



Intro. Number Theory

Notation

Background

We will use a bit of number theory to construct:

- Key exchange protocols
- Digital signatures
- Public-key encryption

This module: crash course on relevant concepts

More info: read parts of Shoup's book referenced
at end of module

Notation

From here on:

- N denotes a positive integer.
- p denote a prime.

Notation: $\mathbb{Z}_N = \{0, 1, 2, \dots, N-1\}$

Can do addition and multiplication modulo N

Modular arithmetic

Examples: let $N = 12$

$$9 + 8 = 5 \quad \text{in } \mathbb{Z}_{12} \quad \{0, 1, \dots, 11\}$$

$$5 \times 7 = 11 \quad \text{in } \mathbb{Z}_{12} \quad 35 = 11 \pmod{12}$$

$$5 - 7 = 10 \quad \text{in } \mathbb{Z}_{12}$$

Arithmetic in \mathbb{Z}_N works as you expect, e.g. $x \cdot (y+z) = x \cdot y + x \cdot z$ in \mathbb{Z}_N

Greatest common divisor

Def: For ints. x, y : $\gcd(x, y)$ is the greatest common divisor of x, y

Example: $\gcd(12, 18) = \underline{6}$

$$\boxed{2} \times 12 - \boxed{1} \times 18 = 6$$

$\uparrow \quad \quad \uparrow$
 $a \quad \quad b$

***Fact:** for all ints. x, y there exist ints. a, b such that

$$a \cdot x + b \cdot y = \gcd(x, y)$$

a, b can be found efficiently using the extended Euclid alg.

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If $\gcd(x, y) = 1$ we say that x and y are relatively prime

Modular inversion

Over the rationals, inverse of 2 is $\frac{1}{2}$. What about \mathbb{Z}_N ?

Def: The **inverse** of x in \mathbb{Z}_N is an element y in \mathbb{Z}_N s.t. $x \cdot y = 1$ in \mathbb{Z}_N

y is denoted x^{-1} .

Example: let N be an odd integer. The inverse of 2 in \mathbb{Z}_N is $\frac{N+1}{2}$

$$2 \cdot \left(\frac{N+1}{2}\right) = N+1 = 1 \text{ in } \mathbb{Z}_N$$

Modular inversion

Which elements have an inverse in \mathbb{Z}_N ?

$$x \cdot y = 1 \pmod{N} ?$$

Lemma: x in \mathbb{Z}_N has an inverse if and only if $\gcd(x, N) = 1$

Proof:

$$\begin{aligned} \gcd(x, N) = 1 &\Rightarrow \exists a, b: a \cdot x + b \cdot N = 1 \Rightarrow a \cdot x = 1 \text{ in } \mathbb{Z}_N \\ &\Rightarrow x^{-1} = a \text{ in } \mathbb{Z}_N \end{aligned}$$

$$\gcd(x, N) > 1 \Rightarrow \forall a: \gcd(a \cdot x, N) > 1 \Rightarrow \underline{a \cdot x \neq 1} \text{ in } \mathbb{Z}_N$$

$$\gcd(x, N) = 2 \Rightarrow \forall a: a \cdot x \text{ is even} \Rightarrow \frac{\text{even}}{a \cdot x} \neq \frac{\text{odd}}{b \cdot N + 1}$$

More notation

Def: \mathbb{Z}_N^* = (set of invertible elements in \mathbb{Z}_N) =
= $\{ x \in \mathbb{Z}_N : \gcd(x, N) = 1 \}$

Examples:

