

# 18.783 Elliptic Curves

## Lecture 9

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# The discrete logarithm problem

## Definition

Let  $G$  be a finite group. For  $\alpha \in G$  and  $\beta \in \langle \alpha \rangle$  we define

$$\log_{\alpha} \beta := \min\{x \in \mathbb{Z}_{\geq 1} : \alpha^x = \beta\}.$$

The **discrete logarithm problem** (DLP) is to compute  $\log_{\alpha} \beta$  given  $\alpha, \beta \in \langle \alpha \rangle$ .

More generally, we can ask, given  $\alpha, \beta \in G$ , compute  $\log_{\alpha} \beta$  or determine  $\beta \notin \langle \alpha \rangle$ .

DLP-based cryptography relies on the assumption that this is a hard problem.

## Example

In  $G = \mathbb{F}_{101}^{\times}$  we have  $\log_3 37 = 24$  since  $3^{24} \equiv 37 \pmod{101}$ .

In  $G = \mathbb{F}_{101}^{+}$  we have  $\log_3 37 = 46$  since  $46 \cdot 3 \equiv 37 \pmod{101}$ .

One of these problems can be solved in quasilinear time!

The other one can be solved in subexponential (in some cases quasipolynomial) time!

## Some generalizations

### Definition

For  $\alpha, \beta \in G$  we define

$$\text{ord}_\alpha \beta := \min\{y \in \mathbb{Z}_{\geq 1} : \beta^y \in \langle \alpha \rangle\}.$$

The **extended discrete logarithm problem** is to compute the pair  $(x, y)$  where  $x = \log_\alpha \beta^y$  and  $y = \text{ord}_\alpha \beta$ , given  $\alpha, \beta \in G$ .

### Definition

Given  $\alpha_1, \dots, \alpha_r \in G$  and  $n_1, \dots, n_r \in \mathbb{Z}$  such that every  $\beta \in G$  has a unique representation as

$$\beta = \alpha_1^{e_1} \cdots \alpha_r^{e_r} \quad (1 \leq e_i \leq n_i),$$

the **vector discrete logarithm problem** is to compute  $(e_1, \dots, e_r)$  for a given  $\beta \in G$ .

## The discrete logarithm problem in a cyclic group

We will focus on the original DLP, with  $\beta \in \langle \alpha \rangle$ . WLOG we may assume  $G = \langle \alpha \rangle$ .

Let  $N = \#G$  be the order of the cyclic group  $G$ . We have an isomorphism

$$\begin{aligned} G &\xrightarrow{\sim} \mathbb{Z}/N\mathbb{Z} \\ \beta &\rightarrow \log_{\alpha} \beta \\ \alpha^x &\leftarrow x \end{aligned}$$

The Euclidean algorithm solves the DLP in  $\mathbb{Z}/N\mathbb{Z}$  in quasilinear time.

DLP-based cryptography is based on the assumption that there is no way to compute the isomorphism  $G \simeq \mathbb{Z}/N\mathbb{Z}$  without solving the DLP in  $G$  (note that the Euclidean algorithm does not work in the additive group  $\mathbb{Z}/N\mathbb{Z}$ , it uses ring operations in  $\mathbb{Z}$ ).

To analyze the difficulty of the DLP in general (and the efficiency of solutions), we will use a computational model that forces algorithms to work entirely in  $G$ .

# Generic group algorithms

## Definition

A **generic group algorithm** (or just a **generic algorithm**) is one that interacts with an abstract group  $G$  solely through a **black box** (sometimes called an **oracle**).

Group elements are opaquely encoded as bit-strings via a map  $\text{id}: G \rightarrow \{0, 1\}^m$  chosen by the black box. The black box supports the following operations.

- **identity**: output  $\text{id}(1_G)$ .
- **inverse**: given input  $\text{id}(\alpha)$ , output  $\text{id}(\alpha^{-1})$ .
- **compose**: given inputs  $\text{id}(\alpha)$  and  $\text{id}(\beta)$ , output  $\text{id}(\alpha\beta)$ .
- **random**: output  $\text{id}(\alpha)$  for a uniformly distributed random element  $\alpha \in G$ .

