

RSA, integer factorization, record computations

Aurore Guillevic

Inria Nancy, France

MIT, April 28, 2021

Course 6.857: Computer and Network Security <http://courses.csail.mit.edu/6.857/2021/>
These slides at <https://members.loria.fr/AGuillevic/files/teaching/21-MIT-RSA240.pdf>

Outline

Introduction on RSA

Integer Factorization

- Naive methods

- Quadratic sieve

Sieving

Number Field Sieve

Record computations: RSA-240, RSA-250

Attacks on the RSA cryptosystem

- Two French episodes

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Introduction: public-key cryptography

Introduced in 1976 (Diffie–Hellman, DH) and 1977 (Rivest–Shamir–Adleman, RSA)

Asymmetric means distinct public and private keys

- encryption with a public key
- decryption with a private key
- deducing the private key from the public key is a very hard problem

Two hard problems:

- Integer factorization (for RSA)
- Discrete logarithm computation in a finite group (for Diffie–Hellman)

Public-key encryption: 1977, Rivest, Shamir, Adleman (RSA)

Public parameters:

- modulus $N = p \cdot q$
- encryption key $e = 3$ or $2^{16} + 1$

Private data:

- p, q distinct large safe primes
- private decryption key $d = e^{-1} \bmod \varphi(N) = (p - 1)(q - 1)$

Ciphertext $c = m^e \bmod N$ for a message m encoded as integer in $[0, N - 1]$

Decryption: $m = c^d = m^{ed} \bmod N$

It works because $ed = 1 \bmod (p - 1)(q - 1)$

Hard tasks without knowing p, q if N is large enough:

- computing $\varphi(N) = (p - 1)(q - 1)$,
- computing a square root $\sqrt{x} = x^{1/2} \bmod N$,
- computing an e -th root $x^{1/e} \bmod N$.

RSA, how does it work?

The security relies on the hardness of computing d from N, e .

p, q are required to compute $\varphi(N)$

→ security relies on the hardness of **integer factorization**.

Usecases:

`ssh-keygen` (linux), SSL, PGP: Enigmail on Thunderbird, Protonmail...

Choosing key sizes

Symmetric ciphers (AES): key sizes are 128, 192 or 256 bits.

Perfect symmetric cipher: trying all keys of size n bits takes 2^n tests

→ **brute-force search**

perfect symmetric cipher with secret key in $[0, 2^n - 1]$, of n bits $\leftrightarrow n$ bits of security

For RSA with N of length(N) bits:

n bits of security \leftrightarrow the best (mathematical) attack should take at least 2^n steps

- what is the fastest attack?
- how much time does it take with respect to length(N)?

RSA keys are much larger.

Cipher suite: a pair of symmetric and asymmetric ciphers offering the same level of security.

Particles

n	2^n	Examples
32	$2^{32} = 10^{9.6}$	number of humans on Earth
47	$2^{47} = 10^{14.2}$	distance Earth - Sun in millimeters ($149.6 \cdot 10^{12}$) number of operations in one day on a processor at 2 GHz
56	$2^{55.8} = 10^{16.8}$	number of operations in one year on a processor at 2 GHz
79	$2^{79} = 10^{23.8}$	Avogadro number: atoms of Carbon 12 in 1 mol
82	$2^{82.3} = 10^{24.8}$	mass of Earth in kilogrammes
100	$2^{100} = 10^{30}$	number of operations in $13.77 \cdot 10^9$ years (age of the universe) on a processor at 2 GHz
155	$2^{155} = 10^{46.7}$	number of molecules of water on Earth
256	$2^{256} = 10^{77.1}$	number of electrons in universe

Courtesy Marine Minier

Boiling water

Universal Security; From bits and mips to pools, lakes – and beyond
Arjen Lenstra, Thorsten Kleinjung, and Emmanuel Thomé
<https://hal.inria.fr/hal-00925622>

- 2^{90} operations require enough energy to boil the lake of Genève
- 2^{114} operations: boiling all the water on Earth
- 2^{128} operations: boiling 16,000 planets like the Earth

Choosing key sizes

For RSA with N of length(N) bits:

n bits of security \leftrightarrow the best (mathematical) attack should take at least 2^n steps

- fastest factorization: with the Number Field Sieve algorithm

- Complexity: $e^{\sqrt[3]{(64/9+o(1))(\ln N)(\ln \ln N)^2}}$

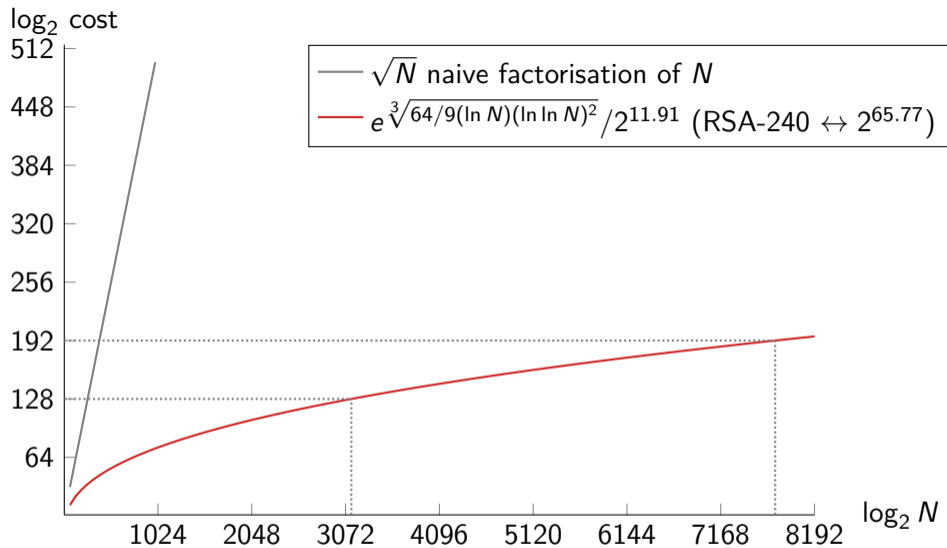
- $+o(1)$ not known

- $e^{\sqrt[3]{(64/9+0)(\ln N_{\text{RSA-240}})(\ln \ln N_{\text{RSA-240}})^2}} = 2^{77.68}$

- RSA-240 in $2^{65.77}$ operations $\rightarrow 2^{65.77}/2^{77.68} = 2^{-11.91}$

Replace unknown $+o(1)$ by scaling factor $2^{-11.91}$

(A. Lenstra, Verheul, Asiacrypt'01)



RSA-240: 953 core-years, Intel Xeon Gold 6130 CPUs as a reference (2.1GHz)
 $\approx 953 \cdot 365.25 \cdot 24 \cdot 60 \cdot 60 \cdot 2.1 \cdot 10^9 \approx 2^{65.77}$

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Attacks on the RSA cryptosystem

Naive way 1: Testing all primes up to square root of N

Trial division: testing all the primes up to \sqrt{N}

But if there are too many primes to test, it never ends

- $x / \ln x$ prime numbers between 1 and x (with $\ln \exp(1) = 1$)
- $\sqrt{N} / \ln \sqrt{N}$ prime numbers between 1 and \sqrt{N}

N (bits)	N (digits)	$\sqrt{N} / \ln \sqrt{N}$
256	77	2^{122} 10^{37}
512	154	2^{249} 10^{75}
768	231	2^{376} 10^{114}
1024	308	2^{504} 10^{152}
1280	385	2^{632} 10^{191}
1536	462	2^{759} 10^{229}
1792	539	2^{887} 10^{267}
2048	617	2^{1015} 10^{306}

Naive way 2: testing all primes around square root of N

If p and q are of the same length (in bits), test all prime factors between $\lfloor \sqrt{N}/2 \rfloor$ and $\lfloor \sqrt{N} \rfloor$.