1. for prime p, $\mathbb{Z}_p^* = \underline{\mathbb{Z}_p \setminus \{0\}} = \{1, 2, \dots, p-1\}$ \downarrow
2. $\mathbb{Z}_{12}^* = \{1, 5, 7, 11\}$ $x, N \Rightarrow ax + bN = 1 \pmod{N}$
 $\text{e.g., } 5, 7, 11, 13, 17, 19, 23, 25, 29, 31, 35, 37, 41, 43, 47, 49, 53, 55, 59, 61, 65, 67, 71, 73, 77, 79, 83, 85, 89, 91, 95, 97, 101, 103, 107, 109, 113, 115, 119, 121, 125, 127, 131, 133, 137, 139, 143, 145, 149, 151, 155, 157, 161, 163, 167, 169, 173, 175, 179, 181, 185, 187, 191, 193, 197, 199, 203, 205, 209, 211, 215, 217, 221, 223, 227, 229, 233, 235, 239, 241, 245, 247, 251, 253, 257, 259, 263, 265, 269, 271, 275, 277, 281, 283, 287, 289, 293, 295, 299, 301, 305, 307, 311, 313, 317, 319, 323, 325, 329, 331, 335, 337, 339, 343, 345, 349, 351, 355, 357, 361, 363, 367, 369, 373, 375, 379, 381, 385, 387, 391, 393, 397, 399, 403, 405, 409, 411, 415, 417, 421, 423, 427, 429, 433, 435, 439, 441, 445, 447, 451, 453, 457, 459, 463, 465, 469, 471, 475, 477, 481, 483, 487, 489, 493, 495, 499, 501, 505, 507, 511, 513, 517, 519, 523, 525, 529, 531, 535, 537, 541, 543, 547, 549, 553, 555, 559, 561, 563, 567, 569, 573, 575, 579, 581, 585, 587, 591, 593, 597, 599, 603, 605, 609, 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4585, 4587, 4591, 4593, 4597, 4599, 4603, 4605, 4609, 4611, 4613, 4617, 4619, 4623, 4625, 4629, 4631, 4635, 4637, 4641, 4643, 4647, 4649, 4653, 4655, 4659, 4661, 4663, 4667, 4669, 4673, 4675, 4679, 4681, 4685, 4687, 4691, 4693, 4697, 4699, 4703, 4705, 4709, 4711, 4713, 4717, 4719, 4723, 4725, 4729, 4731, 4735, 4737, 4741, 4743, 4747, 4749, 4753, 4755, 4759, 4761, 4763, 4767, 4769, 4773, 4775, 4779, 4781, 4785, 4787, 4791, 4793, 4797, 4799, 4803, 4805, 4809, 4811, 4813, 4817, 4819, 4823, 4825, 4829, 4831, 4835, 4837, 4841, 4843, 4847, 4849, 4853, 4855, 4859, 4861, 4863, 4867, 4869, 4873, 4875, 4879, 4881, 4885, 4887, 4891, 4893, 4897, 4899, 4903, 4905, 4909, 4911, 4913, 4917, 4919, 4923, 4925, 4929, 4931, 4935, 4937, 4941, 4943, 4947, 4949, 4953, 4955, 4959, 4961, 4963, 4967, 4969, 4973, 4975, 4979, 4981, 4985, 4987, 4991, 4993, 4997, 4999, 5003, 5005, 5009, 5011, 5013, 5017, 5019, 5023, 5025, 5029, 5031, 5035, 5037, 5041, 5043, 5047, 5049, 5053, 5055, 5059, 5061, 5063, 5067, 5069, 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5561, 5563, 5567, 5569, 5573, 5575, 5579, 5581, 5585, 5587, 5591, 5593, 5597, 5599, 5603, 5605, 5609, 5611, 5613, 5617, 5619, 5623, 5625, 5629, 5631, 5635, 5637, 5641, 5643, 5647, 5649, 5653, 5655, 5659, 5661, 5663, 5667, 5669, 5673, 5675, 5679, 5681, 5685, 5687, 5691, 5693, 5697, 5699, 5703, 5705, 5709, 5711, 5713, 5717, 5719, 5723, 5725, 5729, 5731, 5735, 5737, 5741, 5743, 5747, 5749, 5753, 5755, 5759, 5761, 5763, 5767, 5769, 5773, 5775, 5779, 5781, 5785, 5787, 5791, 5793, 5797, 5799, 5803, 5805, 5809, 5811, 5813, 5817, 5819, 5823, 5825, 5829, 5831, 5835, 5837, 5841, 5843, 5847, 5849, 5853, 5855, 5859, 5861, 5863, 5867, 5869, 5873, 5875, 5879, 5881, 5885, 5887, 5891, 5893, 5897, 5899, 5903, 5905, 5909, 5911, 5913, 5917, 5919, 5923, 5925, 5929, 5931, 5935, 5937, 5941, 5943, 5947, 5949, 5953, 5955, 5959, 5961, 5963, 5967, 5969, 5973, 5975, 5979, 5981, 5985, 5987, 5991, 5993, 5997, 5999, 6003, 6005, 6009, 6011, 6013, 6017, 6019, 6023, 6025, 6029, 6031, 6035, 6037, 6041, 6043, 6047, 6049, 6053, 6055, 6059, 6061, 6063, 6067, 6069, 6073, 6075, 6079, 6081, 6085, 6087, 6091, 6093, 6097, 60$

