Post-quantum cryptography for developers

Daniel J. Bernstein
Do applications have to worry about quantum computers?
2021 Jaques: Quantum Landscape

![Quantum Landscape Diagram](image)

**Error Rate**

**Number of Qubits**

- Useful quantum chemistry without error correction
- Logical qubits can be classically simulated
- Surface codes work
- RSA is broken

- We are here

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2022 Jaques: Quantum Landscape

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“Useful” quantum chemistry without error correction

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We are here

Honeywell 2021
Google 2022
IBM 2020
JQI 2021
Innsbruck 2021
Google 2019
Rigetti 2022

Number of Qubits

100 1 2 3 4 5 6 7 8 9

10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}

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Computers ➔ disaster ➙ algorithms

Graph shows quantum computers advancing on the critical axes: #qubits, error rate.
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2023.01 Bernstein: “It’s fascinating to see how the historical data in the bottom-left corner [of that graph] leads readers to guess the number of years to the top right without realizing that the top right is a moving target.”

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2023.08 Regev: improvement to Shor’s algorithm.
Computers → disaster ← algorithms

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So: when will RSA-2048 be broken?

Global Risk Institute 2023 survey of 37 people working on quantum computing shows wide range of predictions regarding chance of RSA-2048 break by year $Y$.
e.g. $Y = 2038$: 6 say $>95%$; 4 say $>70%$; 10 say $\sim50%$; 10 say $<30%$; 7 say $<5%$.

My assessment: reaches $50\%$ by $Y = 2029$; $50\%$ for public demonstration by $Y = 2032$.

Note that attackers are ahead of the public.
"You always say it's 10 years away!" — No.
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“You always say it’s 10 years away!”—No. See the bets I placed in 2014, 2017, and 2023.
Reasons to take action right now

I hope quantum computing somehow fails. But if it works then it breaks RSA-2048 and ECC-256. “Wait and see” isn’t safe:

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- Attackers are already recording ciphertexts today to decrypt later.
- Some environments are very slow to roll out new software for encryption+signatures.
- We’ll need even more time to fix whatever screwups happen.
Which post-quantum primitives should we implement?
Trust the NIST competition?

Out of the 69 round-1 submissions to the competition in 2017: 48% are broken by now. (AES-128 was the minimum security level allowed in the competition. Broken means: smallest proposed parameters are now known to be easier to break than AES-128.)
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Out of the 28 submissions selected by NIST in 2019 for round 2: 36% are broken by now.
When the breaks were published

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Always wear your seatbelt

SIKE: the last break ever?
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e.g. 2019 Google–Cloudflare experiments:
CECPQ2 used ntruhrss701 + X25519;
CECPQ2b used sikep434 (broken!) + X25519.
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e.g. Chrome supports kyber768 + X25519.
Also: try not to crash the car


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If application can’t handle the pk size, then use lattices, but cautiously: e.g., McEliece for identity keys + lattices for forward secrecy + ECC so you’re definitely not losing security.

Use biggest available lattice dimensions to leave a security margin: ntruhps40961229, sntrup1277, frodokem1344, ntruhrss1373.
Trigger warning:
Trigger warning: PATENTS

If you find patents traumatic, or if you have a policy to not learn about patents, please skip the next slide.
Lattice patents

Google Patents finds, e.g., 3997 results for “post-quantum”. Mostly uninteresting, but we know some examples of problems. Patent analysis has not been systematic.


NIST says it has a license for 2010 GAM patent (LPR) and 2012 Ding patent if you use exactly the Kyber standard. Those patents still cover newhope, saber, ntrulpr, etc.

Zhao says “Kyber is covered by our patents”.
Where can we find code to reuse?
Sources of post-quantum software

Design teams typically submitted a “portable” reference implementation and a faster Intel/AMD implementation to SUPERCOP. Usually teams maintain web pages, often pointing to further implementations. Most implementations today are repackaged copies of those, sometimes translated into other languages. PQClean and liboqs include tweaks for MSVC portability.

I’m optimistic about future of microlibraries such as libmceliece (and lib25519).
What should we watch out for in implementing post-quantum primitives?
Randomness is used in tricky ways

The bug was in the function rej_gamma1m1 in poly.c and consisted of accidentally overwriting a variable prior to using it. . . . the result of the bug was that the same randomness ended up being used for pairs of consecutive coefficients . . . This reuse of randomness can easily be exploited to recover the secret key and we thus emphasize that the software, in the state submitted to NIST, should not be used in any real application.

—Dilithium comment, January 2018
And other tricky ways

... the new Falcon implementation published on 2019-08-02 had two severe bugs in the sampler; one table was wrong, and a scaling factor was applied at the wrong place. ... Produced signatures were valid but leaked information on the private key. ... The fact that these bugs existed in the first place shows that the traditional development methodology (i.e. ‘being super careful’) has failed.

—Falcon comment, September 2019
Timing leaks from, e.g., `memcmp`

Experiments show that the attack code is able to extract the secret key for all security levels using about $2^{30}$ decapsulation calls.

—FrodoKEM attack paper (“A key-recovery timing attack on post-quantum primitives using the Fujisaki-Okamoto transformation and its application on FrodoKEM”), June 2020
Misimplementing `memcmp`

It looks like the FrodoKEM team also fixed the timing oracle [GJN20] badly and caused a more serious security problem while trying to do that. . . . A decryption failure is very likely to be ignored by this rejection mechanism because the selector will be 0 with a high probability even in case of a mismatch, the failed decryption will be used and returned to the caller . . . I’d assume that the key recovery attacks of [GJN20] are even easier to mount with this new, more powerful oracle.

—FrodoKEM comment, December 2020
I noticed various " /KYBER_Q" occurrences with variable inputs. In at least one case, line 190 of crypto_kem/kyber768/ref/poly.c, this is clearly a secret input. I’d expect measurable, possibly exploitable, timing variations … [Maybe compilers] convert divisions to multiplications, but this depends very much on compiler options. Within available tools to scan for variable-time instructions, a few (e.g., saferewrite) know how to check for divisions but most don’t.

—Kyber comment (from me), December 2023; see also my subsequent attack demo
During our analysis, we stumbled upon another source of timing variability in several patched implementations of Kyber. We believe, the aforementioned division operations were not considered to be problematic since they were present in the encryption procedure whose ciphertext output is considered to be public. However, the encryption procedure is also used for re-encryption in the FO transformed decapsulation procedure.

—Kyber comment, December 2023
Another reason for seatbelts

KyberSlash: the last \textit{implementation} break ever?
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Implementing post-quantum primitives is more *complex* than implementing ECC, and the community has many years fewer experience with what goes wrong.

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Some tools that I recommend: negative tests; known-randomness tests; timing-variability scanners; tools for formal verification.