On the hardness of the NTRU problem

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NTRU

Algorithmic problem based on lattices

- post-quantum
- efficient
- used in Falcon and NTRU / NTRUPrime (NIST finalists)
- old (for lattice-based crypto)

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Definition (informal)

An NTRU instance is

$$h = f \cdot g^{-1} \bmod q,$$

where $f, g \in \mathbb{Z}$ and $|f|, |g| \ll \sqrt{q}$.

Decision-NTRU: Distinguish $h = f \cdot g^{-1} \bmod q$ from h uniform

Search-NTRU: Recover (f, g) from h.

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RLWE

Another lattice-based algorithmic problem

- post-quantum
- efficient
- used in NewHope (NIST round 2)

[SSTX09] Stehlé, Steinfeld, Tanaka, and Xagawa. Efficient public key encryption based on ideal lattices. Asiacrypt.

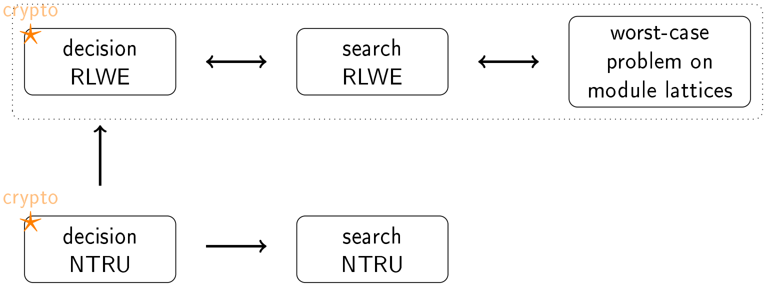
[LPR10] Lyubashevsky, Peikert, and Regev. On ideal lattices and learning with errors over rings. Eurocrypt.

NTRU vs RLWE

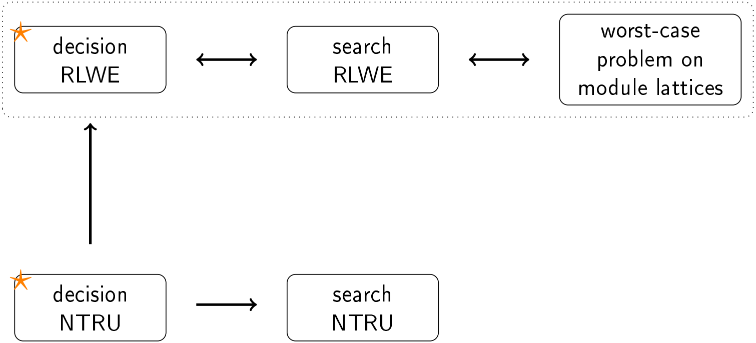
- both are efficient
- both are versatile (but RLWE a bit more)
- NTRU is older

NTRU vs RLWE

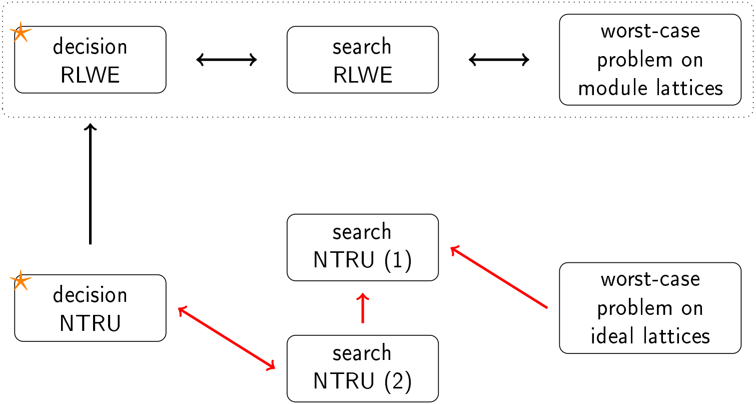
- both are efficient
- both are versatile (but RLWE a bit more)
- NTRU is older
- RLWE has better security guarantees



Our result


decision RLWE
search RLWE
worst-case problem on module lattices
decision NTRU
search NTRU