Solving modular linear equations

Solve: $\mathbf{a \cdot x + b = 0}$ in \mathbb{Z}_N

Solution: $\mathbf{x = -b \cdot a^{-1}}$ in \mathbb{Z}_N

Find a^{-1} in \mathbb{Z}_N using extended Euclid. Run time: $O(\log^2 N)$

What about modular quadratic equations?

next segments



Intro. Number Theory

Fermat and Euler

Review

N denotes an n -bit positive integer. p denotes a prime.

- $Z_N = \{ 0, 1, \dots, N-1 \}$

- $(Z_N)^* = (\text{set of invertible elements in } Z_N) =$
 $= \{ x \in Z_N : \gcd(x, N) = 1 \}$

$$\log^2 N$$
$$n = O(\log N)$$

Can find inverses efficiently using Euclid alg.: time = $O(\underline{n}^2)$

Fermat's theorem (1640)

Thm: Let p be a prime

$$\forall x \in (\mathbb{Z}_p)^* : x^{p-1} = 1 \text{ in } \mathbb{Z}_p \Rightarrow x \cdot \underbrace{x^{p-2}}_{\text{circled in red}}$$

Example: $p=5$. $3^4 = 81 = 1$ in \mathbb{Z}_5

$$\mathbb{Z}_5^* = \{1, 2, 3, 4\}$$
$$\mathbb{Z}_p^*$$

$$\text{So: } x \in (\mathbb{Z}_p)^* \Rightarrow x \cdot x^{p-2} = 1 \Rightarrow x^{-1} = x^{p-2} \text{ in } \mathbb{Z}_p$$

another way to compute inverses, but less efficient than Euclid

Application: generating random primes

Suppose we want to generate a large random prime

say, prime p of length 1024 bits (i.e. $p \approx 2^{1024}$)

$$\mathbb{Z}_p \Rightarrow \forall x. \quad x^{p-1} = 1 \pmod{p}$$

Step 1: choose a random integer $p \in [2^{1024}, 2^{1025}-1]$

Step 2: test if $2^{p-1} = 1$ in \mathbb{Z}_p

$$2^{p-1} = 1 \pmod{p}$$

If so, output p and stop. If not, goto step 1.

Simple algorithm (not the best).

$$\Pr[p \text{ not prime}] < 2^{-60}$$

The structure of $(\mathbb{Z}_p)^*$

Thm (Euler): $(\mathbb{Z}_p)^*$ is a **cyclic group**, that is

$$\exists g \in (\mathbb{Z}_p)^* \text{ such that } \{1, g, g^2, g^3, \dots, g^{p-2}\} = (\mathbb{Z}_p)^*$$

g is called a **generator** of $(\mathbb{Z}_p)^*$

Example: $p=7$. $\{1, 3, 3^2, 3^3, 3^4, 3^5\} = \{1, 3, 2, 6, 4, 5\} = (\mathbb{Z}_7)^*$