How many primes in $[1, 2^n]$? approximately $2^n / \ln 2^n$

How many primes in $[2^{n-1}, 2^n]$? approximately $(1/2) \times 2^n / \ln 2^n$

Still completely impracticable.

(Trial division usually to detect prime factors up to 10^6 (78498 distinct prime factors, $10^6 / \ln 10^6 = 72382.4$) or 10^7 (664579 distinct prime factors, $10^7 / \ln 10^7 = 620420.7$))

Historical steps in integer factorization

- 1975, Morrison, Brillhard, continued fraction method CFRAC (factorization of $2^{2^7} + 1 = 2^{128} + 1$) (see the *Cunningham project* <https://homes.cerias.purdue.edu/~ssw/cun/>)
 $2^{128} + 1 = 340282366920938463463374607431768211457 =$
 $59649589127497217 \times 5704689200685129054721$
- 1981, Dixon, random squares method
- 70's, unpublished: Schroepel, Linear Sieve
- 1982, Pomerance, Quadratic Sieve
- 1987, Lenstra, Elliptic Curve Method (ECM)
- 1993, Buhler, Lenstra, Pomerance, General Number Field Sieve

Strong joint work of researchers and manufacturers of computers in the US
(*before* the Personal Computer)

Square roots modulo N

In \mathbb{R} or \mathbb{C} , if x is a square, it has two square roots \sqrt{x} and $-\sqrt{x}$.

But in $\mathbb{Z}/N\mathbb{Z}$ with $N = pq$ strange things happen: **four** square roots.

$N = 2021$

```
for i in range(-N//2, N//2):  
    if (i**2 % N) == 1:  
        print(i)
```

Two pairs of square roots of $x = 1$: $(1, -1)$ and $(-988, 988)$

$$988^2 = 1^2 \pmod{2021}$$

$$\iff 988^2 - 1^2 = 0 \pmod{2021}$$

$$\iff (988 - 1) \times (988 + 1) = 0 \pmod{2021}$$

Compute a gcd (greatest common divisor):

$\gcd(988 - 1, 2021) = 47$, $\gcd(988 + 1, 2021) = 43$.

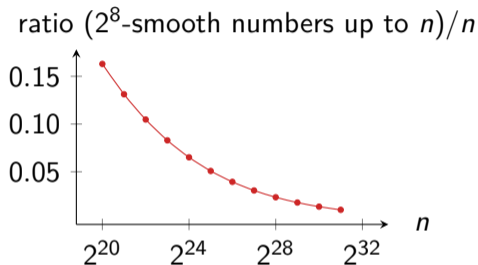
$N = 43 \times 47$

Smooth numbers

B -smooth

A positive integer n is B -smooth \iff
 n factors as a product of primes up to B
 $n = 2^{e_1} 3^{e_2} 5^{e_3} \dots p_i^{e_i}$ and $p_i \leq B$.

B -smooth integers are quite common:
10% of 22-bit integers are 8-bit smooth
5% of 25-bit integers are 8-bit smooth
1% of 31-bit integers are 8-bit smooth



For very large integers:

$$\text{Proba}(n \text{ is } B\text{-smooth}) = \text{Dickman-}\rho(\log n / \log B)$$

Factorization with the Quadratic Sieve

N to be factored

If $X^2 \equiv Y^2 \pmod{N}$ and $X \not\equiv \pm Y \pmod{N}$, then $\gcd(X \pm Y, N)$ gives a factor of N .

Find such X, Y .

Factorization with the Quadratic Sieve

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Set $m = \lfloor \sqrt{N} \rfloor$, set bounds A, B

For many small $a \leq A$, compute $n_a = (a + m)^2 - N$

if n_a is B -smooth, store the relation $n_a = p_1^{e_1} p_2^{e_2} \cdots p_j^{e_j}$ with all primes $p_i \leq B$

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Find a combination s.t. $n_{a_1} n_{a_2} \cdots n_{a_i} = p_1^{e_1} p_2^{e_2} \cdots p_k^{e_k}$ and all e_i even

$X = (a_1 + m)(a_2 + m) \cdots (a_i + m) \pmod{N}$, $Y = \sqrt{n_{a_1} n_{a_2} \cdots n_{a_i}} \pmod{N}$

If $X \not\equiv \pm Y \pmod{N}$, computes $\gcd(X - Y, N)$.

Factorization with the Quadratic Sieve: example

$$N = 2021, m = \lfloor \sqrt{N} \rfloor = 44$$

Smoothness bound $B = 19$

$\mathcal{F} = \{2, 3, 5, 7, 11, 13, 17, 19\}$ small primes up to B , $i = \#\mathcal{F} = 8$

B -smooth integer: $n = p_1^{e_1} p_2^{e_2} \cdots p_i^{e_i}$, all $p_i \leq B$ primes

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is $n = (a + m)^2 - N$ smooth for small a ?

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$$(2 + m)^2 - N = 95 = 5 \cdot 19$$

$$(5 + m)^2 - N = 380 = 2^2 \cdot 5 \cdot 19 \rightarrow$$

$$(17 + m)^2 - N = 1700 = 2^2 \cdot 5^2 \cdot 17$$

2 5 17 19

$$\begin{bmatrix} 0 & 1 & 0 & 1 \\ 2 & 1 & 0 & 1 \\ 2 & 2 & 1 & 0 \end{bmatrix}$$

exponents

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exponents
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Left kernel: $\begin{bmatrix} 1 & 1 & 0 \end{bmatrix}$

$$(2 + m)^2(5 + m)^2 \equiv 2^2 \cdot 5^2 \cdot 19^2 \pmod{N}$$

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$$\begin{array}{cccc} 2 & 5 & 17 & 19 \end{array}$$