Our result


decision
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NTRU (1)
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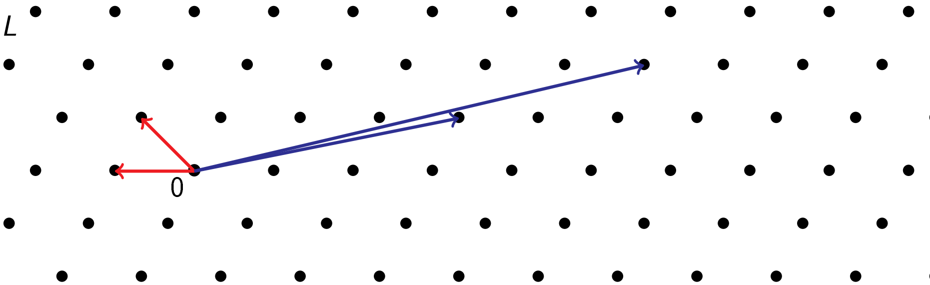
ideal lattices

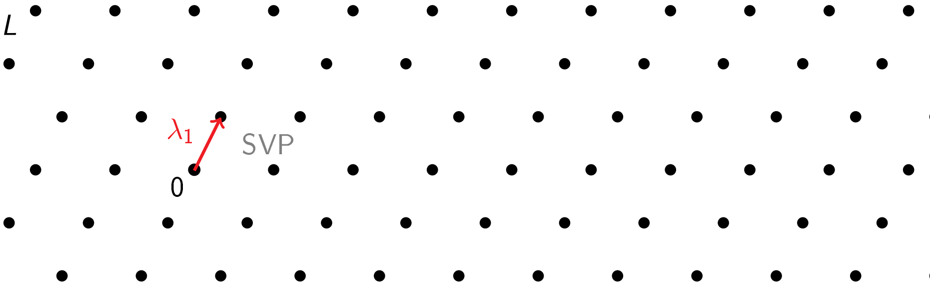
Lattices and ideals

Lattices



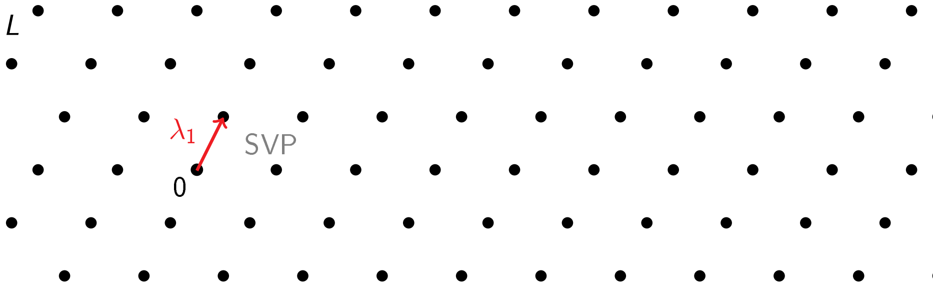
- $L = \{Bx \mid x \in \mathbb{Z}^n\}$ is a lattice
- $B \in \mathrm{GL}_n(\mathbb{R})$ is a basis
- n is the dimension of L

Shortest vector problem



SVP : Shortest Vector Problem

Shortest vector problem

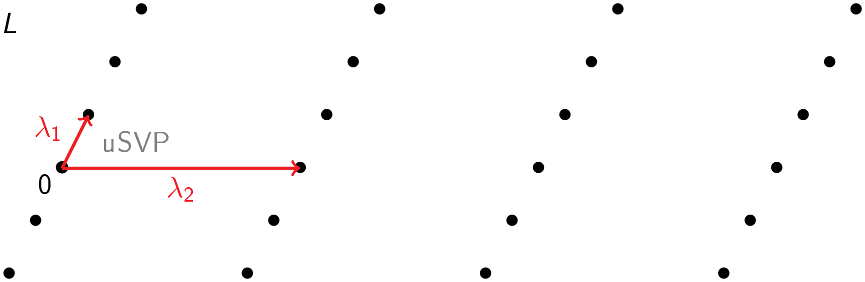


SVP : Shortest Vector Problem

Supposedly hard to solve when n is large

- even with a quantum computer
- even for some structured lattices (e.g., ideal lattices)

