Post-Quantum Cryptography

CS7NS5/CSU44032
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Top Level Message

- Don’t panic
- Cryptographers are studying new public key algorithms that aim to provide good security even in the face of a cryptographically relevant quantum computer (CRQC)
- Engineers are considering how to integrate those algorithms into protocols and applications
- Hybrid cryptographic solutions (using both “classic” algorithms and post-quantum algorithms) will be deployed at scale in the next few years
  - Some are already deployed

Resources

- A good “for engineers” slide deck from DJB (Jan 2024):
  - https://cr.yp.to/talks/2024.01.11/slides-djb-20240111-pqcrypto-4x3.pdf
- IETF working group considering PQ effects on protocols
  - https://datatracker.ietf.org/wg/pquip/documents/
- Ericsson: "Quantum-Resistant Cryptography", John Mattsson et al (40pp)
  - https://arxiv.org/abs/2112.00399
- 2021 ICANN-sponsored backgrounder by Hilarie Orman (a very good security/crypto person and a really excellent writer!)
  - https://eprint.iacr.org/2021/1637.pdf
- Some PQ algs described from a mathematical perspective
  - https://www.mdpi.com/2227-7390/10/15/2579

Overview

- The quantum computing problem for cryptography
- Cryptographically relevant quantum computer (CRPQ)
- Effects on “classic” cryptography
- When does this matter?
- NIST PQ Competition Algorithms
- Hash-based (Stateful) signatures
- Hybrid application/protocol approaches
- Quantum Key Distribution

Quantum Computing

- Classical computers (today’s) based on binary bits; Quantum computers based on (coherent) qubits that allow running algorithms that explore many different values at once
- Many, many well-resourced people are working to develop quantum computers that could improve on current classic computers
  - There will be other uses for quantum computers, they’re not only for breaking crypto
- CRQCs do not exist, and might never… Or they might… someday, we don’t know
- At present, quantum computers seem unlikely to be general purpose computers, seems more like each hardware device will be built to solve a particular problem
- Current experiments only support tiny numbers of physical qubits (up to ~1000)
- Error-correction/de-coherence problem means many physical qubits needed for each logical qubit – there are many practical problems that need to be overcome to get a CRQC