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exponents
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$$\text{Left kernel: } \begin{bmatrix} 1 & 1 & 0 \end{bmatrix}$$

$$(2 + m)^2(5 + m)^2 \equiv 2^2 \cdot 5^2 \cdot 19^2 \pmod{N}$$

$$\underbrace{(46 \cdot 49)^2}_X \equiv \underbrace{(2 \cdot 5 \cdot 19)^2}_Y \pmod{N}$$

Factorization with the Quadratic Sieve: example

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$$X = 2254 \equiv 233 \pmod{N}, Y = 190 \pmod{N}$$

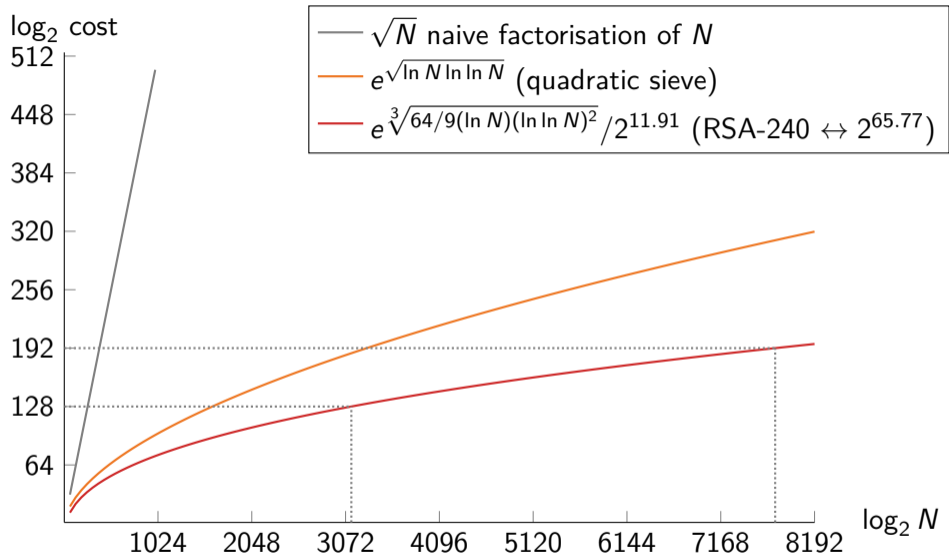
$$\gcd(X - Y, N) = 43, \gcd(X + Y, N) = 47$$

$$N = 43 \cdot 47$$

Quadratic Sieve: limitations for large numbers

Complexity: $e^{\sqrt{(1+o(1)) \ln N \ln \ln N}}$

- $n = (a + m)^2 - N \approx 2A\sqrt{N}$
Factor integers of size $\approx 2A\sqrt{N}$
- $\#\mathcal{F} = \#\{\text{primes up to } B\} \approx B / \ln B$
- Computes left kernel of huge linear system modulo 2



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Sieving: Detect smooth numbers without factoring

Eratosthenes sieve

Array $T[1 \dots n - 1]$ of integers from 2 up to n

At iteration i , each non-marked integer in $T[1 \dots i]$ is prime

For each non-marked $p_i = T[i]$ starting with $p_1 = T[1] = 2$:

Mark as composite all multiples $T[i + kp_i]$, $1 \leq k \leq (n - i)/p_i$

[2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]

Sieving: Detect smooth numbers without factoring

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Sieving: Detect smooth numbers without factoring

Quadratic sieve

1. Initialize array $T[1 \dots A]$ with $T[a] = (a + m)^2 - N$
2. For each prime p_i from 2 to B
 - 2.1 Solve $(x + m)^2 - N \equiv 0 \pmod{p_i} \rightarrow$ roots $x_0, x_1 \in [0, p_i - 1]$
 - 2.2 Update T : divide by p_i the cells $T[x_{0,1} + kp_i]$ for all $0 \leq k \leq (A - x_{0,1})/p_i$
 - 2.3 Consider higher powers $p_i^{e_i}$: solve $((x_{0,1} + m)^2 - N)/p_i \equiv 0 \pmod{p_i} \dots$
3. $T[a] = 1 \iff (a + m)^2 - N$ is B -smooth

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$(a + m)^2 - N$ is larger than a machine-word:

store $\log_2((a + m)^2 - N)$ at step (1) and subtract $\log_2 p_i$ at step (2)

$T[a] = 0 \iff (a + m)^2 - N$ is B -smooth (up to rounding errors)

Recompute $(a + m)^2 - N$ and factor it

\rightarrow factor only the smooth ones

Sieving: Detect smooth numbers without factoring

Quadratic sieve

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3. $T[a] = 0 \iff (a + m)^2 - N$ is B -smooth

1987: ECM factoring

Do not sieve up to B , set a sieving bound $B_0 < B$

For all $T[a] \leq$ ECM-bound,

recompute and run ECM on $(a + m)^2 - N$ with bound B

Store the B -smooth ones for the linear algebra step.

Sieving: Detect smooth numbers without factoring

$$N = 2021, B = 19, A = 20, a \in \{0, \dots, A\}$$

$$T = [-85, 4, 95, 188, 283, 380, 479, 580, 683, 788, 895, \\ 1004, 1115, 1228, 1343, 1460, 1579, 1700, 1823, 1948, 2075]$$

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$$p_i = 2, x_0 = 1, T[1 + 2k]/2^2$$

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$$p_i = 2, x_0 = 1, T[1 + 2k]/2^2$$

$$[-85, 1, 95, 47, 283, 95, 479, 145, 683, 197, 895, \\ 251, 1115, 307, 1343, 365, 1579, 425, 1823, 487, 2075]$$

Sieving: Detect smooth numbers without factoring

$$N = 2021, B = 19, A = 20, a \in \{0, \dots, A\}$$

$$T = [-85, 4, 95, 188, 283, 380, 479, 580, 683, 788, 895, \\ 1004, 1115, 1228, 1343, 1460, 1579, 1700, 1823, 1948, 2075]$$

$$p_i = 2, x_0 = 1, T[1 + 2k]/2^2$$

$$p_i = 5, x_0 = 0, T[0 + 5k]/5$$

$$[-85, 1, 95, 47, 283, 95, 479, 145, 683, 197, 895, \\ 251, 1115, 307, 1343, 365, 1579, 425, 1823, 487, 2075]$$

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$$p_i = 2, x_0 = 1, T[1 + 2k]/2^2$$

$$p_i = 5, x_0 = 0, T[0 + 5k]/5$$

$$[-17, 1, 95, 47, 283, 19, 479, 145, 683, 197, 179, \\ 251, 1115, 307, 1343, 73, 1579, 425, 1823, 487, 415]$$

Sieving: Detect smooth numbers without factoring

$$N = 2021, B = 19, A = 20, a \in \{0, \dots, A\}$$

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$$p_i = 2, x_0 = 1, T[1 + 2k]/2^2$$

$$p_i = 5, x_0 = 0, T[0 + 5k]/5$$

$$p_i = 5, x_1 = 2, T[2 + 5k]/5$$

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$$p_i = 2, x_0 = 1, T[1 + 2k]/2^2$$

