Practical Invalid Curve Attack Using Quadratic Twist

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Abstract

We present the common structure of the attack and give some insight to efficiently exploit quadratic twists. This paper has primarily an expository role.

1 Introduction

The so called *Invalid curve attack* is a real threat for cryptographic protocols based on elliptic curves. The attack has first been presented in [2] and the use of twists was described in[4]. OpenPGP.js prior to 4.2.0 was found to be vulnerable[1]. Bluetooth was proved to be vulnerable to a "Fixed Coordinate" variant [3]. The SafeCurves website and the associated paper [1] point out as

> An ECC implementor can stop an invalid-curve attack by checking whether the input point Q satisfies the correct curve equation; [...] But this creates a conflict between simplicity and security. An implementation that does not include this check is simpler and more likely to be produced, and will pass typical functionality tests.

As a side note, it is also at heart of many Capture The Flag and cryptographic challenges on dedicated platforms.

The rest of the paper is organized as follows. Section 2 recalls the basics mathematical concepts used in the sequel, we recall basics facts about discrete logarithm problem (DLP) and twists of elliptic curves. Section 3 presents the general setting of the attack and ways to exploit poor implementation and weak curves. Section 4 is a complete walktrhought an example. This paper has primarily an expository role.

2 Background Material

Notations : We will denote by $\mathbb{F}_q$ the finite field with $q = p^n$ elements where $p \geq 5$ and $n \in \mathbb{N} - \{0\}$. We will denote by $E/\mathbb{F}_q$ an elliptic curve defined over $\mathbb{F}_q$. The reader is assumed to be familiar with basic theory of elliptic curves.

Short Weierstrass equations. The characteristic p being different from 2 and 3, every elliptic curve $E/\mathbb{F}_q$ may be written as

$$E : y^2 = x^3 + ax + b, \quad a, b \in \mathbb{F}_q.$$

This is a so called *short Weierstrass form* of the curve E *defined over* $\mathbb{F}_q$.

Remark 1.
1. The characteristic p being greater than 5 is not a restriction in our context since p will usually be a large prime.
2. A short Weierstrass form is not unique. This will be completed in the subsection about twists.

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k = GF(11**2)
u = k(2)
E = EllipticCurve(k,[1,1])
E_ = EllipticCurve(k,[u**(-4),u**(-6)])
E.is_isomorphic(E_)
E.isomorphism_to(E_)
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Automorphisms. Let $E_1/\mathbb{F}_q$ and $E_2/\mathbb{F}_q$ be elliptic curves. These curves may be seen over $\overline{\mathbb{F}_q}$ that is, the coefficients of their equation may be seen as lying in $\overline{\mathbb{F}_q}$ instead of in $\mathbb{F}_q$. Every geometric isomorphism of elliptic curve ϕ from $E_1/\overline{\mathbb{F}_q}$ to $E_2/\overline{\mathbb{F}_q}$ has an affine part of the form

$$\phi(x, y) = (u^2x + r, u^3y + su^2x + t). \tag{1}$$

for $u \in \overline{\mathbb{F}_q}^*$, $r, s, t \in \overline{\mathbb{F}_q}$. We will denote geometric isomorphism as $\phi/\overline{\mathbb{F}_q}$. The isomorphism ψ is said to be *defined over* $\mathbb{F}_q$ or *rational* if $u, r, s, t \in \mathbb{F}_q$, we will denote it by $\psi/\mathbb{F}_q$.

For a sake of clarity we will stick to the notation ϕ for geometric isomorphism and ψ for rational isomorphisms.

[1] https://www.cve.org/CVERecord?id=CVE-2019-9155

Proposition 1. Let $E_i/\mathbb{F}_q$, $i \in \{1;2\}$ be elliptic curves given by short Weierstrass equations.

$$E_i : y^2 = x^3 + a_i x + b_i, \quad a_i, b_i \in \mathbb{F}_q.$$

A geometric isomorphism ϕ has the form

$$\phi(x, y) = (u^2 x, u^3 y).$$

Proof. This is included as a first step to fully understand isomorphisms in the quadratic twist case.
Let $(x, y) \in E_1$ and ϕ as given by (1). Applying ϕ to the equation of E_1 and expanding yields

$$\begin{aligned}
&y^2 = x^3 + a_1 x + b_1 \\
&\Leftrightarrow (u^3 y + s u^2 x + t)^2 = (u^2 x + r)^3 + a_1(u^2 x + r) + b_1 \\
&\Leftrightarrow u^6 y^2 + s^2 u^4 x^2 + t^2 + 2u^5 sxy + 2u^3 ty + 2tsu^2 x = u^6 x^3 + 3ru^4 x^2 + 3r^2 u^2 x + r^3 + a_1 u^2 x + a_1 r + b_1 (*)
\end{aligned}$$

