NTRU Prime: round-3 updates

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https://ntruprime.cr.yp.to

2021.06
Predicting post-quantum disasters

Deployed post-quantum system turns out to be breakable

Nobody studied the relevant weakness in the attack surface

Community didn’t have enough time to carefully review everything

Careful security review was much more complicated than necessary

Design decisions didn’t prioritize minimizing the attack surface

NTRU Prime
https://ntruprime.cr.yp.to
Public attacks are still picking low-hanging fruit

Eurocrypt 2020 Bellare–Davis–Günther:
Instantaneous break of Round2 (a lattice submission with “provable security”) via CCA hashing details.
CCA hashing details in NewHope “questionable”.
CCA hashing details in ten submissions okay but “brittle”.
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Why were these attacks not published in 2017? 2018? 2019? NISTPQC security reviewers are massively overloaded. Focusing on round-3 candidates helps, but is it enough?
Lattice attacks keep getting better

2018 Laarhoven–Mariano saved “between a factor 20 to 40 in the time complexity for SVP”.

2018 Bai–Stehlé–Wen introduced new variant of BKZ producing “bases of better quality” for “same cost” of SVP.

2018 Aono–Nguyen–Shen adapted “recent quantum tree algorithms” to enumeration.

2018 Anvers–Vercauteren–Verbauwhede showed that “an attacker can significantly reduce the security of (Ring/Module)-LWE/LWR based schemes that have a relatively high failure rate” and that for LAC-128 “the failure rate is $2^{48}$ times bigger than estimated”.

NTRU Prime https://ntruprime.cr.yp.to
Lattice attacks keep getting better, part 2

2018 Hamburg observed that the first published Round5 design had disastrously high failure rate, $2^{-55}$.

2019 Pellet-Mary–Hanrot–Stehlé broke through the previously claimed half-exponential approximation-factor barrier for number-theoretic attacks against Ideal-SVP.

2019 Guo–Johansson–Yang presented faster attacks against some systems that use error correction to (try to) reduce decryption failures. Violated security claims of LAC.

2020 Bellare–Davis–Günther broke Round2. (See above.)

Lattice attacks keep getting better, part 3

2020 Doulgerakis–Laarhoven–de Weger presented “faster [sieving] methods” for SVP.

2020 Albrecht–Bai–Fouque–Kirchner–Stehlé–Wen reduced the exponent of enumeration from $\approx 0.187 \beta \log_2 \beta$ to $\approx 0.125 \beta \log_2 \beta$. Combined with 2018 Aono–Nguyen–Shen, reduces post-quantum security levels of lattice-based systems.

2020 Bernard–Roux-Langlois improved the algorithm of 2019 Pellet-Mary–Hanrot–Stehlé; showed experimentally that in small dimensions the improved algorithm reaches much better approximation factors. How well does this scale to larger dimensions?
So what do we do?

Sensible reaction to drumbeat of advances in lattice attacks: **Lattices are dangerous! Avoid them!**

Why were we considering lattices in the first place?
So what do we do?

Sensible reaction to drumbeat of advances in lattice attacks: **Lattices are dangerous! Avoid them!**
Why were we considering lattices in the first place?

1. Common answer: “provable security”. But this didn’t stop any of the post-2017 advances in attacks, didn’t save the broken systems; won’t stop further advances.
So what do we do?

Sensible reaction to drumbeat of advances in lattice attacks: **Lattices are dangerous! Avoid them!**
Why were we considering lattices in the first place?

1. Common answer: “provable security”. But this didn’t stop any of the post-2017 advances in attacks, didn’t save the broken systems; won’t stop further advances.

2. Much better argument specifically for small lattices: **Maybe the application requires a small lattice system**—Frodo is too big, SIKE is too slow, etc.
Subject to the small-lattice requirement, NTRU Prime is the only submission systematically designed to **eliminate unnecessary complications in security review:** eliminate decryption failures, eliminate cyclotomics, etc.
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Does this work? Yes: every improvement in NTRU Prime attacks has been a general improvement against small lattices, while various small-lattice submissions have suffered from classes of attacks that NTRU Prime had already eliminated.
Example: decryption failures

Many attack advances. Some security claims broken. More and more pages of increasingly complicated analysis.

2021 D’Anvers–Batsleer: “We first improve the state-of-the-art multitarget decryption failure attack using a levelled approach”, point out “three inaccuracies in the directional failure boosting calculation for the simplified scheme of [11]”, show that “this traditional approach of calculating the directional failure boosting cost is not directly applicable to practical schemes such as Kyber and Saber due to compression of the ciphertexts”, etc.
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NTRU Prime, 2014: “prefer to avoid the mess of figuring out whether an attacker can trigger decryption failures.”
Proactive, not reactive

Proactive

Attack tool is identified

Design systems to eliminate the tool

Reactive

Attack tool is identified

First attacks are developed

Better attacks are developed

Devastating attacks are developed

Design systems to eliminate the attacks

NTRU Prime

https://ntruprime.cr.yp.to
Example: cyclotomics

2013.07: Cyclotomic lattices give subfields, automorphisms, etc. to attacker. Conclusion: “should switch” from cyclotomics to “random prime-degree extensions with big Galois groups”.