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$$p_i = 5, x_1 = 2, T[2 + 5k]/5$$

$$[-17, 1, 19, 47, 283, 19, 479, 29, 683, 197, 179, \\ 251, 223, 307, 1343, 73, 1579, 85, 1823, 487, 415]$$

Sieving: Detect smooth numbers without factoring

$$N = 2021, B = 19, A = 20, a \in \{0, \dots, A\}$$

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$$p_i = 5, x_0 = 0 + 4 \cdot 5, T[0 + 4 \cdot 5 + 5^2 k]/5, x_1 = 2 + 3 \cdot 5, T[2 + 3 \cdot 5 + 5^2 k]/5$$

$$[-17, 1, 19, 47, 283, 19, 479, 29, 683, 197, 179, \\ 251, 223, 307, 1343, 73, 1579, 85, 1823, 487, 415]$$

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$$p_i = 5, x_0 = 0 + 4 \cdot 5, T[0 + 4 \cdot 5 + 5^2 k]/5, x_1 = 2 + 3 \cdot 5, T[2 + 3 \cdot 5 + 5^2 k]/5$$

$$[-17, 1, 19, 47, 283, 19, 479, 29, 683, 197, 179, \\ 251, 223, 307, 1343, 73, 1579, 17, 1823, 487, 83]$$

Sieving: Detect smooth numbers without factoring

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$$p_i = 17, x_0 = 0, x_1 = 14$$

$$[-17, 1, 19, 47, 283, 19, 479, 29, 683, 197, 179, \\ 251, 223, 307, 1343, 73, 1579, 17, 1823, 487, 83]$$

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$$p_i = 17, x_0 = 0, x_1 = 14$$

$$[-1, 1, 19, 47, 283, 19, 479, 29, 683, 197, 179, \\ 251, 223, 307, 79, 73, 1579, 1, 1823, 487, 83]$$

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$$p_i = 5, x_0 = 0 + 4 \cdot 5, T[0 + 4 \cdot 5 + 5^2k]/5, x_1 = 2 + 3 \cdot 5, T[2 + 3 \cdot 5 + 5^2k]/5$$

$$p_i = 17, x_0 = 0, x_1 = 14$$

$$p_i = 19, x_0 = 2, x_1 = 5$$

$$[-1, 1, 19, 47, 283, 19, 479, 29, 683, 197, 179, \\ 251, 223, 307, 79, 73, 1579, 1, 1823, 487, 83]$$

Sieving: Detect smooth numbers without factoring

$$N = 2021, B = 19, A = 20, a \in \{0, \dots, A\}$$

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$$p_i = 5, x_0 = 0 + 4 \cdot 5, T[0 + 4 \cdot 5 + 5^2 k]/5, x_1 = 2 + 3 \cdot 5, T[2 + 3 \cdot 5 + 5^2 k]/5$$

$$p_i = 17, x_0 = 0, x_1 = 14$$

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$$[-1, 1, 1, 47, 283, 1, 479, 29, 683, 197, 179, 251, 223, 307, 79, 73, 1579, 1, 1823, 487, 83]$$

Outline

Introduction on RSA

Integer Factorization

Sieving

Number Field Sieve

Record computations: RSA-240, RSA-250

Attacks on the RSA cryptosystem

Nowadays' method: the Number Field Sieve

- developed in the 80's and 90's
- reduce the size of the numbers to be factored from $A_1\sqrt{N}$ to $A_2^d\sqrt[d]{N}$ for a smaller $A_2 < A_1$ and $d \in \{3, 4, 5, 6\}$
- two huge steps: collecting relations, solving a large sparse system



Carl Pomerance.

A tale of two sieves.

Notices of the AMS, 43(12):1473–1485, Dec 1996.

<http://www.ams.org/notices/199612/pomerance.pdf>


The development of the NFS algorithm

1985 ElGamal: Discrete logarithms in $GF(p^2)$ with quadratic number fields

1986 Coppersmith, Odlyzko, Schroepel:
factoring with a quadratic number field (Gaussian integers)

1988 J. M. Pollard, Factoring with cubic integers. Factorization of $F_7 = 2^{2^7} + 1$.
Special Number Field.

1993 Lenstra, Lenstra, Manasse, Pollard. The Number Field Sieve.

 Arjen K. Lenstra and Hendrik W. Lenstra Jr., editors.
The development of the number field sieve, volume 1554 of *Lect. Note. Math.*
Springer, 1993.

<http://doi.org/10.1007/BFb0091534>

Factorization with NFS: recap

1. Polynomial selection: find two irreducible polynomials in $\mathbb{Z}[x]$ sharing a common root m modulo N
2. Relation collection: computes many smooth relations
3. Filtering: remove singletons, densify and shrink the matrix
4. Linear algebra: takes logarithms mod 2 of the relations: large sparse matrix over \mathbb{F}_2 , computes left kernel
5. Characters: find a combination of the vectors of the kernel so that $X^2 \equiv Y^2 \pmod{N}$
6. Square root: computes X, Y
7. Factor N : computes $\gcd(X - Y, N)$

Outline

Introduction on RSA

Integer Factorization

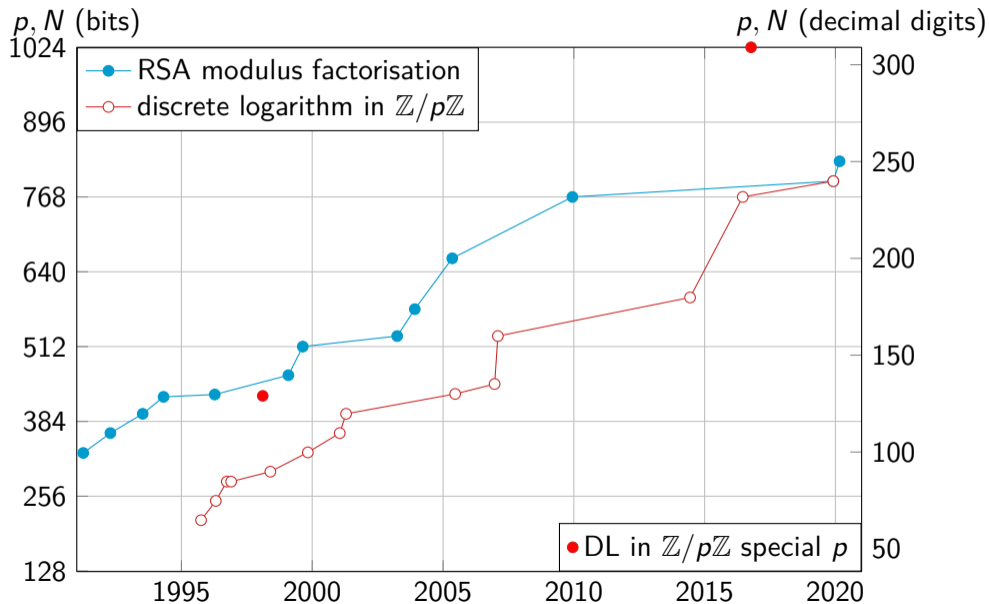
Sieving

Number Field Sieve

Record computations: RSA-240, RSA-250

Attacks on the RSA cryptosystem

Record computations



Latest record computations

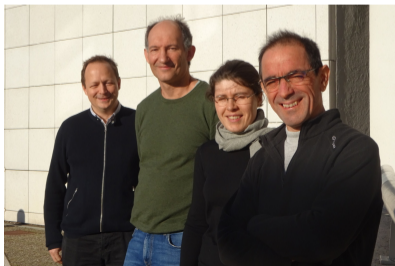
 Fabrice Boudot, Pierrick Gaudry, Aurore Guillevic, Nadia Heninger, Emmanuel Thomé, and Paul Zimmermann.