Not every elem. is a generator: $\{1, 2, 2^2, 2^3, 2^4, 2^5\} = \{1, 2, 4\}$

Order

For $g \in (Z_p)^*$ the set $\{1, g, g^2, g^3, \dots\}$ is called $\{1, 2, 4\}$
the group generated by g , denoted $\langle g \rangle$

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Def: the **order** of $g \in (Z_p)^*$ is the size of $\langle g \rangle$

$$\text{ord}_p(g) = |\langle g \rangle| = (\text{smallest } a > 0 \text{ s.t. } g^a = 1 \text{ in } Z_p)$$

Examples: $\text{ord}_7(3) = \underline{6}$; $\text{ord}_7(2) = 3$; $\text{ord}_7(1) = 1$

$\{1, 2, 4\}$

Thm (Lagrange): $\forall g \in (Z_p)^*$: $\text{ord}_p(g)$ divides $p-1$

Euler's generalization of Fermat (1736)

Def: For an integer N define $\varphi(N) = |(Z_N)^*|$ (Euler's φ func.)

Examples: $\varphi(12) = |\{1,5,7,11\}| = 4$; $\varphi(p) = p-1$

For $N=p \cdot q$: $\varphi(N) = N - p - q + 1 = (p-1)(q-1)$

Thm (Euler): $\forall x \in (Z_N)^* : x^{\varphi(N)} = 1 \text{ in } Z_N$

Handwritten notes: Z_p^* , $x^{p-1} = 1 \text{ in } Z_p^*$, N is prime.

Example: $5^{\varphi(12)} = 5^4 = 625 = 1 \text{ in } Z_{12}$

Generalization of Fermat. Basis of the RSA cryptosystem



Intro. Number Theory

Modular e 'th roots

Modular e'th roots

We know how to solve modular linear equations:

$$\underline{a \cdot x + b = 0} \quad \text{in } \mathbb{Z}_N$$

$$\text{Solution: } \underline{x = -b \cdot a^{-1}} \quad \text{in } \mathbb{Z}_N$$

What about higher degree polynomials?


Example: let p be a prime and $c \in \underline{\mathbb{Z}_p}$. Can we solve:

$$x^2 - c = 0 \quad , \quad y^3 - c = 0 \quad , \quad z^{37} - c = 0 \quad \text{in } \mathbb{Z}_p$$

Modular e'th roots

Let p be a prime and $c \in \mathbb{Z}_p$.

Def: $x \in \mathbb{Z}_p$ s.t. $x^e = c$ in \mathbb{Z}_p is called an **e'th root** of c .

Examples: $7^{1/3} = 6$ in \mathbb{Z}_{11}  $6^3 = 216 = 7$ in \mathbb{Z}_{11}^*

$$3^{1/2} = 5 \text{ in } \mathbb{Z}_{11}$$

$2^{1/2}$ does not exist in \mathbb{Z}_{11}

$$1^{1/3} = 1 \text{ in } \mathbb{Z}_{11}$$

$\nexists x \in \mathbb{Z}_{11}$ s.t. $x^2 = 2 \pmod{11}$

The easy case

When does $c^{1/e}$ in \mathbb{Z}_p exist? Can we compute it efficiently?

The easy case: suppose $\gcd(e, p-1) = 1$

Then for all c in $(\mathbb{Z}_p)^*$: $c^{1/e}$ exists in \mathbb{Z}_p and is easy to find.

$$\phi(p) = p-1$$

$$c^{p-1} = 1 \pmod p$$

$$\gcd(e, p-1)$$

Proof: let $d = e^{-1}$ in \mathbb{Z}_{p-1} . Then

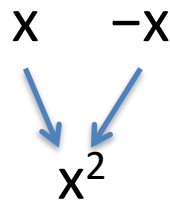
$$c^{1/e} = c^d \text{ in } \mathbb{Z}_p$$

$$d \cdot e = 1 \text{ in } \mathbb{Z}_{p-1} \Rightarrow \exists k \in \mathbb{Z}: d \cdot e = (p-1) + 1 \Rightarrow$$

$$\Rightarrow [c^d]^e = c^{d \cdot e} = c^{k \cdot (p-1) + 1} = [c^{p-1}]^k \cdot c = [c] \text{ in } \mathbb{Z}_p$$

