Elliptic Curves in Crypto, part I

The discrete logarithm problem in $\mathbb{Z}_p$

Problem Instance $I = (p, \alpha, \beta)$, where $p$ is prime, $\alpha \in \mathbb{Z}_p$ is a primitive element, and $\beta \in \mathbb{Z}_p^*$.  

Objective Find the unique integer $a$, $0 \leq a \leq p - 2$, such that  

$$\alpha^a \equiv \beta \pmod{p}.$$  

We will denote this integer $a$ by $\log_\alpha \beta$.

ECDL analog  

$I = (E, p, Q)$  

$E$ elliptic curve  

$P, Q \in E$, points  

Find $k$ such that $Q = kP$  

$k$ integer
The Generalized Discrete Logarithm Problem

- Given is a finite cyclic group \( G \) with the group operation \( \circ \) and cardinality \( n \).
- We consider a primitive element \( a \in G \) and another element \( \beta \in G \).
- The discrete logarithm problem is finding the integer \( x \), where \( 1 \leq x \leq n \), such that:

\[
\beta = a \circ a \circ a \ldots = a^x
\]

\( x \) times

or, in additive notation

\[
x \text{ int, } \alpha, \beta \in G \\
\beta = \alpha + \alpha + \ldots + \alpha = x \alpha
\]

\( x, \alpha \rightarrow x \alpha, \beta \) easy

\( \alpha, \beta \rightarrow x \) infeasible to compute
Elliptic Curves over the Reals

**Definition 6.3:** Let \( a, b \in \mathbb{R} \) be constants such that \( 4a^3 + 27b^2 \neq 0 \). A *non-singular elliptic curve* is the set \( E \) of solutions \( (x, y) \in \mathbb{R} \times \mathbb{R} \) to the equation

\[
y^2 = x^3 + ax + b,
\]

(6.4)
together with a special point \( \mathcal{O} \) called the *point at infinity.*

\[
y^2 = x^3 - 4x
\]
\[ y^2 = x^3 - x \]
Point addition

trouble makers
(better not on EC over F)
Elliptic Curves Modulo a Prime

**Definition 6.4:** Let $p > 3$ be prime. The elliptic curve $y^2 = x^3 + ax + b$ over $\mathbb{Z}_p$ is the set of solutions $(x, y) \in \mathbb{Z}_p \times \mathbb{Z}_p$ to the congruence

$$y^2 \equiv x^3 + ax + b \pmod{p}, \quad (6.6)$$

where $a, b \in \mathbb{Z}_p$ are constants such that $4a^3 + 27b^2 \not\equiv 0 \pmod{p}$, together with a special point $\mathcal{O}$ called the point at infinity.

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

If $x_2 = x_1$ and $y_2 = -y_1$, then $P + Q = \mathcal{O}$;

$$P + Q = (x_3, y_3), \text{ where}$$

$$x_3 = \lambda^2 - x_1 - x_2$$

$$y_3 = \lambda(x_1 - x_3) - y_1,$$

$$\lambda = \begin{cases} 
(y_2 - y_1)(x_2 - x_1)^{-1}, & \text{if } P \neq Q \\
(3x_1^2 + a)(2y_1)^{-1}, & \text{if } P = Q.
\end{cases}$$

$$P + \mathcal{O} = \mathcal{O} + P = P$$
In cryptography, we are interested in elliptic curves module a prime $p$:

**Definition: Elliptic Curves over prime fields**

The elliptic curve over $\mathbb{Z}_p$, $p \geq 3$ is the set of all pairs $(x, y) \in \mathbb{Z}_p$ which fulfill

$$y^2 = x^3 + ax + b \mod p$$

together with an imaginary point of infinity $\theta$, where $a, b \in \mathbb{Z}_p$ and the condition

$$4a^3 + 27b^2 \neq 0 \mod p.$$ 

Note that $\mathbb{Z}_p = \{0, 1, \ldots, p - 1\}$ is a set of integers with modulo $p$ arithmetic.
$4a^3 + 27b^2 = 0 \rightarrow \text{singular EC}$

$\not= 0$

6.4 has 3 different roots in $\mathbb{C}$

**Defining $P + Q$**

Suppose $P, Q \in E$, where $P = (x_1, y_1)$ and $Q = (x_2, y_2)$. We consider three cases:

1. $x_1 \neq x_2$
2. $x_1 = x_2$ and $y_1 = -y_2$
3. $x_1 = x_2$ and $y_1 = y_2$

In case 1, we define $L$ to be the line through $P$ and $Q$. $L$ intersects $E$ in the two points $P$ and $Q$, and it is easy to see that $L$ will intersect $E$ in one further point, which we call $R'$. If we reflect $R'$ in the $x$-axis, then we get a point which we name $R$. We define $P + Q = R$.

