

Digital Signatures

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July 24, 2018

Group Theory Recap

Groups

Definition

A set G with a binary operation \star defined on it is called a group if

- the operation \star is associative,
- there exists an identity element $e \in G$ such that for any $a \in G$

$$a \star e = e \star a = a,$$

- for every $a \in G$, there exists an element $b \in G$ such that

$$a \star b = b \star a = e.$$

Example

- Modulo n addition on $\mathbb{Z}_n = \{0, 1, 2, \dots, n-1\}$

Cyclic Groups

Definition

A finite group is a group with a finite number of elements. The order of a finite group G is its cardinality.

Definition

A cyclic group is a finite group G such that each element in G appears in the sequence

$$\{g, g \star g, g \star g \star g, \dots\}$$

for some particular element $g \in G$, which is called a generator of G .

Example

$\mathbb{Z}_6 = \{0, 1, 2, 3, 4, 5\}$ is a cyclic group with a generator 1

\mathbb{Z}_n and \mathbb{Z}_n^*

- For an integer $n \geq 1$, $\mathbb{Z}_n = \{0, 1, 2, \dots, n-1\}$
 - Operation is addition modulo n
 - \mathbb{Z}_n is cyclic with generator 1
- For an integer $n \geq 2$, $\mathbb{Z}_n^* = \{i \in \mathbb{Z}_n \setminus \{0\} \mid \gcd(i, n) = 1\}$
 - Operation is multiplication modulo n
 - $|\mathbb{Z}_n^*| = n-1$ if n is a prime
 - \mathbb{Z}_n^* is cyclic if n is a prime
- **Definition:** If G is a cyclic group of order q with generator g , then for $h \in G$ the unique $x \in \mathbb{Z}_q$ which satisfies $g^x = h$ is called the discrete logarithm of h with respect to g .
- Finding DLs is easy in \mathbb{Z}_n
- Finding DLs is hard in \mathbb{Z}_n^*

Cryptography based on the Discrete Logarithm Problem

Diffie-Hellman Protocol

- Alice and Bob wish to generate a shared secret key using a public channel
 1. Alice runs a group generation algorithm to get (G, q, g) where G is a cyclic group of order q with generator g .
 2. Alice chooses a uniform $x \in \mathbb{Z}_q$ and computes $h_A = g^x$.
 3. Alice sends (G, q, g, h_A) to Bob.
 4. Bob chooses a uniform $y \in \mathbb{Z}_q$ and computes $h_B = g^y$. He sends h_B to Alice. He also computes $k_B = h_A^y$.
 5. Alice computes $k_A = h_B^x$.

By construction, $k_A = k_B$.

- An adversary capable of finding DLs in G can learn the key

El Gamal Encryption

- Suppose Bob wants to send Alice an encrypted message
- Alice publishes her public key $\langle G, q, g, h \rangle$
 - G is a cyclic group of order q with generator g
 - $h = g^x$ where $x \in \mathbb{Z}_q$ is Alice's secret key
- **Encryption:** For message $m \in G$, Bob chooses a uniform $y \in \mathbb{Z}_q$ and outputs ciphertext

