

A little (Computational) Number Theory and Group Theory

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Differently from the pure mathematics approach, we will also be interested in **how quickly** we can solve various problems

In particular, we are interested in whether the problems at hand can be solved in **polynomial time**

Representing Integers

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- An elementary operation involving integers with b bits requires time $\Theta(b)$

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- Arrays of digits
- E.g., each entry in the array is a byte and stores a digit in base 256

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$$\begin{aligned} \text{Encodes: } & 74 \cdot 256^8 + 241 \cdot 256^7 + 176 \cdot 256^6 + 81 \cdot 256^5 + 206 \cdot 256^4 + 92 \cdot 256^3 + 108 \cdot 256^2 + 31 \cdot 256 + 42 \\ & = 1\,382\,474\,571\,160\,304\,230\,186 \end{aligned}$$

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= 1 382 474 571 160 304 230 186 Requires 71 bits to represent (does not fit in a 64-bit word)

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Recall the difference between polynomial-time and pseudopolynomial-time algorithms

Running times are measured as a function of the input length

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An algorithm that takes an integer n and runs in time $\Theta(n)$ is **not** a polynomial-time algorithm

- The running time is polynomial w.r.t. the **value** of the integer n
- It is not polynomial in the length of the input, i.e., the number of bits needed to represent n
- As a function of the input length η , the time complexity is $\Theta(2^\eta)$
- This is an **exponential-time** algorithm!

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The grade-school algorithms for addition and multiplication (over big integers) run in polynomial-time

- Adding n and m requires time $O(\log n + \log m)$
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Fix $m = 2$. Given n , compute 2^n .

- What's the size of the input?
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- What's the size of the input? $\Theta(\log n)$
- What's the size of the output? $\Theta(n)$
- We cannot even write out the result in polynomial-time

Reminder: Modular arithmetic

Proposition: Let a be an integer and let N be a positive integer. There exist unique integers q, r for which $a = qN + r$ and $0 \leq r < N$.

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We can reduce intermediate values during computation of additions and products:

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Example:

$$(7236782 \cdot 23392301) \bmod 100 = (82 \cdot 1) \bmod 100 = 82$$

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Recursion depth: $O(\log b)$

The non-recursive part of each call involves a constant number of polynomial-time operations

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Two integers a, b are coprime if $\gcd(a, b) = 1$

Theorem: b is invertible modulo N if and only if b and N are coprime.

Bézout's identity

Bézout's identity: Let a, b be positive integers. Then there exist integers X, Y such that $Xa + Yb = \gcd(a, b)$. Furthermore, $\gcd(a, b)$ is the smallest positive integer that can be expressed in this way.

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- Let X and Y be such that $XN + Yb = \gcd(N, b) = 1$
- Since $XN + Yb = 1$ we have $0 + Yb = 1 \pmod{N} \implies Y$ is an inverse for b .

Group Theory: Some Definitions

A group is a pair (G, \circ) , where G is a set, $\circ : G \times G \rightarrow G$ is a binary operation, and the following conditions are satisfied:

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The **order** of a group is the cardinality $|G|$ of G . If G is a finite set, then the group is **finite**.

If the operation \circ is commutative (i.e., $a \circ b = b \circ a$ for all $a, b \in G$) then the group is **Abelian**.

Examples

Which of these are groups?

- $(\{0\}, +)$
- $(\mathbb{Z}, +)$
- (\mathbb{Z}, \cdot)
- $(\mathbb{Q} \setminus \{0\}, +)$
- $(\mathbb{Q} \setminus \{0\}, \cdot)$
- $(\{1, \dots, N - 1\}, \circ)$ where $a \circ b = ab \pmod N$
- $(\{0, 1\}^n, \oplus)$

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- (\mathbb{Z}, \cdot) Not a group. No inverse for 0, no inverse for 2, ...
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In the following we will only consider finite Abelian groups!

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Keep in mind that it is still **not** a regular addition or multiplication, but the group operation instead!

