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FINAL REPORT

Cryptanalysis of ECC-based Algorithms

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List of Abbreviations

Abbreviation	Full Name
BSGS	Baby-Step Giant-Step
CRT	Chinese Remainder Theorem
CSPRNG	Cryptographically Secure Pseudo-Random Number Generator
DLP	Discrete Log Problem
ECC	Elliptic Curve Cryptography
ECDH	Elliptic Curve Diffie–Hellman
ECDLP	Elliptic Curve Discrete Logarithm Problem
ECDSA	Elliptic Curve Digital Signature Algorithm
ECIES	Elliptic Curve Integrated Encryption Scheme
FIPS	Federal Information Processing Standards
HMAC	Hash-based Message Authentication Code
HNP	Hidden Number Problem
LLL	Lenstra–Lenstra–Lovász
MOV	Menezes–Okamoto–Vanstone
NIST	National Institute of Standards and Technology
RFC	Request for Comments
RNG	Random Number Generator
SECG	Standards for Efficient Cryptography Group
SP	Special Publication
SSH	Secure Shell
TLS	Transport Layer Security

I Overview

Elliptic Curve Cryptography (ECC) is a public-key cryptographic scheme that relies on the algebraic structure of elliptic curves over finite fields. Compared to traditional algorithms such as RSA, ECC offers equivalent levels of security while requiring significantly shorter key lengths [1]. This characteristic enables faster computation, reduced storage requirements, and lower power consumption, making ECC particularly well-suited for resource-constrained environments such as mobile devices and embedded systems. As a result, ECC has been widely adopted in secure communication protocols, digital signatures, and blockchain-based technologies [2, 3].

Recognizing the growing importance of ECC, the U.S. National Institute of Standards and Technology (NIST) has standardized its use for digital signatures in FIPS 186 [4] and for key establishment schemes in SP 800-56A [5]. FIPS 186-4 recommends fifteen elliptic curves with varying security levels. However, since these curves were introduced more than fifteen years ago, advancements in cryptographic research have prompted the development of newer elliptic curves that offer improved security margins, performance benefits, and ease of secure implementation [6].

In response to these developments, NIST organized the 2015 Workshop on Elliptic Curve Cryptography Standards, where stakeholders expressed strong interest in modernizing ECC standards [7]. Subsequently, NIST solicited public feedback on potential revisions to FIPS 186-4, including the inclusion of new elliptic curves and digital signature schemes. Throughout 2016, efforts were made to review these inputs and revise the standards accordingly.

II Mathematical Background

An elliptic curve in Weierstrass form is given by the equation:

$$y^2 = x^3 + Ax + B, \quad \text{where } 4A^3 + 27B^2 \neq 0$$

An elliptic curve (EC) is defined over a field F when $A, B \in F$ [8]. The condition $4A^3 + 27B^2 \neq 0$ ensures the curve is non-singular.

Let $P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$ be points on an elliptic curve E . Then their sum $P_3 = (x_3, y_3) = P_1 + P_2$ is calculated as follows:

$$P_3 = \begin{cases} (m^2 - x_1 - x_2, m(x_1 - x_3) - y_1), & \text{if } P_1 \neq P_2, \text{ where } m = \frac{y_2 - y_1}{x_2 - x_1} \\ (m^2 - 2x_1, m(x_1 - x_3) - y_1), & \text{if } P_1 = P_2 \text{ and } y_1 \neq 0, \text{ where } m = \frac{3x_1^2 + A}{2y_1} \\ \mathcal{O}, & \text{if } x_1 = x_2 \text{ and } y_1 = -y_2 \pmod{p} \\ \mathcal{O}, & \text{if } P_1 = P_2 \text{ and } y_1 = 0 \\ P_1, & \text{if } P_2 = \mathcal{O} \\ P_2, & \text{if } P_1 = \mathcal{O} \end{cases}$$

Point scalar multiplication is defined as repeated addition:

$$nP = \underbrace{P + P + \cdots + P}_{n \text{ times}}$$

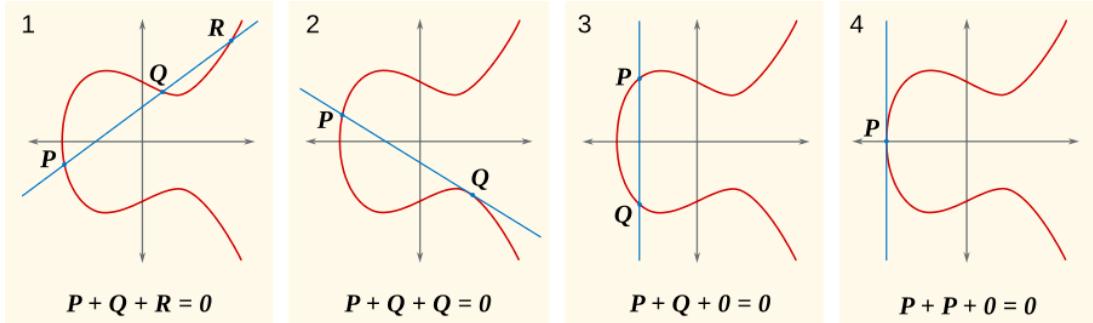


Figure 1: Addition and Multiplication on an Elliptic Curve [1]

II.1 Order

In elliptic curve theory, the **order** of an elliptic curve E over a finite field \mathbb{F}_p (where p is a prime number) is the total number of points on the curve, including the *point at infinity* \mathcal{O} . It is denoted as:

$$\#E(\mathbb{F}_p)$$

Computing the order of an elliptic curve is essential in cryptographic applications. The **Hasse Theorem** provides a bound for this value:

$$|\#E(\mathbb{F}_p) - (p + 1)| \leq 2\sqrt{p}$$

Therefore, we have:

$$\#E(\mathbb{F}_p) \in [p + 1 - 2\sqrt{p}, p + 1 + 2\sqrt{p}]$$

Advanced algorithms such as **Schoof's algorithm** [9] and its variants (e.g., Schoof–Elkies–Atkin algorithm) are used to compute the exact number of points efficiently.

II.2 Subgroup Order

A **subgroup** of an elliptic curve group over \mathbb{F}_p is a set of points that is closed under the elliptic curve group operation (addition and scalar multiplication).

Given a point P on the curve, the subgroup generated by P is defined as:

$$\langle P \rangle = \{\mathcal{O}, P, 2P, 3P, \dots, (n-1)P\}$$

where n is the smallest positive integer such that:

$$nP = \mathcal{O}$$

Then, n is called the **order of the point P** . By **Lagrange's Theorem**, the order of any subgroup divides the order of the full elliptic curve group:

$$\text{ord}(P) \mid \#E(\mathbb{F}_p)$$

If $\#E(\mathbb{F}_p)$ is a prime number (or n is a large prime factor of $\#E(\mathbb{F}_p)$ and P generates a subgroup of this prime order), then this forms a secure basis for cryptographic applications [8].

II.3 Finding a Base Point

In **Elliptic Curve Cryptography (ECC)**, a **base point P** (also known as a generator point) is used to generate public-private key pairs. A good base point must satisfy [10]:

- $P \in E(\mathbb{F}_p)$ — the point lies on the curve.
- $\text{ord}(P)$ is a large prime number.
- $kP \neq \mathcal{O}$ for any small positive integer k (this is implied if $\text{ord}(P)$ is prime and large).

This ensures resistance against small subgroup attacks and improves the overall security of ECC systems. Curves used in practice are selected such that their order is either a large prime or has a large prime factor [11].

II.4 Discrete Logarithm Problem

The security of ECC relies on the hardness of the **Elliptic Curve Discrete Logarithm Problem (ECDLP)** [12, 13]. Given two points P and Q on the curve such that:

$$Q = kP$$

for some unknown scalar k , the ECDLP is the problem of finding k , given only P and Q .

This problem is believed to be computationally infeasible to solve efficiently for properly chosen curves and parameters. It is the foundation of widely used cryptographic protocols, such as:

- ECDSA — Elliptic Curve Digital Signature Algorithm [4, 14]
- ECDH — Elliptic Curve Diffie–Hellman Key Exchange [5]
- ECIES — Elliptic Curve Integrated Encryption Scheme

III Elliptic Curves In The Context Of Cryptography

Elliptic Curve Cryptography (ECC) translates the mathematical properties of **elliptic curves** into cryptographic applications, yielding powerful public-key encryption schemes. The security foundation of ECC lies in the computational **difficulty of the Elliptic Curve Discrete Logarithm Problem (ECDLP)**. Given a point P on the curve and a point $Q = kP$ (where k is an integer), finding k (the discrete logarithm of Q to the base P) is considered computationally infeasible when the curve parameters are chosen correctly. This inherent difficulty forms the basis for the security of ECC algorithms.

In the context of cryptography, the primary applications of elliptic curves include:

1. **Key Exchange:** Enabling two parties to establish a shared secret key over an insecure public channel.
2. **Digital Signatures:** Providing a means to verify the integrity and non-repudiation of data.

Key components of an ECC system typically involve:

- **Elliptic Curve (E):** Defined over a **finite field** \mathbb{F}_p (or \mathbb{F}_{2^m}), along with parameters A and B .
- **Base Point (G):** A point on the curve with a large order, serving as the “generator” for cryptographic operations.
- **Group Order (n):** The total number of points on the curve (including the point at infinity), or the order of the subgroup generated by the base point G . This n is often a large prime number to ensure security.
- **Private Key (d):** A randomly chosen secret integer d from the range $[1, n - 1]$.
- **Public Key (Q):** Computed by multiplying the base point G by the private key d , i.e., $Q = dG$.

III.1 Elliptic Curve Diffie-Hellman (ECDH)

ECDH is a variant of the Diffie-Hellman key exchange protocol, allowing two parties (Alice and Bob) to establish a shared secret key over an insecure channel. The security of ECDH relies on the hardness of the ECDLP.

How it works:

- **Parameter Setup:** Alice and Bob agree on an **elliptic curve** E , a **finite field** \mathbb{F}_p , and a **base point** G with order n .
- **Alice:**
 - Chooses a random private key $d_A \in [1, n - 1]$.
 - Computes her public key $Q_A = d_A G$.
 - Sends Q_A to Bob.
- **Bob:**

