

Number Theory & Cryptographic Hardness Assumptions

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- One-way functions
- Prime numbers
- Modular Arithmetic

Basic Group Theory

Factoring Assumption & RSA

Cyclic Groups

- Cyclic Groups and Generators
- The Discrete Logarithm
- Diffie-Hellman Assumptions
- Subgroups of \mathbb{Z}_p^*
- Elliptic Curves

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Introduction

One-way functions

“One goal of this chapter is to introduce various problems believed to be hard, and to present conjectured one-way functions based on those problems.”

“[I]n the public-key setting all known constructions rely on hard number-theoretic problems.”

Introduction

One-way functions

The inverting experiment $Invert_{\mathcal{A},f}(n)$

1. Choose uniform $x \in \{0, 1\}^n$, and compute $y := f(x)$.
2. \mathcal{A} is given 1^n and y as input, and outputs x' .
3. The output of the experiment is defined to be 1 if $f(x') = y$, and 0 otherwise.

Introduction

One-way functions

Definition 7.1

A function $f : \{0, 1\}^* \leftarrow \{0, 1\}^*$ is one-way if the following two conditions hold:

1. **(Easy to compute):** There exists a polynomial-time algorithm M_f computing f ; that is, $M_f(x) = f(x)$ for all x .
2. **(Hard to compute):** For every probabilistic polynomial-time algorithm \mathcal{A} , there is a negligible function $negl$ such that

$$\Pr [Invert_{\mathcal{A}, f}(n) = 1] \leq negl(n)$$

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Introduction

Divisibility

For two integers $a, b \in \mathbb{Z}$, a divides b , written as $a \mid b$, if there exists an integer c such that $ac = b$.

The *greatest common divisor* of two integers a, b , written $\gcd(a, b)$, is the largest integer c such that $c \mid a$ and $c \mid b$. We say that a and b are relatively prime if $\gcd(a, b) = 1$.

Introduction

Primes

A positive integer $p > 1$ is *prime* if it has no factors; that is, it has only two divisors: 1 and itself.

A positive integer greater than 1 that is not a prime is called a *composite*. That is because all composites can be uniquely expressed as a product of primes.

$$N = \prod p_i^{e_i}$$

where p_i are distinct primes and $e_i \geq 1$ for all i .

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Division with remainders

Proposition 8.1

Let a be an integer and let b be a positive integer. Then there exist unique integers q, r for which $a = qb + r$ and $0 \leq r < b$.

Modulo Reduction

We define $[a \bmod N]$ to be equal to this r . Note that $0 \leq [a \bmod N] < N$.

Modular Arithmetic

congruence Modulo

We say that a and b are *congruent modulo* N , written as $a \equiv b \pmod{N}$, if $[a \pmod{N}] = [b \pmod{N}]$. Note that $a \equiv b \pmod{N}$ if and only if $N \mid (a - b)$.

Example

$$36 \equiv 21 \pmod{15} \text{ as } 15 \mid (36 - 21).$$

Congruence modulo is an equivalence functions as it is reflexive ($\forall a, a \equiv a \pmod{N}$), symmetric ($a \equiv b \pmod{N} \Rightarrow b \equiv a \pmod{N}$), and transitive ($a \equiv b \pmod{N} \wedge b \equiv c \pmod{N} \Rightarrow a \equiv c \pmod{N}$).

Modular Arithmetic

congruence Modulo

Congruence module respects addition and multiplication

Example

$$[25 \cdot 2 \bmod 5] = [25 \bmod 5] \cdot [2 \bmod 5] = 25 \cdot 2 \equiv 50 \bmod 5$$

Modular Arithmetic

congruence Modulo

Congruence modulo does not (in general) respect division.