Identifying coefficients of xy and y with those of $y^2 = x^3 + a_2 x + b_2$ yields $s = 0, t = 0$ (recall that $u \neq 0$ and $p \neq 2$).

$$(*) \Leftrightarrow u^6 y^2 = u^6 x^3 + 3ru^4 x^2 + 3r^2 u^2 x + r^3 + a_1 u^2 x + a_1 r + b_1$$

Then, identifying the coefficient of x^2 with the short equation of E_2 yields $r = 0$ (here we use $p \neq 3$). Thus $\phi(x, y) = (u^2 x, u^3 y)$. We conclude with the following computations that will be used in the sequel.

$$\begin{aligned}
&u^6 y^2 = u^6 x^3 + a_1 u^2 x + b_1 \\
&\Leftrightarrow y^2 = x^3 + \frac{a_1}{u^4} x + \frac{b_1}{u^6} \\
&\Leftrightarrow \frac{a_1}{u^4} = a_2, \quad \frac{b_1}{u^6} = b_2 (**)
\end{aligned}$$

□

Proposition 2. Assume $p \geq 5$. Let $E/\mathbb{F}_q$ be an elliptic curves given by short Weierstrass equations.

$$E_i : y^2 = x^3 + ax + b, \quad a, b \in \mathbb{F}_q.$$

The *j-invariant of E* is defined to be

$$j(E) = 1728 \frac{4a^3}{4a^3 + 27b^2}.$$

Given two elliptic curves E_1, E_2 defined over $\mathbb{F}_q$, there exists a geometric isomorphism $\phi/\overline{\mathbb{F}_q}$ from E_1 to E_2 if and only if $j(E_1) = j(E_2)$.

Remark 2.

1. We insist that the j-invariant classifies **geometric** isomorphism classes of elliptic curves over $\mathbb{F}_q$.
2. Since $p \geq 5$, $j(E) \notin \{0, 1728\}$ is equivalent to $a, b \in \mathbb{F}_q^*$.
3. !!! Revoir définie sur k et à coeff dans k

2.1 Twists of Elliptic Curves

Twists. Non trivial twists of $E/\mathbb{F}_q$ are elliptic curves $E'/\mathbb{F}_q$ being isomorphic to E when viewed over $\overline{\mathbb{F}_q}$ but not isomorphic to E when viewed over $\mathbb{F}_q$.

Definition 1. Le $E/\mathbb{F}_q$ be an elliptic curve. A *twist of E* is an elliptic curve $E_t/\mathbb{F}_q$ such that there is a geometric isomorphism $\phi/\overline{\mathbb{F}_q}$ of elliptic curves $\phi : E \simeq E_t$. A twist E_t of E is *trivial* if there exists an isomorphism ψ of elliptic curve **defined over** $\mathbb{F}_q$.

Quadratic Twists. Let $E/\mathbb{F}_q$ be an elliptic curve in short Weierstrass equation $y^2 = x^3 + ax + b$. Recall that $q = p^n$ and $p \geq 5$, so it is possible to write such an equation for E.

Definition 2. Let $d \in \mathbb{F}_q^*$. The *twist E_d of E by d* is the elliptic curve given in short Weierstrass equation

$$E_d : y^2 = x^3 + d^2 ax + d^3 b.$$

Remark 3. We did not specify that E_d is a non trivial twist of E. Actually, let δ be a square root of d in $\overline{\mathbb{F}_q}$ i.e. $\delta^2 = d$, then

$$\begin{aligned}
&\phi : E \to E_d \\
&(x, y) \mapsto (\frac{x}{d}, \frac{y}{d\delta})
\end{aligned}$$

is a geometric isomorphism from E to E_d. It matches the relations (**) concluding proof of Proposition 1 with $a_1 = a, b_1 = b, a_2 = ad^2, b_2 = bd^3$ and $d = \frac{1}{u}$.

Proposition 3. Assume that $j(E) \neq 0, 1728$. The twist E_d is trivial if and only if $d \in (\mathbb{F}_q^*)^2$.

Proof. ($\Rightarrow$) Assume that there exists a rational isomorphism ψ from E to E_d. According to Proposition 1, there exists $u \in \mathbb{F}_q^*$

$$\psi(x, y) = (u^2 x, u^3 y)$$

According to (**), $\frac{a}{u^4} = ad^2$ and $\frac{b}{u^6} = bd^3$. Recall that since $p \geq 5$, the assumption about $j(E)$ is equivalent to $a, b \neq 0$. Thus $\frac{1}{u^4} = d^2$, $\frac{1}{u^6} = d^3$ and $d = \frac{d^3}{d^2} = \frac{1}{u^2} \in (\mathbb{F}_q^*)^2$.