In the description above we used multiplicative notation; in additive notation the outputs would be  $\text{id}(0_G)$ ,  $\text{id}(-\alpha)$ ,  $\text{id}(\alpha + \beta)$ , respectively.

# Generic algorithms for DLP

## Example (Linear search)

Compute  $\alpha, 2\alpha, 3\alpha, \dots, x\alpha = \beta$ . This uses  $O(N)$  group operations.

## Example (Baby-steps giant-steps)

Pick  $r, s \in \mathbb{Z}_{\geq 1}$  with  $rs > N$  and compute

**baby-steps** :  $0, \alpha, 2\alpha, \dots, i\alpha, \dots (r-1)\alpha,$

**giant-steps** :  $\beta, \beta - r\alpha, \beta - 2r\alpha, \dots, \beta - jr\alpha, \dots \beta - (s-1)r\alpha.$

A collision between the  $i$ th baby-step and the  $j$ th giant-step yields the relation

$$i\alpha = \beta - jr\alpha$$

with  $0 \leq i < r$  and  $0 \leq j < s$ . If  $i = j = 0$  then  $\log_{\alpha} \beta = N$ , else  $\log_{\alpha} \beta = i + jr$ .

For  $r \approx s$  this uses  $O(\sqrt{N})$  group operations.

## The Pohlig-Hellman algorithm

Suppose  $N = N_1N_2$  with  $N_1 \perp N_2$ . Then  $\mathbb{Z}/N\mathbb{Z} \simeq \mathbb{Z}/N_1\mathbb{Z} \oplus \mathbb{Z}/N_2\mathbb{Z}$  and we have

$$\begin{aligned}x &\mapsto (x \bmod N_1, x \bmod N_2) \\(M_1x_1 + M_2x_2) \bmod N &\leftarrow (x_1, x_2)\end{aligned}$$

where

$$\begin{aligned}M_1 &= N_2(N_2^{-1} \bmod N_1) \equiv \begin{cases} 1 \bmod N_1, \\ 0 \bmod N_2, \end{cases} \\M_2 &= N_1(N_1^{-1} \bmod N_2) \equiv \begin{cases} 0 \bmod N_1, \\ 1 \bmod N_2. \end{cases}\end{aligned}$$

Note that computing  $M_1$  and  $M_2$  involves no group operations.

It thus costs nothing in our computational model which only counts group operations, but its bit complexity is quasilinear in any case (so it is indeed negligible).

## The Pohlig-Hellman algorithm

Let  $N = N_1N_2$  with  $N_1 \perp N_2$ , define  $M_1, M_2$  as above, and let

$$x_1 := x \bmod N_1 \quad \text{and} \quad x_2 := x \bmod N_2,$$

so that  $x = M_1x_1 + M_2x_2$ , and  $\beta = (M_1x_1 + M_2x_2)\alpha$ . We then have

$$N_2\beta = M_1x_1N_2\alpha + M_2x_2N_2\alpha.$$

The order of  $N_2\alpha$  is  $N_1$  (since  $N_1 \perp N_2$ ), and  $M_1 \equiv 1 \pmod{N_1}$ ,  $M_2 \equiv 0 \pmod{N_1}$  yield

$$N_2\beta = x_1N_2\alpha.$$

We similarly find that  $N_1\beta = x_2N_1\alpha$ , and therefore

$$x_1 = \log_{N_2\alpha} N_2\beta, \quad x_2 = \log_{N_1\alpha} N_1\beta.$$

If we know  $x_1$  and  $x_2$  then we can compute  $x = (M_1x_1 + M_2x_2) \bmod N$ .

## The Pohlig-Hellman algorithm

Applying  $N = N_1 N_2$  with  $N_1 \perp N_2$  recursively reduces to the case where  $N = p^e$  is a prime power using  $O(n \log n)$  group operations, where  $n = \log N$ .