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If $b < 0$ then compute $h = g^{-1}$ and then $h^{|b|}$. For $b \geq 0$:

Divide and conquer:

- If $b = 0$ return 1
- If b is even: recursively compute $x = g^{b/2}$ and return $x \cdot x$
- If b is odd: recursively compute $x = g^{(b-1)/2}$ and return $x \cdot x \cdot g$

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If the group operation can be computed in polynomial-time, then group exponentiation can be performed in polynomial-time

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- **Closure:** Pick $a, b \in \mathbb{Z}_N^*$, and let a', b' be their inverses. Notice that $ab \pmod{N}$ is invertible modulo N (the inverse is $a'b'$)
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Consequence: If p is a prime number then $\{1, 2, \dots, p - 1\}$ is an Abelian group under multiplication modulo p .

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Since $gg_i = gg_j \implies g^{-1}gg_i = g^{-1}gg_j \implies g_i = g_j$ we have $g_i \neq g_j \implies gg_i \neq gg_j$

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Then:

$$g_1g_2 \dots g_m = (gg_1)(gg_2) \dots (gg_m)$$

(Each side of the equation contains only distinct elements, since the order of G is m , all elements are multiplied)

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$$g_1g_2 \dots g_m = (gg_1)(gg_2) \dots (gg_m) = g^m(g_1g_2 \dots g_m)$$

(Each side of the equation contains only distinct elements, since the order of G is m , all elements are multiplied)

Fermat's little theorem

Theorem: Let G be a finite group of order m and let $g \in G$. Then $g^m = 1$.

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In \mathbb{Z}_N (under addition modulo N):

- For all $a \in \mathbb{Z}_N$, we have $N \cdot a = 0$.

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- For all $a \in \mathbb{Z}_p^*$ where p is prime, we have $a^{p-1} = 1$

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Proof: Write x as $qm + r$ with $r \in \{0, \dots, m - 1\}$. $g^x = g^{qm+r} = (g^m)^q \cdot g^r = 1^q \cdot g^r = g^r$. \square

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Corollary: Let G be a finite group of order $m > 1$. Let $e > 0$ be an integer, and define the function $f : G \rightarrow G$ as $f_e(g) = g^e$. If $\gcd(e, m) = 1$ then

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Proof: We just need to show 2) since this implies that f_e is injective and surjective, i.e., a bijection.

$$f_d(f_e(g)) = (g^e)^d = g^{ed} = g^{ed \bmod m} = g^{1 \bmod m} = g. \quad \square$$

Roadmap

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- Use the “hardness” of this problem to build secure public-key schemes

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Generating Prime numbers

We will be interested in working with prime numbers

The security parameter n will be related to the number of bits of the prime numbers

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- Repeat up to t times:
 - Choose a number p u.a.r. among all n -bit numbers
Pick r u.a.r. in $\{0, 1\}^{n-1}$ and let $p \leftarrow 1\|r$.
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The algorithm has a polynomial running time and fails with negligible probability!

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In practice randomized algorithm are used, since they are faster and fail with negligible probability.

- The Miller-Rabin primality test is a probabilistic polynomial-time algorithm with one-sided error
 - If n is prime, the Miller-Rabin primality test reports n as prime with certainty
 - If n is composite, the Miller-Rabin primality test might report n as prime, but only with negligible probability.

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Define a factoring experiment $w\text{-Factor}_{\mathcal{A}}(n)$ for a given algorithm \mathcal{A} :

- Two n -bit integers x_1, x_2 are chosen u.a.r., and $N = x_1 \cdot x_2$ is computed
- N is sent to \mathcal{A}
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With probability $1 - (\frac{1}{2})^2 = \frac{3}{4}$ at least one of x_1 and x_2 is even $\implies N$ is even $\implies \mathcal{A}$ wins the experiment.

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Let GenModulus be a polynomial-time algorithm that, on input 1^n , outputs a triple (N, p, q) where $N = pq$, and p and q are n -bit primes, except with a probability negligible in n .

