NISTPQC is so much fun! 10900qmmP

Lorenz Panny

Technische Universiteit Eindhoven

Costa Adeje, Tenerife, 31 January 2018

NISTPQC

- Not a competition.
- 69 submissions published on December 21st 2017.
- First complete break: 3 hours later.

NISTPQC

BIG QUAKE. BIKE. CFPKM. Classic McEliece. Compact LWE. CRYSTALS-DILITHIUM. CRYSTALS-KYBER. DAGS. Ding Key Exchange. DME. DRS. DualModeMS. Edon-K. EMBLEM & R.EMBLEM. FALCON. FrodoKEM. GeMSS. Giophantus. Gravity-SPHINCS. Guess Again. Gui. HILA5. HiMQ-3. HK17. HQC. KINDI. LAC. LAKE. LEDAkem. LEDApkc. Lepton. LIMA. Lizard. LOCKER. LOTUS. LUOV. McNie. Mersenne-756839. MQDSS. NewHope. NTRUEncrypt. pqNTRUSign. NTRU-HRSS-KEM. NTRU Prime. NTS-KEM. Odd Manhattan. OKCN/AKCN/CNKE. Ouroboros-R. Picnic. pqRSA encryption. pqRSA signature. pqsigRM. QC-MDPC KEM. qTESLA. RaCoSS. Rainbow. Ramstake. RankSign. RLCE-KEM. Round2. RQC. RVB. SABER. SIKE. SPHINCS+. SRTPI. Three Bears. Titanium. WalnutDSA.

(slide stolen from Daniel J. Bernstein)

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— 'Guess Again' NISTPQC submission document

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(WITH POSSIBLE DECRYPTION ERRORS)

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Guess Again

[...] legitimate sender has an advantage over the eavesdropper since the sender [...] knows exactly what the transmitted secret bit is. [...] instead of making the receiver guess the transmitted bit we make the sender guess the receiver's decryption key [...].

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Alice transmits a single bit $m \in \{0, 1\}$ to Bob:

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- Pick $a \xleftarrow{\text{random}} \{B \ldots n-1\}$ and let $A := \text{random\_walk}(a, s)$. Repeat this until $A \lessgtr B$.
- If $s = f$, send (m, a). Else send $(1 \oplus m, a)$.

Repeat many times to increase success probability.

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Argument: Bit m is flipped with probability $\frac{1}{2}$, thus secure. (?)

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Distribution of a conditional on $(\lesseqgtr, s)$:

s	A	a	flip?
f	$< B$	slightly biased towards B	0
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$\Longrightarrow$ In expectation, a of 'flipped' ciphertexts are smaller.

Guessed Again ✓

```
def recover_bit(ct, bit):
  assert bit < len(ct) // 4000
  ts = [struct.unpack('BB', ct[i:i+2])
        for i in range(4000*bit, 4000*(bit+1), 2)]
  xs, ys = [a for a, b in ts if b == 1], [a for a, b in ts if b == 2]
  return sum(xs) / len(xs) >= sum(ys) / len(ys)

def decrypt(ct):
  res = sum(recover_bit(ct, b) << b
            for b in range(len(ct) // 4000))
  return int.to_bytes(res, len(ct) // 4000 // 8, 'little')
```

Guessed Again ✓

[...] our protocol is IND-CCA2 secure against any passive adversary, even computationally unbounded one.

[...] "Computationally unbounded" here includes all possible computers, quantum or not.

— 'Guess Again' NISTPQC submission document

RVB

- Chebyshev polynomials:

$$T_0 = 1$$
$$T_1 = t$$
$$T_n = 2t \cdot T_{n-1} - T_{n-2}$$

- Commutative semigroup under composition:

$$T_a \circ T_b = T_b \circ T_a = T_{a \cdot b}$$

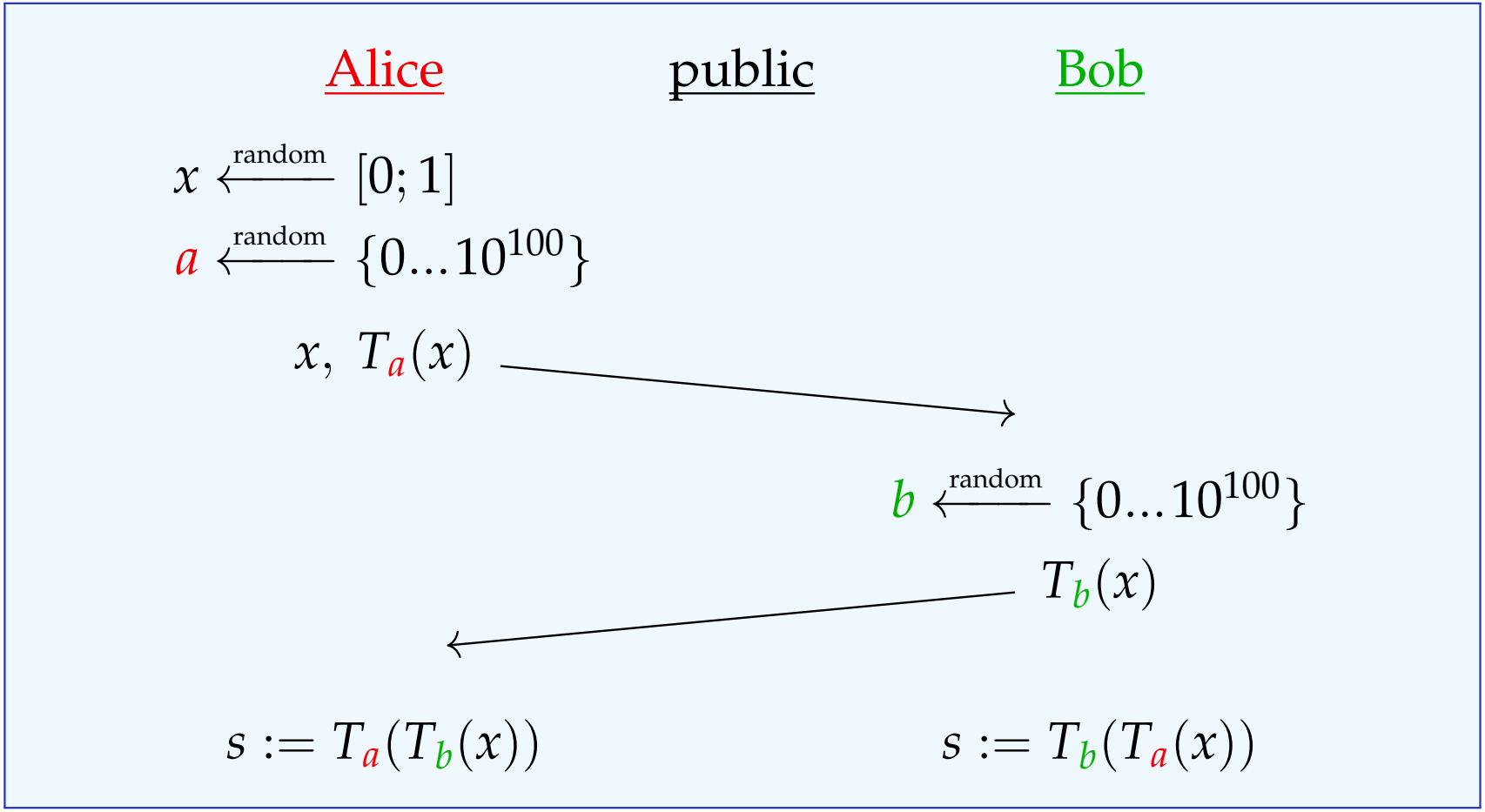
...screams Diffie-Hellman, but it is secure?

RVB

Fear not: for behold, I bring you good tidings of great joy!

> *Given x, $y = T_a(x)$, there is no efficiant way to compute the secret parameter a from $T_a(x)$, even if a quantum computer [...] is used for the attack, as will be shown.*
>
> — 'RVB' NISTPQC submission document

RVB



All computations using high-precision floating point numbers.

RVB

- Trigonometry:[1]

$$\cos(n \cdot \alpha) = T_n(\cos \alpha) \qquad \forall \alpha \in \mathbb{R}.$$

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- B–D'A–DS–K now implicitly assume α and β are rational and multiply by $d = \operatorname{lcm}(\textit{denominators})$:

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- Extremely unrealistic: $\arccos(\mathbb{Q}) \cap \mathbb{Q} = \{0\}$.
  $\Longrightarrow$ Rounding errors all over the place.