$$\langle g^y, h^y \cdot m \rangle.$$

- **Decryption:** From ciphertext $\langle c_1, c_2 \rangle$, Alice recovers

$$\hat{m} := c_2 \cdot c_1^{-x}$$

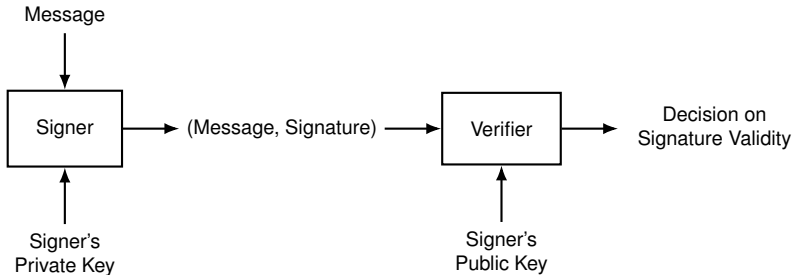
Schnorr Identification Scheme

- Let G be a cyclic group of order q with generator g
- Identity corresponds to knowledge of private key x where $h = g^x$
- A prover wants to prove that she knows x to a verifier without revealing it
 1. Prover picks $k \leftarrow \mathbb{Z}_q$ and sends initial message $I = g^k$
 2. Verifier sends a challenge $r \leftarrow \mathbb{Z}_q$
 3. Prover sends $s = rx + k \bmod q$
 4. Verifier checks $g^s \cdot h^{-r} \stackrel{?}{=} I$
- Passive eavesdropping does not reveal x
 - (I, r) is uniform on $G \times \mathbb{Z}_q$ and $s = \log_g(I \cdot y^r)$
 - Transcripts with same distribution can be simulated without knowing x
 - Choose r, s uniformly from \mathbb{Z}_q and set $I = g^s \cdot h^{-r}$
- If a cheating prover can generate two responses, he can implicitly compute discrete logarithm
 - Section 19.1 of Boneh-Shoup

Digital Signatures

Digital Signatures

- Digital signatures prove that the signer knows private key
- Interactive protocols are not feasible in practice



Schnorr Signature Algorithm

- Based on the Schnorr identification scheme
- Let G be a cyclic group of order q with generator g
- Let $H : \{0, 1\}^* \mapsto \mathbb{Z}_q$ be a cryptographic hash function
- Signer knows $x \in \mathbb{Z}_q$ such that public key $h = g^x$
- **Signer:**
 1. On input $m \in \{0, 1\}^*$, chooses $k \leftarrow \mathbb{Z}_q$
 2. Sets $I := g^k$
 3. Computes $r := H(I, m)$
 4. Computes $s = rx + k \bmod q$
 5. Outputs (r, s) as signature for m
- **Verifier**
 1. On input m and (r, s)
 2. Compute $I := g^s \cdot h^{-r}$
 3. Signature valid if $H(I, m) \stackrel{?}{=} r$
- Example of Fiat-Shamir transform
- Patented by Claus Schnorr in 1988

Digital Signature Algorithm

- Part of the Digital Signature Standard issued by NIST in 1994
- Based on the following identification protocol
 1. Suppose prover knows $x \in \mathbb{Z}_q$ such that public key $h = g^x$
 2. Prover chooses $k \leftarrow \mathbb{Z}_q^*$ and sends $I := g^k$
 3. Verifier chooses uniform $\alpha, r \in \mathbb{Z}_q$ and sends them
 4. Prover sends $s := [k^{-1} \cdot (\alpha + xr) \bmod q]$ as response
 5. Verifier accepts if $s \neq 0$ and

$$g^{\alpha s^{-1}} \cdot h^{rs^{-1}} \stackrel{?}{=} I$$

- Digital Signature Algorithm
 1. Let $H : \{0, 1\}^* \mapsto \mathbb{Z}_q$ be a cryptographic hash function
 2. Let $F : G \mapsto \mathbb{Z}_q$ be a function, not necessarily CHF
 3. **Signer:**
 - 3.1 On input $m \in \{0, 1\}^*$, chooses $k \leftarrow \mathbb{Z}_q^*$ and sets $r := F(g^k)$
 - 3.2 Computes $s := [k^{-1} \cdot (H(m) + xr)] \bmod q$
 - 3.3 If $r = 0$ or $s = 0$, choose k again
 - 3.4 Outputs (r, s) as signature for m
 4. **Verifier**
 - 4.1 On input m and (r, s) with $r \neq 0, s \neq 0$ checks

$$F\left(g^{H(m)s^{-1}} h^{rs^{-1}}\right) \stackrel{?}{=} r$$

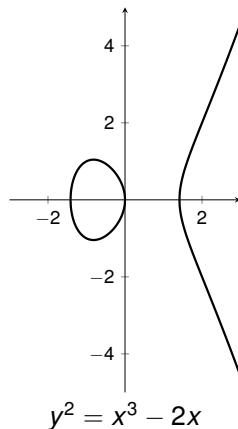
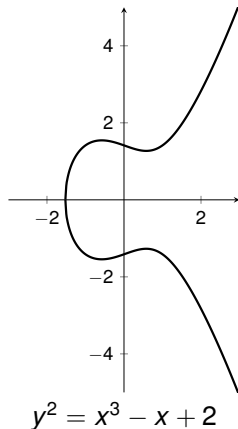
Elliptic Curves Over Real Numbers