Unique shortest vector problem



uSVP : unique Shortest Vector Problem

uSVP = SVP restricted to lattices with $\lambda_1 \ll \lambda_2$

Ideal lattices

- $R = \mathbb{Z}[X]/(X^n + 1)$ with $n = 2^k$ (or $R = \mathbb{Z}$)
- $K = \mathbb{Q}[X]/(X^n + 1)$ (or $K = \mathbb{Q}$)

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(Principal) Ideals: $I = \langle z \rangle = \{zr \mid r \in R\}$

(e.g., $\langle 2 \rangle = \{2x \mid x \in \mathbb{Z}\}$)

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Embedding:

$$\sigma : \quad K = \mathbb{Q}[X]/(X^n+1) \;\rightarrow\; \mathbb{Q}^n$$

$$r = \sum_{i=0}^{n-1} r_i X^i \;\mapsto\; (r_0, \cdots, r_{n-1})$$

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$\sigma(\langle 2 \rangle) \subset \mathbb{Q}$

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ideal-SVP: Given $\langle z \rangle$, find $rz \in \langle z \rangle$ such that $\|\sigma(rz)\|$ is small

The different NTRU problems

NTRU instances

$R_q := R/(qR)$

NTRU instance

A (γ, q)-NTRU instance is $h \in R_q$ s.t.

- $h = f/g \bmod q$ (or $gh = f \bmod q$)
- $\|f\|, \|g\| \leq \frac{\sqrt{q}}{\gamma}$ (if $y = \sum_{i=0}^{n-1} y_i X^i \in R$, then $\|y\| = \sqrt{\sum_i y_i^2}$)

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The pair (f, g) is a trapdoor for h.

Claim: if (f, g) and (f', g') are two trapdoors for the same h,

$$\frac{f'}{g'} = \frac{f}{g} =: h_K \in K \quad \text{(division performed in K)}$$

Decisional NTRU problem

dNTRU

The (γ, q)-decisional NTRU problem ((γ, q)-dNTRU) asks, given $h \in R_q$, to decide whether

- $h \leftarrow \mathcal{D}$ where $\mathcal{D}$ is a distribution over (γ, q)-NTRU instances
- $h \leftarrow \mathcal{U}(R_q)$

Search NTRU problems

$\mathrm{NTRU}_{\mathrm{vec}}$

The (γ, q)-search NTRU vector problem ($(\gamma, q)\text{-}\mathrm{NTRU}_{\mathrm{vec}}$) asks, given a $(\gamma, q)\text{-}\mathrm{NTRU}$ instance h, to recover $(f, g) \in R^2$ s.t.

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(Recall $h_K = f/g \in K$ for any trapdoor (f, g))
$\Leftrightarrow$ recover $(\alpha f, \alpha g)$ for any $\alpha \in K$

(The two problems exist in worst-case and average-case variants)

NTRU is a (module) lattice problem

NTRU lattice: For $h \in R$, define Λ_h (module) lattice with basis

$$B_h = \begin{pmatrix} 1 & 0 \\ h & q \end{pmatrix} \quad \text{(in columns)}$$

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- if $h \leftarrow \mathcal{U}(R_q)$
  $\Rightarrow \lambda_1(\Lambda_h) \approx \lambda_2(\Lambda_h) \approx \sqrt{q}$

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$\mathrm{NTRU}_{\mathrm{vec}}$: recover $(f, g) \leftrightarrow$ find a shortest vector in Λ_h

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$\mathrm{NTRU}_{\mathrm{vec}}$: recover $(f, g) \leftrightarrow$ find a shortest vector in Λ_h

$\mathrm{NTRU}_{\mathrm{mod}}$: recover $\alpha \cdot (f, g) \leftrightarrow$ find the direction where Λ_h is dense

What we know about NTRU

Previous works

Reductions:

[SS11, WW18] If $f, g \leftarrow D_{R,\sigma}$ with $\sigma \geq \mathrm{poly}(n) \cdot \sqrt{q}$ then $f/g \approx \mathcal{U}(R_q)$ (cyclotomic fields)

- dNTRU is provably hard when $\gamma \leq \frac{1}{\mathrm{poly}(n)}$

[SS11] Stehlé and Steinfeld. Making NTRU as secure as worst-case problems over ideal lattices. Eurocrypt.

