

Diffie-Hellman Problem and Cryptography

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- 1** Cyclic Groups and Discrete Logarithms
- 2** Diffie-Hellman Assumptions and Applications
- 3** The ElGamal Encryption Scheme
- 4** Elliptic Curve Cryptography

1 Cyclic Groups and Discrete Logarithms

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Cyclic Groups and Generators

\mathbb{G} is finite and $g \in \mathbb{G}$, $\langle g \rangle \stackrel{\text{def}}{=} \{g^0, g^1, \dots\} = \{g^0, g^1, \dots, g^{i-1}\}$.

- The **order** of g is the smallest positive integer i with $g^i = 1$.
- \mathbb{G} is a **cyclic group** if $\exists g$ has order $m = |\mathbb{G}|$. $\langle g \rangle = \mathbb{G}$, g is a **generator** of \mathbb{G} .

- Is \mathbb{Z}_6^* , \mathbb{Z}_7^* , or \mathbb{Z}_8^* with \cdot cyclic?

Discrete Logarithm

If \mathbb{G} is a cyclic group of order q , then \exists a generator $g \in \mathbb{G}$ such that $\{g^0, g^1, \dots, g^{q-1}\} = \mathbb{G}$.

- $\forall h \in \mathbb{G}$, \exists a unique $x \in \mathbb{Z}_q$ such that $g^x = h$.
- $x = \log_g h$ is the **discrete logarithm of h with respect to g** .
- If $g^{x'} = h$, then $\log_g h = [x' \bmod q]$.
- $\log_g 1 = 0$ and $\log_g(h_1 \cdot h_2) = [(\log_g h_1 + \log_g h_2) \bmod q]$.

Show an instance of DL problem in \mathbb{Z}_7^*

Overview of Discrete Logarithm Algorithms

- Given a generator $g \in \mathbb{G}$ and $y \in \langle g \rangle$, find x such that $g^x = y$.
- **Brute force**: $\mathcal{O}(q)$, $q = \text{ord}(g)$ is the order of $\langle g \rangle$.
- **Baby-step/giant-step** method [Shanks]: $\mathcal{O}(\sqrt{q} \cdot \text{polylog}(q))$.
- **Pohlig-Hellman** algorithm: when q has small factors.
- **Index calculus** method: $\mathcal{O}(\exp(\sqrt{n \cdot \log n}))$.
- The best-known algorithm is the **general number field sieve** with time $\mathcal{O}(\exp(n^{1/3} \cdot (\log n)^{2/3}))$.

Using Prime-Order Groups

Theorem 1

If \mathbb{G} is of prime order, then \mathbb{G} is cyclic. All $g \in \mathbb{G}$ except the identity are generators.

It is proved from **Lagrange's theorem**: $\langle g \rangle$ is a subgroup of \mathbb{G} , and $|\langle g \rangle| \mid |\mathbb{G}|$. See <https://brilliant.org/wiki/lagranges-theorem/>.

Why using prime-order groups?

- The discrete logarithm problem is hardest in such groups.
- Finding a generator in such groups is trivial.
- Any non-zero exponent will be invertible modulo the order.
- A necessary condition for the DDH problem to be hard is that $\text{DH}_g(h_1, h_2)$ by itself should be indistinguishable from a random group element. This is (almost) true for such groups.

Generating Prime-Order (Sub)Groups in \mathbb{Z}_p^*

- $y \in \mathbb{Z}_p^*$ is a **quadratic residue modulo** p if $\exists x \in \mathbb{Z}_p^*$ such that $x^2 \equiv y \pmod{p}$. (Q: show QRs in \mathbb{Z}_7^*)
- The set of QR is a subgroup with order $(p-1)/2$ ($x^2 \equiv (p-x)^2 \pmod{p}$).
- p is a **strong prime** if $p = 2q + 1$ with q prime.

Algorithm 1: A group generation algorithm \mathcal{G}

input : Security parameter 1^n

output: Cyclic group \mathbb{G} , its order q , and a generator g

- 1 **generate** a random $(n+1)$ -bit strong prime p
 - 2 $q := (p-1)/2$
 - 3 **choose** an arbitrary $x \in \mathbb{Z}_p^*$ with $x \not\equiv \pm 1 \pmod{p}$
 - 4 $g := x^2 \pmod{p}$
 - 5 **return** p, q, g
-

The Discrete Logarithm Assumption

The discrete logarithm experiment $\text{DLog}_{\mathcal{A}, \mathcal{G}}(n)$:

- 1 Run a group-generating algorithm $\mathcal{G}(1^n)$ to obtain (\mathbb{G}, q, g) , where \mathbb{G} is a cyclic group of order q (with $\|q\| = n$), and g is a generator of \mathbb{G} .
- 2 Choose $h \leftarrow \mathbb{G}$. ($x' \leftarrow \mathbb{Z}_q$ and $h := g^{x'}$)
- 3 \mathcal{A} is given \mathbb{G}, q, g, h , and outputs $x \in \mathbb{Z}_q$.
- 4 $\text{DLog}_{\mathcal{A}, \mathcal{G}}(n) = 1$ if $g^x = h$, and 0 otherwise.