Elliptic Curves over Reals

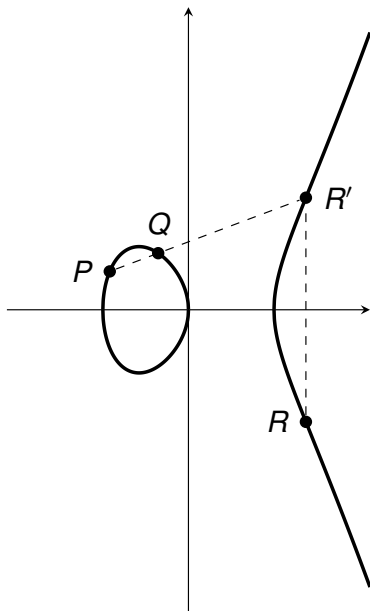
The set E of real solutions (x, y) of

$$y^2 = x^3 + ax + b$$

along with a “point of infinity” \mathcal{O} . Here $4a^3 + 27b^2 \neq 0$.



Point Addition (1/3)



$$P = (x_1, y_1), Q = (x_2, y_2)$$

$$x_1 \neq x_2$$

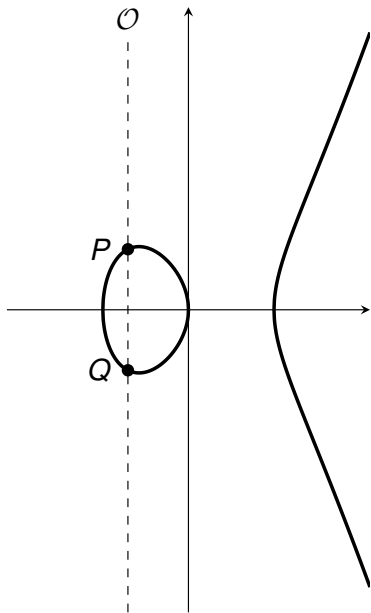
$$P + Q = R$$

$$R = (x_3, y_3)$$

$$x_3 = \left(\frac{y_2 - y_1}{x_2 - x_1} \right)^2 - x_1 - x_2$$

$$y_3 = \left(\frac{y_2 - y_1}{x_2 - x_1} \right) (x_1 - x_3) - y_1$$

Point Addition (2/3)

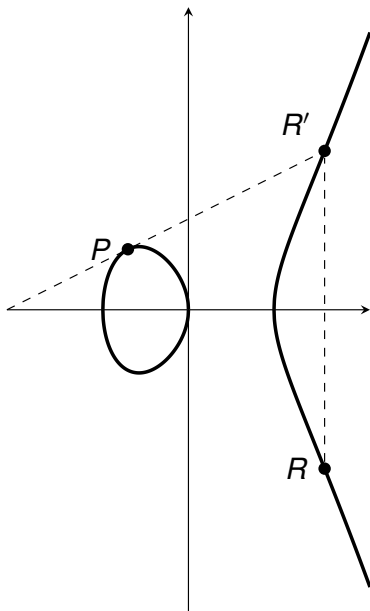


$$P = (x_1, y_1), Q = (x_2, y_2)$$

$$x_1 = x_2, y_1 = -y_2$$

$$P + Q = \mathcal{O}$$

Point Addition (3/3)



$$P = (x_1, y_1), Q = (x_2, y_2)$$

$$x_1 = x_2, y_1 = y_2 \neq 0$$

$$P + Q = R$$

$$R = (x_3, y_3)$$

$$x_3 = \left(\frac{3x_1^2 + a}{2y_1} \right)^2 - 2x_1$$

$$y_3 = \left(\frac{3x_1^2 + a}{2y_1} \right) (x_1 - x_3) - y_1$$

Elliptic Curves Over Finite Fields

Fields

Definition

A set F together with two binary operations $+$ and $*$ is a field if

- F is an abelian group under $+$ whose identity is called 0
- $F^* = F \setminus \{0\}$ is an abelian group under $*$ whose identity is called 1
- For any $a, b, c \in F$

$$a * (b + c) = a * b + a * c$$

Definition

A finite field is a field with a finite cardinality.