The case $e=2$: square roots

If p is an odd prime then $\gcd(2, p-1) \neq 1$



Fact: in \mathbb{Z}_p^* , $x \rightarrow x^2$ is a 2-to-1 function

Example: in \mathbb{Z}_{11}^* :

1	10	2	9	3	8	4	7	5	6
<u>1</u>		<u>4</u>		<u>9</u>		<u>5</u>		<u>3</u>	

Def: x in \mathbb{Z}_p is a **quadratic residue (Q.R.)** if it has a square root in \mathbb{Z}_p

p odd prime \Rightarrow the # of Q.R. in \mathbb{Z}_p is $(p-1)/2 + 1$

Euler's theorem

Thm: x in $(\mathbb{Z}_p)^*$ is a Q.R. $\iff x^{(p-1)/2} = 1$ in \mathbb{Z}_p (p odd prime)

$x^{\frac{p-1}{2}}$

Example:

in \mathbb{Z}_{11} :	1^5	2^5	3^5	4^5	5^5	6^5	7^5	8^5	9^5	10^5
=	<u>1</u>	-1	<u>1</u>	<u>1</u>	<u>1</u>	-1	-1	-1	<u>1</u>	-1

Note: $x \neq 0 \Rightarrow \underline{x^{(p-1)/2}} = \underline{(x^{p-1})^{1/2}} = \underline{1^{1/2}} \in \underline{\{1, -1\}}$ in \mathbb{Z}_p

\mathbb{Z}_p^* 勒让德符号

Def: $x^{(p-1)/2}$ is called the Legendre Symbol of x over p (1798)

Computing square roots mod p

Suppose $p \equiv 3 \pmod{4}$

Lemma: if $c \in (\mathbb{Z}_p)^*$ is Q.R. then $\sqrt{c} = c^{(p+1)/4}$ in \mathbb{Z}_p

Proof: $\left[c^{\frac{p+1}{4}} \right]^2 = c^{\frac{p+1}{2}} = \underbrace{c^{\frac{p-1}{2}}}_{=1} \cdot c = c \quad \text{in } \mathbb{Z}_p$

When $p \equiv 1 \pmod{4}$, can also be done efficiently, but a bit harder

run time $\approx \underline{\underline{O(\log^3 p)}}$

$\log^2 N$

Solving quadratic equations mod p

Solve: $a \cdot x^2 + b \cdot x + c = 0$ in Z_p

Solution: $x = \frac{-b \pm \sqrt{b^2 - 4 \cdot a \cdot c}}{2a}$ in Z_p

- Find $(2a)^{-1}$ in Z_p using extended Euclid.
- Find square root of $b^2 - 4 \cdot a \cdot c$ in Z_p (if one exists)
using a square root algorithm

Computing e 'th roots mod N ??

Let N be a composite number and $e > 1$

When does $c^{1/e}$ in \mathbb{Z}_N exist? Can we compute it efficiently?

$\phi(N)$

$$c^{1/e} = c^d \quad \text{gcd.}(e, \phi(N))$$

$$d = e^{-1} \bmod (\phi(N)).$$

Answering these questions requires the factorization of N
(as far as we know)