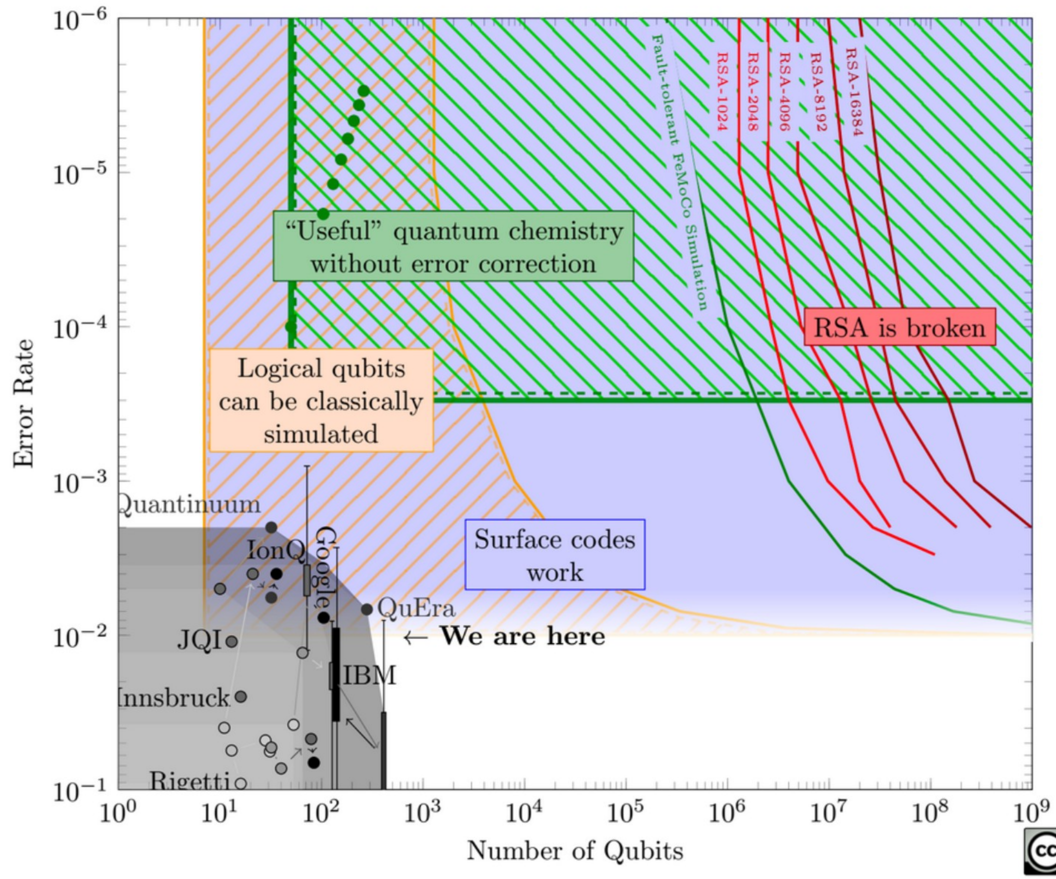
The quantum problem

- No real impact on hash functions
- Grover's algorithm is a more efficient brute-force attack/search meaning attacks on 128-bit keys take 2^64 operations (not speedy ops nor easy to parallelise so far)
  - Easy solution, if even needed: use 256 bit symmetric keys (AES-256/ChaCha20)
- **Shor's algorithm** describes how to quickly factor integers and hence break RSA
  - Variants solve discrete log problem, breaking (EC)DH
  - Hard solution: new post-quantum (PQ) algorithms
- Beware though: attacks only get worse – new quantum attacks may well be discovered in future (even before a cryptographically relevant quantum computer exists)

When is this a problem?

- Signals intelligence agencies seem to like to store all ciphertext, as far as practical, so we should assume all ciphertexts/cryptographic sessions are stored somewhere
- If a cryptographically relevant quantum computer were to exist in 20xx then data that is protected today using classic public key algorithms, and that will still be sensitive in 20xx, is at risk now
  - Data that will not be sensitive in 20xx is unaffected
  - Don’t forget long-lived meta-data: phone numbers, email addresses, usernames
- So: analyse what data you’re dealing with that will be sensitive in 10, 20, 30 years time and keep an eye on developments
- There are usable or nearly-usable hybrid approaches for protecting data against the **“record-now-decrypt-later” attack** now (more later)

Quantum Landscape 2024



Logarithmic Scale

=> We are a long way off "broken RSA"