Prime Fields

- $\mathbb{F}_p = \{0, 1, 2, \dots, p-1\}$ where p is prime
- $+$ and $*$ defined on \mathbb{F}_p as

$$x + y = x + y \bmod p,$$

$$x * y = xy \bmod p.$$

- \mathbb{F}_5

+	0	1	2	3	4
0	0	1	2	3	4
1	1	2	3	4	0
2	2	3	4	0	1
3	3	4	0	1	2
4	4	0	1	2	3

*	0	1	2	3	4
0	0	0	0	0	0
1	0	1	2	3	4
2	0	2	4	1	3
3	0	3	1	4	2
4	0	4	3	2	1

- In fields, division is multiplication by multiplicative inverse

$$\frac{x}{y} = x * y^{-1}$$

Characteristic of a Field

Definition

Let F be a field with multiplicative identity 1. The characteristic of F is the smallest integer p such that

$$\underbrace{1 + 1 + \cdots + 1 + 1}_{p \text{ times}} = 0$$

Examples

- \mathbb{F}_2 has characteristic 2
- \mathbb{F}_5 has characteristic 5
- \mathbb{R} has characteristic 0

Theorem

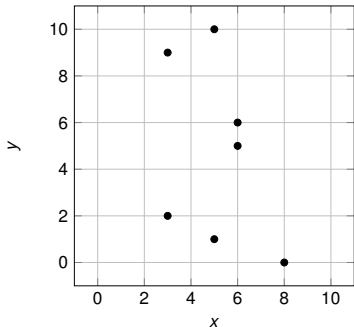
The characteristic of a finite field is prime

Elliptic Curves over Finite Fields

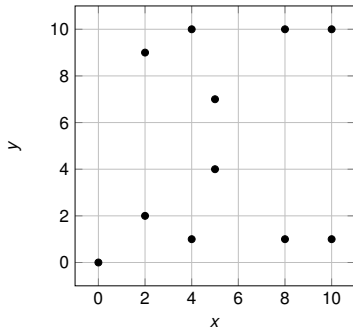
For $\text{char}(F) \neq 2, 3$, the set E of solutions (x, y) in \mathbb{F}^2 of

$$y^2 = x^3 + ax + b$$

along with a “point of infinity” \mathcal{O} . Here $4a^3 + 27b^2 \neq 0$.



$$y^2 = x^3 + 10x + 2 \text{ over } \mathbb{F}_{11}$$



$$y^2 = x^3 + 9x \text{ over } \mathbb{F}_{11}$$

Point Addition for Finite Field Curves

- Point addition formulas derived for reals are used
- Example: $y^2 = x^3 + 10x + 2$ over \mathbb{F}_{11}

+	\mathcal{O}	(3, 2)	(3, 9)	(5, 1)	(5, 10)	(6, 5)	(6, 6)	(8, 0)
\mathcal{O}	\mathcal{O}	(3, 2)	(3, 9)	(5, 1)	(5, 10)	(6, 5)	(6, 6)	(8, 0)
(3, 2)	(3, 2)	(6, 6)	\mathcal{O}	(6, 5)	(8, 0)	(3, 9)	(5, 10)	(5, 1)
(3, 9)	(3, 9)	\mathcal{O}	(6, 5)	(8, 0)	(6, 6)	(5, 1)	(3, 2)	(5, 10)
(5, 1)	(5, 1)	(6, 5)	(8, 0)	(6, 6)	\mathcal{O}	(5, 10)	(3, 9)	(3, 2)
(5, 10)	(5, 10)	(8, 0)	(6, 6)	\mathcal{O}	(6, 5)	(3, 2)	(5, 1)	(3, 9)
(6, 5)	(6, 5)	(3, 9)	(5, 1)	(5, 10)	(3, 2)	(8, 0)	\mathcal{O}	(6, 6)
(6, 6)	(6, 6)	(5, 10)	(3, 2)	(3, 9)	(5, 1)	\mathcal{O}	(8, 0)	(6, 5)
(8, 0)	(8, 0)	(5, 1)	(5, 10)	(3, 2)	(3, 9)	(6, 6)	(6, 5)	\mathcal{O}