Comparing the difficulty of factorization and discrete logarithm: A 240-digit experiment.

In Daniele Micciancio and Thomas Ristenpart, eds., *CRYPTO 2020, Part II*, vol. 12171 of *LNCS*, pp. 62–91. Springer, August 2020.

Factorization of RSA-240 (795 bits) in December 2019 and RSA-250 (829 bits) in February 2020

Video at Crypto'2020: <https://youtube.com/watch?v=Qk207A4H7kU>



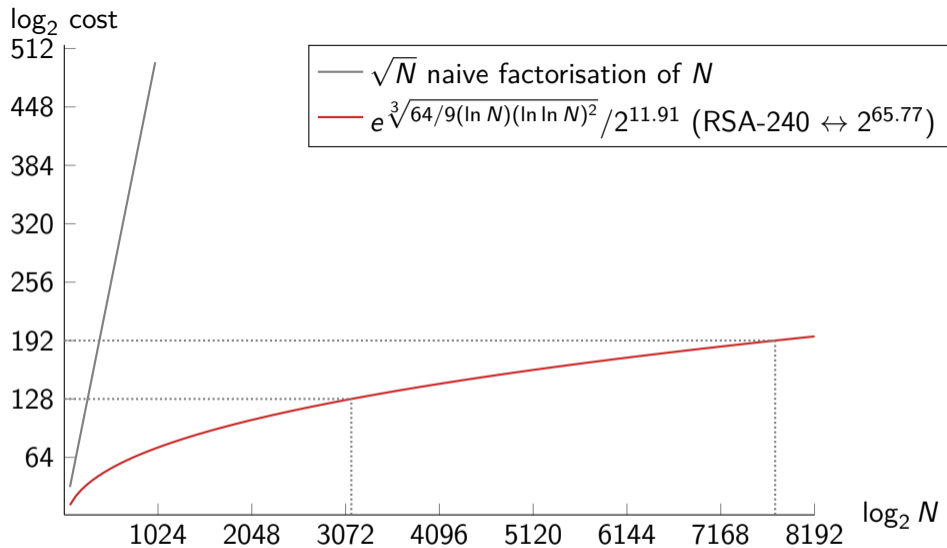
Nancy team

Latest record computations

RSA-240 = 124620366781718784065835044608106590434820374651678805754818
788883289666801188210855036039570272508747509864768438458621
054865537970253930571891217684318286362846948405301614416430
468066875699415246993185704183030512549594371372159029236099,
 p = 509435952285839914555051023580843714132648382024111473186660
296521821206469746700620316443478873837606252372049619334517,
 q = 244624208838318150567813139024002896653802092578931401452041
221336558477095178155258218897735030590669041302045908071447.

Latest record computations

RSA-250 = 214032465024074496126442307283933356300861471514475501779775492
088141802344714013664334551909580467961099285187247091458768739
626192155736304745477052080511905649310668769159001975940569345
7452230589325976697471681738069364894699871578494975937497937,
 p = 641352894770715802787901901705773890848250147429434472081168596
32024532344630238623598752668347708737661925585694639798853367,
 q = 333720275949781565562260106053551142279407603447675546667845209
87023841729210037080257448673296881877565718986258036932062711



RSA-240: 953 core-years, Intel Xeon Gold 6130 CPUs as a reference (2.1GHz)
 $\approx 953 \cdot 365.25 \cdot 24 \cdot 60 \cdot 60 \cdot 2.1 \cdot 10^9 \approx 2^{65.77}$

Breaking the previous record: Why?

- Record computations needed for key-size recommendations
- Open-source software Cado-NFS
- Motivation to improve all the steps
- Testing folklore ideas competitive only for huge sizes
- Exploits improvements of ECM (Bouvier–Imbert PKC'2020)
- Scaling the code for larger sizes improves the running-time on smaller sizes

The CADO-NFS software

Record computations with the CADO-NFS software.

- Important software development effort since 2007.
- 250k lines of C/C++ code, 60k for relation collection only.
- Significant improvements since 2016.
 - improved parallelism: strive to get rid of scheduling bubbles;
 - versatility: large freedom in parameter selection;
 - prediction of behaviour and yield: essential for tuning.
- Open source (LGPL), open development model (gitlab).
Our results can be reproduced.

Factorization of $N = \text{RSA-240}$, 240 decimal digits

Polynomial selection

$$m = 105487753732969860223795041295860517380/17780390513045005995253$$

$$\begin{aligned} f_1 = & 10853204947200x^6 \\ & -4763683724115259920x^5 \\ & -6381744461279867941961670x^4 \\ & +974448934853864807690675067037x^3 \\ & +179200573533665721310210640738061170x^2 \\ & +1595712553369335430496125795083146688523x \\ & -221175588842299117590564542609977016567191860 \end{aligned}$$

$$\begin{aligned} f_0 = & 17780390513045005995253x \\ & -105487753732969860223795041295860517380 \end{aligned}$$

$$\text{Res}(f_0, f_1) = 120N$$

Integers $(a - bm)$ much smaller than

$$\text{Norm}(a - b\alpha) = c_0b^6 + c_1ab^5 + c_2a^2b^4 + c_3a^3b^3 + c_4a^4b^2 + c_5a^5b + c_6a^6,$$

$$f_1 = c_0 + c_1x + \dots + c_6x^6$$

Relation collection with lattice sieving

Most time-consuming part.

How to enumerate (a, b) , and detect smooth $a - b\alpha$, $a - bm$?