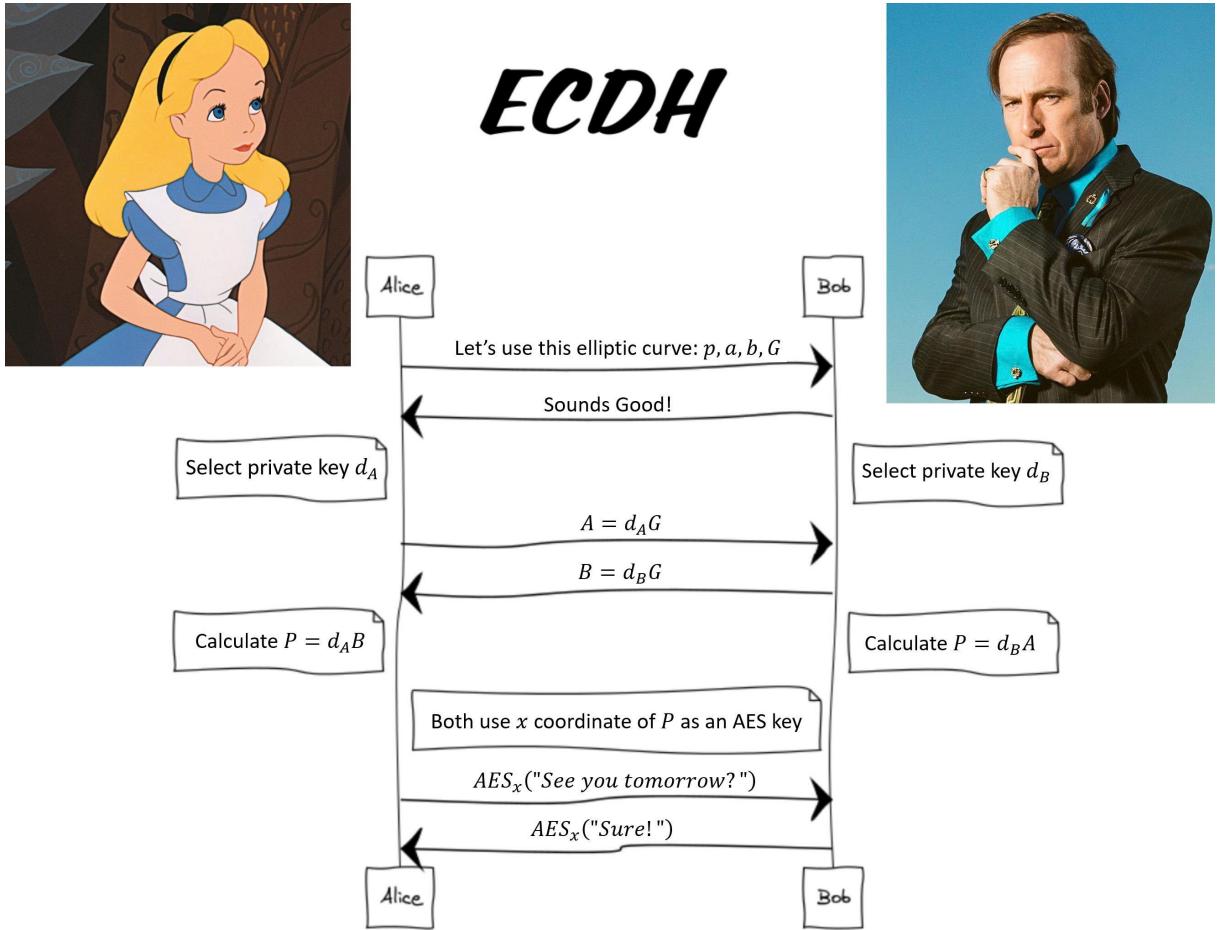


Figure 2: ECDH Flowchart

- Chooses a random private key $d_B \in [1, n - 1]$.
- Computes his public key $Q_B = d_B G$.
- Sends Q_B to Alice.
- **Shared Secret Computation:**
 - Alice computes $K = d_A Q_B = d_A(d_B G) = (d_A d_B)G$.
 - Bob computes $K = d_B Q_A = d_B(d_A G) = (d_B d_A)G$.

III.2 Elliptic Curve Digital Signature Algorithm (ECDSA)

ECDSA is a widely used digital signature algorithm that verifies the authenticity and integrity of messages. It's a variant of the Digital Signature Algorithm (DSA) that employs elliptic curve operations.

How it works:

- **Parameter Setup:** The signer and verifier agree on an **elliptic curve** E , a **finite field** \mathbb{F}_p , and a **base point** G with order n . The signer holds a private key (d_A) and a corresponding public key ($Q_A = d_A G$).
- **Signature Generation** (r, s) for message m :

1. Compute $e = \text{HASH}(m)$ (the message hash).
2. Choose a cryptographically secure random integer $k \in [1, n - 1]$ (the **nonce**). This value is critically important and *must be unique and random* for each signature.
3. Compute the elliptic curve point $P = kG = (x_1, y_1)$.
4. Compute $r = x_1 \bmod n$. If $r = 0$, go back to step 2.
5. Compute $s = k^{-1}(e + r \cdot d_A) \bmod n$. If $s = 0$, go back to step 2.
6. The signature is the pair (r, s) .

- **Signature Verification** (r, s) for message m :

1. Compute $e = \text{HASH}(m)$.
2. Check if r and s are within the range $[1, n - 1]$. If not, the signature is invalid.
3. Compute $w = s^{-1} \bmod n$.
4. Compute $u_1 = e \cdot w \bmod n$.
5. Compute $u_2 = r \cdot w \bmod n$.
6. Compute the point $P' = u_1 G + u_2 Q_A$.
7. If P' is the point at infinity (\mathcal{O}), the signature is invalid.
8. Compute $r' = x_{P'} \bmod n$ (the x-coordinate of point P').
9. The signature is valid if $r' = r$.

Both ECDH and ECDSA effectively leverage the high security offered by ECC with significantly smaller key sizes compared to algorithms based on integer factorization (like RSA) or discrete logarithm problems in finite fields. However, as Part IV will detail, careless implementation or the use of non-standard parameters can lead to severe vulnerabilities.

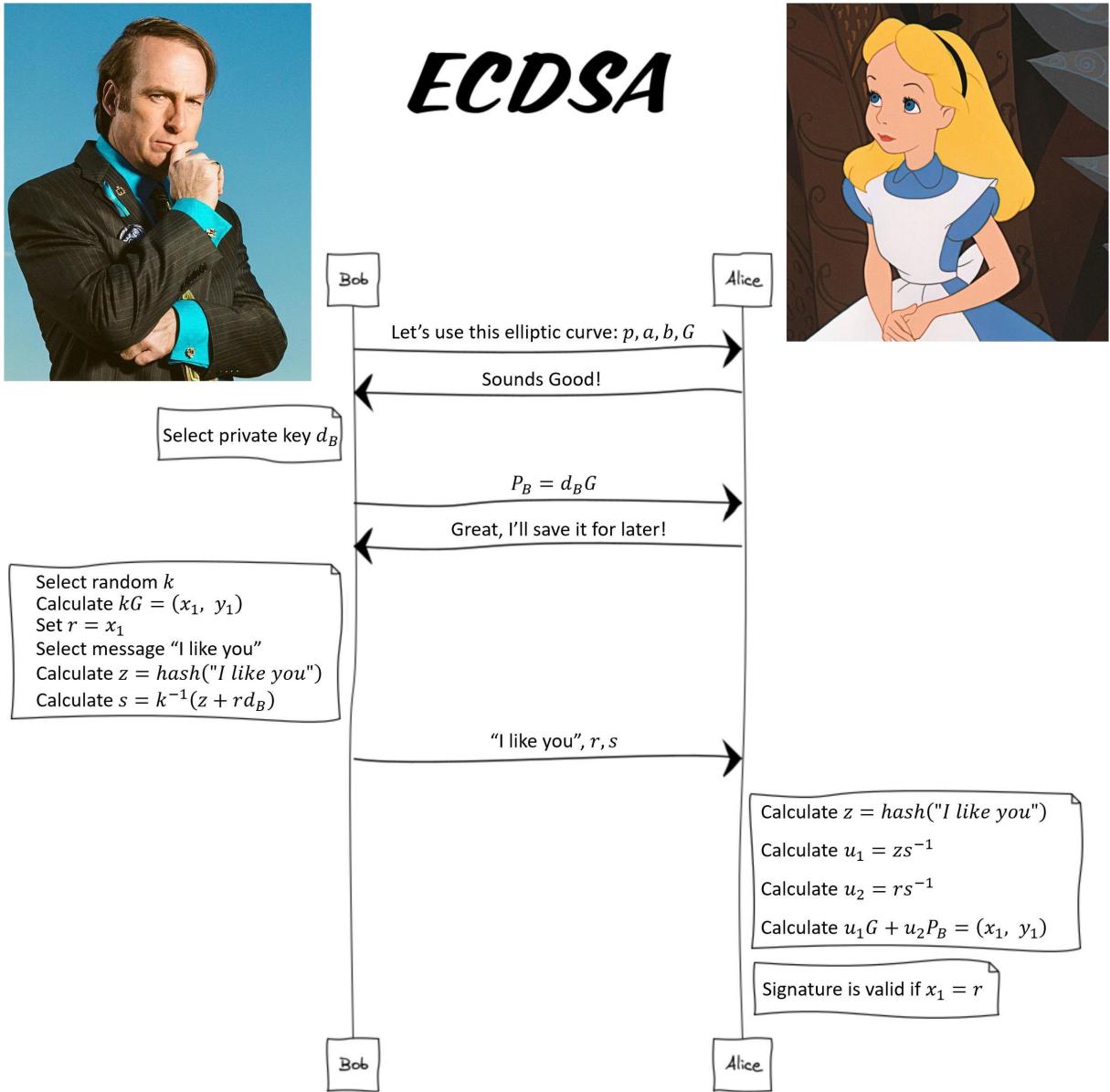


Figure 3: ECDSA Flowchart

IV Elliptic Curves Attack and Threat Analysis

IV.1 Table of Elliptic Curve Cryptography Vulnerabilities

Table 1: Table of Elliptic Curve Cryptography Vulnerabilities

Name	Weakness	Exploit	Countermeasure
Small Order Curve	The group order n of the base point G is a small number, making the ECDLP computationally easy.	Brute-force the key space or use algorithms like Pollard's Rho, which are efficient for small groups.	Choose a curve where the order n is a very large prime number.
Smooth Order Curve	The group order n is composite and made of only small prime factors.	Use the Pohlig-Hellman algorithm to break the main ECDLP into smaller, easy-to-solve DLPs in the subgroups.	Choose a curve where n is a large prime (or has at least one very large prime factor).
Small Private Key Attack	The private key d_a is chosen from a small range, not the full range $[1, n - 1]$.	Brute-force the small key space by computing $d \times G$ for small d until it matches the public key Q_A .	Choose the private key d_a randomly and uniformly from the entire valid range $[1, n - 1]$.
Invalid Curve Attack	Failure to validate that a received public key point Q lies on the correct, secure curve.	Attacker provides a point on a weak curve (e.g., with a small order) to learn information about the victim's secret key.	Always perform full public key validation: check that the point's coordinates satisfy the curve equation.
Singular Elliptic Curves	Using a degenerate (weak) curve where the parameters satisfy $4a^3 + 27b^2 \equiv 0 \pmod{p}$.	Map curve points to a simpler algebraic group where the DLP is easy, then solve for the private key d_a .	Verify that curve parameters satisfy $4a^3 + 27b^2 \not\equiv 0 \pmod{p}$. All standard curves are non-singular.
Supersingular Curves	The curve has a small embedding degree k that allows mapping the ECDLP to a weaker problem.	Use the MOV attack with pairings to transfer the ECDLP to a finite field \mathbb{F}_{p^k} , where it can be solved faster.	Use non-supersingular curves. Modern standard curves (e.g., secp256k1) are chosen for their large embedding degree.

Continued on next page

Table 1: (continued)

Name	Weakness	Exploit	Countermeasure
Anomalous Elliptic Curves	The number of points on the curve (order n) is equal to the characteristic of the field p .	Lift points from $E(\mathbb{F}_p)$ to a related p-adic group where the logarithm is simple to compute, thus solving the ECDLP.	Verify that the curve order n is not equal to the field characteristic p . Use standard, well-vetted curves.
Not Hashing the Message	Signing the raw message m directly instead of its cryptographic hash $H(m)$.	Forge signatures by constructing a valid (r, s) pair and then solving for a message m' that fits the signature.	Always compute $z = \text{HASH}(m)$ before computing the signature, as specified in all standard algorithms.
Nonce Reuse	Using the same secret nonce k to sign two different messages.	Use the two signature equations to algebraically solve for and recover the private key d_a .	Generate a new, unique, and unpredictable nonce k for every signature. Best practice: use deterministic nonces (RFC 6979).
Biased Nonce and Lattice Attacks	The nonce k is not truly random, often due to a flawed Random Number Generator (RNG).	Collect many signatures and use Lattice Attacks to recover the private key d_a from the small, leaked bits of information.	Use a high-quality, cryptographically secure RNG or, preferably, use deterministic nonce generation (RFC 6979).

IV.2 Requirements

- SageMath: open-source mathematics software useful for ECC operations.
- Python 3.x: a high-level programming language.
- PyCryptodome: a Python library for cryptographic algorithms.

IV.3 ECDH Attacks

IV.3.1 Small Order Curve

When the generator point P has a small order $n = \text{ord}(P)$, the ECDLP can be solved relatively easily. If an attacker can force the key exchange to use a point P of small order

n , they can recover the secret key with complexity related to $O(\sqrt{n})$ using algorithms like Baby-Step Giant-Step [15], or even faster for very small n .