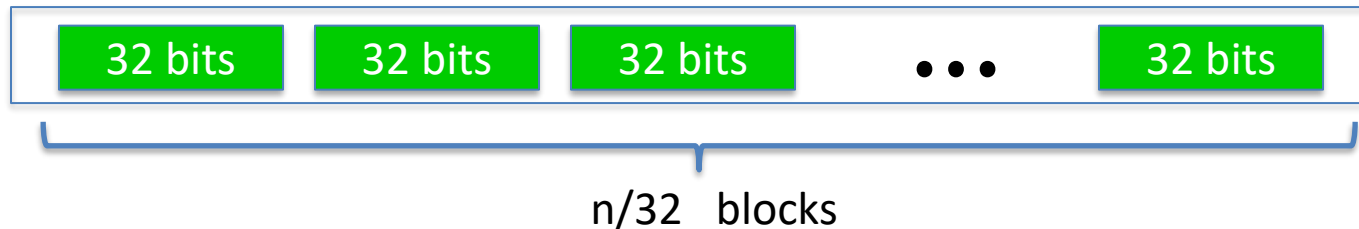


Intro. Number Theory

Arithmetic algorithms

Representing bignums

Representing an n -bit integer (e.g. $n=2048$) on a 64-bit machine



Note: some processors have 128-bit registers (or more) and support multiplication on them

Arithmetic

Given: two n-bit integers

- **Addition and subtraction:** linear time $O(n)$
- **Multiplication:** naively $O(n^2)$. Karatsuba (1960): $O(n^{1.585})$

$\log_2 3$
↓

Basic idea: $(2^b x_2 + x_1) \times (2^b y_2 + y_1)$ with 3 mults.

Best (asymptotic) algorithm: about $O(n \cdot \log n)$.

- **Division with remainder:** $O(n^2)$.

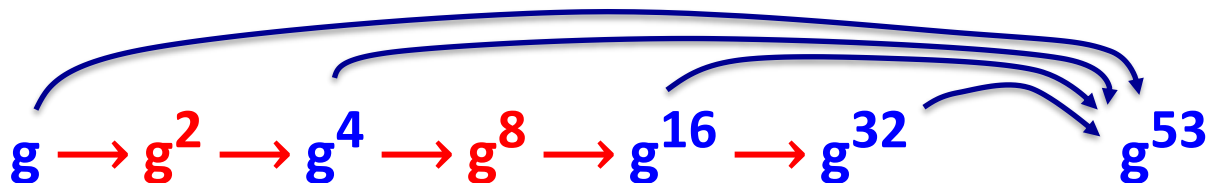
Exponentiation

Finite cyclic group G (for example $G = \mathbb{Z}_p^*$)

Goal: given g in G and x compute g^x $g \cdot g \cdot \dots \cdot g$

Example: suppose $x = 53 = (110101)_2 = 32+16+4+1$

$$\text{Then: } g^{53} = g^{32+16+4+1} = g^{32} \cdot g^{16} \cdot g^4 \cdot g^1$$



The repeated squaring alg.

Input: g in G and $x > 0$; **Output:** g^x

write $x = (\underline{x_n} \ x_{n-1} \ \dots \ x_2 \ x_1 \ x_0)_2$

$y \leftarrow g$, $z \leftarrow 1$

for $i = 0$ to n do:

if $(x[i] == 1)$: $z \leftarrow z \cdot y$

$y \leftarrow y^2$

output z

example: g^{53}

<u>y</u>	<u>z</u>
g^2	g
g^4	g
g^8	g^5
g^{16}	g^5
g^{32}	g^{21}
g^{64}	g^{53}

Running times

Given n -bit int. N :

- **Addition and subtraction in \mathbb{Z}_N :** linear time $T_+ = O(n)$
- **Modular multiplication in \mathbb{Z}_N :** naively $T_x = O(n^2)$
- **Modular exponentiation in \mathbb{Z}_N (g^x):**

$$O((\log x) \cdot T_x) \leq O(\overset{n \cdot n^2}{(\log x) \cdot n^2}) \leq O(n^3)$$



Intro. Number Theory

Intractable problems

Easy problems

- Given composite N and x in Z_N find x^{-1} in Z_N
- Given prime p and polynomial $f(x)$ in $Z_p[x]$
find x in Z_p s.t. $f(x) = 0$ in Z_p (if one exists)

Running time is linear in $\deg(f)$.

... but many problems are difficult

Intractable problems with primes




Fix a prime $p > 2$ and g in $(\mathbb{Z}_p)^*$ of order q .