Example

$$3 \cdot 2 \equiv 6 \equiv 15 \cdot 2 \pmod{24}, \text{ but } 3 \not\equiv 15 \pmod{24}.$$

However; If for a given integer b there exists an integer c such that $bc = 1 \pmod{N}$, then we say that b is *invertible* modulo N , and call c a inverse of b . When b is invertible then we define the inverse as b^{-1} and define division as

$$[a/b \pmod{N}] \stackrel{\text{def}}{=} [ab^{-1} \pmod{N}]$$

Modular Arithmetic

congruence Modulo

Proposition 8.7

Let b, N be integers, with $b \geq 1$ and $N > 1$. Then b is invertible modulo N if and only if $\gcd(b, N) = 1$.

Groups

Abelian groups

Definition 8.9

An abelian group is a finite set \mathbb{G} , with $|\mathbb{G}|$ denoting the order of the set, along with a binary operator \circ for which the following conditions hold:

- ▶ **(Closure:)** For all $g, h \in \mathbb{G}$, $g \circ h \in \mathbb{G}$.
- ▶ **(Existence of an identity:)** There exists an identity $e \in \mathbb{G}$ such that for all $g \in \mathbb{G}$, $e \circ g = g = g \circ e$.
- ▶ **(Existence of inverses:)** For all $g \in \mathbb{G}$ there exists an element $h \in \mathbb{G}$ such that $g \circ h = e = h \circ g$.
- ▶ **(Associativity:)** For all $g, h, j \in \mathbb{G}$, $(g \circ h) \circ j = g \circ (h \circ j)$.
- ▶ **(Commutativity:)** for all $g, h \in \mathbb{G}$, $g \circ h = h \circ g$.

Groups

Additive groups

Example

Let $N > 1$ be an integer. The set $0, \dots, N - 1$ with respect to addition modulo N is an abelian group of order N , where the identity of the group is 0 . We denote this group \mathbb{Z}_N .

Groups

Group exponentiation

It is often useful to describe the group operation applied m times to a fixed element g , where m is a positive integer. When using additive notation we express this $m \cdot g$; that is

$$m \cdot g \stackrel{\text{def}}{=} \underbrace{g + \cdots + g}_{m \text{ times}}$$

Thankfully, the notation adheres to familiar arithmetic rules such as:

$$(mg) + (m'g) = g \cdot (m + m')$$

$$m \cdot (m'g) = g \cdot (mm')$$

$$1 \cdot g = g$$

Groups

Group exponentiation

When using multiplicative notation we express this g^m ; that is

$$g^m \stackrel{\text{def}}{=} \underbrace{g \cdots g}_{m \text{ times}}$$

Thankfully, the notation adheres to familiar arithmetic rules such as:

$$g^m \cdot g^{m'} = g^{m+m'}$$

$$(g^m)^{m'} = g^{mm'}$$

$$g^m \cdot h^m = (gh)^m$$

$$g^1 = g$$

Groups

Inverses

Lemma 8.13

Let \mathbb{G} be a group and $a, b, c \in \mathbb{G}$. If $ac = bc$, then $a = b$.

Proof.

We know that $ac = bc$. Multiplying both sides with the unique inverse c^{-1} of c , we obtain $a = b$. In detail:

$$(ac)c^{-1} = (bc)c^{-1} \Rightarrow a(cc^{-1}) = b(cc^{-1}) \Rightarrow a = b$$



Groups

Group exponentiation

Theorem 8.14

Let \mathbb{G} be a finite group, with $m = |\mathbb{G}|$ as the order of the group. Then for any element $g \in \mathbb{G}$, $g^m = 1$.

Proof.

Fix an arbitrary $g \in \mathbb{G}$, and let g_1, \dots, g_m be the elements of \mathbb{G} . We claim that

$$g_1 \cdots g_m = (gg_1) \cdots (gg_m)$$

Remember that $gg_i = gg_j \Rightarrow g_i = g_j$. Following arithmetic rules we can 'pull out' all occurrences of g and obtain

$$g_1 \cdots g_m = (gg_1) \cdots (gg_m) = g^m \cdot (g_1 \cdots g_m)$$



Groups

Group exponentiation

Corollary 8.17

Let \mathbb{G} be a finite group with $m = |\mathbb{G}|$. Let $e > 0$ be an integer, and define the function $f_e : \mathbb{G} \rightarrow \mathbb{G}$ by $f_e(g) = g^e$. If $\gcd(e, m) = 1$, then f_e is a permutation. Moreover, if $d = e^{-1} \pmod{m}$, then f_d is the inverse of f_e . (Recall proposition 8.7: $\gcd(e, m) = 1$ implies that e is invertible modulo m).

