

Elliptic Curves

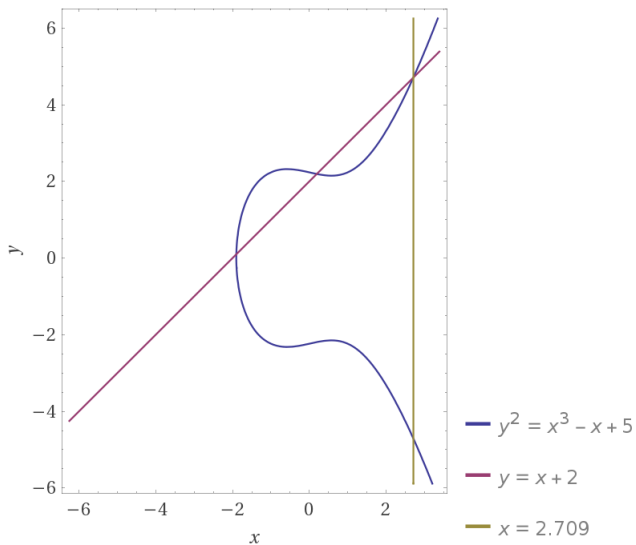
Jake Fisher and Davis Lister

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Group Law for Elliptic Curves

- ▶ Elliptic Curves are a group under the $+$ operation with the set $\{K \times K : y^2 = x^3 + ax + b\} \cup \{\mathcal{O}\}$ where \mathcal{O} is the point at infinity and K is a field. We notate the set represented by an elliptic curve E over a field K , $E(K)$.
- ▶ Let us define the discriminant $\Delta = -16(4a^3 + 27b^2)$. If $\Delta = 0$ the group law does not hold.
- ▶ The $+$ operation is defined geometrically on two points $P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$ thus: draw the secant line and find the third point where it intersects the curve (x', y') , which can include \mathcal{O} , finally find $(x', -y')$, the resulting point.
- ▶ Under the $+$ operation \mathcal{O} is the identity and $(x, y)^{-1} = (x, -y)$.
- ▶ The $+$ operation is closed since each secant line will intersect the curve at exactly one other point. The definition of the operation does not discriminate between P_1 and P_2 . Therefore, $(E(K), +)$ is an abelian group.

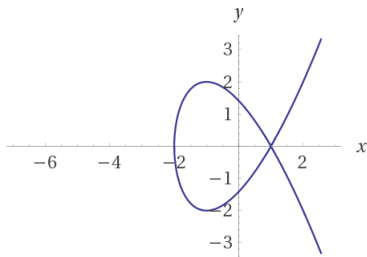
A Visualization of the $+$ Operation over $E(K)$



Computed by Wolfram|Alpha

More on the Discriminant

- ▶ The condition we impose on the discriminant is the is motivated by the need to have a tangent line be well defined at all points on the elliptic curve S . If the tangent line is not defined at a point $P_0 = (x_0, y_0)$, then S is singular.
- ▶ If S is singular, then $P_0 + P_0$ is not well-defined, which breaks the group law.
- ▶ Geometrically, a singularity is a cusp or self-intersection.



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Definition of B -power smooth

- ▶ Let B be a positive integer. The prime factorization of an integer $n = \prod p_i^{e_i}$. If $\forall i \ p_i^{e_i} \leq B$, n is B -power smooth.
- ▶ For instance, 60 is 5-power smooth but 150 is 25-power smooth.