($\Leftarrow$) Conversely, let $\delta \in \mathbb{F}_q^*$ such that $\delta^2 = d$. Then

$$\psi(x, y) = \left(\frac{x}{d}, \frac{y}{d\delta}\right)$$

is a rational isomorphism from E to E_d. □

Proposition 4. Assume that $E/\mathbb{F}_q$ has $j(E) \neq 0, 1728$. Then a twist $E_t/\mathbb{F}_q$ of $E/\mathbb{F}_q$ is either trivial or E_d for some $d \in (\mathbb{F}_q^*) \backslash (\mathbb{F}_q^*)^2$.

Proof. Assume that $E_t/\mathbb{F}_q$ is a non trivial twist of $E/\mathbb{F}_q$ with isomorphism $\phi : E \to E_t$ given by $\phi(x, y) = (u^2 x, u^3 y)$, $u \in \overline{\mathbb{F}_q}$, $u \notin \mathbb{F}_q$. Let $E_t : y^2 = x^3 + a_t x + b_t$, $a_t, b_t \in \mathbb{F}_q$, thus (**) yields

$$a_t = \frac{a}{u^4}, b_t = \frac{b}{u^6}$$

Then $u^2 = \frac{ba_t}{ab_t} \in \mathbb{F}_q$, i.e. $u \notin \mathbb{F}_q$ but $u^2 \in \mathbb{F}_q$. This means that $u \in \mathbb{F}_{q^2} \backslash \mathbb{F}_q$. Let $d := \frac{1}{u^2}$, then $a_t = d^2 a, b_t = d^3 b$ and $\phi(x, y) = \left(\frac{x}{d}, \frac{uy}{d}\right)$. □

Remark 4.

1. Proposition 3 is wrong if $p < 5$.

   `example de courbe envoye a Steven sur F3`

2. Since $p \geq 5$, $j(E) \notin \{0, 1728\}$ is equivalent to $a, b \in \mathbb{F}_q^*$. The reader may ask in what extend this is a restriction.

Order of group of rational points. The group of rational points $E(\mathbb{F}_q)$ has order $\sharp E(\mathbb{F}_q) = q + 1 - t$ where t is the *Trace of Frobenius*. An extensive description of the Frobenius endomorphism is out scope for this paper, we only need some basics facts we recall below.

Proposition 5.

1. **(Hasse Bound)** One has $|t| \leq 2\sqrt{q}$.
2. One has $\sharp E_d(\mathbb{F}_q) = q + 1 + t$.

- Donner exemple avec E smooth Et aussi et écrire le morphism
- dans la remarque sur j différent de 0,1728. Dire que a ou b = 0 est peut commun pour l'usage crypto (courbes anormales ou supersing)

2.2 Discrete Logarithm Problem

Definition 3. Let G be a group in multiplicative notation. The **Discrete Logarithm Problem** (DLP) is : given $g, h \in G$ find $a \in \mathbb{Z}$ such that $h = g^a$.

Remark 5.

1. The group law on an elliptic curve is usually written in additive notation. So the DLP for elliptic curves may be rephrased : given $P, G \in E(\mathbb{F}_q)$ find $a \in \mathbb{Z}$ such that $P = aG$.

Solving the DLP

- Polhig Helman, BSGS, Rho.
- Expliquer que connaitre d modulo "suffisament" de premiers peut suffire, pas modulo "tous" les premiers.
- Sage Discretelog vs Q.log(P)

3 Invalid Curve Attack

3.1 General Setting

Position du problème : les algo de multiplication d*P n'utilisent que le coeff a de E, on peut passer (x,y) n'étant pas sur E.

- DLP peut etre trop dur sur E à cause de d'un ordre pas assez smooth.
- Si on peut faire calculer k*T pour T sur une autre courbe E' on peut trouver T modulo les premiers de l'ordre de E'.
- si le twist a un ordre avec d'autres facteurs premier que E alors on connait k modulo de nouveaux premiers.
- cela peut suffire à retrouver k (CRT)

3.2 Exploiting Ladders and twists

- L'importance des ladders cf Safe Curves
- L'importance des multiplications où on ne passe que le x.

References

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[4] P.-A. Fouque, R. Lercier, D. Réal, and F. Valette. Fault Attack on Elliptic Curve with Montgomery Ladder Implementation. In *FDTC '08. 5th Workshop on Fault Diagnosis and Tolerance in Cryptography*, pages 92–98. IEEE-CS Press, August 2008.