Proof.

Since \mathbb{G} is finite, the second part of the claim implies the first; this, we need only show that f_d is the inverse of f_e . This is true because for any $g \in \mathbb{G}$ we have

$$f_d(f_e(g)) = f_d(g^e) = (g^e)^d = g^{ed} = g$$



Groups

Multiplicative groups

As discussed, the set $Z_N = \{0, \dots, N - 1\}$ is a group under addition modulo N . Now we define the group under multiplication under modulo N , for any $N > 1$, to be given as

$$\mathbb{Z}_N^* \stackrel{\text{def}}{=} \{b \in \{1, \dots, N - 1\} \mid \gcd(b, N) = 1\}$$

Proposition 8.18

Let $N > 1$ be an integer. Then \mathbb{Z}_N^* is an abelian group under multiplication modulo N .

Groups

Multiplicative groups

We define $\phi(N) \stackrel{\text{def}}{=} |\mathbb{Z}_N^*|$ to be the order of the group \mathbb{Z}_N^* . Lets first consider the case where $N = p$ is prime. Then all elements in $\{1, \dots, p - 1\}$ are relatively prime to p , and so the order of \mathbb{Z}_p^* is given as $\phi(p) = p - 1$.

In the case where N is a composite of two primes $N = pq$, then the order of the group \mathbb{Z}_N^* is given as $\phi(N) = (p - 1)(q - 1)$ (proof is omitted for brevity).

Example

Take $N = 15 = 5 \cdot 3$. Then $\mathbb{Z}_{15}^* = \{1, 2, 4, 7, 8, 11, 13, 14\}$, and $\phi(15) = (5 - 1)(3 - 1) = 8$.

The factoring assumption

The weak factoring experiment $\text{wFactor}_{\mathcal{A}}(n)$

1. Choose two uniform n -bit integers n_1, n_2 .
2. Compute $N := n_1 \cdot n_2$
3. \mathcal{A} is given N , and outputs $n'_1, n'_2 > 1$.
4. The output of the experiment is defined to be 1 if $n'_1 \cdot n'_2 = N$, or otherwise 0.

The factoring problem is hard if:

$$\Pr [\text{wFactor}_{\mathcal{A}}(n) = 1] \leq \text{negl}(n)$$

The factoring assumption

Finding primes

Theorem

Bertrand's postulate For any $n > 1$, the fraction of n -bit integers that are prime is at least $1/3n$.

The most efficient way of finding primes is to select a random n – bit integer and check if it is prime. The probability of *not* finding a prime in a polynomial number of tries, e.g. $t = 3n^2$, is negligible in n as:

$$\left(1 - \frac{1}{3n}\right)^t \leq (e^{-1})^n = e^{-n}$$

The factoring assumption

The factoring experiment $\text{Factor}_{\mathcal{A}, \text{GenModulus}}(n)$

1. Run $\text{GenModulus}(1^n)$ to obtain (N, p, q) .
2. \mathcal{A} is given N , and outputs $p', q' > 1$.
3. The output of the experiment is defined to be 1 if $p' \cdot q' = N$, or otherwise 0.

Definition 8.45

Factoring is hard relative to GenModulus if for all probabilistic polynomial-time algorithms \mathcal{A} there exists a negligible function negl such that

$$\Pr [\text{Factor}_{\mathcal{A}, \text{GenModulus}}(n) = 1] \leq \text{negl}(n)$$

The RSA assumption

The RSA experiment $RSA\text{-}inv_{\mathcal{A}, GenRSA}(n)$

1. Run $GenRSA(1^n)$ to obtain (N, e, d)
2. Choose a uniform $y \in \mathbb{Z}_N^*$.
3. \mathcal{A} is given N, e, y , and outputs $x \in \mathbb{Z}_N^*$.
4. The output of the experiment is defined to be 1 if $x^e = y \pmod N$, and 0 otherwise.

