Elliptic and Hyperelliptic Curve Cryptography

An Introduction

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Elliptic Curves
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Hyperelliptic Curves
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Elliptic Curves

Definition

- Elliptic curve $E$ over field $\mathbb{K}$ is defined by
  \[ y^2 + a_1 xy + a_3 y = x^3 + a_2 x^2 + a_4 x + a_6, \quad a_i \in \mathbb{K} \]

- The set of $\mathbb{K}$-rational points $E(\mathbb{K})$ is defined as
  \[ E(\mathbb{K}) = \{(x, y) \in \mathbb{K} \times \mathbb{K} \mid y^2 + a_1 xy + a_3 y = x^3 + a_2 x^2 + a_4 x + a_6\} \cup \{\infty\} \]

- $\infty$ is called point at infinity

Theorem

There exists an addition law on $E$ and the set $E(\mathbb{K})$ is a group
Elliptic Curves over $\mathbb{R}$

\[ y^2 = x^3 + 4x^2 + 4x + 3 \]

\[ y^2 = x^3 - 7x + 6 \]
Addition Law on Elliptic Curves

Adding two points

Doubling a point

\[ y^2 = x^3 - 7x + 6 \]
Addition Law on Elliptic Curves

By definition: three points on a line sum to zero!

Let $P_1 \oplus P_2 = P_3$, with $P_i = (x_i, y_i) \in E$

- If $x_1 = x_2$ and $y_1 + y_2 + a_1 x_2 + a_3 = 0$, then $P_1 \oplus P_2 = \infty$,
- Else

$$
\begin{align*}
\lambda & = (y_2 - y_1)/(x_2 - x_1) \\
\nu & = (y_1 x_2 - y_2 x_1)/(x_2 - x_1)
\end{align*}
$$

$$
\begin{align*}
\lambda & = (3x_1^2 + 2a_2 x_1 + a_4 - a_1 y_1)/(2y_1 + a_1 x_1 + a_3) \\
\nu & = (-x_1^3 + a_4 x_1 + 2a_6 - a_3 y_1)/(2y_1 + a_1 x_1 + a_3)
\end{align*}
$$

The point $P_3 = P_1 \oplus P_2$ is given by

$$
\begin{align*}
x_3 & = \lambda^2 + a_1 \lambda - a_2 - x_1 - x_2 \\
y_3 & = -(\lambda + a_1)x_3 - \nu - a_3
\end{align*}
$$
Elliptic Curves over Finite Fields

The elliptic curve $y^2 = x^3 + x + 3 \mod 23$
Hyperelliptic Curves

Definition

- Hyperelliptic curve $H$ over field $\mathbb{K}$ is defined by
  \[ y^2 + h(x)y = f(x) \quad h(x), f(x) \in \mathbb{K}[x] \]
  
  with $\deg(h(x)) \leq g$ and $\deg(f(x)) = 2g + 1$

- $g \in \mathbb{N}$ is called the genus of $H$

- The set of $\mathbb{K}$-rational points on $H$ is defined as
  \[ H(\mathbb{K}) := \{(x, y) \in \mathbb{K} \times \mathbb{K} | y^2 + h(x)y = f(x)\} \cup \{\infty\} \]

- For $\Char(\mathbb{K}) > 2$, can take $h(x) = 0$

Note: elliptic curves are hyperelliptic curves of genus 1
Addition Law on Hyperelliptic Curve

- When \( g \geq 2 \), the points \( H(\mathbb{K}) \) do not form a group!
- Need to work with \( \mathbb{K} \)-rational points on Jacobian \( J_H(\mathbb{K}) \)
- By definition: \( J_H(\mathbb{K}) \) is the smallest group in which \( H(\mathbb{K}) \) embeds, i.e. \( H(\mathbb{K}) \subsetneq J_H(\mathbb{K}) \)
- For elliptic curves: \( E(\mathbb{K}) \approx J_E(\mathbb{K}) \)
- Generalisation of group law on elliptic curve: zeros of a polynomial sum to zero
- \( \#J_H(\mathbb{F}_q) \approx q^g \) for genus \( g \) hyperelliptic curve over \( \mathbb{F}_q \)
Construction of Jacobian

- Let $\mathbb{F}_q$ be a finite field with $q = p^n$
- Let $\overline{\mathbb{F}}_q = \bigcup_{k=1}^{\infty} \mathbb{F}_{q^k}$ be its algebraic closure
- A divisor on $H$ is a finite formal sum
  \[ D = \sum_i m_i [P_i], \text{ with } P_i \in H(\overline{\mathbb{F}}_q) \]