Special- q (spq) Sieving

2-dimension array T of norm of $i - j\alpha$ all multiple of prime q_k

Allow Parallelization

Consider all primes $q_i \in [0.8G, 7.4G]$ ($G=10^9$) s.t. $\exists q$

- for $q_i \in [0.8G, 2.1G]$: **Lattice Sieve** on both sides
- for $q_i \in [2.1G, 7.4G]$: **Lattice Sieve** for f_1 (large norms) and **Factorization Tree** for f_0 (much smaller norms)

spq $\approx 3.0e8 \approx 2^{28}$

Sieve area per spq: $\mathcal{A} = [-2^{15}, 2^{15}] \times [0, 2^{16}]$, $\#\mathcal{A} = 2^{32}$

Relations look like

small primes, special- q , large primes

✓	$5^2 \cdot 11 \cdot 23 \cdot 287093 \cdot 870953 \cdot 20179693 \cdot 28306698811 \cdot 47988583469$	$2^3 \cdot 5 \cdot 7 \cdot 13 \cdot 31 \cdot 61 \cdot 14407 \cdot 26563253 \cdot 86800081 \cdot 269845309 \cdot 802234039 \cdot 1041872869 \cdot 5552238917 \cdot 12144939971 \cdot 15856830239$
✓	$3 \cdot 1609 \cdot 77699 \cdot 235586599 \cdot 347727169 \cdot 369575231 \cdot 9087872491$	$2^3 \cdot 3 \cdot 5 \cdot 13 \cdot 19 \cdot 23 \cdot 31 \cdot 59 \cdot 239 \cdot 3989 \cdot 7951 \cdot 2829403 \cdot 31455623 \cdot 225623753 \cdot 811073867 \cdot 1304127157 \cdot 78955382651 \cdot 129320018741$
✓	$5 \cdot 1381 \cdot 877027 \cdot 15060047 \cdot 19042511 \cdot 11542780393 \cdot 13192388543$	$2^4 \cdot 5 \cdot 13 \cdot 31 \cdot 59 \cdot 823 \cdot 2801 \cdot 26539 \cdot 2944817 \cdot 3066253 \cdot 87271397 \cdot 108272617 \cdot 386616343 \cdot 815320151 \cdot 1361785079 \cdot 12322934353$
✓	$2^3 \cdot 5^2 \cdot 173 \cdot 971 \cdot 613909489 \cdot 929507779 \cdot 1319454803 \cdot 2101983503$	$2^7 \cdot 3^2 \cdot 5 \cdot 29 \cdot 1021 \cdot 42589 \cdot 190507 \cdot 473287 \cdot 31555663 \cdot 654820381 \cdot 802234039 \cdot 19147596953 \cdot 23912934131 \cdot 52023180217$
✗	$2^2 \cdot 15193 \cdot 232891 \cdot 19514983 \cdot 139295419 \cdot 540260173 \cdot 606335449$	$2^2 \cdot 3^4 \cdot 13 \cdot 19 \cdot 74897 \cdot 1377667 \cdot 55828453 \cdot 282012013 \cdot 802234039 \cdot 3350122463 \cdot 35787642311 \cdot 37023373909 \cdot 128377293101$
✗	$2^2 \cdot 5^4 \cdot 439 \cdot 1483 \cdot 13121 \cdot 21383 \cdot 67751 \cdot 452059523 \cdot 33099515051$	$2^2 \cdot 3^3 \cdot 11 \cdot 13 \cdot 19 \cdot 5023 \cdot 3683209 \cdot 98660459 \cdot 802234039 \cdot 1506372871 \cdot 4564625921 \cdot 27735876911 \cdot 32612130959 \cdot 45729461779$

small primes: abundant \rightarrow dense column in the matrix

large primes: rare \rightarrow sparse column, limit to 2 or 3 on each side.

Relations look like

small primes, special- q , large primes

- ✓ $5^2 \cdot 11 \cdot 23 \cdot 287093 \cdot 870953 \cdot 20179693 \cdot 28306698811 \cdot 47988583469$ $2^3 \cdot 5 \cdot 7 \cdot 13 \cdot 31 \cdot 61 \cdot 14407 \cdot 26563253 \cdot 86800081 \cdot 269845309 \cdot 802234039 \cdot 1041872869 \cdot 5552238917 \cdot 12144939971 \cdot 15856830239$
- ✓ $3 \cdot 1609 \cdot 77699 \cdot 235586599 \cdot 347727169 \cdot 369575231 \cdot 9087872491$ $2^3 \cdot 3 \cdot 5 \cdot 13 \cdot 19 \cdot 23 \cdot 31 \cdot 59 \cdot 239 \cdot 3989 \cdot 7951 \cdot 2829403 \cdot 31455623 \cdot 225623753 \cdot 811073867 \cdot 1304127157 \cdot 78955382651 \cdot 129320018741$
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- ✓ $2^3 \cdot 5^2 \cdot 173 \cdot 971 \cdot 613909489 \cdot 929507779 \cdot 1319454803 \cdot 2101983503$ $2^7 \cdot 3^2 \cdot 5 \cdot 29 \cdot 1021 \cdot 42589 \cdot 190507 \cdot 473287 \cdot 31555663 \cdot 654820381 \cdot 802234039 \cdot 19147596953 \cdot 23912934131 \cdot 52023180217$

small primes: abundant \rightarrow dense column in the matrix

large primes: rare \rightarrow sparse column, limit to 2 or 3 on each side.

Before linear algebra: filtering step

as many cheap combinations as possible \rightarrow smaller matrix

Relation collection looks like

```
1  [||||||||||||| 100.0%] 17 [||||||||||||| 100.0%] 33 [||||||||||||| 100.0%] 49 [||||||||||||| 100.0%]
2  [||||||||||||| 100.0%] 18 [||||||||||||| 100.0%] 34 [||||||||||||| 100.0%] 50 [||||||||||||| 100.0%]
3  [||||||||||||| 100.0%] 19 [||||||||||||| 100.0%] 35 [||||||||||||| 100.0%] 51 [||||||||||||| 100.0%]
4  [||||||||||||| 100.0%] 20 [||||||||||||| 100.0%] 36 [||||||||||||| 100.0%] 52 [||||||||||||| 100.0%]
5  [||||||||||||| 100.0%] 21 [||||||||||||| 100.0%] 37 [||||||||||||| 100.0%] 53 [||||||||||||| 100.0%]
6  [||||||||||||| 100.0%] 22 [||||||||||||| 100.0%] 38 [||||||||||||| 100.0%] 54 [||||||||||||| 100.0%]
7  [||||||||||||| 100.0%] 23 [||||||||||||| 100.0%] 39 [||||||||||||| 100.0%] 55 [||||||||||||| 100.0%]
8  [||||||||||||| 100.0%] 24 [||||||||||||| 100.0%] 40 [||||||||||||| 100.0%] 56 [||||||||||||| 100.0%]
9  [||||||||||||| 100.0%] 25 [||||||||||||| 100.0%] 41 [||||||||||||| 100.0%] 57 [||||||||||||| 100.0%]
10 [||||||||||||| 100.0%] 26 [||||||||||||| 100.0%] 42 [||||||||||||| 100.0%] 58 [||||||||||||| 100.0%]
11 [||||||||||||| 100.0%] 27 [||||||||||||| 100.0%] 43 [||||||||||||| 100.0%] 59 [||||||||||||| 100.0%]
12 [||||||||||||| 100.0%] 28 [||||||||||||| 100.0%] 44 [||||||||||||| 100.0%] 60 [||||||||||||| 100.0%]
13 [||||||||||||| 100.0%] 29 [||||||||||||| 100.0%] 45 [||||||||||||| 100.0%] 61 [||||||||||||| 100.0%]
14 [||||||||||||| 100.0%] 30 [||||||||||||| 100.0%] 46 [||||||||||||| 100.0%] 62 [||||||||||||| 100.0%]
15 [||||||||||||| 100.0%] 31 [||||||||||||| 100.0%] 47 [||||||||||||| 100.0%] 63 [||||||||||||| 100.0%]
16 [||||||||||||| 100.0%] 32 [||||||||||||| 100.0%] 48 [||||||||||||| 100.0%] 64 [||||||||||||| 100.0%]
Mem[||||||||||||| 170G/188G] Tasks: 365, 119 thr; 65 running
Swp[||||||||||||| 0K/3.72G] Load average: 65.01 64.26 52.02
Uptime: 00:42:24
```