2014.02: First complete NTRU Prime cryptosystem, with maximum-size Galois groups and no decryption failures. Also introduced subfield-logarithm attack—subexponential time against some extreme cases of STOC 2009 Gentry FHE. All of this was before poly-time break of cyclotomics for the FHE system, and before the NISTPQC decryption-failure mess. (Very similar recommendations to avoid subfields and automorphisms in discrete-log cryptography were published years before those features turned into devastating attacks.) NIST's statements get this history backwards, hiding the cryptographer's ability to proactively protect against risks.

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Four plausible scenarios for the future of attacks

Attacks published so far:

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If cyclotomics are weak:
- Cyclo
- Prime
- Gentry broken
- KEM broken

If Gentry’s system is weak:
- Cyclo
- Prime
- Gentry broken broken
- KEM ok ok

If lattices are weak:
- Cyclo
- Prime
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Four further scenarios—split between showing security advantages of NTRU Prime and showing security disadvantages of NTRU Prime—are logically possible but harder to explain as developments from the current situation.
Four plausible scenarios for the future of attacks

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Is it still small? Yes—often even higher security!

Example: Say an application requires ≤1024 bytes for each public key and each ciphertext.
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Example: Say an application requires $\leq 1024$ bytes for each public key and each ciphertext. Maximum achievable pre-quantum $\log_2$ Core-SVP level across all of the parameter sets proposed for standardization:

- $106$ with NTRU ($\text{ntruhps2048509}$).
- $112$ (claimed 118?) with (round-3) Kyber ($\text{kyber512}$).
- $118$ with SABER ($\text{lightsaber}$).
- $129$ with Streamlined NTRU Prime ($\text{sntrup653}$).
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- $129$ with Streamlined NTRU Prime (sntrup653).

Vary $1024 \Rightarrow$ sometimes (e.g.) Kyber has higher Core-SVP.
The big picture is that each candidate is competitive.
See https://cr.yp.to/papers.html#categories.
Another aspect of sizes: fitting into hardware

CARDIS 2020: Complete constant-time sntrup761 using 1841 FPGA slices with 14 BRAMs, 19 DSPs.

(Xilinx Zynq Ultrascale+: Artix-7, plus ARM not used here.)

Update: Complete constant-time sntrup761 using 1367 FPGA slices with 11.5 BRAMs, 19 DSPs.

Runs at 271.6 MHz. Cycle counts:
1289959 keygen, 119250 enc, 260307 dec.

https://github.com/AdrianMarotzke/SNTRUP

With somewhat more area, can achieve far fewer cycles; but TCO analysis suggests that small area is more important.
NTRU Prime speeds are competitive

Almost all KEMs reported in pqm4 (as of 2021.06.02) have slower enc and slower dec than sntrup761.
NTRU Prime speeds are competitive

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Pre-quantum log\(_2\) Core-SVP levels for the exceptions:

- 106 for ntruhps2048509: 563499 enc, 536107 dec.
- 112 (118?) for kyber90s512: 449428 enc, 460732 dec.
- 112 (118?) for kyber512: 555947 enc, 516170 dec.
- 118 for lightsaber: 484733 enc, 460133 dec.
- 136 for ntruhrss701: 375974 enc, 867459 dec.
- 153 for sntrup761: 698943 enc, 565268 dec.
Security (vertical) vs. enc + dec time (horizontal)

NTRU Prime

https://ntruprime.cr.yp.to
Security vs. enc time + dec time + 1000 \cdot \text{ctbytes}

![Graph showing security vs. enc time + dec time + 1000 \cdot \text{ctbytes}](https://ntruprime.cr.yp.to)
Stability: another win for security reviewers

NTRU Prime has an unchanged family of trapdoor functions throughout round 1, round 2, and round 3. See round-3 submission for analysis of how modules, errors, etc. would complicate security review.

CCA conversion included various hashing safeguards in round 1. Added further defenses in round 2. Unchanged in round 3. \(\Rightarrow\) NTRU Prime is fully compatible between round 2 and round 3, when users choose the same parameters.

Have always recommended the same parameter set: dimension \(p = 761\), modulus \(q = 4591\).
Many fully specified and implemented parameter sets

Dimension:  
653  761  857  953  1013  1277

Pre-quantum log$_2$ Core-SVP:  
129  153  175  196  209  270

Post-quantum log$_2$ Core-SVP:  
117  139  159  178  190  245

See submission for other metrics, analysis of Core-SVP flaws.