Definition 2

The discrete logarithm problem is hard relative to \mathcal{G} if \forall PPT algorithm \mathcal{A} , $\exists \text{negl}$ such that

$$\Pr[\text{DLog}_{\mathcal{A}, \mathcal{G}}(n) = 1] \leq \text{negl}(n).$$

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Diffie-Hellman Assumptions

- **Computational Diffie-Hellman (CDH) problem:**

$$\text{DH}_g(h_1, h_2) \stackrel{\text{def}}{=} g^{\log_g h_1 \cdot \log_g h_2}$$

- **Decisional Diffie-Hellman (DDH) problem:**

Distinguish $\text{DH}_g(h_1, h_2)$ from a random group element h' .

Definition 3

DDH problem is hard relative to \mathcal{G} if \forall PPT \mathcal{A} , \exists negl such that

$$|\Pr[\mathcal{A}(\mathbb{G}, q, g, g^x, g^y, g^z) = 1] - \Pr[\mathcal{A}(\mathbb{G}, q, g, g^x, g^y, g^{xy}) = 1]| \\ \leq \text{negl}(n).$$

Intractability of DL, CDH and DDH

DDH is easier than CDH and DL.

Secure Key-Exchange Experiment

The key-exchange experiment $\text{KE}_{\mathcal{A}, \Pi}^{\text{eav}}(n)$:

- 1 Two parties holding 1^n execute protocol Π . Π results in a **transcript** trans containing all the messages sent by the parties, and a **key** k that is output by each of the parties.
- 2 A random bit $b \leftarrow \{0, 1\}$ is chosen. If $b = 0$ then choose $\hat{k} \leftarrow \{0, 1\}^n$ u.a.r, and if $b = 1$ then set $\hat{k} := k$.
- 3 \mathcal{A} is given trans and \hat{k} , and outputs a bit b' .
- 4 $\text{KE}_{\mathcal{A}, \Pi}^{\text{eav}}(n) = 1$ if $b' = b$, and 0 otherwise.

Definition 4

A key-exchange protocol Π is secure in the presence of an eavesdropper if \forall PPT \mathcal{A} , \exists negl such that

$$\Pr[\text{KE}_{\mathcal{A}, \Pi}^{\text{eav}}(n) = 1] < \frac{1}{2} + \text{negl}(n).$$

Diffie-Hellman Key-Exchange Protocol



$$(\mathbb{G}, q, g) \leftarrow \mathcal{G}$$

$$\begin{array}{ccc} x \leftarrow \mathbb{Z}_q & & \\ h_1 := g^x & \xrightarrow{\mathbb{G}, q, g, h_1} & \\ & & y \leftarrow \mathbb{Z}_q \\ & \xleftarrow{h_2} & h_2 := g^y \\ k_A := h_2^x & & k_B := h_1^y \end{array}$$

Q: $k_A = k_B = k = ?$

$\widehat{\text{KE}}_{\mathcal{A}, \Pi}^{\text{eav}}$ denote an experiment where if $b = 0$ the adversary is given $\hat{k} \leftarrow \mathbb{G}$.

Theorem 5

If DDH problem is hard relative to \mathcal{G} , then DH key-exchange protocol Π is secure in the presence of an eavesdropper (with respect to the modified experiment $\widehat{\text{KE}}_{\mathcal{A}, \Pi}^{\text{eav}}$).

Security

Insecurity against active adversaries (Man-In-The-Middle).

Proof of Security in DH Key-Exchange Protocol

Proof.

$$\begin{aligned}\Pr \left[\widehat{\text{KE}}_{\mathcal{A}, \Pi}^{\text{eav}} = 1 \right] \\ = \frac{1}{2} \cdot \Pr \left[\widehat{\text{KE}}_{\mathcal{A}, \Pi}^{\text{eav}} = 1 | b = 1 \right] + \frac{1}{2} \cdot \Pr \left[\widehat{\text{KE}}_{\mathcal{A}, \Pi}^{\text{eav}} = 1 | b = 0 \right]\end{aligned}$$

If $b = 1$, then give true key; otherwise give random g^z .