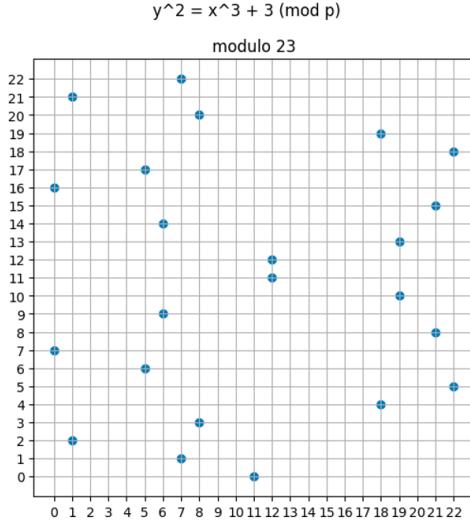


Figure 4: Small order curve illustration

Baby-step Giant-step (BSGS): [15]

1. Let $n = \text{ord}(P)$, and $m = \lceil \sqrt{n} \rceil$.
 2. **Baby steps:** Compute and store jP for $j = 0$ to $m - 1$.
 3. **Giant steps:** Compute $Q - imP$ for $i = 0$ to $m - 1$.
 4. Find i, j such that $Q - imP = jP$; then $k = (im + j) \pmod n$.

```

==== Baby-Step Giant-Step Attack Details ====
[+] Problem Statement:
    Given: H = kG where k is unknown

[+] Generator point G:
x = 0x47783729240721c9c8a48a92fe2df51e445ac6f3e559e234096
y = 0xfedb591d0e4540cb48459fae209a64265182277e63633d68ad

[+] Public key H:
x = 0xab6f8236a04936fb0e795e79dca736d1ef2deb7e4cdf4c6eb3c
y = 0x39a9a35c7dc23b0745bb17d791fa815fa0cc88a4bda8db365c8

[+] Find k in range [1, 0xffffffff]

[+] Step 1: Calculate m = ceil(sqrt(n))
m = 0x10000

[+] Step 2: Baby Steps - calculate and store jG for j in [0, m)
Formula: Store (jG, j) in table where j = 0,1,2,...,m-1

First few baby steps:

j = 0x0:
jG:
x = 0x0
y = 0x1

j = 0x1:
jG:
x = 0x47783729240721c9c8a48a92fe2df51e445ac6f3e559e234096
y = 0xfedb591d0e4540cb48459fae209a64265182277e63633d68ad

j = 0x2:
jG:
x = 0x51b72b5d29680d912f0874ce19b75900eec2feeae658dcc6ba0
y = 0x794d2810e2322ac956df3cc65bac243feeae45b08b04f78aebd5

```

```

[+] Step 3: Precompute -mG for giant steps
-mG:
x = 0x3c641e1b8e277c7221497a3a857282567f32635d1e1457175c0
y = 0x20ece6eab72931dc0b6b454372101ed244d37970b80dde82b9e

[+] Step 4: Giant Steps - Calculate H + i(-mG) for i in [0, m)
Formula: For each i, check if H + i(-mG) is in baby_steps table

Giant step iterations:

i = 0x0:
Current point:
x = 0xab6f8236a04936fb0e795e79dca736d1ef2deb7e4cdf4c6eb3c
y = 0x39a9a35c7dc23b0745bb17d791fa815fa0cc88a4bda8db365c8

i = 0x1:
Current point:
x = 0x1be547219a9fe9a1f75a4e5c0330b3c6884f92734350c73e47c
y = 0x5ab38a5821d8ff0ab331183fdd8bed550f06b253fa10ac22015

i = 0x2:
Current point:
x = 0xaa5d22bfa6b585d5cd5aacbc8ef800b180c18bfabb13cb31e49
y = 0x40939e8fa2acee1e4aeb490126345e2c18b2d8967f41591ab31

... (continuing for all i up to m-1) ...

[+] Solution found!
i = 0x476f
j = 0x9de1
k = i*m + j = 0x476f9de1
[+] Time taken: 4.17 seconds

[+] Attack successful!
[+] Recovered key matches true private key:
k = 0x476f9de1

```

Figure 5: Baby-step Giant-step (BSGS) Demo

Pollard's Rho: [16]

1. Initialize a random point $R_0 = a_0P + b_0Q$.
2. Generate a pseudorandom sequence $R_{i+1} = f(R_i)$, where f is a function that maps points to points, and keep track of coefficients a_i, b_i such that $R_i = a_iP + b_iQ$.
3. Detect a collision $R_i = R_j$ for $i \neq j$.
4. This implies $(a_i - a_j)P + (b_i - b_j)Q = \mathcal{O}$. If $b_i - b_j \not\equiv 0 \pmod{n}$, then $Q = -\frac{a_i - a_j}{b_i - b_j}P$. So $k \equiv -\frac{a_i - a_j}{b_i - b_j} \pmod{n}$.

Countermeasure: To prevent small order attacks (also known as subgroup confinement attacks), two main strategies are employed:

1. **Parameter Selection:** The elliptic curve parameters must be chosen such that the order of the base point G , denoted by n , is a large prime number. This ensures that

the cyclic subgroup generated by G does not contain any small subgroups (other than the trivial one). Standard curves like `secp256k1` and `P-256` are defined with this property. The cofactor $h = \#E(\mathbb{F}_p)/n$ should be small (ideally $h = 1$).

2. **Point Validation:** When a public key (a point Q) is received from an external entity, it must be validated before use. The validation must check that (a) the point's coordinates are valid and lie on the specified curve, (b) the point is not the point at infinity \mathcal{O} , and (c) the point lies in the correct subgroup. The last check is done by verifying that $nQ = \mathcal{O}$. Since n is prime, this confirms that the order of Q is n , thus preventing an attacker from supplying a point of a small order.

IV.3.2 Smooth Order Curve

If the order n of the generator point P is a composite number whose prime factors are all small (i.e., n is smooth), then the ECDLP can be solved efficiently using the Pohlig-Hellman algorithm [17].

Pohlig-Hellman Algorithm [17]

Let $Q = kP$, $n = \text{ord}(P)$, and the prime factorization of n be:

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

The algorithm works by finding $k \pmod{p_i^{e_i}}$ for each i , and then combining these results using the Chinese Remainder Theorem (CRT) to find $k \pmod{n}$.

1. For each prime power factor $p_i^{e_i}$ of n :
 - (a) Let $n' = n/p_i^{e_i}$. Compute $P' = n'P$ and $Q' = n'Q$.
 - (b) The order of P' is $p_i^{e_i}$. We need to solve $k_i P' = Q'$, where $k \equiv k_i \pmod{p_i^{e_i}}$.
 - (c) To find $k_i \pmod{p_i^{e_i}}$, we can write $k_i = c_0 + c_1 p_i + \dots + c_{e_i-1} p_i^{e_i-1}$, where $0 \leq c_j < p_i$.
 - (d) Solve for c_j iteratively. For c_0 , solve $c_0(p_i^{e_i-1} P') = (p_i^{e_i-1} Q')$. This is a DLP in a group of order p_i , solvable by BSGS or Pollard's Rho if p_i is small.
 - (e) Repeat for c_1, c_2, \dots by adjusting Q' at each step.
2. Use CRT to combine the congruences $k \equiv k_i \pmod{p_i^{e_i}}$ to find $k \pmod{n}$.

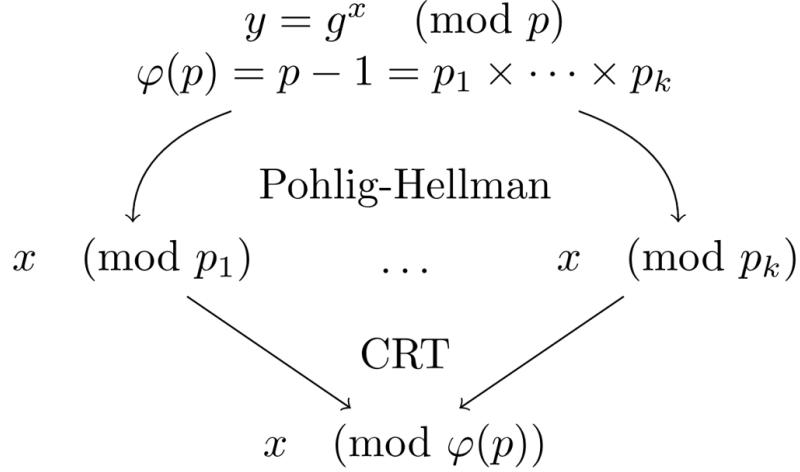


Figure 6: Pohlig-Hellman strategy on a smooth-order group

The complexity is dominated by solving the DLPs in subgroups of order p_i , which is roughly $O(\sum \sqrt{p_i})$ if BSGS is used for each subproblem, or $O(\sqrt{p_{\max}})$, where p_{\max} is the largest prime factor of n . For example, if n is a 128-bit number with its largest prime factor being 30 bits, the problem's complexity can drop from roughly 2^{64} (for general ECDLP) to around 2^{15} , making the attack feasible.

```

Curve defined on GF(115792089210356248762697446949407573530086143415290314195533631308867097853951)
Generator G: (5873958911161196271583544993606157139975695246024583626828087769866632269, 86857039837890738158800656283739100419083698574723918755107056633620633897772)
Order of G: 11579208921035624876269744694940757352983406581957583176174383474827192619340
Factorization of order: 2^2 * 5 * 7 * 13 * 617 * 4759 * 8260807 * 144722299 * 928070153503 * 2590206143359 * 13389517011401 * 56307812771039
=====
The order is a 'smooth number', making Pohlig-Hellman attack feasible.
  
```

Figure 7: Server exposes a weak curve with a smooth order

```

=====
Curve defined on GF(115792089210356248762697446949407573530086143415290314195533631308867097853951)
Generator G: (5873958911161196271583544993606157139975695246024583626828087769866632269, 86857039837890738158800656283739100419083698574723918755107056633620633897772)
Order of G: 11579208921035624876269744694940757352983406581957583176174383474827192619340
Factorization of order: 2^2 * 5 * 7 * 13 * 617 * 4759 * 8260807 * 144722299 * 928070153503 * 2590206143359 * 13389517011401 * 56307812771039
=====
The order is a 'smooth number', making Pohlig-Hellman attack feasible.
=====
Server listening on 127.0.0.1:65432
Connected by ('127.0.0.1', 55342)
Generated secret: 3944780467231389085169975382438316624206831059812918511701629174747519693953
Public key Q = n*g: (1138063817615967500842309101056684471334701523323125613287928130768335981007, 44688454783358427363615604210131103661887509617655693584106067780670394098835)
  
```

Figure 8: The server accepts the client's connection and generates a new secret/public key pair (n , Q) for the challenge

```
[2] Solving ECDLP to find the secret 'n'...
[*] Order of P: 11579208921035624876269744694048757352983406531957682176174383474027102619248
[*] Prime factors of order: 2^2 * 5 * 13 * 617 * 4759 * 8266867 * 144722299 * 928670153503 * 2590266143359 * 13389517011401 * 56307812771839
[*] Solving DLP for each prime factor subgroup...
[6] - Found x = 1 (mod 4)
- Found x = 3 (mod 5)
- Found x = 4 (mod 7)
- Found x = 12 (mod 13)
- Found x = 532 (mod 617)
- Found x = 2958 (mod 4759)
- Found x = 8267713 (mod 8266867)
[58] - Found x = 134607432 (mod 144722299)
[58] - Found x = 352648914274 (mod 928670153503)
[75] - Found x = 1676396098108 (mod 2590266143359)
[83] - Found x = 2677251911718 (mod 13389517011401)
[92] - Found x = 25479305330342 (mod 56307812771839)
[100] - Found x = 13389517011401

[*] Combining results using Chinese Remainder Theorem (CRT)...
[*] Recovered Secret: 3944784672313996851699735624383166242060310590129185117816291747519693953
[*] Verification successful: secret * P == Q

[3] Decrypting the flag using the recovered secret...
[*] Decrypted flag (bytes): b'FLAG{Pohlig_Hellman_Algorithm_is_super_effective_against_smooth_order_groups!}'

[4] Sending decrypted flag to server for verification...

[5] Server response:
SUCCESS: Well done! You recovered the secret flag.
```

Figure 9: The client executes the Pohlig-Hellman attack: it solves the DLP for each small prime factor of the order, then uses the Chinese Remainder Theorem (CRT) to recover the full secret key, decrypts the flag, and receives a success confirmation from the server

Countermeasure: The solution to the Pohlig-Hellman attack is straightforward and fundamental to modern ECC. The order n of the generator point P must not be a smooth number. Specifically, for a curve to be considered secure, its order n must be a prime number or have a very large prime factor. For 256-bit security, the largest prime factor of n (and typically n itself) must be approximately 256 bits long. This ensures that the largest subproblem in the Pohlig-Hellman attack, $O(\sqrt{p_{\max}})$, is computationally infeasible. All standardized curves used for cryptography (e.g., NIST P-curves, SECG curves) are carefully constructed to have a prime order or an order with a very large prime factor.