Consider the function: $x \mapsto \underline{g^x}$ in \mathbb{Z}_p

Now, consider the inverse function:

$$\text{Dlog}_g(g^x) = x \quad \text{where } x \text{ in } \{0, \dots, q-2\}$$

Example:

in \mathbb{Z}_{11} :	1,	2,	3,	4,	5,	6,	7,	8,	9,	10
										
$\text{Dlog}_2(\cdot)$:	0,	1,	8,	2,	4,	9,	7,	3,	6,	5

DLOG: more generally

Let **G** be a finite cyclic group and **g** a generator of G

$$G = \{ 1, g, g^2, g^3, \dots, g^{q-1} \} \quad (q \text{ is called the order of } G)$$

Def: We say that **DLOG is hard in G** if for all efficient alg. A:

$$\Pr_{g \leftarrow G, x \leftarrow \mathbb{Z}_q} [\text{A}(G, q, g, g^x) = x] < \text{negligible}$$

Example candidates:

- (1) $(\mathbb{Z}_p)^*$ for large p, (2) Elliptic curve groups mod p

Computing Dlog in $(\mathbb{Z}_p)^*$ (n-bit prime p)

Best known algorithm (GNFS): run time $\exp(\tilde{O}(\sqrt[3]{n}))$

\mathbb{Z}_p^*

$e^{\sqrt[3]{n}}$

cipher key size

modulus size

Elliptic Curve
group size

80 bits

1024 bits

160 bits

128 bits

3072 bits

256 bits

256 bits (AES)

15360 bits

512 bits

As a result: slow transition away from (mod p) to elliptic curves

An application: collision resistance

Choose a group G where Dlog is hard (e.g. $(\mathbb{Z}_p)^*$ for large p)

Let $q = |G|$ be a prime. Choose generators g, h of G

For $x, y \in \{1, \dots, q\}$ define $H(x, y) = g^x \cdot h^y$ in G

\hookrightarrow 解決 Dlog.

Lemma: finding collision for $H(.,.)$ is as hard as computing $\text{Dlog}_g(h)$

Proof: Suppose we are given a collision $H(x_0, y_0) = H(x_1, y_1)$

then $g^{x_0} \cdot h^{y_0} = g^{x_1} \cdot h^{y_1} \Rightarrow \underline{g^{x_0-x_1} = h^{y_1-y_0}} \Rightarrow h = g^{x_0-x_1 / \underbrace{y_1-y_0}_{\neq 0}}$

Intractable problems with composites

Consider the set of integers: (e.g. for $n=1024$)

$$\mathbb{Z}_{(2)}(n) := \{ N = p \cdot q \text{ where } \underline{p, q} \text{ are } \underline{n\text{-bit primes}} \}$$

Problem 1: Factor a random N in $\mathbb{Z}_{(2)}(n)$ (e.g. for $n=1024$)

Problem 2: Given a polynomial $\mathbf{f(x)}$ where $\text{degree}(f) > 1$
and a random N in $\mathbb{Z}_{(2)}(n)$

find x in \mathbb{Z}_N s.t. $f(x) = 0$ in \mathbb{Z}_N

The factoring problem

Gauss (1805):

“The problem of distinguishing prime numbers from composite numbers and of resolving the latter into their prime factors is known to be one of the most important and useful in arithmetic.”

Best known alg. (NFS): run time $\exp(\tilde{O}(\sqrt[3]{n}))$ for n-bit integer

Current world record: **RSA-829** (250 digits)

- Work: two years on hundreds of machines
- Factoring a 1024-bit integer: about 1000 times harder
⇒ likely possible this decade

2048

Further reading

- A Computational Introduction to Number Theory and Algebra, V. Shoup, 2008 (V2), Chapter 1-4, 11, 12

Available at [//shoup.net/ntb/ntb-v2.pdf](http://shoup.net/ntb/ntb-v2.pdf)

End of Segment