- Set of all divisors is denoted $\text{Div}_H(\overline{\mathbb{F}}_q)$
- Degree of $D$ is $\sum_i m_i$, $\text{Div}_H^0(\overline{\mathbb{F}}_q) = \text{degree zero divisors}$
- For $P = (x, y)$ let $P^\sigma = (x^q, y^q)$ and $D^\sigma = \sum_i m_i [P_i^\sigma]$
- $D$ is called $\mathbb{F}_q$-rational if $D^\sigma = D$
- For $P = (x, y)$, define the opposite as $-P = (x, -y - h(x))$
Construction of Jacobian

Let $F(x, y) \in \mathbb{F}_q[x, y]$ be a polynomial and define

$$\text{Div}(F(x, y)) = \sum \text{ord}_P(F(x, y))[P] - (\ast)[\infty]$$

- $\text{ord}_P(F(x, y))$ measures order of vanishing at $P$
- $(\ast)$ chosen such that degree is zero
- Define for rational function $F(x, y)/G(x, y)$ the divisor

$$\text{Div}(F/G) = \text{Div}(F) - \text{Div}(G)$$

- These are called the principal divisors $P_H(\overline{\mathbb{F}}_q)$

Definition

The $\mathbb{F}_q$-rational points on the Jacobian of $H$ are defined as

$$J_H(\mathbb{F}_q) = \text{Div}_0^H(\mathbb{F}_q)/(P_H(\mathbb{F}_q))$$
Computing in Jacobian

**Definition**

A divisor $D = \sum m_i [P_i] - (\ast)\infty \in \text{Div}_H^0$ is called **reduced** if:

1. All $m_i \geq 0$ and $m_i \leq 1$ if $P_i$ is equal to its opposite
2. If $P_i \neq -P_i$, then only one of them occurs in the sum
3. $\sum m_i \leq g$

**Theorem**

*Every element in $J_H(\mathbb{F}_q)$ can be uniquely represented by a reduced divisor*
Mumford Representation

- Let \( D = \sum m_i[P_i] - (\ast)\infty \) be reduced with \( P_i = (x_i, y_i) \)
- Define \( u(x) = \prod_i (x - x_i)^{m_i} \) and \( v(x) \) such that
  \[
  v(x_i) = y_i
  \]
- Choose \( \deg(v) < \deg(u) \leq g \) and
  \[
  u(x)|v(x)^2 + h(x)v(x) - f(x)
  \]
- \((u(x), v(x))\) is called Mumford representation of \( D \)
- Can add two such representations using Cantor’s algorithm
- For small genus: explicit formulae
Cantor’s algorithm

**Input:** Divisors $D_1 = [u_1, v_1]$ and $D_2 = [u_2, v_2]$

**Output:** A divisor $D$ representing the sum $D_1 + D_2$ in $J_C(\mathbb{F}_q)$

1. $d_1 = \text{gcd}(u_1, u_2) = e_1 u_1 + e_2 u_2$
2. $d = \text{gcd}(d_1, v_1 + v_2 + h) = c_1 d_1 + c_2 (v_1 + v_2 + h)$
3. $s_1 = c_1 e_1$, $s_2 = c_1 e_2$, $s_3 = c_2$
4. $u = (u_1 u_2) / d^2$, $v = (s_1 u_1 v_2 + s_2 u_2 v_1 + s_3 (v_1 v_2 + f)) / d \mod u$
5. $u' = (f - vh - v^2) / u$, $v' = (-h - v) \mod u'$
6. If $\deg(u') > g$ then $u = u'$, $v = v'$, goto 5
7. Make $u'$ monic by dividing it by its leading coefficient
8. Output $D = [u', v']$. 
Elliptic and Hyperelliptic Curve DLP

- Let $G$ be an abelian group generated by $P \in G$
- Let $Q = s \cdot P$, then the DLP is to compute $s$ given $P$ and $Q$
- Classically: $G = \mathbb{F}_q^\times$
- For $G = E(\mathbb{F}_q)$, the DLP is called ECDLP
- For $G = J_H(\mathbb{F}_q)$, the DLP is called HECDLP

Note: can translate primitives based on DLP to ECDLP and HECDLP setting
Security of ECDLP/HECDLP: General Attacks

- Exhaustive search: impossible if group order \( > 2^{80} \)
- Pohlig-Hellman: suppose \( \#J_H(\mathbb{F}_q) = p_1^{s_1} \cdot p_2^{s_2} \cdots p_k^{s_k} \), then can reduce HECDLP to subgroups of order \( p_i \)
  \[ \Rightarrow \#J_H(\mathbb{F}_q) \text{ should have large prime divisor } p \]
- Pollard rho & lambda: random walk, constant space, time complexity is \( O(\sqrt{N}) \)

**Conclusion:**

- \( \#J_H(\mathbb{F}_q) \) should be at least \( 2^{160} \) and divisible by large prime \( p \)
- Best general attack is *exponential* in \( p \)
Security of ECDLP: Specific Attacks

Let $r$ be largest prime factor of $\#J_H(F_q)$ then:

- Index calculus attack: if genus of $H$ is $> 2$, then index calculus applies and is faster than Pollard-Rho

- Multiplicative reduction: reduce HECDLP on $J_H(F_q)$ to DLP in $F_{q^k}^\times$, with $k$ smallest integer with $q^k \equiv 1 \mod r$,

- Additive reduction: if $r = p$, then HECDLP can be mapped to $F_p, +$, and thus trivial to solve

- Weil descent: if $H$ is defined over $F_{q^e}$, then sometimes possible to find curve $X$ over $F_q$ with $J_H(F_{q^e}) \leftrightarrow J_X(F_q)$, and apply index calculus in $J_X(F_q)$
Security of ECDLP/HECDLP: Good Curves

Conclusion:

- Let $\mathbb{F}_q$ with $q = p$ prime or $q = p^n$ with $n$ prime
- Genus of $H$ is either 1 or 2
- Let $r$ be largest prime factor of $\#J_H(\mathbb{F}_q)$ then:
  - $r > 2^{160}$
  - $p \nmid r$
  - Smallest $k$ with $q^k \equiv 1 \pmod{r}$ is $> 50$
- Efficiency: require $\#J_H(\mathbb{F}_q)/r$ to be small
Comparison with RSA & DSA: Security

Key lengths in bits for equivalent cryptographic strength
Overview

Key Agreement Primitives
- ECDH: EC Diffie-Hellman Secret Value Derivation
- ECMQV: EC Menezes-Qu-Vanstone Secret Value Derivation

Signature Primitives
- ECNR: EC Nyberg-Rueppel Signatures
- ECDSA: EC Digital Signature Algorithm

Encryption Primitives
- ECIES: EC Integrated Encryption Scheme
EC Digital Signature Algorithm (ECDSA)

- **ECDSA** is elliptic curve analog of DSA
- Used to provide data origin authentication, data integrity and non-repudiation
- Standards for ECC (including ECDSA & ECIES):
  - ANSI X9.62, X9.63
  - NIST FIPS 186-2
  - IEEE 1363-2000
  - ISO/IEC 14888-3, 9796-4, 15946
  - SECG
EC Key Pair Generation

- **Domain parameters**
  - Elliptic curve $E$ over finite field $\mathbb{F}_q$
  - Point $G \in E(\mathbb{F}_q)$, $n = \text{ord}(G)$ and cofactor $h = \#E(\mathbb{F}_q)/n$

- **Private and public key**
  - Select random integer $d$ in the interval $[1, n - 1]$
  - Compute $Q = d \cdot G$
  - **Public key** is $Q$, **Private key** is $d$
ECDSA Signature Generation

To sign a message $m$ do the following:

1. Select a random integer $k$ with $1 \leq k \leq n - 1$
2. Compute $k \cdot G = (x_1, y_1)$ and $r \equiv x_1 \mod n$. If $r = 0$ go to step 1
3. Compute $k^{-1} \mod n$
4. Compute $e = \text{HASH}(m)$
5. Compute $s \equiv k^{-1}(e + dr) \mod n$. If $s = 0$ go to step 1
6. The signature for the message $m$ is $(r, s)$
ECDSA Signature Verification

To verify a signature \((r, s)\) on \(m\) do the following:

1. Verify that \(r\) and \(s\) are integers in the interval \([1, n - 1]\)
2. Compute \(e = \text{HASH}(m)\)
3. Compute \(w \equiv s^{-1} \mod n\)
4. Compute \(u_1 \equiv ew \mod n\) and \(u_2 \equiv rw \mod n\)
5. Compute \(u_1 \cdot G + u_2 \cdot Q = (x_1, y_1)\) and \(v \equiv x_1 \mod n\)
6. Accept signature if and only if \(v = r\)
<table>
<thead>
<tr>
<th></th>
<th>Elliptic curve over $\mathbb{F}_{2^{233}}$</th>
<th>RIM pager</th>
<th>PalmPilot</th>
<th>Pentium II</th>
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</thead>
<tbody>
<tr>
<td>Key Generation</td>
<td>1,552</td>
<td>2,573</td>
<td>3.11</td>
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<tr>
<td>ECDSA Signing</td>
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<tr>
<td>ECDSA Verifying</td>
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<td>7.87</td>
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</table>

<table>
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<tr>
<th></th>
<th>2048-bit modulus</th>
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<td>RSA Key Generation</td>
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<td>—</td>
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<td>RSA Verifying ($e = 2^{16} + 1$)</td>
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</tbody>
</table>

More info: Brown et al.: PGP in Constrained Wireless Devices
Conclusions

- (Hyper)elliptic curves provide an alternative to RSA & DSA
- No sub-exponential time algorithm to solve HECDLP
- Smaller key sizes, sometimes faster than DSA & RSA, more future proof
- Typical applications: PDA’s, phones, smart cards, …