IV.3.3 Not Smooth Order & Small Private Key

Suppose the generator's order n factors into primes, but the largest prime factor is too large to solve the ECDLP practically using Pohlig-Hellman—for example, a 256-bit order n with a 128-bit largest prime factor p_{\max} . In this case, Pohlig-Hellman would require about $O(\sqrt{p_{\max}}) \approx O(2^{64})$ operations, which is infeasible.

However, if the private key k is known to be small—say, $k < K_{\text{bound}}$ where K_{bound} is significantly smaller than n (e.g., k is 64 bits instead of 256 bits)—the attack can still succeed. Even though the group has approximately 2^{256} points, the public key $Q = kP$ lies within the first K_{bound} multiples of P .

An attacker can try to find $k \pmod m$ where m is a product of small prime factors of n such that $m > K_{\text{bound}}$. Then, one can simply iterate through possible values of k or use BSGS/Pollard's Rho restricted to the range $[0, K_{\text{bound}} - 1]$ [16, 15]. More effectively, if k is small, one can run BSGS or Pollard's Rho directly to find k , with complexity $O(\sqrt{K_{\text{bound}}})$. This does not directly use the Pohlig-Hellman structure but attacks the small key assumption.

The text seems to imply a hybrid approach: run Pohlig-Hellman on the smooth part of n . If $k \pmod{m_{\text{smooth}}} = k_0$ is found, and m_{smooth} covers enough bits of k (e.g., if $K_{\text{bound}} < m_{\text{smooth}}$), then $k = k_0$. If K_{bound} is larger, the search space for k is reduced.

Countermeasure: The security of an ECC system relies on the assumption that the private key is a large, unpredictable number. To prevent attacks targeting a small private

key, the key k must be generated using a Cryptographically Secure Pseudo-Random Number Generator (CSPRNG). The key should be chosen uniformly at random from the full range $[1, n - 1]$, where n is the order of the generator point. This ensures that the search space for the key is as large as the group order, making brute-force attacks or algorithms like BSGS/Pollard's Rho infeasible. A 32-bit or 64-bit private key on a 256-bit curve offers no more than 16-bit or 32-bit security, respectively.

IV.3.4 Invalid Curve Attack

An invalid curve attack occurs when a party (e.g., a server) accepts a point from another party (e.g., a client or an attacker) and performs ECC operations without verifying that the point actually lies on the agreed-upon elliptic curve $E : y^2 = x^3 + Ax + B$ over \mathbb{F}_p . The formulas for point addition and doubling involve the curve parameter A , but not B directly (unless specific conditions like $y_1 = 0$ for doubling are met, or in the verification $y^2 = x^3 + Ax + B$).

Doubling	Addition ($P_1 \neq P_2$)
If $y_1 = 0$ then $2P_1 = \mathcal{O}$, else $\lambda = \frac{3x_1^2 + A}{2y_1}$ $x_3 = \lambda^2 - 2x_1$ $y_3 = \lambda(x_1 - x_3) - y_1$	If $x_1 = x_2$ (so $y_1 = -y_2$), $P_1 + P_2 = \mathcal{O}$. Else, $\lambda = \frac{y_2 - y_1}{x_2 - x_1}$ $x_3 = \lambda^2 - x_1 - x_2$ $y_3 = \lambda(x_1 - x_3) - y_1$

Table 1. Doubling and Addition laws over $E(\mathbb{F}_p) : y^2 = x^3 + Ax + B$

An attacker can send a point (x_A, y_A) that is not on E but on a different curve $\tilde{E} : y^2 = x^3 + Ax + \tilde{B}$, where $\tilde{B} = y_A^2 - x_A^3 - Ax_A \pmod{p}$. If the server computes $d_S \cdot (x_A, y_A)$ using its private key d_S , the computation effectively happens on \tilde{E} . The attacker can choose \tilde{E} such that its order $\#\tilde{E}(\mathbb{F}_p)$ is smooth or has small subgroups [18]. By observing the result $d_S(x_A, y_A)$ on \tilde{E} , the attacker learns information about $d_S \pmod{n_i}$, where n_i is the order of (x_A, y_A) on \tilde{E} . If the attacker sends points from several such maliciously chosen curves $\tilde{E}_1, \tilde{E}_2, \dots, \tilde{E}_t$:

$$\begin{cases} y^2 = x^3 + Ax + \tilde{B}_1 \pmod{p} & (\text{leaks } d_S \pmod{n_1}, \text{ where } n_1 \text{ is small or smooth}) \\ y^2 = x^3 + Ax + \tilde{B}_2 \pmod{p} & (\text{leaks } d_S \pmod{n_2}) \\ \vdots \\ y^2 = x^3 + Ax + \tilde{B}_t \pmod{p} & (\text{leaks } d_S \pmod{n_t}) \end{cases}$$

If $\text{lcm}(n_1, n_2, \dots, n_t)$ is greater than or equal to the order of the generator on the original curve (or at least large enough to determine d_S), then the secret key d_S can be recovered using the Chinese Remainder Theorem (CRT) [19]. This is particularly effective if the n_i are small prime powers.

Countermeasure: The defense against the invalid curve attack is to perform **full point validation** on any public key received from an untrusted source before using it in any cryptographic operation (like a key exchange). The validation must consist of:

1. **Coordinate Check:** Ensure the point coordinates (x, y) are in the valid range for the field \mathbb{F}_p .

2. Curve Equation Check: Verify that the point (x, y) satisfies the curve equation:
 $y^2 \equiv x^3 + Ax + B \pmod{p}$.

This check guarantees that the point lies on the intended, secure curve E , and not on a weak, attacker-chosen curve \tilde{E} . While this validation adds a small computational overhead, it is critical for security in protocols where parties exchange public keys.

IV.3.5 Singular Elliptic Curves

A cryptographically secure elliptic curve must be non-singular, meaning its discriminant $\Delta = -(4A^3 + 27B^2) \neq 0 \pmod{p}$. If $\Delta \equiv 0 \pmod{p}$, the curve is singular, and the ECDLP can be reduced to a simpler problem [8].

Cusp If $4A^3 + 27B^2 \equiv 0 \pmod{p}$ and the singular point is a cusp (e.g., for the curve $y^2 = x^3 \pmod{p}$, we have $A = 0, B = 0$), the group of non-singular points $E_{ns}(\mathbb{F}_p)$ is isomorphic to the additive group $(\mathbb{F}_p, +)$. The isomorphism can be given by:

$$\psi : E_{ns}(\mathbb{F}_p) \rightarrow (\mathbb{F}_p, +), \quad (x, y) \mapsto \frac{x}{y} \text{ (if } y \neq 0\text{)}, \quad \mathcal{O} \mapsto 0$$

The DLP $Q = kP$ on $E_{ns}(\mathbb{F}_p)$ becomes $q_{\text{iso}} = k \cdot p_{\text{iso}}$ in \mathbb{F}_p (under the isomorphism, p_{iso} is the image of P , and q_{iso} is the image of Q). So $k = q_{\text{iso}} \cdot p_{\text{iso}}^{-1} \pmod{p}$, which is trivial to solve if $p_{\text{iso}} \neq 0$.

```

Sage: %load ./src/elliptic_curve/elliptic_curve.py
--- DEMO TẤM CỘNG ĐIỂM CUSP (SAGE) ---
Phương trình: y^2 = x^3 + 0x^2 + 0x + 0 (mod 88250384390554718917360759821895903693851462463793480219062805905509824804087)
--> Đường cong có điểm kỳ dị (Singular Curve).
- Cusp tại (0, 0)

Server Private Key: 1774347702445750649887454859738383011192446003108335140924843790962046747813
Server Public Key (P_server): 68585649362857443297072276510600964438118175193209206395064585099473272795037, 2831785822454434864078265582635043472369
7696385663321727853205690694307475878
Phương trình: y^2 = x^3 + 0x^2 + 0x + 0 (mod 88250384390554718917360759821895903693851462463793480219062805905509824804087)
--> Đường cong có điểm kỳ dị (Singular Curve).
- Cusp tại (0, 0)
Client nhận thông tin từ Server.
Client Private Key: 14078967307089777907800508457949431352370093273824058603278818804105716702022
Client Public Key: 42416285759075681351709363706539324050298224824081416690347913607470235463884, 143281071255965361987363940706778178233129971044872
62260246872835872407328777

Server tính toán khóa chung: 69847481511593034668600706095592839172580738842191503950680318673060169215681, 72626950226734110746345057929903020700364
173521126693775130103371261333053995
Client tính toán khóa chung: 69847481511593034668600706095592839172580738842191503950680318673060169215681, 72626950226734110746345057929903020700364
173521126693775130103371261333053995

Đang thực hiện tấn công bằng phương pháp ánh xạ vào nhóm con...
--> Phát hiện Cusp. Áp dụng tấn công Cusp.

--- Bắt đầu tấn công CUSP ---
1. Xác định đa thức  $f(x) = x^3 + 0x^2 + 0x + 0$ 
2. Tìm nghiệm của  $f(x) = [(0, 0)]$ 
Điểm cơ sở G: (1, 1)
Khóa công khai P_server: (68585649362857443297072276510600964438118175193209206395064585099473272795037, 28317858224544348640782655826350434723697696
385663321727853205690694307475878)
3. Xác định cusp tại  $x = \alpha = 0$  (vi có nghiệm bội 3).
4. Ánh xạ các điểm vào nhóm cộng tinh  $\mathbb{Z}_p$  (ánh xạ  $\phi(x, y) = (x - \alpha) / y$ )
    Tính  $u = \phi(G) = (1 - 0) / 1 = 1$ 
    Tính  $v = \phi(P_server) = (68585649362857443297072276510600964438118175193209206395064585099473272795037 - 0) / 28317858224544348640782655826350434
723697696385663321727853205690694307475878 = 177434770244575064988745485973838011192446003108335140924843790962046747813
5. Giải bài toán Logarit Rõi rắc trong nhóm cộng tinh:  $v = k * u \Rightarrow k = v / u$ 
    Khóa riêng k = 177434770244575064988745485973838011192446003108335140924843790962046747813 / 1 = 177434770244575064988745485973838011192446003
108335140924843790962046747813
!!! TẤM CỘNG THÀNH CÔNG !!!
Khóa riêng của Server được suy ra: 177434770244575064988745485973838011192446003108335140924843790962046747813$ 
```

Figure 10: Cusp Demo

Node If $4A^3 + 27B^2 \equiv 0 \pmod{p}$ and the singular point is a node (e.g., for $y^2 = x^3 + Ax^2 = x^2(x + A) \pmod{p}$, we have $B = 0$ and $A \neq 0$), the group of non-singular

points $E_{ns}(\mathbb{F}_p)$ is isomorphic to the multiplicative group (\mathbb{F}_p^*, \times) if the slopes at the node are in \mathbb{F}_p , or to the multiplicative group of a quadratic extension field otherwise. Assuming it's isomorphic to \mathbb{F}_p^* : For a curve like $y^2 = x^2(x + t)$, an isomorphism is:

$$\psi : E_{ns}(\mathbb{F}_p) \rightarrow (\mathbb{F}_p^*, \times), \quad (x, y) \mapsto \frac{y + \alpha x}{y - \alpha x} \text{ (for some } \alpha \text{ related to the slopes at the node), } \mathcal{O} \mapsto 1$$