Definition 8.46

The RSA problem is hard relative to $GenRSA$ if for all probabilistic polynomial-time adversaries \mathcal{A} there exists a negligible function $negl$ such that

$$\Pr [RSA\text{-}inv_{\mathcal{A}, GenRSA}(n) = 1] \leq negl(n)$$

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Cyclic Groups

Cyclic Groups and Generators p.316-319

Let \mathbb{G} be a finite group of order m , for any $g \in \mathbb{G}$ we say:

$\langle g \rangle = \{g^0, g^1, \dots, g^{i-1}\}$ is a subgroup of \mathbb{G} with order i and $i|m$

where $i \leq m$ is the smallest positive integer with $g^i = 1$.

Properties

- ▶ if $i = m$ then $\mathbb{G} = \langle g \rangle$ is a cyclic group.
- ▶ if \mathbb{G} is cyclic and m is prime, then all elements of \mathbb{G} , except 1, are generators.

Cyclic Groups

Examples p.316-319

Theorem 8.56

If p is prime then \mathbb{Z}_p^* is a cyclic multiplicative group of order $p - 1$.

Example 8.60

Consider the (multiplicative) group \mathbb{Z}_7^* , which is cyclic by Theorem 8.56. We have $\langle 2 \rangle = \{1, 2, 4\}$, and so 2 is not a generator.

However,

$$\langle 3 \rangle = \{1, 3, 2, 6, 4, 5\} = \mathbb{Z}_7^*$$

and so 3 is a generator of \mathbb{Z}_7^* .

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The Discrete Logarithm p.319-320

The general notation of a cyclic group:

$$\mathbb{G} = \langle g \rangle = \{g^x, \text{ for each } x \in \mathbb{Z}_q\}$$

For a random sample $h \in \mathbb{G}$, we call $x = \log_g h$ the discrete logarithm of h with respect to g from the context of \mathbb{G} .

Cyclic Groups

The Discrete Logarithm

The discrete logarithm experiment p.319-320

- ▶ Run $\mathcal{G}(1^n) \rightarrow (\mathbb{G}, q, g)$
- ▶ Choose $h \in_{\mathbb{R}} \mathbb{G}$
- ▶ \mathcal{A} is given (\mathbb{G}, q, g, h) and returns $x \in \mathbb{Z}_q$
- ▶ Experiment outputs 1 if $g^x = h$, 0 otherwise

The discrete logarithm problem is hard relative to \mathcal{G} if for all probabilistic polynomial-time algorithms \mathcal{A}

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

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Diffie-Hellman Assumptions p.320-321

Computational Diffie-Hellman

Given (\mathbb{G}, q, g) and $h_1, h_2 \in \mathbb{G}$, that means $h_1 = g^{x_1}$, $h_2 = g^{x_2}$, it is hard to compute:

$$DH_g(h_1, h_2) = g^{x_1 \cdot x_2} = h_1^{x_2} = h_2^{x_1}$$

Decisional Diffie-Hellmann

Given (\mathbb{G}, q, g) and $h_1, h_2, h' \in \mathbb{G}$, it is hard to distinguish whether

$$h' \stackrel{?}{=} DH_g(h_1, h_2)$$

Cyclic Groups

Diffie-Hellman Assumptions p.320-321

Definition 8.63

We say that the DDH problem is hard relative to \mathcal{G} if for all probabilistic polynomial-time algorithms \mathcal{A}

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

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Subgroups of \mathbb{Z}_p^* p.322-324

Theorem 8.64

Let $p - 1 = r \cdot q$, with p and q primes. Define

$$\mathbb{G} = \{[h^r \pmod p] \mid h \in \mathbb{Z}_p^*\}$$

Then \mathbb{G} is a subgroup of \mathbb{Z}_p^* of order q .