[WW18] Wang and Wang. Provably secure NTRUEncrypt over any cyclotomic field. SAC.

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[Pei16] Peikert. A decade of lattice cryptography. Foundations and Trends in TCS.

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Attacks: (polynomial time)

[LLL82] dNTRU, $\mathrm{NTRU}_{\mathrm{mod}}$ broken if $\gamma \geq 2^n$

[LLL82] Lenstra, Lenstra, Lovász. Factoring polynomials with rational coefficients. Mathematische Annalen.

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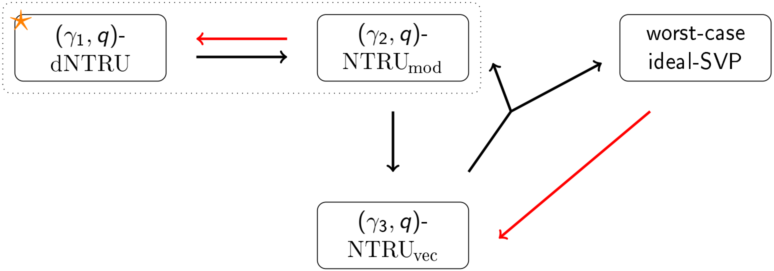
[ABD16, CJL16] dNTRU, $\mathrm{NTRU}_{\mathrm{mod}}$ broken if $(\log q)^2 \geq n \cdot \log \frac{\sqrt{q}}{\gamma}$
[KF17] (e.g., $q \approx 2^{\sqrt{n}}$ and $\gamma = \sqrt{q}/\mathrm{poly}(n)$)

[ABD16] Albrecht, Bai, and Ducas. A subfield lattice attack on overstretched NTRU assumptions. Crypto.

[CJL16] Cheon, Jeong, and Lee. An algorithm for NTRU problems. LMS J Comput Math.

[KF17] Kirchner and Fouque. Revisiting lattice attacks on overstretched NTRU parameters. Eurocrypt

Our results (with more details)



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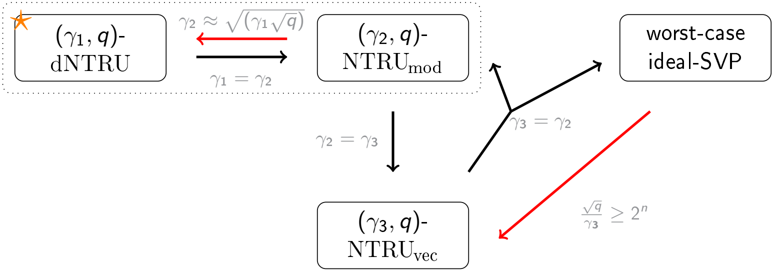

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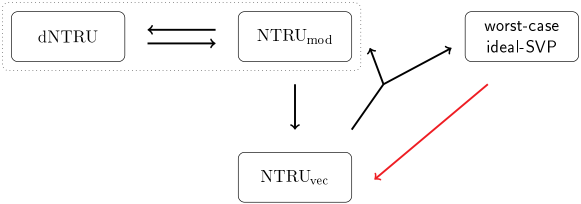
Techniques



dNTRU
$\mathrm{NTRU}_{\mathrm{mod}}$
worst-case
ideal-SVP
$\mathrm{NTRU}_{\mathrm{vec}}$

From ideal-SVP to $\mathrm{NTRU}_{\mathrm{vec}}$

Objective: Transform an ideal I into an NTRU instance h

- $I = \langle z \rangle = \{z \cdot r \mid r \in R\}$
- g short vector of I

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$$
\begin{aligned}
& g = z \cdot r && (r \in R) \\
\Leftrightarrow\ & g \cdot \frac{q}{z} = qr && \\
\Leftrightarrow\ & g \cdot h = f \bmod q &&
\end{aligned}
$$