The DLP $Q = kP$ on $E_{ns}(\mathbb{F}_p)$ becomes $q_{\text{iso}} = p_{\text{iso}}^k \pmod{p}$ in \mathbb{F}_p^* . This is the standard DLP in \mathbb{F}_p^* , which is solvable using algorithms like Index Calculus if $p - 1$ is smooth.

```
--- DEMO TẤN CÔNG ĐIỂM NODE (SAGE) ---
Phương trình: y^2 = x^3 + 0x^2 + 0x + 0 (mod 4368590184733545720227961182704359358435747188309319510520316493183539079703)
--> Đường cong có điểm kỳ dị (singular curve).
- nghiệm bậc 1 nhưng không phải kỳ dị.
- NODE tại (0, 0)

Server Private Key: 3963903911833444099026001790250531678485652182452420312170405092086735621359
Server Public Key (P_Server): 25829289742434653537195305669979374502255237854818288211138499777818633265, 24216835734464979725071723858817932601763
70025964652384676141384239699096612
Phương trình: y^2 = x^3 + 1x^2 + 0x + 0 (mod 4368590184733545720227961182704359358435747188309319510520316493183539079703)
--> Đường cong có điểm kỳ dị (singular curve).
- nghiệm bậc 1 nhưng không phải kỳ dị.
- NODE tại (0, 0)

Client nhận thông tin từ Server.
Client Private Key: 3148307491845914075234668701774100789664133225119932240627572231999951703717
Client Public Key: 2607999445155124521921560392767070564838166227503653732184303353615980600667, 2209887194341070936543460055353234058849175265583108
086927695796686612239736

Server tính toán khóa chung: 1708468882496469409479494789312397395143071325509346490101840190232427299088, 324039587955982067401671500644224002097225
2770675563605002833346932459319562
Client tính toán khóa chung: 212026943726322725852123348070766205725931557925073644004429358755347738812, 2805559804044711301635114633534825270105752
101823238892898367825941960934790

Đang thực hiện tấn công bằng phương pháp ánh xạ vào nhóm con...
--> Phát hiện NODE. Áp dụng tấn công Node.
Double root: α = 0
Simple root: β = 4368590184733545720227961182704359358435747188309319510520316493183539079702
Parameter t = √(α - β) = 1
u = (G.y + t(G.x - α))/(G.y - t(G.x - α)) = 279008948418973326431645528486086898184818969568893370111751307437688429389
v = (P.y + t(P.x - α))/(P.y - t(P.x - α)) = 340207723175084690625457449822305818658748895713528012942099395183471638683
Private key found: k = 3963903911833444099026001790250531678485652182452420312170405092086735621359
!!! TẤN CÔNG THÀNH CÔNG !!!
Khóa riêng của Server được suy ra: 3963903911833444099026001790250531678485652182452420312170405092086735621359
Khóa riêng suy ra TRÙNG KHỐP với khóa riêng thực tế của Server.
```

Figure 11: Node Demo

Countermeasure: The use of singular curves must be strictly avoided. This is achieved through two layers of protection:

- Standardized Parameters:** Only use well-vetted, standardized elliptic curves (e.g., from NIST, SECG, Brainpool). These curves have been verified to be non-singular and to possess other important security properties.
- Parameter Validation:** If a system must accept custom curve parameters (p, A, B) , it must first verify the curve's validity before using it. This includes checking that the discriminant $\Delta = -(4A^3 + 27B^2)$ is non-zero modulo p . This ensures the curve is not singular and the group structure is not vulnerable.

IV.3.6 Supersingular Curves

MOV Attack [20]

The MOV attack (Menezes-Okamoto-Vanstone) reduces the ECDLP on certain elliptic curves $E(\mathbb{F}_p)$ to the standard DLP in a small extension field \mathbb{F}_{p^k} . The integer k is called the **embedding degree**, which is the smallest positive integer such that $n \mid (p^k - 1)$, where $n = \#E(\mathbb{F}_p)$ or $n = \text{ord}(P)$. If k is small (e.g., $k \leq 6$, or generally small enough

that DLP in \mathbb{F}_{p^k} is feasible), the curve is vulnerable. Curves for which k is small are often (but not always) **supersingular** curves. The attack uses a non-degenerate bilinear pairing, such as the Weil pairing $e_n : E[n] \times E[n] \rightarrow \mu_n(\mathbb{F}_{p^k})$, where $E[n]$ are points of order n and $\mu_n(\mathbb{F}_{p^k})$ is the group of n -th roots of unity in \mathbb{F}_{p^k} . The key property is $e_n(aP, bQ) = e_n(P, Q)^{ab}$. Given P (generator of order n) and $Q = mP$, the goal is to find m .

1. Choose a point $R \in E(\mathbb{F}_{p^k})$ such that $R \notin \langle P \rangle$ and $e_n(P, R) \neq 1$.
2. Compute $\alpha = e_n(P, R) \in \mathbb{F}_{p^k}^*$.
3. Compute $\beta = e_n(Q, R) = e_n(mP, R) = e_n(P, R)^m = \alpha^m \in \mathbb{F}_{p^k}^*$.
4. Solve the DLP $\beta = \alpha^m$ for m in the field $\mathbb{F}_{p^k}^*$.

If k is small, this DLP can be much easier to solve than the original ECDLP. For instance, if p is a 160-bit prime and $k = 2$, the DLP is in \mathbb{F}_{p^2} (a 320-bit field), which might be significantly easier than ECDLP over a 160-bit group. Cryptographically chosen curves usually have very large embedding degrees [1].

```
(sage_env) phuc@CHAUHOANGPHUC66:/mnt/d/UITerK18/HK4/Mat_ma_hoc/Cryptanalysis-on-ECC-based-Algorithms/MOV_Attack$ sage solve.sage
2
Pairing points to F*p^k
DLP solving initiated.....
29618469991922269
b'crypto{MOV_attack_on_non_supersingular_curves}\x02\x02'
```

Figure 12: MOV Attack Demo

Countermeasure: To prevent the MOV attack, elliptic curves used for cryptography must have a **large embedding degree k** . A large k ensures that the DLP in the extension field \mathbb{F}_{p^k} is at least as difficult to solve as the original ECDLP on the curve. During the curve selection process, candidate curves are tested to ensure their embedding degree is sufficiently large. For this reason, cryptographers almost always choose **ordinary (non-supersingular) curves**, as they typically have very large embedding degrees, making the MOV attack impractical.

IV.3.7 Anomalous Elliptic Curves

Smart Attack [21]

This attack, proposed by Nigel Smart, applies to elliptic curves where the number of points over \mathbb{F}_p is equal to p , i.e., $\#E(\mathbb{F}_p) = p$. Such curves are called anomalous curves. This condition implies that the trace of Frobenius $t = p + 1 - \#E(\mathbb{F}_p) = p + 1 - p = 1$.

The Smart attack provides a linear-time algorithm (in terms of $\log p$) for solving the ECDLP on these curves. The attack involves lifting the points $P, Q \in E(\mathbb{F}_p)$ to points P', Q' on the same elliptic curve but defined over the p -adic numbers \mathbb{Q}_p . This is done using Hensel's Lemma to find p -adic y -coordinates corresponding to the x -coordinates from \mathbb{F}_p .

If $Q = kP$ in $E(\mathbb{F}_p)$, then $Q' - kP'$ reduces to the point at infinity O modulo p . This means $Q' - kP'$ is in the kernel of the reduction map $E(\mathbb{Q}_p) \rightarrow E(\mathbb{F}_p)$. At a crucial step uses the p -adic elliptic logarithm $\psi : E_1(\mathbb{Q}_p) \rightarrow p\mathbb{Z}_p$, which is an isomorphism under certain conditions. The relationship becomes:

$$\psi(pQ') - k\psi(pP') \equiv 0 \pmod{p^N\mathbb{Z}_p} \quad (\text{for sufficiently large } N) \quad (1)$$

This allows solving for k :

$$k \equiv \frac{\psi(pQ')}{\psi(pP')} \pmod{p} \quad (2)$$

The p-adic logarithms can be computed efficiently. Such curves are generally avoided in practice

Countermeasure: Ensure that $\#E(\mathbb{F}_p) \neq p$ during curve parameter generation and validation.

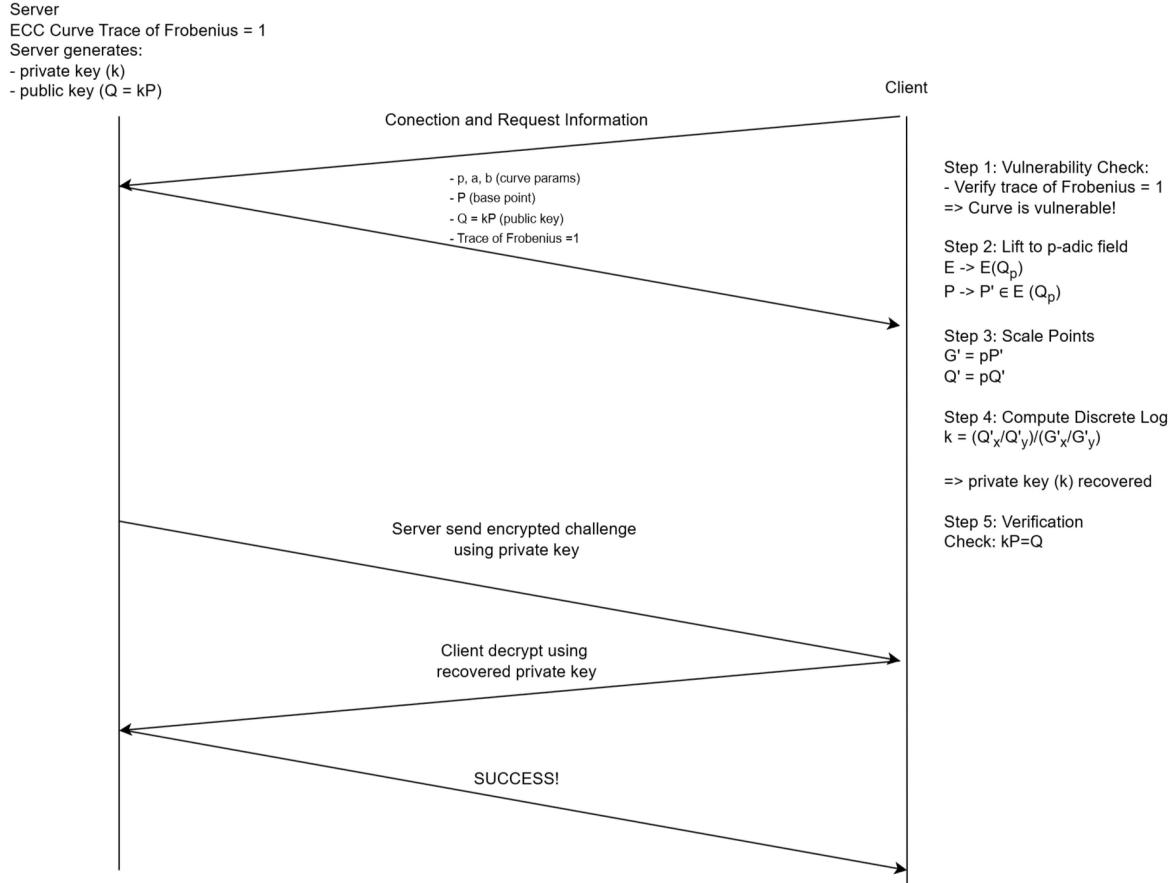


Figure 13: Smart Attack Diagram (Conceptual Illustration)

