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

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$= 1\,382\,474\,571\,160\,304\,230\,186$

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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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Recusion 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 $Xa + Yb = \mathrm{gcd}(a, b)$. Furthermore, $\mathrm{gcd}(a, b)$ is the smallest positive integer that can be expressed in this way.

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

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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?

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

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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!

Group Theory: Additive and Multiplicative Notations

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Keep in mind that they are **not** the 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 $x = g^{(b-1)/2} \mod N$ 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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Let $\mathbb{Z}_N^* = \{0 < x < N \mid \text{gcd}(x, N) = 1\}$. The set $\mathbb{Z}_N^*$ is an Abelian group under multiplication modulo N.

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Consequence: If p is a prime number then $\{1, 2, \ldots, p-1\}$ is an Abelian group under multiplication modulo p.

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Multiplying both sides by $(g_1 g_2 \ldots g_m)^{-1}$

$$(g_1 g_2 \ldots g_m)^{-1}(g_1 g_2 \ldots g_m) = g^m (g_1 g_2 \ldots g_m)(g_1 g_2 \ldots g_m)^{-1}$$

Fermat's little theorem

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

Proof in the Abelian case:

Let $G = \{g_1, g_2, \ldots, g_m\}$.

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

Then:

$$g_1 g_2 \ldots g_m = (gg_1)(gg_2)\ldots(gg_m) \ = g^m(g_1 g_2 \ldots g_m)$$

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- For all $a \in \mathbb{Z}_N$, we have $N \cdot a = 0$. $\underbrace{a + a + \cdots + a}_{N \text{ times}} = Na = 0 \pmod{N}$.

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In $\mathbb{Z}_N^*$ (under multiplication modulo N):

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

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

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

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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 $f : G \to G$ 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 injective and surjective, i.e., a bijection.

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

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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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Negligible

The algorithm fails with negligible proability!

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Can we check whether a number N is prime in polynomail time?

I.e., in time $O(\log^k N)$ for some constant k.

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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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A fist attempt to formalize the hardness of factoring. Define a factoring experiment w-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 $\mathcal{A}$
- $\mathcal{A}$ outputs two integers x'_1, x'_2
- The outcome of the experiment is 1 if $x'_1, x'_2 > 1$ and $x'_1 \cdot x'_2 = N$. Otherwise the outcome is 0.

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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 probability negligible in n.

The Factoring Assumption

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

- Run $\mathsf{GenModulus}(1^n)$ 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 not p and q (can be shown to be equivalent to factoring N)

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Pick $e \in \mathbb{Z}_N^*$ 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)

e-th roots of x

Since $(x^e)^d = x$ we can think of x^d as the e-th root of x

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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 $\phi(N)$
  - ???

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:

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The algorithm is allowed to fail with negligible probability.

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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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The RSA assumption and the factoring assumption

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

$$\Downarrow$$

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