- $h = q/z,\ f = 0$
- $\|f\|, \|g\|$ small

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⚠ Not an NTRU instance ($h \in K$ is not in R_q)

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$$\boxed{\begin{aligned} & g = z \cdot r && (r \in R) \\ \Leftrightarrow\ & g \cdot \frac{q}{z} = qr && \\ \Leftrightarrow\ & g \cdot \left\lfloor \frac{q}{z} \right\rceil = -g \cdot \left\{ \frac{q}{z} \right\} \bmod q && \\ \Leftrightarrow\ & g \cdot h = f \bmod q && \end{aligned}}$$

$$\{x\} = x - \lfloor x \rceil$$

- $h = \lfloor q/z \rceil$, $f = -g\{q/z\}$
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This is an NTRU instance

From ideal-SVP to $\mathrm{NTRU}_{\mathrm{vec}}$ (2)

Summing up: If $I = \langle z \rangle = \{z \cdot r \mid r \in R\}$ and z known

- can construct an NTRU instance h from I
  - any short $g \in I$ provides a trapdoor (f, g) for h

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What we need to conclude the reduction:

- any trapdoor (f', g') for h is such that $g' \in I$
  - g' solution to ideal-SVP in I

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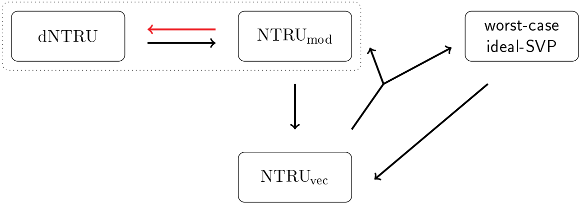
And for non principal ideals?

- $I = R \cap \langle z \rangle$ and z easily computed
  - everything still works with this z

Techniques



From $\mathrm{NTRU}_{\mathrm{mod}}$ to dNTRU

Objective: given $h = f/g \bmod q$, recover $h_K = f/g \in K$ (division in K)

Can use an oracle: given $h \in R_q$, outputs

- YES if $h = f/g \bmod q$, with f, g small $(\leq B)$
- NO otherwise

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Idea:

- take $x, y \in R$
- create $h' = x \cdot h + y = \frac{xf+yg}{g} \bmod q$
- query the oracle on h'
- learn whether $xf + yg$ is small or not

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$\Rightarrow$ we can choose x and y

$\Rightarrow$ we can modify the coordinates one by one

From $\mathrm{NTRU}_{\mathrm{mod}}$ to dNTRU (2)

Simplified problem

$f, g \in \mathbb{R}$ secret, $B \geq 0$ unknown.
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Objective: recover f/g

From $\mathrm{NTRU}_{\mathrm{mod}}$ to dNTRU (2)

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Algorithm:

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- Solve for f/g

More technical details

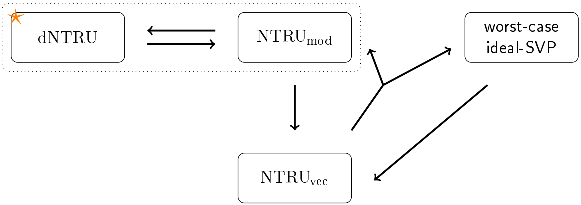
We do not have a perfect oracle

- need to handle distributions
- use the "oracle hidden center" framework [PRS17]

[PRS17] Peikert, Regev, and Stephens-Davidowitz. Pseudorandomness of ring-LWE for any ring and modulus. STOC.

Conclusion

Conclusion and open problems



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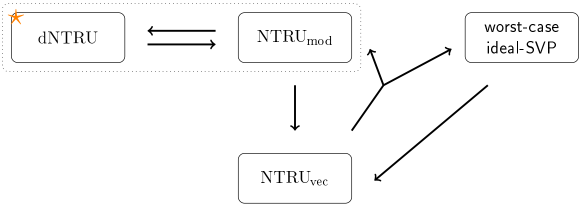

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Thank you