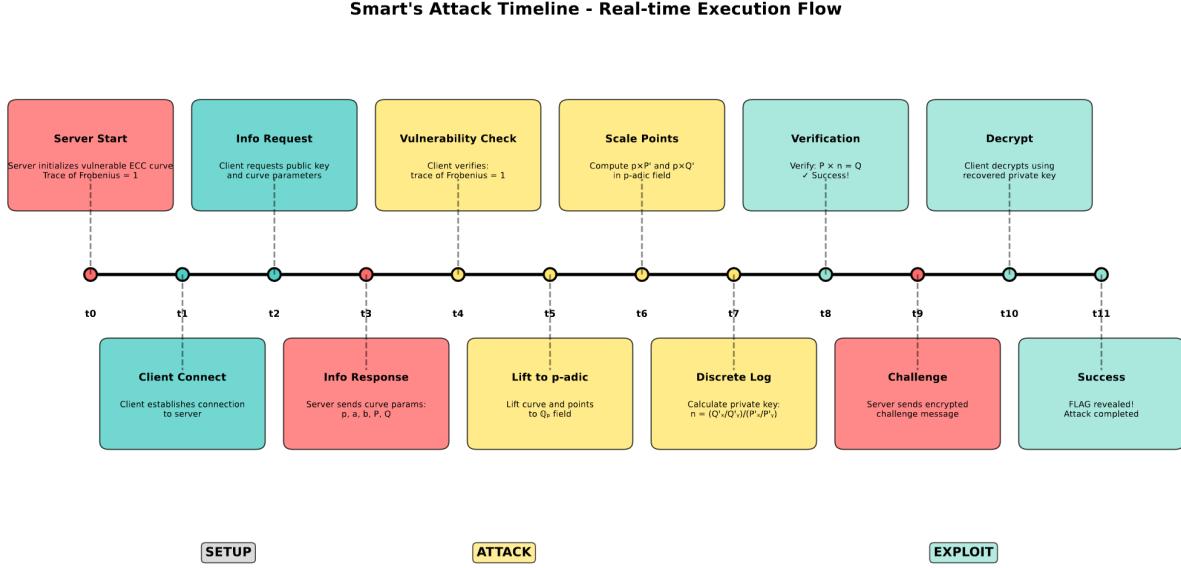


Figure 14: Smart Attack Timeline (Conceptual Illustration)

```
(sage_enr) [1]: /home/cuonghoangphuc66/Cryptography/smartAttack$ python run_demo.py
Smart's Attack Demo
This demo shows how Smart's Attack can break ECC with trace of Frobenius = 1
=====
Starting server...
Waiting 3 seconds for server to start...
Starting client attack...
It's prime
Trace of Frobenius: 1
Vulnerable to Smart's Attack: True
Server initialized with private key: 543479304263404346990617261983667862742125258741595901597880442711506907538558702859268801866398877885837577453751622575888466447375259873669418211773866
PUBKEY: 0x5f3636a89167a6fbfb7...
Server listening on localhost:8888
Waiting for connections...
Smart's Attack Demo - Client
Attacking ECC server with vulnerable curve...
Connected to server localhost:8888
*** PHASE 1: Getting server information ===
Host: localhost (127.0.0.1, 47364)
Curve parameters received:
Order: 543479304263404346990617261983667862742125258741595901597880442711506907538558702859268801866398877885837577453751622575888466447375259873669418211773866
Trace of Frobenius: 1
Basic point: 0xf150d024d0u2z8fd1... , 0x5f3636a89167a6fbfb7...
Public Key Q: (0x5851fffa8c5abc359b..., 0x690d4f71d7aac0f8fd1...)
Vulnerable to Smart's Attack: True

*** PHASE 2: Performing Smart's Attack ===

*** STARTING SMART'S ATTACK ===
Trace of Frobenius: 1
/ Curve is vulnerable (trace == 1)
lifts points to p-adic field...
Lifting points to p-adic field...
Computing discrete logarithm...
/ Private key found: 543479304263404346990617261983667862742125258741595901597880442711506907538558702859268801866398877885837577453751622575888466447375259873669418211773866
/ Attack successful! Private key verified.

*** PHASE 3: Testing with server challenge ===
Encrypted challenge received
/ Challenge decrypted successfully!
Decrypted message: This is a secret flag: FLAG{sm4rt_4tt4ck_d3m0}

*** ATTACK SUMMARY ===
target curve trace of Frobenius: 1
PUBKEY: 0x5f3636a89167a6fbfb7...
Attack status: SUCCESS
Connection closed with ('127.0.0.1', 47364)

Shutting down server...

Done completed!
```

Figure 15: Smart Attack Demo (Conceptual Illustration of SageMath use)

Countermeasure: The defense against the Smart attack is to ensure that the curve being used is not anomalous. During the parameter generation and validation phase, the order of the curve $\#E(\mathbb{F}_p)$ must be computed (e.g., using Schoof's algorithm). If it is found that $\#E(\mathbb{F}_p) = p$, the curve must be rejected. All standard, recommended curves have been checked to ensure they are not anomalous.

IV.4 ECDSA Signature Scheme

The Elliptic Curve Digital Signature Algorithm (ECDSA) [4] generation process is as follows: Let n be the order of the base point G . Let d_A be the private key and $Q_A = d_A G$ be the public key. To sign a message m :

1. Compute: $e = \text{HASH}(m)$ using a cryptographic hash function (e.g., SHA-256).
2. Let z be the leftmost L_n bits of e , where L_n is the bit length of n . (Often, z is e taken as an integer modulo n).
3. Choose a cryptographically secure random integer $k \in [1, n - 1]$ (the nonce).
4. Compute the curve point $(x_1, y_1) = kG$.
5. Compute $r = x_1 \pmod{n}$. If $r = 0$, go back to step 3.
6. Compute $s = k^{-1}(z + rd_A) \pmod{n}$. If $s = 0$, go back to step 3.
7. The signature is the pair (r, s) .

The security of ECDSA is analyzed in depth in works like [14].

IV.4.1 Not Hashing the Message

If the full message m is not hashed, but instead, z is derived directly from a (possibly truncated) part of m , vulnerabilities can arise. For example, if z is taken from the first L_n bits of m , an attacker could append arbitrary data to m without changing z , and thus the signature (r, s) would remain valid for the modified message.

Example:

Original signed message m_1 leading to z :

“Please authorize a payment of \$500 to Alice for consulting services.”

Attacker’s altered message m_2 (if only the prefix is used for z):

“Please authorize a payment of \$500 to Alice for consulting services. Also, transfer \$100,000 to Mallory’s offshore account.”

If z is derived only from the first part, both messages might yield the same z , and thus the same signature would validate m_2 . This highlights the importance of hashing the *entire* message that is to be signed.

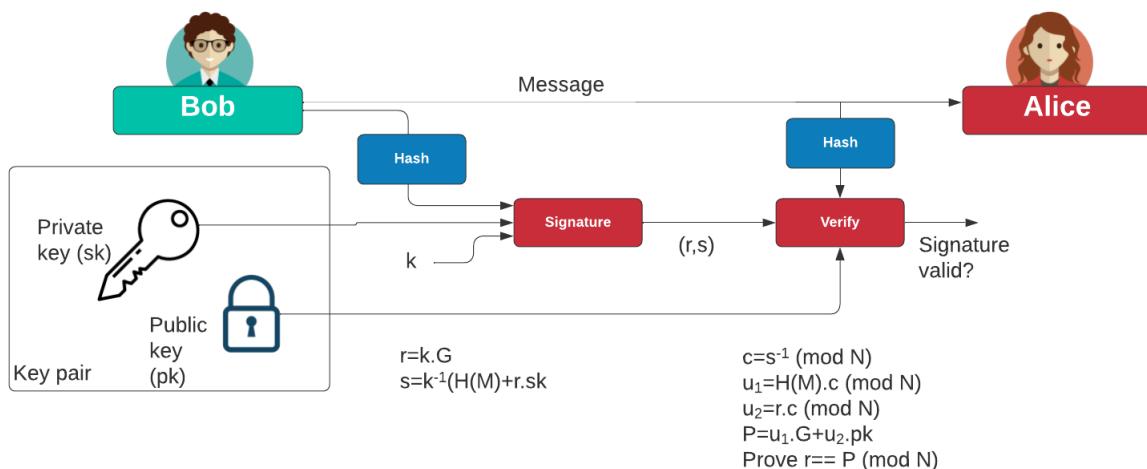


Figure 16: Outline of ECDSA

```
(base) phuc@CHAUHOANGPHUC66:~/mnt/d/UITerK18/HK4/Mat ma hoc/Cryptanalysis-on-ECC-based-Algorithms/not_hasin_g_messages_EDCSA$ python client.py
public_key: b3b7e7f747643d7733b84e14de84b8544605c26a40603387e0d2f8ccff8980362ec22b3166772ff79796dc10fe20af836a86175134d675801fb6e8a35fc5c6dd
Original Message: Please authorize a payment of $500 to Alice for consulting services.
Signature: 310a2086470a1fd9b64abbe94f3352e47c4f5cfed59bd3cadcb99673db03007810d30ff62afb13e2f6bf3ecb2bd4
S0ab298344c2bf2b0bd085493e19e
VALID: True
(base) phuc@CHAUHOANGPHUC66:~/mnt/d/UITerK18/HK4/Mat ma hoc/Cryptanalysis-on-ECC-based-Algorithms/not_hasin_g_messages_EDCSA$ python attacker.py
Đã nhận public key: b3b7e7f747643d7733b84e14de84b8544605c26a40603387e0d2f8ccff8980362ec22b3166772ff79796dc10fe20af836a86175134d675801fb6e8a35fc5c6dd
Message: Please authorize a payment of $500 to Alice for consulting services.
Evil Message: Please authorize a payment of $500 to Alice and $100,000 to Mallory's offshore account.
Stolen Signature: 310a2086470a1fd9b64abbe94f3352e47c4f5cfed59bd3cadcb99673db03007810d30ff62afb13e2f6bf3ecb2bd45ab08298344c2bf2b0bd098e5fd593e19e
SUCCESS! The evil message was accepted by the server.
(base) phuc@CHAUHOANGPHUC66:~/mnt/d/UITerK18/HK4/Mat ma hoc/Cryptanalysis-on-ECC-based-Algorithms/not_hasin_g_messages_EDCSA$
```

Figure 17: Not Hashing Message Demo

Countermeasure: The rule is simple and absolute: a digital signature must apply to the **entire message** being authenticated. This is accomplished by first computing a cryptographic hash (e.g., SHA-256) of the full, unambiguously-defined message. The resulting hash digest is then used as the input (z) to the signature algorithm. This creates a cryptographic commitment to the entire message content. Any modification to the message will result in a different hash, causing signature verification to fail.