Let  $e_0 = \lceil e/2 \rceil$ ,  $e_1 = \lfloor e/2 \rfloor$ , and write  $x = \log_\alpha \beta$  as  $x = x_0 + p^{e_0} x_1$ , where we have  $0 \leq x_0 < p^{e_0}$  and  $0 \leq x_1 < p^{e_1}$ . Then

$$\begin{aligned}\beta &= (x_0 + p^{e_0} x_1) \alpha \\ p^{e_1} \beta &= x_0 p^{e_1} \alpha + x_1 p^e \alpha \\ x_0 &= \log_{p^{e_1} \alpha} p^{e_1} \beta.\end{aligned}$$

We also have  $\beta - x_0 \alpha = p^{e_0} x_1 \alpha$ , and therefore

$$x_1 = \log_{p^{e_0} \alpha} (\beta - x_0 \alpha).$$

If  $N$  is not prime, this again reduces the computation of  $\log_\alpha \beta$  to the computation of two smaller discrete logarithms (of roughly equal size) using  $O(n)$  group operations.

## The Pohlig-Hellman algorithm

If we use the baby-steps giant-steps algorithm to solve the prime order cases we obtain a total complexity of

$$O\left(n \log n + \sum e_i \sqrt{p_i}\right)$$

group operations, where  $N = p_1^{e_1} \cdots p_r^{e_r}$  and  $n = \log N$ .

If  $p$  is the largest prime factor of  $N$  this simplifies to

$$O\left(n \log n + n \sqrt{p}\right)$$

group operations. If  $p = O(n^k)$  for some  $k$ , this is a polynomial-time generic algorithm.

## The Pollard-rho algorithm

Let us view  $G = \langle \alpha \rangle$  as the vertex set  $V$  of a connected graph  $\Gamma$  with edges  $e_{ij} = (\gamma_i, \gamma_j)$  labeled by  $\delta_{ij} = \gamma_j - \gamma_i$  so that  $\gamma_i + \delta_{ij} = \gamma_j$  (this is the Cayley graph).

If we can write each  $\delta_{ij}$  as a linear combination of  $\alpha$  and  $\beta$  then any cycle in this graph gives a linear relation between  $\alpha$  and  $\beta$  that we can use to compute  $\log_{\alpha} \beta$  (provided the coefficients of this relation are invertible modulo  $N$ ).

Consider a random walk in  $\Gamma$  starting at  $v_0 \in V$  defined by a function  $f: V \rightarrow V$ :

$$v_1 = f(v_0)$$

$$v_2 = f(v_1)$$

$$v_3 = f(v_2)$$

$\vdots$

Eventually we will repeat a vertex  $v_{\rho} = v_{\lambda}$  with  $\rho > \lambda$  and then enter an infinite cycle.

# The Pollard-rho algorithm

## Theorem

Let  $V$  be a finite set. For any  $v_0 \in V$ , the expected value of  $\rho$  for a walk from  $v_0$  defined by a random function  $f: V \rightarrow V$  is

$$E[\rho] \sim \sqrt{\pi N/2},$$

as  $\#V = N \rightarrow \infty$ . We also have  $E[\lambda] = E[\sigma] = \frac{1}{2} E[\rho] = \sqrt{\pi N/8}$ , where  $\sigma = \rho - \lambda$ .

# The Pollard-rho algorithm

Fix  $r \approx 20$ . Let  $h: G \rightarrow \{1, \dots, r\}$  be a random function (a **hash function**), pick  $r$  random pairs  $(c_i, d_i) \in \mathbb{Z}/N\mathbb{Z} \times \mathbb{Z}/N\mathbb{Z}$ , define  $\delta_i := c_i\alpha + d_i\beta$ , and define

$$f: \mathbb{Z}/N\mathbb{Z} \times \mathbb{Z}/N\mathbb{Z} \times G \longrightarrow \mathbb{Z}/N\mathbb{Z} \times \mathbb{Z}/N\mathbb{Z} \times G$$
$$(a, b, \gamma) \mapsto (a + c_i, b + d_i, \gamma + \delta_i) \quad (\text{where } i = h(\gamma)).$$

In practice we don't pick  $h$  at random, we could use  $\text{id}(\gamma) \bmod r$ , for example.

We can now use  $f$  to define an  **$r$ -adding** walk, starting from some  $\gamma_0 = a_0\alpha + b_0\beta$  with  $a_0, b_0 \in \mathbb{Z}/N\mathbb{Z}$  chosen at random.