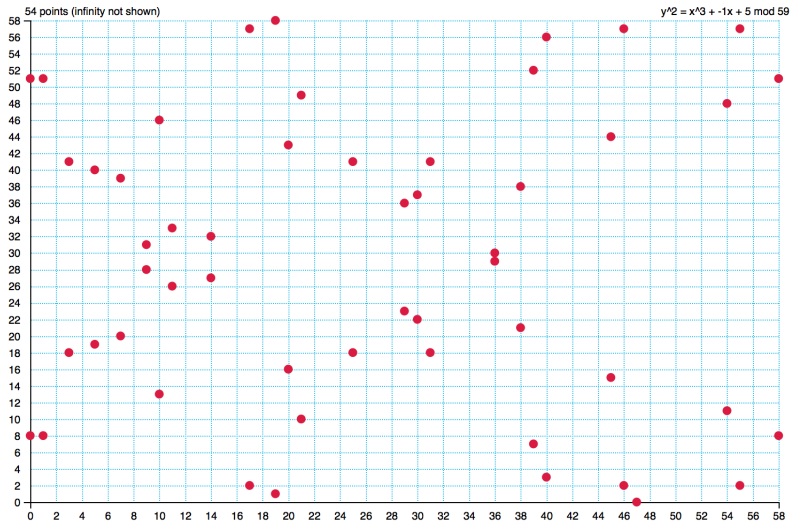
Pollard's p-1 Factoization

- ▶ We wish to find a nontrivial factor of a large positive integer N using the Pollard p-1 method.
- ▶ Let us choose a positive integer B . Suppose that there is a prime factor p of N such that $p - 1$ is B -power smooth.
- ▶ Let us choose $a > 1$ such that a does not divide p . Often we will choose $a = 2$ for convenience.
- ▶ By Fermat's Little Theorem $a^{p-1} \equiv 1 \pmod{p}$.
- ▶ Let $m = \text{lcm}(1, 2, 3, \dots, B)$. Since $p - 1$ is B -power smooth, $p - 1 \mid m \implies p \mid \gcd(a^m - 1, N) > 1$.
- ▶ If $\gcd(a^m - 1, N) < N$, then $\gcd(a^m - 1, N)$ is a nontrivial factor of N .
- ▶ The algorithm becomes more transparent if we consider $m = k(p - 1)$, where $k \in \mathbb{Z}$.

Factoring Magic!

- ▶ An example of integer factorization using Pollard's $p-1$ method.
- ▶ Let $N = 5917$ and let $B = 5$. $m = \text{lcm}(1, 2, 3, 4, 5) = 60$.
- ▶ Note that $2^{60} - 1 = 3416 \pmod{5917}$, and $\text{gcd}(2^{60} - 1, 5917) = \text{gcd}(3416, 5917) = 61$.
- ▶ 61 is a factor of 5917!
- ▶ But if $p - 1$ and $q - 1$ (where $pq = N$) are not B -power smooth, Pollard $p-1$ does not work.
- ▶ The issue is that $(\mathbb{Z}/p\mathbb{Z})^*$ has order $p-1$.
- ▶ Additionally, if $p - 1$ is the product of many small primes, then the algorithm will return N .

Elliptic Curves over Finite Fields



Lenstra's Elliptic Curve Factorization

- ▶ Choose $N, B \in \mathbb{Z}^+$.
- ▶ Compute $m = \text{lcm}(1, 2, \dots, B)$.
- ▶ Choose a random $a \in \mathbb{Z}/N\mathbb{Z}$ such that $4a^3 + 27 \in \mathbb{Z}/N\mathbb{Z}^*$.
Thus, $P = (0, 1)$ is a point on the elliptic curve $y^2 = x^3 + ax + 1$ over $\mathbb{Z}/N\mathbb{Z}$.
- ▶ Attempt to compute mP using the $+$ operation for the group $(E(K), +)$. If at some point we cannot compute a sum of points because $\gcd(x_1 - x_2, N) \neq 1$ (where $x_1 - x_2$ is the denominator of the slope expression we compute in order to execute the $+$ operation), compute and return $\gcd(x_1 - x_2, N)$ if $\gcd(x_1 - x_2, N) \neq N$. If some point $kP = \mathcal{O}$ for $k \leq m$, terminate and output, "Fail." Additionally, if mP can be computed using the $+$ operation, output, "Fail."

Advantages of the Lenstra Method

- ▶ The advantage of the Lenstra method is that if the algorithm fails, we may choose a different elliptic curve and repeat the algorithm.
- ▶ We have more flexibility with our groups since we work with many different groups $E(\mathbb{Z}/N\mathbb{Z})$, which will have order $p + 1 \pm s$.
- ▶ In Pollard $p - 1$ we work with $\mathbb{Z}/N\mathbb{Z}^*$, which always has order $p - 1$.