$0 - \text{infinity, } P + 0 = 0 + P = P$
Let's work out an algebraic formula to compute \( R \). First, the equation of \( L \) is \( y = \lambda x + \nu \), where the slope of \( L \) is

\[
\lambda = \frac{y_2 - y_1}{x_2 - x_1},
\]

and

\[
\nu = y_1 - \lambda x_1 = y_2 - \lambda x_2.
\]

In order to find the points in \( E \cap L \), we substitute \( y = \lambda x + \nu \) into the equation for \( E \), obtaining the following:

\[
(\lambda x + \nu)^2 = x^3 + ax + b,
\]

which is the same as

\[
x^3 - \lambda^2 x^2 + (a - 2\lambda \nu)x + b - \nu^2 = 0. \tag{6.5}
\]

The roots of equation (6.5) are the \( x \)-co-ordinates of the points in \( E \cap L \). We already know two points in \( E \cap L \), namely, \( P \) and \( Q \). Hence \( x_1 \) and \( x_2 \) are two roots of equation (6.5).
Case 2, where \( x_1 = x_2 \) and \( y_1 = -y_2 \), is simple: we define \((x, y) + (x, -y) = 0\) for all \((x, y) \in E\). Therefore \((x, y)\) and \((x, -y)\) are inverses with respect to the elliptic curve addition operation.
Case 3 remains to be considered. Here we are adding a point \( P = (x_1, y_1) \) to itself. We can assume that \( y_1 \neq 0 \), for then we would be in case 2. Case 3 is handled much like case 1, except that we define \( L \) to be the tangent to \( E \) at the point \( P \). A little bit of calculus makes the computation quite simple. The slope of \( L \) can be computed using implicit differentiation of the equation of \( E \):

\[
2y \frac{dy}{dx} = 3x^2 + a.
\]

Substituting \( x = x_1, y = y_1 \), we see that the slope of the tangent is

\[
\lambda = \frac{3x_1^2 + a}{2y_1}.
\]

The rest of the analysis in this case is the same as in case 1. The formula obtained is identical, except that \( \lambda \) is computed differently.
Since equation (6.5) is a cubic equation over the reals having two real roots, the third root, say \( x_3 \), must also be real. The sum of the three roots must be the negative of the coefficient of the quadratic term, or \( \lambda^2 \). Therefore

\[
x_3 = \lambda^2 - x_1 - x_2.
\]

\( x_3 \) is the \( x \)-coordinate of the point \( R' \). We will denote the \( y \)-coordinate of \( R' \) by \( -y_3 \), so the \( y \)-coordinate of \( R \) will be \( y_3 \). An easy way to compute \( y_3 \) is to use the fact that the slope of \( L \), namely \( \lambda \), is determined by any two points on \( L \). If we use the points \( (x_1, y_1) \) and \( (x_3, -y_3) \) to compute this slope, we get

\[
\lambda = \frac{-y_3 - y_1}{x_3 - x_1},
\]

or

\[
y_3 = \lambda(x_1 - x_3) - y_1.
\]

Therefore we have derived a formula for \( P + Q \) in case 1: if \( x_1 \neq x_2 \), then \( (x_1, y_1) + (x_2, y_2) = (x_3, y_3) \), where

\[
x_3 = \lambda^2 - x_1 - x_2,
\]

\[
y_3 = \lambda(x_1 - x_3) - y_1, \quad \text{and}
\]

\[
\lambda = \frac{y_2 - y_1}{x_2 - x_1}.
\]
Vieta's Formulas

Let $s_i$ be the sum of the products of distinct polynomial roots $r_j$ of the polynomial equation of degree $n$