Discrete Logarithm 240 dd

$$r = N + 49204, \ell = (r - 1)/2 \text{ prime}$$

$$f_1 = 39x^4 + 126x^3 + x^2 + 62x + 120$$

$$f_0 = 286512172700675411986966846394359924874576536408786368056 x^3 \\ + 24908820300715766136475115982439735516581888603817255539890 x^2 \\ - 18763697560013016564403953928327121035580409459944854652737 x \\ - 236610408827000256250190838220824122997878994595785432202599$$

$$\text{Res } f_0, f_1 = -540r$$

More balanced integers

Smaller matrix but kernel modulo large prime ℓ

Relations, matrix size, core-years timings

	RSA-240	DLP-240
polynomial selection deg f_0 , deg f_1	76 core-years 1, 6	152 core-years 3, 4
relation collection	794 core-years	2400 core-years
raw relations	8 936 812 502	3 824 340 698
unique relations	6 011 911 051	2 380 725 637
filtering	days	days
after singleton removal	2 603 459 110 × 2 383 461 671	1 304 822 186 × 1 000 258 769
after clique removal	1 175 353 278 × 1 175 353 118	149 898 095 × 149 898 092
after merge	282M rows, density 200	36M rows, density 253
linear algebra	83 core-years	625 core-years
characters, sqrt, ind log	days	days
total	953 core-years $\approx 2^{65.77}$ op.	3177 core-years $\approx 2^{67.51}$ op.

Intel Xeon Gold 6130 CPUs as a reference (2.1GHz)

RSA-240 record computation

- Parameterization strategies
- Extensive simulation framework for parameter choices
- Implementation scales well

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Comparisons:

- Comparing RSA-240 to 10 years old previous record not meaningful
- Comparing DL-240 to previous record (DLP-768, 232 digits, 2016):
On **identical hardware**, our DLP-240 computation would have taken **25% less time** than the 232-digits computation.
- Finite field DLP is not **much** harder than integer factoring.

Outline

Introduction on RSA

Integer Factorization

Sieving

Number Field Sieve

Record computations: RSA-240, RSA-250

Attacks on the RSA cryptosystem

Two French episodes

Attacks on the RSA cryptosystem

Survey paper by Dan Boneh in 1999:



Dan Boneh.

Twenty years of attacks on the RSA cryptosystem.

Notices of the AMS, 46(2):203–213, February 1999.

Too short keys: Humpich episode (1997 in France)

http:

[//www.bibmath.net/crypto/index.php?action=affiche&quoi=moderne/cb](http://www.bibmath.net/crypto/index.php?action=affiche&quoi=moderne/cb)

In 1997, the keys in payment cards were 320-bit long (96 decimal digits)

Serge Humpich: reverse-engineering, yescard, factorization of a 320-bit key

Showed that possible to pay with a non-legitimate card (RATP tickets)

Possible to factor such keys with the *quadratic sieve*

March 4, 2000: the keys of *GIE carte bancaire* and their factors were released on Internet

Nowadays 1152-bit keys (in 2020)

Wrong key sizes: Bitcrypt ransomware (2014)

<https://airbus-cyber-security.com/fr/bitcrypt-broken/>

Fabien Perigaud and Cédric Pernet, Airbus Cybersecurity (formerly Cassidian)

ransomware: encrypt the files of target computers

Asks to pay in bitcoins

Encryption: with AES

AES keys encrypted with RSA

But not RSA-1024 (bits)

$$N = 3129884719662540063950693863716193016278901146429595260054414582 \\ 9335849533528834917800088971765784757175491347320005860302574523$$

1024 bits = 128 bytes but the key was 128 decimal digit long!

Factorization with `cado-nfs`

$$p = 4627583475399516037897017387039865329961620697520288948716924853$$
$$q = 6763540271723193027434512605129229364869394444394656022641769391.$$

RSA and the quantum computer

1994: Peter Shor, algorithm for integer factorization with a quantum computer

Factorization of a n -bit integer requires a perfect quantum computer with $2n$ qbits (quantum bits)

Quantum computer extremely hard to build

Record computation in 2018: $4\,088\,459 = 2017 \times 2027$

RSA-1024 (bits) will be factored before a quantum computer become competitive.

Summary of RSA best practices

Use elliptic curve cryptography.

If that's not an option:

- Choose RSA modulus N at least 2048 bits.
- Use a good random number generator to generate primes.
- Use a secure, randomized padding scheme.

Conclusion

Slides at <https://members.loria.fr/AGuillevic/teaching/>

Invited talk at PKC'2021 next month: [Lattices and Factoring](#) by Léo Ducas
<https://pkc.iacr.org/2021/>

Future Milestones in the forthcoming decades: RSA-896, RSA-1024?

Factorization with NFS: key idea

Reduce further the size of the integers to factor

Choose integer $m \approx \sqrt[d]{N}$

Write N in basis m : $N = c_0 + c_1m + \dots + c_dm^d$

Set $f_1(x) = c_0 + c_1x + \dots + c_dx^d \implies f_1(m) = 0$, set $f_0 = x - m \implies f_0(m) = 0$

Polynomials f_0, f_1 share a common root m modulo N

If f_1 is irreducible, define $\alpha \in \mathbb{C}$ a root of f_1

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Define a map from $\mathbb{Z}[\alpha]$ to $\mathbb{Z}/N\mathbb{Z}$

$$\phi: \mathbb{Z}[\alpha] \rightarrow \mathbb{Z}/N\mathbb{Z}$$

$$\alpha \mapsto m \bmod N \text{ where } f_1(m) = 0 \bmod N$$

ring homomorphism $\phi(a + b\alpha) = a + bm$

$$\phi \left(\underbrace{(a + b\alpha)}_{\text{factor in } \mathbb{Z}[\alpha]} \right) = \underbrace{(a + bm)}_{\text{factor in } \mathbb{Z}} \pmod N$$