$$\begin{aligned}&= \frac{1}{2} \cdot \Pr [\mathcal{A}(g^x, g^y, g^{xy}) = 1] + \frac{1}{2} \cdot \Pr [\mathcal{A}(g^x, g^y, g^z) = 0] \\&= \frac{1}{2} \cdot \Pr [\mathcal{A}(g^x, g^y, g^{xy}) = 1] + \frac{1}{2} \cdot (1 - \Pr [\mathcal{A}(g^x, g^y, g^z) = 1]) \\&= \frac{1}{2} + \frac{1}{2} \cdot (\Pr [\mathcal{A}(g^x, g^y, g^{xy}) = 1] - \Pr [\mathcal{A}(g^x, g^y, g^z) = 1]) \\&\leq \frac{1}{2} + \frac{1}{2} \cdot \text{negl}(n)\end{aligned}$$



Example of DHKE

$$G = \mathbb{Z}_{11}^*$$

The order $q = ?$

The set of quadratic residues ?

Is $g = 3$ a generator?

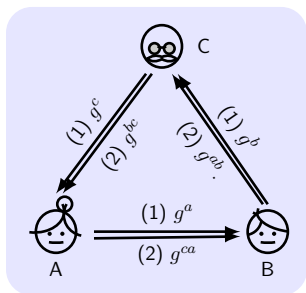
If $x = 3$ and $y = 4$, what's the message from Bob to Alice?

How does Alice compute the key?

How does Bob compute the key?

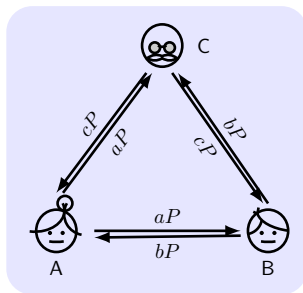
Triparties Key Exchange

DH-based KE in 2 rounds:



$$\text{Key} = g^{abc}.$$

Joux's KE in 1 round:



$$\text{Key} = e(P, P)^{abc} \text{ in bilinear map.}$$

Open Problem

How to exchange keys between 4 parties in one round?

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Lemma on Perfectly-secret Private-key Encryption

Lemma 6

\mathbb{G} is a finite group and $m \in \mathbb{G}$ is an arbitrary element. Then choosing random $k \leftarrow \mathbb{G}$ and setting $c := k \cdot m$ gives the same distribution for c as choosing random $c \leftarrow \mathbb{G}$. I.e., $\forall g \in \mathbb{G}$:

$$\Pr[k \cdot m = g] = 1/|\mathbb{G}|.$$

where the probability is taken over uniform choice of $k \in \mathbb{G}$.

Proof.

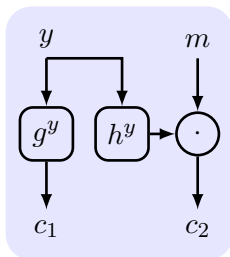
Let $g \in \mathbb{G}$ be arbitrary, then

$$\Pr[k \cdot m = g] = \Pr[k = g \cdot m^{-1}].$$

Since k is chosen *u.a.r.*, the probability that k is equal to the fixed element $g \cdot m^{-1}$ is exactly $1/|\mathbb{G}|$. □

The ElGamal Encryption Scheme

An algorithm \mathcal{G} , on input 1^n , outputs a description of a cyclic group \mathbb{G} , its order q (with $\|q\| = n$), and a generator g .



Construction 7

- **Gen:** run $\mathcal{G}(1^n)$ to obtain (\mathbb{G}, q, g) . A random $x \leftarrow \mathbb{Z}_q$ and $h := g^x$. $pk = \langle \mathbb{G}, q, g, h \rangle$ and $sk = \langle \mathbb{G}, q, g, x \rangle$
- **Enc:** a random $y \leftarrow \mathbb{Z}_q$ and output $\langle c_1, c_2 \rangle = \langle g^y, h^y \cdot m \rangle$
- **Dec:** $m := c_2 / c_1^x$

Theorem 8

If the DDH problem is hard relative to \mathcal{G} , then the ElGamal encryption scheme is CPA-secure.

Example of ElGamal Encryption

Encoding binary strings:

- the subgroup of quadratic residues modulo a strong prime $p = (2q + 1)$.
- a string $\hat{m} \in \{0, 1\}^{n-1}$, $n = \|q\|$.
- map \hat{m} to the plaintext $m = [(\hat{m} + 1)^2 \bmod p]$.
- The mapping is one-to-one and efficiently invertible.

$q = 83$, $p = 2q + 1 = 167$, $g = 2^2 = 4 \pmod{167}$, $\hat{m} = 011101$

The receiver chooses secret key $37 \in \mathbb{Z}_{83}$.