An Example of the Lenstra Method

- ▶ Let us choose $N = 5959$ and $B = 8$.
- ▶ Therefore, $m = 840$ and our random $a = 6$, where $a \in \mathbb{Z} \mid 4a^3 + 27 \neq 0$.
- ▶ Note that $P = (0, 1)$ is on the elliptic curve $y^2 = x^3 + ax + 1$ over $\mathbb{Z}/N\mathbb{Z}$. We now attempt to compute mP .
- ▶ Observe that $60P = (649, 2654)$. Therefore $\lambda \equiv \frac{2653}{649} \pmod{5959}$. Since $649 \not\equiv 0 \pmod{5959}$, which would indicate that the next point were \mathcal{O} , we encounter a contradiction to the group law.
- ▶ Note that $(649, 2654)^{-1} = (649, -2654)$.
- ▶ Therefore, $p = \gcd(649, 5959)$ is a nontrivial factor of N , if $1 < p < N$.
- ▶ $\gcd(649, 5959) = 59 \implies 59$ is a nontrivial factor of 5959 .

Elliptic Curve Cryptography

- ▶ The Diffie-Hellman key exchange can be implemented on an Elliptic Curve.
- ▶ Alice and Bob publicly agree on a prime p and an elliptic curve S over $\mathbb{Z}/p\mathbb{Z}$. They then agree on a point $P \in S(\mathbb{Z}/p\mathbb{Z})$.
- ▶ Alice chooses a private key m and sends Bob mP .
- ▶ Bob chooses a private key n and sends Alice nP .
- ▶ Alice and Bob both compute mnP , their shared secret key.

A Numerical Example of Diffie-Hellman Key Exchange with Elliptic Curves

- ▶ Alice and Bob publicly agree on $p = 571$ and the elliptic curve S given by $y^2 = x^3 - 12x + 5$. They then agree on $P = (16, 324)$.
- ▶ Alice privately computes and sends Bob $39P = (148, 387)$.
Bob privately computes and sends $121P = (465, 556)$.
- ▶ Alice privately computes $39(465, 556) = (202, 445)$, and Bob privately computes $121(148, 387) = (202, 445)$.

Elliptic Curve Discrete Logarithm Problem

- ▶ The security of an elliptic-curve cryptosystem is dependent on the solution to the elliptic curve discrete logarithm problem.
- ▶ Let S be an elliptic curve over $\mathbb{Z}/p\mathbb{Z}$ and $P \in S(\mathbb{Z}/p\mathbb{Z})$.
- ▶ Given Q a multiple of P , we aim to find $n \in \mathbb{Z}$ such that $nP = Q$.
- ▶ The naive approach is to simply check each possible value of n until one arrives at the solution Q . However, the naive approach becomes computationally infeasible as p is sufficiently large.
- ▶ Currently, it appears that the discrete logarithm problem on $E(\mathbb{Z}/p\mathbb{Z})$ is more difficult than the discrete logarithm problem on $\mathbb{Z}/p\mathbb{Z}^*$.
- ▶ An elliptic curve cryptosystem can offer equivalent security to many cryptosystems currently in use with much smaller numbers, which allows for great gains in efficiency.

Why Should You Care?

- ▶ You probably shouldn't.
- ▶ But, if you want to...
- ▶ Elliptic curves are much more space-efficient than other methods – a 1024-bit RSA key is equivalent to a 163-bit ECC key in security.
- ▶ However, because it's not as well-established, it has other potential issues.

Dual_EC_DRBG

- ▶ Published first in 2006.
- ▶ It was pushed by NSA to be standardized, even going so far as to pay a security company \$10 million to use it.
- ▶ Suspected to contain a backdoor.
- ▶ Removed by NIST in 2014.

Applications of Elliptic Curve Cryptography

- ▶ Presently, Bitcoin uses an elliptic curve digital signature algorithm to verify coin ownership.
- ▶ Google also utilizes elliptic curve public keys for encryption and verification.

Public Key Info

Algorithm	Elliptic Curve Public Key (1.2.840.10045.2.1)
Parameters	Elliptic Curve secp256r1 (1.2.840.10045.3.1.7)
Public Key	65 bytes : 04 D1 E6 FF B3 77 D8 A6 ...
Key Size	256 bits
Key Usage	Encrypt, Verify, Derive
Signature	256 bytes : 21 BF D2 FF A4 E4 D4 02 ...