IV.4.2 Nonce Reuse

If the same random nonce k is used to sign two different messages m_1 and m_2 (with corresponding hash values z_1 and z_2), an attacker who obtains both signatures (r, s_1) and (r, s_2) can recover the private key d_A . Since $kG = (x_1, y_1)$ is the same for both, $r = x_1 \pmod{n}$ will be the same. We have:

$$s_1 = k^{-1}(z_1 + rd_A) \pmod{n}$$

$$s_2 = k^{-1}(z_2 + rd_A) \pmod{n}$$

This implies:

$$ks_1 \equiv z_1 + rd_A \pmod{n}$$

$$ks_2 \equiv z_2 + rd_A \pmod{n}$$

Subtracting the two congruences:

$$k(s_1 - s_2) \equiv z_1 - z_2 \pmod{n}$$

If $s_1 \not\equiv s_2 \pmod{n}$ (which happens if $z_1 \not\equiv z_2 \pmod{n}$), then k can be recovered:

$$k \equiv (z_1 - z_2)(s_1 - s_2)^{-1} \pmod{n}$$

Once k is known, the private key d_A can be recovered from either signature equation:

$$d_A \equiv r^{-1}(ks_1 - z_1) \pmod{n}$$

(Requires $r \not\equiv 0 \pmod{n}$, which is a condition for valid signatures). This was famously exploited in the Sony PlayStation 3 hack [22].

```

=====
ECDSA NONCE REUSE ATTACK DEMONSTRATION
Mô phỏng tấn công sử dụng lại nonce trong ECDSA

[SERVER] Private key: 0x44bd46dcacf434c79c8a834eff64b0d2c9da85724bed3c6a0da346eb2757fade
[SERVER] Public key: (0x1e4bd26b9a707fc189f5fe111463eb8abd6763a774802f55dc19a81c400bcc, 0x1b60095571e2f5d7a9d36e6d00a90e49e14ef66b24efab0654195771fdb7e15f)
[SERVER] Vulnerable ECDSA server started on localhost:8888

[ATTACKER] Step 1: Getting server's public key...
[SERVER] New connection from ('127.0.0.1', 33918)
[ATTACKER] Server public key: (0x1e4bd26b9a707fc189f5fe311463eb8abd6763a774802f55dc19a81c400bcc, 0x1b60095571e2f5d7a9d36e6d00a90e49e14ef66b24efab0654195771fdb7e15f)

[ATTACKER] Step 2: Requesting signatures for different messages...
[SERVER] VULNERABLE: Using nonce 0x63fa2e02759110f9cbc7d91d7a4efd75cc1794048235348931fe10ae1493172 for message 1
[ATTACKER] Got signature 1 for message: 'Hello World'
[ATTACKER] r: 0x5aae00f54d7504c87dfe01b14b210177e13e08575b5603c6caf5acff9c9ae9
[ATTACKER] s: 0x90ae00f54d7504c87dfe01b14b210177e13e08575b5603c6caf5acff9c9ae9
[SERVER] VULNERABLE: Reusing nonce 0x63fa2e02759110f9cbc7d91d7a4efd75cc1794048235348931fe10ae1493172 for message 2!
[ATTACKER] Got signature 2 for message: 'Attack Message'
[ATTACKER] r: 0x5aae00f54d7504c87dfe01b14b210177e13e08575b5603c6caf5acff9c9ae9
[ATTACKER] s: 0x94026fc274a1a2f22c02fd0decaceedbf52cc023e8e20fde4af901f9f62ac50

[ATTACKER] Step 3: Analyzing signatures for nonce reuse...
[ATTACKER] Signature 1: r=0x5aae00f54d7504c87dfe01b14b210177e13e08575b5603c6caf5acff9c9ae9
[ATTACKER] Signature 2: r=0x5aae00f54d7504c87dfe01b14b210177e13e08575b5603c6caf5acff9c9ae9
[ATTACKER] s=0x94026fc274a1a2f22c02fd0decaceedbf52cc023e8e20fde4af901f9f62ac50

[ATTACKER] NONCE REUSE DETECTED!
[ATTACKER] r1 == r2, attempting to recover private key...

[ATTACKER] RECOVERED:
[ATTACKER] Nonce: 0x63fa2e02759110f9cbc7d91d7a4efd75cc1794048235348931fe10ae1493172
[ATTACKER] Private Key: 0x44bd46dcacf434c79c8a834eff64b0d2c9da85724bed3c6a0da346eb2757fade
[ATTACKER] PRIVATE KEY RECOVERY SUCCESSFUL!
[ATTACKER] Server's private key has been compromised!
[ATTACKER] Successfully forged signature for: 'I am the server'
[ATTACKER] Forged signature: r=0xe9d94250a400f7f25253c7faf9d8e964f3a91378202f28c027364d084da05b50, s=0xc5ec219b816fd40a0432f1bd8cd3fc2c338599f971b6718b3f5bab354aac679f

=====
ATTACK SUCCESSFUL!
Lỗi hóng nonce reuse đã được khai thác thành công.
Private key của server đã bị lộ!
```

Figure 18: Nonce Reuse Demo

Countermeasure: The nonce k must be unique for every signature and must be kept secret. There are two primary ways to ensure this:

1. **High-Quality Randomness:** Use a Cryptographically Secure Pseudo-Random Number Generator (CSPRNG) to generate a new value for k for each signature. This requires the system's entropy source to be reliable.
2. **Deterministic Nonces (RFC 6979):** This is the modern, preferred solution. The nonce k is generated deterministically from the private key d_A and the message hash z using an HMAC-based construction. This produces a unique and unpredictable nonce for every unique (d_A, z) pair, eliminating the risk of nonce reuse due to a faulty RNG.

IV.4.3 Biased Nonce and Lattice Attacks

One of the most critical requirements for the security of ECDSA is that the nonce k (a random number used once) must be chosen uniformly at random from the interval $[1, n - 1]$ and must be unique for each signature. If the nonce k is not truly random but is "biased" – for example, some bits of k are predictable, k is chosen from a range significantly smaller than n , or k has a special structure due to flaws in the random number generator (RNG) – then an attacker can recover the private key d_A by using lattice-based techniques, provided enough signatures are collected [23].

Principle of Biased Nonce Attacks From the ECDSA signature equation:

$$s = k^{-1}(z + rd_A) \pmod{n}$$

We can rearrange this to express k :

$$k \equiv s^{-1}(z + rd_A) \pmod{n}$$

Alternatively:

$$k \equiv s^{-1}z + s^{-1}rd_A \pmod{n}$$

Suppose an attacker collects m signatures (r_i, s_i) for messages with corresponding hash values z_i (for $i = 1, \dots, m$). For each signature, we have an equation relating the nonce k_i and the private key d_A :

$$k_i \equiv s_i^{-1}z_i + (s_i^{-1}r_i)d_A \pmod{n}$$

Let $u_i = s_i^{-1}z_i \pmod{n}$ and $v_i = s_i^{-1}r_i \pmod{n}$. Then:

$$k_i \equiv u_i + v_id_A \pmod{n}$$

This means that $k_i - v_id_A - u_i$ is a multiple of n . In other words:

$$k_i - v_id_A - u_i = t_in \quad \text{for some integer } t_i.$$

Or, approximately:

$$k_i \approx (v_id_A + u_i) \pmod{n}$$

If the nonces k_i are biased in some way (e.g., they are smaller than a certain threshold X , or certain bits of k_i are 0 or predictable), an attacker can exploit this information.

Using Lattices to Solve the Hidden Number Problem (HNP)

The problem of finding d_A from the above equations, given that the k_i 's have a certain bias, can be modeled as a form of the Hidden Number Problem (HNP) or the Closest Vector Problem (CVP) in a lattice.

One way to construct a lattice is as follows. We are looking for a value d_A (the private key) and "small" values k_1, \dots, k_m (the biased nonces) such that the following equations hold modulo n :

$$k_i - v_id_A \equiv u_i \pmod{n} \quad \text{for } i = 1, \dots, m$$

This can be rewritten as:

$$v_id_A - k_i + u_i \equiv 0 \pmod{n}$$

Or $v_id_A - k_i + u_i = \lambda_i n$ for some integer λ_i .

If we assume that $|k_i| < K_{max}$ (e.g., K_{max} is 2^ℓ if the top ℓ bits of k_i are 0), we can set up a lattice. Consider the lattice L generated by the columns (or rows, depending on convention) of a matrix. The precise construction of the lattice can be complex and depends on the exact assumption about the nonce bias. Prominent approaches are based on the work of Boneh and Durfee, or Howgrave-Graham for HNP.

For instance, if we know that $k_i < K_{max}$ and typically $d_A < n$. A common lattice construction for attacking biased ECDSA nonces involves finding a short vector in a lattice whose basis vectors are derived from the signature equations. Given m signatures, we have $k_is_i \equiv z_i + r_id_A \pmod{n}$. If the top L bits of each k_i are known (e.g., they are zero, so $k_i < 2^{\text{bitlength}(n)-L}$), we can construct a lattice. Consider the set of linear equations modulo n :

$$k_i \equiv u_i + v_id_A \pmod{n}$$

We are searching for d_A and small integers k_i . This is a classic setup for HNP. A lattice can be formed by vectors related to these congruences. For example, a lattice L could be generated by the rows of the following $(m+1) \times (m+1)$ matrix:

$$\begin{pmatrix} n & 0 & \dots & 0 & 0 \\ 0 & n & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & n & 0 \\ v_1 & v_2 & \dots & v_m & C \end{pmatrix}$$

where C is a carefully chosen constant (e.g., 1 or a small integer to give weight to d_A). We are looking for a vector $x = (x_0, x_1, \dots, x_m)$ in this lattice such that if $x = (d_A, \lambda_1, \dots, \lambda_m) \cdot M_{basis}$, then the resulting $k_i = u_i + v_i d_A - \lambda_i n$ are small. More practically, the problem is often framed as finding a vector (d_A, k_1, \dots, k_m) that satisfies the equations and where k_i are small. A common matrix used in lattice attacks on ECDSA (e.g., when L most significant bits of k_i are known for $i = 1, \dots, d$) might look like:

$$M = \begin{pmatrix} n & 0 & \dots & 0 & 0 \\ 0 & n & \dots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \dots & n & 0 \\ s_1^{-1}r_1 & s_2^{-1}r_2 & \dots & s_d^{-1}r_d & X \end{pmatrix}_{(d+1) \times (d+1)}$$

where X is a scaling factor, e.g., $X \approx 1/2^{\text{bitlength}(n)-L}$. The target is to find a short vector in the lattice spanned by the rows of this matrix. Such a vector corresponds to a linear combination of the rows which, when its last component is appropriately scaled, reveals d_A . The other components relate to the nonces k_i .

The LLL algorithm (Lenstra–Lenstra–Lovász) is a powerful tool used to find a basis of "short" vectors for a given lattice. If a vector in this basis (or a specific linear combination thereof) is sufficiently short, it can reveal information about d_A .

Conditions for a Successful Attack The number of signatures m required and the probability of success depend on:

1. **The bias of the nonce k :** The greater the bias (e.g., the more bits of k are known, or the smaller k is compared to n), the fewer signatures are needed. If only a few bits of k are leaked per signature (e.g., 2-3 bits), tens to hundreds of signatures might be required for a successful attack.
2. **The size of n :** The larger the modulus n , the harder the attack becomes, as the search space is larger.
3. **The dimension of the lattice:** The dimension of the lattice (usually related to the number of signatures m) affects the running time of the LLL algorithm. The LLL algorithm has a polynomial time complexity in the dimension of the lattice and the logarithm of the size of its entries.

If an attacker can collect enough signatures with biased nonces, they can construct an appropriate lattice and use the LLL algorithm (or stronger variants like BKZ) to find

a short vector. This short vector often corresponds to a linear (or approximately linear) relationship involving the private key d_A and the known values (r_i, s_i, z_i) , allowing the attacker to solve for d_A .

These attacks underscore the importance of using a cryptographically strong pseudo-random number generator (CSPRNG) to generate the nonce k , or, preferably, using secure deterministic nonce generation methods as described in RFC 6979. RFC 6979 generates the nonce k deterministically from the private key and the message hash, completely eliminating reliance on an RNG at signing time and thereby avoiding issues of biased or repeated nonces.

```
b'Give me da message in hex: '
[DEBUG] Sent 0x21 bytes:
b'63c5ea98fe15683605f22ffecbd70d53\n'
[DEBUG] Received 0x1aa bytes:
b'Here is your signature: (85497716566809710944415565482813148502140554704877171819458118289493361556912298528843521959277908237054963570618820570749007
9128308419568863931520944564684, 616846772435084109321577441016154832104555653743034013137912827642041519847649113915378479934835466812348775536278360215015
9715249614649221082099049751621873)\n'
b'Choose an option:\n'
b'    [1] : Sign message\n'
b'    [2] : Get flag\n'
b'    [3] : Fun           \n'
b'> '
[+] found privkey 33070287473558104295871323776200026636608235044745627367547179319663148505961895606498891086436346029188045854077139423740270154846416882
26897766028407876582
[DEBUG] Sent 0x2 bytes:
b'2\n'
/mnt/d/UITerK18/HK4/Mat ma hoc/Cryptanalysis-on-ECC-based-Algorithms/bias_nonse_ECDSA/exp.py:107: BytesWarning: Text is not bytes; assuming ASCII, no guarantees. See https://docs.pwntools.com/#bytes
io.sendlineafter(b'r:", str(sig[0]))'
[DEBUG] Received 0x3b bytes:
b'Rizz me with signature of 'get flag' and you shall pass\n"
b'r:'
[DEBUG] Sent 0xd bytes:
b'3'074192440136967282965995708181161426289693888711893311528311028590545490804864690494855815207857251436604563269713126312725385472753353923771653808
079688\n'
/mnt/d/UITerK18/HK4/Mat ma hoc/Cryptanalysis-on-ECC-based-Algorithms/bias_nonse_ECDSA/exp.py:108: BytesWarning: Text is not bytes; assuming ASCII, no guarantees. See https://docs.pwntools.com/#bytes
io.sendlineafter(b's:", str(sig[1]))'
[DEBUG] Received 0x3 bytes:
b's:'
[DEBUG] Sent 0x9e bytes:
b'336188817974184996062407834456091854206548964811232130380686079793912019722238453346653353247208657563990654918349207475216536426454648781900457677939
4376369\n'
[DEBUG] Received 0x37 bytes:
b'Congratz! Here is your reward b'random_test_flag_here'\n"
b"Congratz! Here is your reward b'random_test_flag_here'\n"
[*] Stopped process '/home/phuc/miniconda3/envs/sage_env/bin/python' (pid 7779)
```

Figure 19: Biased Nonce Demo

Countermeasure: The vulnerability to biased nonces is a direct consequence of flaws in the nonce generation process. The solutions are the same as for preventing nonce reuse, but the emphasis is on the *quality* of the nonce’s randomness.