RVB

The conclusions of Bergamo et al. are mathematically wrong. [...]

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[...]

Several hundred years ago everybody strongly believed that the sun rotates around the earth.

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Let $\alpha, \beta \in \mathbb{R}$ and $k \in \mathbb{Z}$ such that $\alpha + k\beta \in \mathbb{Z}$.

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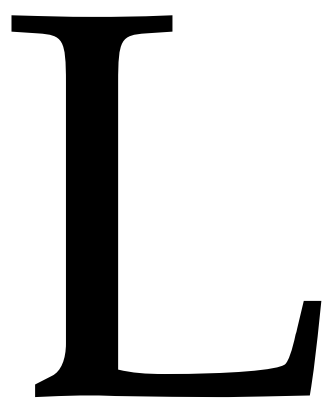

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RVB

Let K be an upper bound for $|k|$ and $B \approx K^2$.
The lattice spanned by the rows of

$$\begin{pmatrix} B & 0 & \lfloor aB \rceil \\ 0 & 1 & \lfloor bB \rceil \\ 0 & 0 & B \end{pmatrix}$$

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with $|\varepsilon| \ll B$. This corresponds to the relation

$$\lfloor aB \rceil + k' \lfloor bB \rceil \equiv \varepsilon \pmod{B},$$

and division by B yields

$$a + k'b \approx 0 \pmod{\mathbb{Z}}.$$

RVB ✓

```
def recover(pk):
    Tx, x = map(RealField(10**4), pk.split('\0')[:2])

    a = arccos(Tx) / arccos(x)
    b = 2*pi / arccos(x)

    # find an integer k such that a + k * b is close to an integer
    B = 10**(len(pk)//2)
    M = matrix([[B, 0, round(a*B)], [0, 1, round(b*B)], [0, 0, B]])
    for l in M.LLL().rows():
        if l[0]:
            k = sign(l[0]) * l[1]
            break

    guess = abs(round(a + k * b))

    # brute-force a small range in case we are slightly off
    for d in range(256):
        for s in (-1, +1):
            if abs(cos((guess + s * d) * arccos(x)) - Tx) < 1e-10:
                return guess + s * d
```

RVB ✓

[...] using the Lenstra–Lenstra–Lovász (LLL) lattice basis reduction algorithm is something that we didn't have on our radar screen. It successfully breaks the entire encryption scheme in almost no time.

The attack is reproducible and well-documented. Congratulations for this great work!

— 'RVB' authors' withdrawal notice

RaCoSS

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- $n = 2400, k = 2060$.
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- Hash function `wrhf` maps to n-bit strings of weight 3.
- Signing a message m: Pick a low-weight $y \in \mathbb{F}_2^n$.
  Compute $v = Hy,\ c = h(v, m),\ z = Sc + y$. Output (z, c).

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  Compute $v = Hy,\ c = h(v, m),\ z = Sc + y$. Output (z, c).
- Verifying $m, (z, c)$: Check that weight$(z) \leq 1564$.
  Compute $v' = Hz + Tc$. Check that $h(v', m) = c$.

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Implementation bug:

```
unsigned char  c[RACOSS_N];
unsigned char  c2[RACOSS_N];

/* ... */

for( i=0 ; i<(RACOSS_N/8) ; i++ )
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...compares only the first 300 coefficients!
Thus, a signature with $c[0 \ldots 299] = 0$ is accepted for

$$\binom{2100}{3} / \binom{2400}{3} \approx 67\%$$

of all messages.

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- another message signed by the first KAT:

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RaCoSS ✓

Linear algebra!

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- Pick $n - k$ columns of H that form an invertible matrix H_1.[2] This can be written as $H_1 = HC$ with $C \in \mathbb{F}_2^{n \times (n-k)}$.[3]

[2] Approximately 29% of all $(n-k) \times (n-k)$ matrices over $\mathbb{F}_2$ are invertible.
[3] For the proposed H, the first $n - k$ columns of H work: $C = (I_{n-k} \mid 0)^T$.

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- Then $Hz = HCz_1 = H_1 z_1 = v + Tc$ as desired.
- Expected weight of z is $\approx \frac{n-k}{2} = 170 \ll 1564$.
- Properly generated signatures have $\mathrm{weight}(z) \approx 261$.

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You should totally **try this at home!**

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Thanks!