Given likelihood of further advances in lattice attacks affecting all small-lattice submissions, NTRU Prime will not add dimensions below 653. 761 is recommended for an extra security margin.

Round-1 NTRU Prime specified only 761. This type of focus simplifies implementations, simplifies security analysis. However, NIST keeps asking for more parameter sets.
Quotient NTRU vs. Product NTRU

Two fully supported options at each size—picking just one would need more transparency from NIST:

- **Streamlined NTRU Prime** (example of Quotient NTRU). As in NTRU submission, security risks from homogeneity. No known patent threats. NTRU patent expired 2017.

- **NTRU LPRime** (example of Product NTRU). As in Kyber+SABER, security risks from extra samples, and from looseness of known QROM IND-CCA2 proofs. Threatened by same patents as Kyber+SABER; see [https://ntruprime.cr.yp.to/faq.html](https://ntruprime.cr.yp.to/faq.html).

Extensive sharing of code and analysis across these options.
Does Quotient NTRU have slow keygen?

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These times are not a bottleneck in any known application. Web-browsing demo using sntrup761 with fast keygen: https://opensslntru.cr.yp.to

NTRU Prime https://ntruprime.cr.yp.to
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**Web-browsing demo** using sntrup761 with fast keygen: [https://opensslntru.cr.yp.to](https://opensslntru.cr.yp.to)
OpenSSL LNTRU software stack

Web browser
epiphany

TLS terminator
stunnel

Back-end web server

OpenSSL
Cryptography and SSL/TLS Toolkit
patched for PQ KEM
in TLS 1.3

 TLS 1.3 key agreement using fast PQ KEM

unmodified software ecosystem

our patches and new software

Patched to support
- private TLS codepoints for sntrup761 and sntrup857 KEM;
- KEM key agreements alongside DH-like KEX;
- KEM mapped on available PKE+KEX primitives;
(required patches are mostly contained in libssl)

- provides EVP methods for sntrup761 and sntrup857 as a combination of PKE+KEX primitives;
- supports keygen batching (thread-local);
- maps PKE+KEX operations to libsntrup761 or libsntrup857 KEM backends;
- dynamically loadable in libcrypto.

New ENGINE
engntru

New KEM libraries
libsntrup761
libsntrup857

rapidly evolving software ecosystem

NTRU Prime
https://ntruprime.cr.yp.to
What exactly does “small” mean?

If the larger NTRU Prime parameters still count as “small”, shouldn’t we also be considering Frodo? Maybe small lattices are weak but Frodo survives!
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But anyone who can afford Frodo-\(m\) can afford \texttt{sntrup}-\(N\) or \texttt{ntrulpr}-\(N\) with much higher security against known attacks. Would an unknown attack be able to close this gap? Unclear.

<table>
<thead>
<tr>
<th></th>
<th>frodokem640</th>
<th>ntrulpr1277</th>
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</thead>
<tbody>
<tr>
<td>key bytes</td>
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<td>1847</td>
</tr>
<tr>
<td>ciphertext bytes</td>
<td>9720</td>
<td>1975</td>
</tr>
<tr>
<td>keygen cycles (Haswell)</td>
<td>1490605</td>
<td>77092</td>
</tr>
<tr>
<td>enc cycles</td>
<td>1922241</td>
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<td>dec cycles</td>
<td>1849960</td>
<td>144582</td>
</tr>
<tr>
<td>Core-SVP</td>
<td>150</td>
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Community confidence in cyclotomic lattices?

Many round-1 lattice KEMs were NewHope variants, so they used cyclotomics by default.

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But 41% of the round-1 lattice submissions

- provided options that do not use cyclotomics;
- in most cases paid heavily in performance for this;
- in most cases expressed concerns regarding security;
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Is NIST actually confident in Kyber?

NIST says Frodo is “a conservative backup in the case of new cryptanalytic results targeting structured lattices being discovered in the third round.”

Why just a backup? Why not proactively standardize Frodo? Is this because NIST claims the risks are negligible?

No: NIST says performance. “NIST’s first priority for standardization is a KEM that would have acceptable performance in widely used applications overall.”

If NIST were actually confident in Kyber then wouldn’t it have said “We don’t see a need for Frodo” and eliminated it?
What NIST was thinking

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What NIST was thinking + didn’t want to tell us

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In fact, NIST had invited some round-3 lattice submitters to attend the talk and the subsequent Q&A session: Dilithium (2×), Falcon (2×), Frodo, Kyber (3×), NTRU (2×), SABER. NIST also invited a SIKE submitter and some others.

Talk slides were posted in response to a FOIA request.
What NIST was thinking: the details

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Should instead be proactively minimizing risks.
Ongoing work on NTRU Prime

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However, if big enough advances in cyclotomic attacks appear this year, NIST will put cyclotomics on hold, see whether NTRU Prime survives round 4, and consider selecting it.