The Factoring Assumption

We can now revise the previous experiment. For an algorithm \mathcal{A} , define $\text{Factor}_{\mathcal{A}, \text{GenModulus}}(n)$ as:

- Run $\text{GenModulus}(1^n)$ to obtain (N, p, q) .
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Recall: this is just an assumption. We don't currently know whether the factoring problem is hard.

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The order of Z_N^* is $\phi(N) = (p - 1) \cdot (q - 1)$

- Trivial to compute if we know p and q
- “Hard” to compute if we know N but none of p and q (can be shown to be equivalent to factoring N)

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Pick $e > 0$ be an integer such that $\gcd(e, \phi(N)) = 1$.

- By the corollary of Fermat’s little theorem, $f_e(x) = x^e$ is a permutation of \mathbb{Z}_N^*
- Let d be the inverse of e modulo $\phi(N)$. Then $f_d(x) = x^d$ is the inverse of f_e .

$$(x^e)^d = (x^d)^e = x$$

(All the operations are performed modulo N)

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- If p and q are not known:
 - Computing $\phi(N)$ is as hard as factoring N
 - We don't know how to compute d without knowing $\phi(N)$
 - ???

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Informally: given a random $y \in \mathbb{Z}_N^*$, computing $y^{1/e}$ is hard

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A possible implementation:

- Generate two n -bit primes p, q chosen u.a.r.
- $N \leftarrow p \cdot q$
- $\phi(N) \leftarrow (p - 1) \cdot (q - 1)$
- Pick some e with $\gcd(e, \phi(N)) = 1$
- $d \leftarrow e^{-1} \pmod{\phi(N)}$
- Output (N, e, d)

The RSA problem

Informally: given a random $y \in \mathbb{Z}_N^*$, computing $y^{1/e}$ is hard

Let GenRSA be a polynomial-time algorithm that, on input 1^n , outputs a triple (N, e, d) where:

- $N = pq$, for two n -bit primes p and q
- $ed = 1 \pmod{\phi(N)}$

The algorithm is allowed to fail with negligible probability.

A possible implementation:

- Generate two n -bit primes p, q chosen u.a.r.
- $N \leftarrow p \cdot q$
- $\phi(N) \leftarrow (p - 1) \cdot (q - 1)$
- Pick some e with $\gcd(e, \phi(N)) = 1$
- $d \leftarrow e^{-1} \pmod{\phi(N)}$
- Output (N, e, d)

The choice of e is not believed to affect the hardness of the RSA problem

Common choices: $e = 3$ or $e = 2^{16} + 1$ for efficiency reasons

The RSA assumption

For an algorithm \mathcal{A} , define the experiment $\text{RSA-inv}_{\mathcal{A}, \text{GenRSA}}(n)$ as:

- Run $\text{GenRSA}(1^n)$ to obtain (N, e, d) .
- Choose $y \in \mathbb{Z}_N^*$ u.a.r.
- Send N, e and y to \mathcal{A}
- \mathcal{A} outputs $x \in \mathbb{Z}_N^*$
- The outcome of the experiment is 1 if x is the e -th root of y , i.e., if $x^e = y$ (or equivalently $y^{1/e} = y^d = x$). Otherwise the outcome is 0.

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Definition: The RSA problem is hard relative to GenRSA if for any probabilistic polynomial-time algorithm \mathcal{A} there exists a negligible function ε such that:

$$\Pr[\text{RSA-inv}_{\mathcal{A}, \text{GenRSA}}(n) = 1] \leq \varepsilon(n).$$

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The RSA assumption: there exists a GenRSA algorithm relative to which the RSA problem is hard.

The RSA assumption and the factoring assumption

The RSA assumption: there exists a GenRSA algorithm relative to which the RSA problem is hard.



The factoring assumption: there exists a GenModulus algorithm relative to which the factoring problem is hard.