1. **Unbiased CSPRNG:** If a random nonce is used, the generator must produce outputs that are statistically uniform across the entire range $[1, n - 1]$. Any predictable pattern can be exploited.
2. **Deterministic Nonces (RFC 6979):** This approach is the most effective countermeasure. The deterministic generation of k from the private key and message hash ensures that the resulting nonce is computationally indistinguishable from a uniformly random value to an attacker. This completely mitigates attacks based on nonce bias and is the industry best practice.

V Proposed Solution

V.1 ECDH (Elliptic Curve Diffie-Hellman) Vulnerabilities

V.1.1 Curve Agreement and Trust: Critical Security Considerations in ECDH

In Elliptic Curve Diffie-Hellman (ECDH), both parties must agree on the elliptic curve parameters (p, A, B, G, n, h) at the beginning of the key exchange protocol. This agreement is a fundamental security requirement detailed in standards like [5].

The Main Risk: Untrusted Curve Parameters

If one party (Alice) allows the other party (Bob, potentially an attacker or a Man-in-the-Middle) to supply the curve parameters, Bob can choose parameters that weaken the security of the exchange for Alice. This can lead to:

1. **Reduced ECDLP difficulty:** Bob can choose a curve where the ECDLP is easy (e.g., a singular curve [8], a supersingular curve vulnerable to the MOV attack [20], an anomalous curve vulnerable to Smart's attack [21], or a curve whose order is small or smooth [17]). Alice would compute her shared secret using her private key on this weak curve, allowing Bob to determine Alice's private key (or the shared secret directly).
2. **Invalid Curve Attacks:** As described in Section IV.B.4, Bob can provide a point that is not on the intended curve but on a different curve \tilde{E} where computations are done. Alice, using her private key d_A , would compute $d_A P_B$ on \tilde{E} . If \tilde{E} has a small order subgroup containing P_B , Bob learns $d_A \pmod{\text{ord}_{\tilde{E}}(P_B)}$ [19].
3. **Small Subgroup Attacks:** Even if the main curve E is secure, Bob might provide a point P_B that belongs to a small subgroup of E . Alice computes $d_A P_B$. The resulting shared secret $d_A d_B G$ will then also be in this small subgroup. Bob can then test possible shared secrets (since there are few of them).

To mitigate this, Alice must either:

- Only use standardized, well-vetted curve parameters (e.g., from NIST [4], SECG [10], or widely trusted curves like Curve25519 [6]).
- If Bob provides curve parameters, Alice must rigorously validate them (check for non-singularity, estimate order, check for known weaknesses). This is complex and generally discouraged.
- If Bob provides a public key (a point P_B), Alice must validate that P_B is on the agreed curve and is not the point at infinity. She should also verify that P_B has the correct order (i.e., $n P_B = \mathcal{O}$ and P_B is not in any small subgroups, often checked by $h P_B \neq \mathcal{O}$ if h is small and n is prime). Point validation is a key defense [19].

V.1.2 Solution Architecture

To prevent the classes of attacks associated with ECDH (e.g., invalid curve attacks [18], malicious parameter injection, weak key reuse), the architecture must be built on strong cryptographic primitives, strict validation mechanisms, and properly modularized components.

Cryptographic Algorithms and Protocols

- **Use Standardized Curves:** Exclusively use well-known and vetted elliptic curves such as those specified in NIST FIPS 186-4 [4], SECG SEC 2 [10], or modern high-security curves like Curve25519 [6] and Ed25519. Avoid custom or non-standard curves unless thoroughly analyzed by experts [11].
- **Point Validation:** Always validate incoming public keys (points). This includes:
 1. Checking if the coordinates are in the correct range (e.g., $0 \leq x, y < p$).
 2. Verifying that the point satisfies the curve equation $y^2 \equiv x^3 + Ax + B \pmod{p}$.
 3. Ensuring the point is not the point at infinity \mathcal{O} .
 4. Verifying that the point lies in the correct subgroup of prime order n . This is typically done by checking $nP = \mathcal{O}$. For curves with cofactor $h > 1$, also check that P is not in any small subgroup. This can be done by verifying $hP \neq \mathcal{O}$ if P is supposed to generate the full group of order hn , or by working with hP_B if the key derivation only needs a point in the prime order subgroup.
- **Secure Key Generation:** Private keys must be generated using a cryptographically secure pseudo-random number generator (CSPRNG) and be of appropriate length (e.g., close to the bit length of n).
- **Ephemeral Keys (ECDHE):** For key exchange, prefer Elliptic Curve Diffie-Hellman Ephemeral (ECDHE). In ECDHE, both parties generate a new key pair for each session, providing forward secrecy. This prevents compromise of past session keys if a long-term private key is compromised.

V.2 ECDSA (Elliptic Curve Digital Signature Algorithm) Vulnerabilities

V.2.1 Nonce Management is Critical

The security of ECDSA heavily relies on the uniqueness and unpredictability of the per-signature nonce k .

- **Prevent Nonce Reuse:** As shown in Section IV.C.2, reusing k for different messages with the same private key leads to private key recovery [22]. Implementations must ensure k is never repeated.
- **Prevent Biased Nonces:** Nonces must be uniformly random or generated deterministically in a way that prevents bias (e.g., as per RFC 6979). Biased nonces can be exploited by lattice attacks [23]. Using a CSPRNG is essential if nonces are generated randomly.
- **Deterministic ECDSA (RFC 6979):** To avoid issues with faulty RNGs leading to nonce reuse or bias, consider implementing deterministic ECDSA as specified in RFC 6979. This standard defines a way to generate k deterministically from the private key and the message hash, ensuring uniqueness and good distribution properties while removing reliance on an external RNG at signing time.

V.2.2 Signature and Message Integrity

- **Hash the Entire Message:** Always hash the entire message being signed, as discussed in Section IV.C.1. The hash input should unambiguously represent the data being protected.
- **Proper Signature Verification:** When verifying a signature (r, s) :
 1. Check that $r, s \in [1, n - 1]$.
 2. Compute $e = \text{HASH}(m)$ and let z be the integer derived from e .
 3. Compute $w = s^{-1} \pmod{n}$.
 4. Compute $u_1 = zw \pmod{n}$ and $u_2 = rw \pmod{n}$.
 5. Compute the curve point $(x_1, y_1) = u_1G + u_2Q_A$.
 6. If $(x_1, y_1) = \mathcal{O}$, the signature is invalid.
 7. The signature is valid if and only if $r \equiv x_1 \pmod{n}$.
- **Protect Against Fault Attacks:** Implementations on physical devices should consider countermeasures against fault injection attacks (e.g., Bellcore attack variants) that might corrupt computations to leak key material [24, 18].

VI Deployment

To ensure the secure deployment of our ECC-based cryptosystem, we propose the following strategies to mitigate risks and enhance security:

VI.1 Use Recommended Curves and Strong Keys

To prevent attacks exploiting weaknesses in elliptic curves, carefully select curves that are verified and standardized. We strongly recommend using curves such as:

- **Curve25519** (and its signature counterpart Ed25519): Known for high security, efficiency, and resistance to many side-channel and invalid curve attacks due to its Montgomery/Edwards form and careful parameter selection [6]. The use of specific curve forms like Edwards or Hessian can also improve resistance to side-channel attacks [25].
- **NIST P-curves (P-256, P-384, P-521)**: Standardized by NIST [4] and widely supported, though they require more careful implementation to avoid certain pitfalls compared to newer curves.
- Other curves from SECG [10] or those vetted by projects like SafeCurves [11]. For example, Curve448 (Ed448).

These curves are endorsed by standards like NIST and SECG, and modern recommendations often favor curves like Curve25519 for new deployments. For further details, refer to:

SECG Guidelines: <https://www.secg.org/sec2-v2.pdf>

Standard Curve Specifications: <https://neuromancer.sk/std/> (This is a useful compilation, but primary sources like NIST/SECG should be consulted.)

SafeCurves: <https://safecurves.cr.yp.to>

Ensure private keys are generated using a cryptographically secure random number generator and have a bit length comparable to the order of the curve's base point.

VI.2 Prevent Invalid Curve Attacks

To counter invalid curve attacks (Section IV.B.4), the server (or any party receiving an ECC point) must validate all untrusted user inputs. Specifically:

- **Full Point Validation:** Before using any externally supplied point $P = (x, y)$ in cryptographic operations:
 1. Verify that x and y coordinates are in the field \mathbb{F}_p (i.e., $0 \leq x, y < p$).
 2. Verify that the point satisfies the curve equation: $y^2 \equiv x^3 + Ax + B \pmod{p}$.
 3. Verify that the point is not the point at infinity \mathcal{O} .
 4. Verify that the point is in the correct (large prime order n) subgroup. This is done by checking $nP = \mathcal{O}$. For curves with a small cofactor $h > 1$, it is also common to check that $P \neq \mathcal{O}$ after multiplying by h (i.e., $hP \neq \mathcal{O}$) to ensure it is not in a small cofactor subgroup, or alternatively ensure that the key derivation works with hP . Most modern curve choices (like Curve25519) simplify this by having small cofactors (e.g., $h = 8$ for Curve25519, $h = 4$ for Ed25519) and specific protocols for their use. Validating points is crucial [19].

- Implement strict input validation for all parameters to reject malformed or malicious data.

Using curves in Montgomery or Edwards form (like Curve25519/Ed25519) can intrinsically avoid some of these checks or make them simpler [6].

VI.3 Regular Security Updates and Testing

To maintain the integrity of the cryptosystem:

- Regularly update cryptographic libraries (e.g., OpenSSL, libsodium, PyCryptodome) and dependencies to patch known vulnerabilities.
- Conduct periodic security audits, including code reviews and penetration testing, focusing on the cryptographic implementation and protocol logic.
- Stay informed about new research in ECC cryptanalysis and adjust security measures accordingly.
- Upgrade to the latest secure versions of ECC implementations as new standards emerge or older ones are found to have weaknesses [7].

VI.4 Recommended Curves for Specific Applications

For applications such as key exchange (e.g., ECDH) or digital signatures (e.g., ECDSA), we recommend using standardized and well-vetted curves like:

- **Curve25519 (for ECDH, often called X25519) and Ed25519 (for signatures):** Ideal for high-speed cryptography, widely adopted in modern protocols (TLS 1.3, SSH, Signal), and designed with several safety features [6].
- **NIST P-256 (secp256r1):** Widely deployed but has more "special-case" handling requirements in implementation than Curve25519. Still considered secure if implemented correctly, as per [4].

The choice may also depend on interoperability requirements with existing systems. Careful selection of curves is paramount for security [11].

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