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Factorization in $\mathbb{Z}[\alpha]$

Factor $N = 2021$

$$m = 38, 7 + 15m + m^2 = N, f_1(x) = x^2 + 15x + 7, f_0 = x - m$$

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To factor $a - b\alpha \in \mathbb{Z}[\alpha]$,

compute $\text{Norm}(a - b\alpha) \in \mathbb{Z}$ and factor in \mathbb{Z}

→ To factor N , factor many smaller integers.

a, b	$a - bm = \text{factor in } \mathbb{Z}$	$a^2 + 15ab + 7b^2$	factor in $\mathbb{Z}[\alpha]$
-23,2	$-99 = -3^2 \cdot 11$	$-133 = -7 \cdot 19$	$(7^+)(19^+)$
-22,1	$-60 = -2^2 \cdot 3 \cdot 5$	$161 = 7 \cdot 23$	$(7^+)(23^+)$
-16,1	$-54 = -2 \cdot 3^3$	$23 = 23$	(23^-)
-14,1	$-52 = -2^2 \cdot 13$	$-7 = -7$	(7^-)
-13,1	$-51 = -3 \cdot 17$	$-19 = -19$	(19^-)
-9,2	$-85 = -5 \cdot 17$	$-161 = -7 \cdot 23$	$(7^+)(23^-)$
-8,5	$-198 = -2 \cdot 3^2 \cdot 11$	$-361 = -19^2$	$(19^-)^2$
-8,15	$-578 = -2 \cdot 17^2$	$-161 = -7 \cdot 23$	$(7^+)(23^+)$
-7,1	$-45 = -3^2 \cdot 5$	$-49 = -7^2$	$(7^-)^2$
-6,13	$-500 = -2^2 \cdot 5^3$	$49 = 7^2$	$(7^+)^2$
-2,1	$-40 = -2^3 \cdot 5$	$-19 = -19$	(19^+)
-1,1	$-39 = -3 \cdot 13$	$-7 = -7$	(7^+)
-1,2	$-77 = -7 \cdot 11$	$-1 = -1$	
5,4	$-147 = -3 \cdot 7^2$	$437 = 19 \cdot 23$	$(19^-)(23^-)$
6,1	$-32 = -2^5$	$133 = 7 \cdot 19$	$(7^+)(19^-)$
7,6	$-221 = -13 \cdot 17$	$931 = 7^2 \cdot 19$	$(7^-)^2(19^+)$

Example in $\mathbb{Z}[\alpha]$: Matrix

Build the matrix of relations:

- one row per (a, b) pair s.t. both sides are smooth
- one column per prime $\{2, 3, 5, 7, 11, 13, 17\}$
- one column per prime ideal $(7^+), (7^-), (19^+), (19^-), (23^+), (23^-)$
- store the exponents mod 2

Example in $\mathbb{Z}[\alpha]$: Matrix

$$M = \begin{matrix} & \begin{matrix} 2 & 3 & 5 & 7 & 11 & 13 & 17 & (7^+) & (7^-) & (19^+) & (19^-) & (23^+) & (23^-) \end{matrix} \\ \begin{matrix} 0 & 2 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \end{matrix} \\ \begin{matrix} 2 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \end{matrix} \\ \begin{matrix} 1 & 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{matrix} \\ \begin{matrix} 2 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 \end{matrix} \\ \begin{matrix} 1 & 2 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 \end{matrix} \\ \begin{matrix} 1 & 0 & 0 & 0 & 0 & 0 & 2 & 1 & 0 & 0 & 0 & 1 & 0 \end{matrix} \\ \begin{matrix} 0 & 2 & 1 & 0 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 \end{matrix} \\ \begin{matrix} 2 & 0 & 3 & 0 & 0 & 0 & 0 & 2 & 0 & 0 & 0 & 0 & 0 \end{matrix} \\ \begin{matrix} 3 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 1 & 0 & 2 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \end{matrix} \\ \begin{matrix} 5 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \end{matrix} \\ \begin{matrix} 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 2 & 1 & 0 & 0 & 0 \end{matrix} \end{matrix}$$

Example in $\mathbb{Z}[\alpha]$: Matrix

	2	3	5	7	11	13	17	(7 ⁺)	(7 ⁻)	(19 ⁺)	(19 ⁻)	(23 ⁺)	(23 ⁻)
$M =$	0	0	0	0	1	0	0	1	0	1	0	0	0
	0	1	1	0	0	0	0	1	0	0	0	1	0
	1	1	0	0	0	0	0	0	0	0	0	0	1
	0	0	0	0	0	1	0	0	1	0	0	0	0
	0	1	0	0	0	0	1	0	0	0	1	0	0
	0	0	1	0	0	0	1	1	0	0	0	0	1
	1	0	0	0	1	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	0	1	0	0	0	1	0
	0	0	1	0	0	0	0	0	0	0	0	0	0
	0	0	1	0	0	0	0	0	0	0	0	0	0
	1	0	1	0	0	0	0	0	0	1	0	0	0
	0	1	0	0	0	1	0	1	0	0	0	0	0
	0	0	0	1	1	0	0	0	0	0	0	0	0
	0	1	0	0	0	0	0	0	0	0	1	0	1
	1	0	0	0	0	0	0	1	0	0	1	0	0
	0	0	0	0	0	1	1	0	0	1	0	0	0

mod 2

Example: from left kernel in GF(2) to factorization

$$\text{ker } M \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

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$$\text{Relations \#9 and \#10: } \left| \begin{array}{l} (-7 - m) = -45 = -3^2 \cdot 5 \\ (-6 - 13m) = -500 = -2^2 \cdot 5^3 \end{array} \right| \begin{array}{l} -7 - \alpha = (7^-)^2 \\ -6 - 13\alpha = (7^+)^2 \end{array}$$

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$(-7 - m)(-6 - 13m) = 150^2$, but $(-7 - \alpha)(-6 - 13\alpha) = -49 - 98\alpha$ **not square**
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$$(-13 - m)(-6 - 13m)(-2 - m)(-1 - m)(6 - m)(7 - 6m) = 530400^2$$

$$(-13 - \alpha)(-6 - 13\alpha)(-2 - \alpha)(-1 - \alpha)(6 - \alpha)(7 - 6\alpha) = -3113264 - 6456485\alpha \text{ not square}$$

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$$(-49 - 98\alpha)(-3113264 - 6456485\alpha) = (-12103 - 25137\alpha)^2 \text{ square}$$

$$X = 150 \cdot 530400 = 1314 \text{ mod } N$$

$$Y = (-12103 - 25137m) = 750 \text{ mod } N$$

$$\text{gcd}(X - Y, N) = 47, \text{ gcd}(X + Y, N) = 43$$

$$N = 43 \cdot 47$$