$$a_n x^n + a_{n-1} x^{n-1} + \ldots + a_1 x + a_0 = 0,$$

where the roots are taken $i$ at a time (i.e., $s_i$ is defined as the symmetric polynomial $\Pi_i (r_1, \ldots, r_n)$). $s_i$ is defined for $i = 1, \ldots, n$. For example, the first few values of $s_i$ are

$$s_1 = r_1 + r_2 + r_3 + r_4 + \ldots$$

$$s_2 = r_1 r_2 + r_1 r_3 + r_1 r_4 + r_2 r_3 + \ldots$$

$$s_3 = r_1 r_2 r_3 + r_1 r_2 r_4 + r_2 r_3 r_4 + \ldots,$$

and so on. Then Vieta's formulas states that

$$s_i = (-1)^i \frac{a_{n-i}}{a_n}.$$

The theorem was proved by Viète (also known as Vieta, 1579) for positive roots only, and the general theorem was proved by Girard.
\[ a_3 \ x^3 + a_2 \ x^2 + a_1 \ x + a_0 = a_3 (x - r_1) (x - r_2) (x - r_3) = a_3 \left[ x^3 - (r_1 + r_2 + r_3) x^2 + (r_1 \ r_2 + r_1 \ r_3 + r_2 \ r_3) x - r_1 \ r_2 \ r_3 \right] \]

\[ s_1 = \sum_{i=1}^{3} r_i = -\frac{a_2}{a_3} \]

\[ s_2 = \sum_{i,j}^{3} r_i \ r_j \]

\[ = r_1 \ r_2 + r_1 \ r_3 + r_2 \ r_3 = \frac{a_1}{a_3} \]

\[ s_3 = \sum_{i,j,k}^{3} r_i \ r_j \ r_k \]

\[ = r_1 \ r_2 \ r_3 = -\frac{a_0}{a_3} \]
Computations on Elliptic Curves (ctd.)

- Generating a group of points on elliptic curves based on point addition operation \( P + Q = R \), i.e., \((x_P, y_P) + (x_Q, y_Q) = (x_R, y_R)\)

- Geometric Interpretation of point addition operation
  - Draw straight line through \( P \) and \( Q \); if \( P = Q \) use tangent line instead
  - Mirror third intersection point of drawn line with the elliptic curve along the x-axis

- Elliptic Curve Point Addition and Doubling Formulas

\[
x_3 = s^2 - x_1 - x_2 \mod p \quad \text{and} \quad y_3 = s(x_1 - x_3) - y_1 \mod p
\]

where

\[
s = \begin{cases} 
\frac{y_2 - y_1}{x_2 - x_1} \mod p & \text{if } P \neq Q \text{ (point addition)} \\
\frac{3x_1^2 + a}{2y_1} \mod p & \text{if } P = Q \text{ (point doubling)}
\end{cases}
\]
Example 6.7  Let $E$ be the elliptic curve $y^2 = x^3 + x + 6$ over $\mathbb{Z}_{11}$.

\[ \pm z^{(11+1)/4} \pmod{11} = \pm z^3 \pmod{11}. \]

$\mathbb{F}_{11}$ in action in secp256k1

<table>
<thead>
<tr>
<th>$x$</th>
<th>$x^2 + x + 6 \pmod{11}$</th>
<th>quadratic residue?</th>
<th>$y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>yes</td>
<td>4, 7</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>yes</td>
<td>5, 6</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>yes</td>
<td>2, 9</td>
</tr>
<tr>
<td>6</td>
<td>8</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>yes</td>
<td>2, 9</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td>yes</td>
<td>3, 8</td>
</tr>
<tr>
<td>9</td>
<td>7</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>yes</td>
<td>2, 9</td>
</tr>
</tbody>
</table>

\[ \alpha = (2, 7) \quad 2\alpha = (5, 2) \quad 3\alpha = (8, 3) \]

\[ 4\alpha = (10, 2) \quad 5\alpha = (3, 6) \quad 6\alpha = (7, 9) \]

\[ 7\alpha = (7, 2) \quad 8\alpha = (3, 5) \quad 9\alpha = (10, 5) \]

\[ 10\alpha = (8, 8) \quad 11\alpha = (5, 9) \quad 12\alpha = (2, 4) \]
Example: Let $E$ be the elliptic curve $y^2 = x^3 + x + 1$ over $\mathbb{Z}_{17}$. Let's find the points on $E$.