Note that if  $(a_{j+1}, b_{j+1}, \gamma_{j+1}) = f(a_j, b_j, \gamma_j)$ , the value of  $\gamma_{j+1}$  depends only on  $\gamma_j$ , not on  $a_j$  or  $b_j$ , so this defines a random walk on  $V$ .

# The Pollard-rho algorithm

## Algorithm (Pollard- $\rho$ )

Given  $\alpha$ ,  $N = |\alpha|$ ,  $\beta \in \langle \alpha \rangle$ , compute  $\log_\alpha \beta$  as follows:

1. Compute  $\delta_i = c_i\alpha + d_i\beta$  for  $r \approx 20$  randomly chosen pairs  $c_i, d_i \in \mathbb{Z}/N\mathbb{Z}$ .
2. Compute  $\gamma_0 = a_0\alpha + b_0\beta$  for randomly chosen  $a_0, b_0 \in \mathbb{Z}/N\mathbb{Z}$ .
3. Compute  $(a_j, b_j, \gamma_j) = f(a_{j-1}, b_{j-1}, \gamma_{j-1})$  for  $j \geq 1$  until  $\gamma_k = \gamma_j$  with  $k > j$ .
4.  $\gamma_k = \gamma_j$  implies  $a_j\alpha + b_j\beta = a_k\alpha + b_k\beta$ . Provided that  $b_k - b_j$  is invertible in  $\mathbb{Z}/N\mathbb{Z}$ , we return  $\log_\alpha \beta = \frac{a_j - a_k}{b_k - b_j} \in \mathbb{Z}/N\mathbb{Z}$ ; otherwise start over at step 1.

This algorithm terminates with probability 1 and its output is always correct. It is a Las Vegas algorithm with expected running time  $O(\sqrt{N})$ .

As written it uses  $O(\sqrt{N})$  space, because we have to store all the  $\gamma_j$  to detect  $\gamma_k = \gamma_j$ .

## Floyd's cycle detection method (aka the tortoise and the hare)

We now modify Step 3 of the algorithm to compute

$$\begin{aligned}(a_j, b_j, \gamma_j) &= f(a_{j-1}, b_{j-1}, \gamma_{j-1}) \\ (a_k, b_k, \gamma_k) &= f(f(a_{k-1}, b_{k-1}, \gamma_{k-1})).\end{aligned}$$

The triple  $(a_j, b_j, \gamma_j)$  is the **tortoise**, and the triple  $(a_k, b_k, \gamma_k)$  is the **hare**.

Once the tortoise enters the cycle, the hare (already in the cycle) will collide with the tortoise within  $\sigma = \rho - \lambda$  iterations.

The expected number of iterations is  $E[\lambda + \sigma/2] = 3/4 E[\rho]$ , but each iteration uses 3 group operations, making the algorithm slower by a factor of  $9/4$ . Still, this achieves a time complexity of  $O(\sqrt{N})$  group operations while storing just  $O(1)$  group elements.

The  $9/4$  can be reduced to  $1 + o(1)$  using **distinguished points** (see notes for details).

## A generic lower bound

### Theorem (Shoup 1997)

Let  $G = \langle \alpha \rangle$  be a group of order  $N$ . Let  $\mathcal{B}$  be a black box for  $G$  using a random identification map  $id: G \hookrightarrow \{0, 1\}^m$ . Let  $\mathcal{A}: \{0, 1\}^m \times \{0, 1\}^m \rightarrow \mathbb{Z}/N\mathbb{Z}$  be a randomized generic group algorithm that makes at most  $s - 4\lceil \lg N \rceil$  calls to  $\mathcal{B}$ , for some integer  $s$ , and let  $x$  denote a random element of  $\mathbb{Z}/N\mathbb{Z}$ . Then

$$\Pr_{x, id, \tau} [\mathcal{A}(id(\alpha), id(x\alpha)) = x] < \frac{s^2}{2p},$$

where  $\tau$  denotes random coin-flips made by  $\mathcal{A}$  and  $p$  is the largest prime factor of  $N$ .

### Corollary

Let  $G$  be a cyclic group of prime order  $N$ . Every generic Las Vegas algorithm for the discrete logarithm problem in  $G$  uses an expected  $\Omega(\sqrt{N})$  group operations.

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