The public key is $pk = \langle 167, 83, 4, [4^{37} \bmod 167] = 76 \rangle$.

$\hat{m} = 011101 = 29$, $m = [(29 + 1)^2 \bmod 167] = 65$.

Choose $y = 71$, the ciphertext is

$\langle [4^{71} \bmod 167], [76^{71} \cdot 65 \bmod 167] \rangle = \langle 132, 44 \rangle$.

Decryption: $m = [44 \cdot (132^{37})^{-1}] \equiv [44 \cdot 66] \equiv 65 \pmod{167}$.

65 has the two square roots 30 and 137, and $30 < q$, so $\hat{m} = 29$.

Proof of Security of ElGamal Encryption Scheme

Proof.

Idea: Prove that Π is secure in the presence of an eavesdropper by reducing an algorithm D for DDH problem to the eavesdropper \mathcal{A} .

Modify Π to $\tilde{\Pi}$: the encryption is done by choosing random $y \leftarrow \mathbb{Z}_q$ and $z \leftarrow \mathbb{Z}_q$ and outputting the ciphertext:

$$\langle g^y, g^z \cdot m \rangle.$$

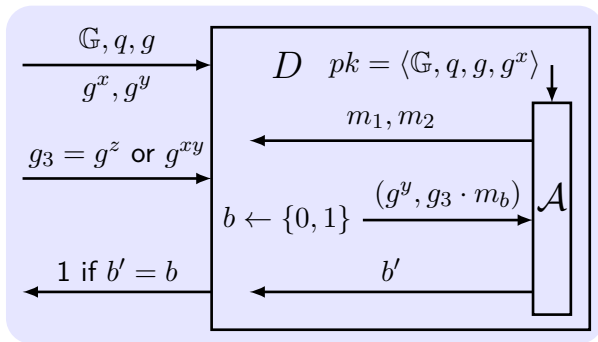
- $\tilde{\Pi}$ is not an encryption scheme.
- g^y is independent of m .
- $g^z \cdot m$ is a random element independent of m (Lemma 6).

$$\Pr [\text{PubK}_{\mathcal{A}, \tilde{\Pi}}^{\text{eav}}(n) = 1] = \frac{1}{2}.$$



Proof (Cont.)

D receives $(\mathbb{G}, q, g, g^x, g^y, g_3)$ where g_3 equals either g^{xy} or g^z , for random x, y, z :



Case I: $g_3 = g^z$, ciphertext is $\langle g^y, g^z \cdot m_b \rangle$.

$$\Pr[D(g^x, g^y, g^z) = 1] = \Pr[\text{PubK}_{\mathcal{A}, \tilde{\Pi}}^{\text{eav}}(n) = 1] = \frac{1}{2}.$$

Case II: $g_3 = g^{xy}$, ciphertext is $\langle g^y, g^{xy} \cdot m_b \rangle$.

$$\Pr[D(g^x, g^y, g^{xy}) = 1] = \Pr[\text{PubK}_{\mathcal{A}, \Pi}^{\text{eav}}(n) = 1] = \varepsilon(n).$$

Since the DDH problem is hard,

$$\begin{aligned} \text{negl}(n) &\geq |\Pr[D(g^x, g^y, g^z) = 1] - \Pr[D(g^x, g^y, g^{xy}) = 1]| \\ &= \left| \frac{1}{2} - \varepsilon(n) \right|. \end{aligned}$$

Constructing the ciphertext of the message $m \cdot m'$.

Given $pk = \langle g, h \rangle$, $c = \langle c_1, c_2 \rangle$, $c_1 = g^y$, $c_2 = h^y \cdot m$,

Method I: compute $c'_2 := c_2 \cdot m'$, and $c' = \langle c_1, c'_2 \rangle$.

$$\frac{c'_2}{c_1^x} = ?$$

Method II: compute $c''_1 := c_1 \cdot g^{y''}$, and $c''_2 := c_2 \cdot h^{y''} \cdot m'$.

$$c''_1 = g^y \cdot g^{y''} = g^{y+y''} \text{ and } c''_2 = ?$$

so $c'' = \langle c''_1, c''_2 \rangle$ is an encryption of $m \cdot m'$.

- **Sharing public parameters:** \mathcal{G} generates parameters \mathbb{G}, q, g .
 - generated “once-and-for-all”.
 - used by multiple receivers.
 - each receiver must choose their own secret values x and publish their own public key containing $h = g^x$.

Parameter sharing

In the case of ElGamal, the public parameters can be shared. In the case of RSA, can parameters be shared?