Proof

- ▶ \mathbb{G} is a subgroup of \mathbb{Z}_p^*
- ▶ order of \mathbb{G} is q if $\exists f_r : \mathbb{Z}_p^* \rightarrow \mathbb{G}$ and f_r is a $r - to - 1$ function

Cyclic Group

Subgroups of \mathbb{Z}_p^* p.322-324

Properties

- ▶ because q is prime, all elements of \mathbb{G} except 1 are generators
- ▶ to choose uniform element from \mathbb{G} :

pick $h \in_{\mathbb{R}} \mathbb{Z}_p^*$, output $[h^r \pmod p]$

- ▶ to check if any element $h \in \mathbb{Z}_p^*$ is also in \mathbb{G} , check

$$h^q \stackrel{?}{=} 1 \pmod p$$

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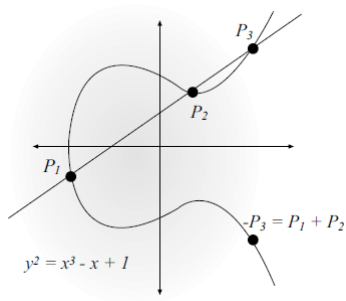
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Elliptic Curves p.325-332



▶ $P + \mathcal{O} = \mathcal{O} + P = P$

▶ if $P = (x, y)$ then
 $-P = (x, -y)$

▶ $P - P = \mathcal{O}$

$$4A^3 + 27B^2 \neq 0 \pmod{p}$$

Definition

$$E(\mathbb{Z}_p) = \{(x, y) | x, y \in \mathbb{Z}_p \text{ and } y^2 = x^3 + Ax + B \pmod{p}\} \cup \{\mathcal{O}\}$$

Cyclic Group

Elliptic Curves p.325-332

Calculations

To compute the addition of $P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$, we calculate $P_1 + P_2 = P_3(x_3, y_3)$:

1. calculate the slope $m = \left[\frac{y_2 - y_1}{x_2 - x_1} \pmod{p} \right]$
2. the line P_1P_2 is $y = m \cdot (x - x_1) + y_1 \pmod{p}$
3. coordinates of P_3 are
 $x_3 = [m^2 - x_1 - x_2 \pmod{p}]$ & $y_3 = [m(x_1 - x_3) - y_1 \pmod{p}]$

When $P_1 = P_2$ then $2P_1 = P_3(x_3, y_3)$ where:

- ▶ $x_3 = [m^2 - 2x_1 \pmod{p}]$ & $y_3 = [m(x_1 - x_3) - y_1 \pmod{p}]$
- ▶ $m = \left[\frac{3x_1^2 + A}{2y_1} \right]$

Cyclic Group

Elliptic Curves Efficiency

Affine Coordinates vs. Projective coordinates

- ▶ affine coordinates: $P = (x, y) = (X/Z \bmod p, Y/Z \bmod p)$
- ▶ projective coordinates: $P = (X, Y, Z)$

Addition of $P_1 + P_2 =$

$$P_3 = \left(m^2 - \frac{X_1}{Z_1} - \frac{X_2}{Z_2}, m \left(\frac{X_1}{Z_1} - m^2 + \frac{X_1}{Z_1} + \frac{X_2}{Z_2} \right) - \frac{Y_1}{Z_1}, 1 \right)$$

$$m = \frac{\frac{Y_2}{Z_2} - \frac{Y_1}{Z_1}}{\frac{X_2}{Z_2} - \frac{X_1}{Z_1}} = \frac{Y_2 Z_1 - Y_1 Z_2}{X_2 Z_1 - X_1 Z_2}$$

Cyclic Group

Elliptic Curves Efficiency p.325-332

Projective Coordinates

$$P_3 = (vw, u(v^2X_1Z_2 - w) - v^3Y_1Z_2, Z_1Z_2v^3)$$

$$u = Y_2Z_1 - Y_1Z_2$$

$$v = X_2Z_1 - X_1Z_2$$

$$w = u^2Z_1Z_2 - v^3 - 2v^2X_1Z_2$$

Point compression

- ▶ only coordinate x is needed
- ▶ y is computable from the elliptic curve $E : y^2 = f(x) \pmod{p}$
- ▶ one extra bit b needed for deciding what value y_b to use