- The set $E \cup \mathcal{O}$ is closed under addition
- In fact, its a group

Bitcoin's Elliptic Curve: secp256k1

- $y^2 = x^3 + 7$ over \mathbb{F}_p where

$$p = \underbrace{\text{FFFFFFFF} \dots \text{FFFFFFFF}}_{48 \text{ hexadecimal digits}} \text{ FFFFFFFF FFFFFFFC2F}$$
$$= 2^{256} - 2^{32} - 2^9 - 2^8 - 2^7 - 2^6 - 2^4 - 1$$

- $E \cup \mathcal{O}$ has cardinality n where

$$n = \text{FFFFFFFF FFFFFFFF FFFFFFFF FFFFFFFF}$$
$$\text{BAAEDCE6 AF48A03B BFD25E8C D0364141}$$

- Private key is $k \in \{1, 2, \dots, n-1\}$
- Public key is kP where $P = (x, y)$

$$x = \text{79BE667E F9DCBBAC 55A06295 CE870B07}$$
$$\text{029BFCDB 2DCE28D9 59F2815B 16F81798,}$$
$$y = \text{483ADA77 26A3C465 5DA4FBFC 0E1108A8}$$
$$\text{FD17B448 A6855419 9C47D08F FB10D4B8.}$$

Point Multiplication using Double-and-Add

- Point multiplication: kP calculation from k and P
- Let $k = k_0 + 2k_1 + 2^2k_2 + \cdots + 2^mk_m$ where $k_i \in \{0, 1\}$
- Double-and-Add algorithm
 - Set $N = P$ and $Q = \mathcal{O}$
 - for $i = 0, 1, \dots, m$
 - if $k_i = 1$, set $Q \leftarrow P + N$
 - Set $N \leftarrow 2N$
 - Return Q

Why ECC?

- For elliptic curves $E(\mathbb{F}_q)$, best DL algorithms are exponential in $n = \lceil \log_2 q \rceil$

$$C_{EC}(n) = 2^{n/2}$$

- In \mathbb{F}_p^* , best DL algorithms are sub-exponential in $N = \lceil \log_2 p \rceil$
 - $L_p(v, c) = \exp\left(c(\log p)^v (\log \log p)^{(1-v)}\right)$ with $0 < v < 1$
- Using GNFS method, DLs can be found in $L_p(1/3, c_0)$ in \mathbb{F}_p^*

$$C_{CONV}(N) = \exp\left(c_0 N^{1/3} (\log(N \log 2))^{2/3}\right)$$

- Best algorithms for factorization have same asymptotic complexity
- For similar security levels

$$n = \beta N^{1/3} (\log(N \log 2))^{2/3}$$

- Key size in ECC grows slightly faster than cube root of conventional key size
 - 173 bits instead of 1024 bits, 373 bits instead of 4096 bits

ECDSA in Bitcoin

- **Signer:** Has private key k and message m
 1. Compute $e = \text{SHA-256}(\text{SHA-256}(m))$
 2. Choose a random integer j from \mathbb{Z}_n^*
 3. Compute $jP = (x, y)$
 4. Calculate $r = x \bmod n$. If $r = 0$, go to step 2.
 5. Calculate $s = j^{-1}(e + kr) \bmod n$. If $s = 0$, go to step 2.
 6. Output (r, s) as signature for m
- **Verifier:** Has public key kP , message m , and signature (r, s)
 1. Calculate $e = \text{SHA-256}(\text{SHA-256}(m))$
 2. Calculate $j_1 = es^{-1} \bmod n$ and $j_2 = rs^{-1} \bmod n$
 3. Calculate the point $Q = j_1P + j_2(kP)$
 4. If $Q = \mathcal{O}$, then the signature is invalid.
 5. If $Q \neq \mathcal{O}$, then let $Q = (x, y) \in \mathbb{F}_p^2$. Calculate $t = x \bmod n$. If $t = r$, the signature is valid.
- As n is a 256-bit integer, signatures are 512 bits long
- As j is randomly chosen, ECDSA output is random for same m

References

- Sections 10.3, 11.4, 12.5 of *Introduction to Modern Cryptography*, J. Katz, Y. Lindell, 2nd edition
- Section 19.1 of *A Graduate Course in Applied Cryptography*, D. Boneh, V. Shoup, www.cryptobook.us
- Chapter 2 of *An Introduction to Bitcoin*, S. Vijayakumaran, www.ee.iitb.ac.in/~sarva/bitcoin.html