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- Discrete Logarithm Problem is constructed geometrically in Elliptic Curve Group.
- ECC was suggested independently by Neal Koblitz and Victor S. Miller in 1985.
- Analogy to DL, DHKE, ElGamal encryption and DSA: ECDL, ECDHKE, ElGamal ECC, ECDSA
- **Efficiency:** ECG vs. \mathbb{Z}_p^* : more efficient (faster) for the honest parties, but that are equally hard for an adversary to break. Both 1024-bit \mathbb{Z}_p^* and 132-bit ECG need 2^{66} steps.

Elliptic Curve Groups

- **Elliptic curve group:** points with “addition” operation on a plane algebraic curve in a finite field:

$$y^2 \equiv x^3 + Ax + B \pmod{p}$$

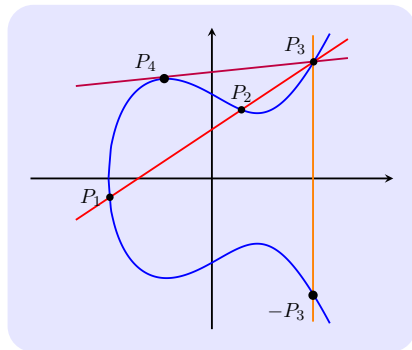
where $A, B \in \mathbb{Z}_p$ are constants with $4A^3 + 27B^2 \not\equiv 0 \pmod{p}$.

- $\hat{E}(\mathbb{Z}_p)$ is the set of pairs $(x, y) \in \mathbb{Z}_p \times \mathbb{Z}_p$:

$$\hat{E}(\mathbb{Z}_p) \stackrel{\text{def}}{=} \{(x, y) \mid x, y \in \mathbb{Z}_p \wedge y^2 \equiv x^3 + Ax + B \pmod{p}\}$$

- $E(\mathbb{Z}_p) \stackrel{\text{def}}{=} \hat{E}(\mathbb{Z}_p) \cup \{\mathcal{O}\}$, \mathcal{O} is identity, “**point at infinity**”.

“Addition” on Points of Elliptic Curves



Every line intersects the curve in 3 points:

- count twice if tangent.
- count \mathcal{O} at the vertical infinity of y -axis.

“**Addition**” on points:

- $P + \mathcal{O} = \mathcal{O} + P = P$.
- If P_1, P_2, P_3 are co-linear, then $P_1 + P_2 + P_3 = \mathcal{O}$.

Some equations:

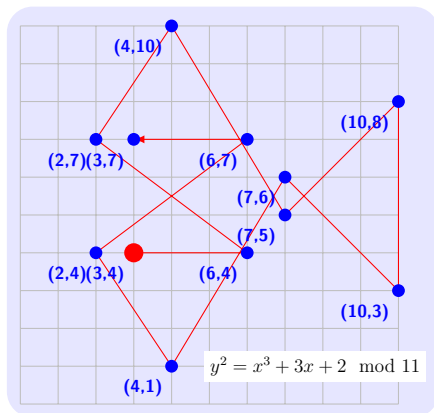
$$-P = (x, -y), P_1 + P_2 = -P_3, 2P_4 = -P_3, dP = P + (d-1)P$$

$$\text{Key generation: } sk = (P, d); pk = (P, Q = dP)$$

A Toy Example of ECDHKE

What is the key?¹

In ECDHKE protocol, Alice sends aP , Bob sends bP , and the key is $(a \cdot b)P$. Alice generates $P = (3, 4)$, $a = 5$ and receive $(7, 6)$.



¹The example is generated from <https://grau.de/code/elliptic2/>

Elliptic Curve Cryptosystems in Practices

TLS 1.3 (RFC8446) standardizes mandatory-to-implement ECC.

P256 or secp256r1 for DSA and DHKE

- $p := 2^{256} - 2^{224} + 2^{192} + 2^{96} - 1$
- $y^2 = x^3 - 3x + b$, $b :=$ 5ac635d8 aa3a93e7 b3ebbd55 769886bc 651d06b0 cc53b0f6 3bce3c3e 27d2604b
- It is not clear how b is designed. NOT **twist secure** as the DLP in its twist is not hard. NSA implemented a backdoor into the P256 curve based Dual_EC_DRBG algorithm.

Curve25519 for DHKE

- $p := 2^{255} - 19$
- $y^2 = x^3 + 486662 \cdot x^2 + x$ (Montgomery curve)
- The curve is generated by a point $P = (9, y)$
- It is twist secure and more understandable than P256.

- DHKE protocol, ElGamal encryption from CDH, DDH from Discrete Logarithm Problem in prime-order cyclic groups.
- Elliptic curve cryptography is more efficient and widely used.