<table>
<thead>
<tr>
<th>$x$</th>
<th>$x^3 + x + 1$</th>
<th>quad. residue?</th>
<th>$y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>yes</td>
<td>1,16</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>yes</td>
<td>1,16</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>yes</td>
<td>6,11</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>yes</td>
<td>5,12</td>
</tr>
<tr>
<td>10</td>
<td>8</td>
<td>yes</td>
<td>5,12</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>DNA</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>7</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>yes</td>
<td>1,16</td>
</tr>
<tr>
<td>14</td>
<td>5</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>8</td>
<td>yes</td>
<td>5,12</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>yes</td>
<td>4,13</td>
</tr>
</tbody>
</table>

Thus $E$ has 18 points on it. They are $\{ (0, 1), (0, 16), (4, 1), (4, 16), (6, 6), (6, 11), (9, 5), (9, 12), (10, 5), (10, 12), (11, 0), (13, 1), (15, 16), (15, 5), (15, 12), (16, 4), (16, 13), 0 \}$.

Is $E$ cyclic?

18 elements
Elliptic curve \( y^2 = x^3 + x + 1 \) example cont’d:

Let \( \alpha = (0, 1) \). We compute the multiples of \( \alpha \).

\[
\begin{align*}
\alpha &= (0, 1) \\
2\alpha &= (13, 1) \\
3\alpha &= (4, 16) \\
4\alpha &= (9, 12) \\
5\alpha &= (16, 4) \\
6\alpha &= (10, 12) \\
7\alpha &= (6, 6) \\
8\alpha &= (15, 12) \\
9\alpha &= (11, 0) \\
10\alpha &= (15, 5) \\
11\alpha &= (6, 11) \\
12\alpha &= (10, 5) \\
13\alpha &= (16, 13) \\
14\alpha &= (9, 5) \\
15\alpha &= (4, 1) \\
16\alpha &= (13, 16) \\
17\alpha &= (0, 16) \\
18\alpha &= 0
\end{align*}
\]

We can now compute an example of the ElGamal encryption using this elliptic curve:

Suppose that \( \alpha = (0, 1) \) and Bob’s secret exponent is \( a = 5 \), so

\[
\beta = 5\alpha = (16, 4).
\]

Encryption is

\[
e_K( x, k ) = ( k(0, 1), x + k(16, 4) )
\]

where \( x \in E \) and \( 0 \leq k \leq 17 \).

Decryption is

\[
d_K( y_1, y_2 ) = y_2 - 5y_1
\]

Try encrypting and decrypting the message \( (15, 12) \).
The points on an elliptic curve and the point at infinity \( \theta \) form cyclic subgroups.

\[
\begin{align*}
2P &= (5,1) + (5,1) = (6,3) \\
3P &= 2P + P = (10,6) \\
4P &= (3,1) \\
5P &= (9,16) \\
6P &= (16,13) \\
7P &= (0,6) \\
8P &= (13,7) \\
9P &= (7,6) \\
10P &= (7,11) \\
11P &= (13,10) \\
12P &= (0,11) \\
13P &= (16,4) \\
14P &= (9,1) \\
15P &= (3,16) \\
16P &= (10,11) \\
17P &= (6,14) \\
18P &= (5,16) \\
19P &= \theta
\end{align*}
\]

This elliptic curve has order \( #E = |E| = 19 \) since it contains 19 points in its cyclic group.

\[ P = (5,1) \]

Chapter 9 of *Understanding Cryptography* by Christof Paar and Jan Pelzl
PointCompress(P) = (x, y mod 2), where P = (x, y) ∈ E.

PointCompress : E\{0\} → Z_p × Z_2,

\[ p \equiv 3 \mod 4 \implies y = z^{(p+1)/4} \mod p \]

Algorithm 6.4: PointDecompress(x, i)

\[ z \leftarrow x^3 + ax + b \mod p \]
if z is a quadratic non-residue modulo p
then return ("failure")
else \[
\begin{cases} 
    y \leftarrow \sqrt{z} \mod p \\
    \text{if } y \equiv i \pmod{2} \\
    \text{then return }(x, y) \\
    \text{else return }(x, p - y)
\end{cases}
\]

HP: US patent 6252960 B1 1998
expires in 2018

130+ crypto and EC patents:
NSA, Certicom, RSA Security, HP, Harris