_0 \in E_p$  of large order
- Secret  $x$ , compute  $P_a = xP_0$
- **Public:**  $(E_p, P_0, P_a)$  | **Private:**  $x$

**Encryption:** For message  $m_i \in E_p$

- Choose random  $k$
- $\gamma = kP_0$ ,  $\delta = kP_a + m_i$
- Send  $(\gamma, \delta)$

**Decryption:**  $m_i = \delta - x\gamma$

#### **i** Original Text - ElGamal EC

#### Key generation

Each entity (A) creates a key pair (public and private) as follows:

- A chooses an elliptic curve  $E_p$  with  $p$ , a large prime number ( $\text{len}(p)$  bits) and a point  $P_0 \in E_p$ .
- A generates a random number  $x$ , such that  $1 \leq x \leq p$  and computes  $P_a = xP_0$

- (multiplication by a scalar on  $E_p$ , for which efficient algorithms exist).
- The public key of A is  $(E_p, P_0, P_a)$ , the private key of A is  $x$ .

### Encryption

Entity B obtains  $(E_p, P_0, P_a)$ , the authentic public key of A.

- B transforms its plaintext into a series of integers  $m_i$ , such that  $m_i \in E_p$  for all  $i$ .
- For each message  $m_i$ :
  - B generates a **unique** random number  $k$ , such that  $1 \leq k \leq p$ .
  - B computes  $\gamma := kP_0$  and  $\delta := kP_a + m_i$  and sends the ciphertext  $c := (\gamma, \delta)$ .

### Decryption

- A uses its private key  $x$  to compute:  $x\gamma = xkP_0 = kP_a$ .
- A retrieves the plaintext by computing:  $\delta - kP_a = kP_a + m_i - kP_a = m_i$ .

The security of the scheme relies on **ECDLP**!

It is also necessary to **authenticate** the exchanged public parts to avoid the previously described man-in-the-middle attacks.

The properties of the protocol are identical to the  $\mathbb{Z}_p^*$  case.

### 💡 Quick Revision - ElGamal EC

**Principle:** same as ElGamal on  $E_p$

**Operations:** + and scalar multiplication on points

**Security:** ECDLP

**Authentication:** necessary against MitM

**Advantage:** short keys