https://sam-jaques.appspot.com/quantum_landscape_2024

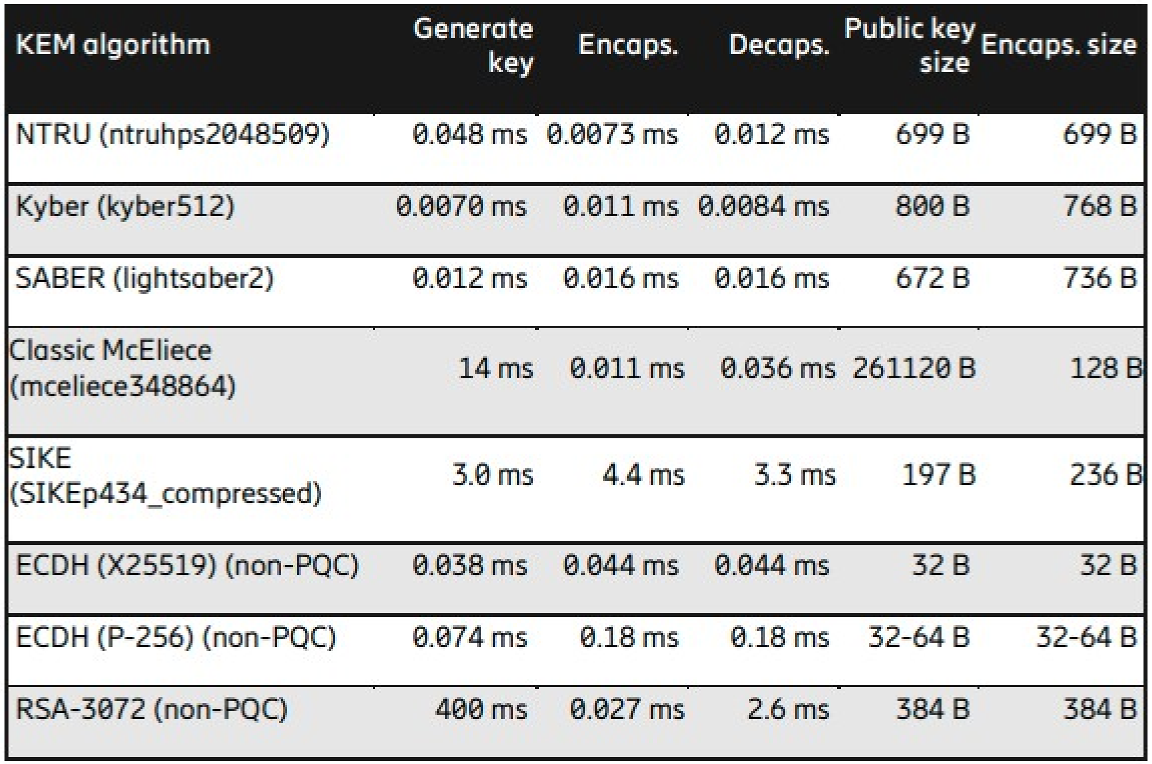
NIST Competition

- Started in 2017, first “winners” in 2022, appears to have attracted best talent for entries https://csrc.nist.gov/projects/post-quantum-cryptography
- Looking for Key Encapsulation Mechanisms (KEMs) and Signature algs
  - KEMs more pressing – alternative to RSA key transport or (EC)DH key establishment
  - Signatures less urgent and we had stateful sigs already (more later)
- After 3 elimination rounds, some winners announced in July 2022
- KEM: **Kyber** (aka ML-KEM) https://doi.org/10.6028/NIST.FIPS.203
- Signature: **Dilithium** (aka ML-DSA) https://doi.org/10.6028/NIST.FIPS.204 and
- **SPHINCS+** (aka SLH-DSA) https://doi.org/10.6028/NIST.FIPS.205 and **FALCON** https://falcon-sign.info/falcon.pdf will become FIPS 206 sometime
- NIST’s standardisation process for ML-KEM, ML-DSA and SLH-DSA is complete

NIST Competition: winner all right?

- As well as announcing winners NIST also announced a “round 4” of evaluation for more KEMs and issued a new call for submissions for signatures
- BUT...
  - Kyber IPR situation wasn’t quite clean so NIST agreed/paid-for licenses https://csrc.nist.gov/csrc/media/Projects/post-quantum-cryptography/documents/selected-algos-2022/nist-pqc-license-summary-and-excerpts.pdf
    - Not sure if that’ll be enough, time will tell
  - NTRUprime was not selected but proponents and some deployments (esp SSH) continue working on that
  - Selected signature schemes may create an API issue for large to-be-signed values
  - One of the round 4 KEM algorithms (SIKE) was busted in August 2022 https://www.schneier.com/blog/archives/2022/08/sike-broken.html
  - One of the round 3 signature finalists (Rainbow) had been busted in Feb 2022 https://eprint.iacr.org/2022/214

BUSTED

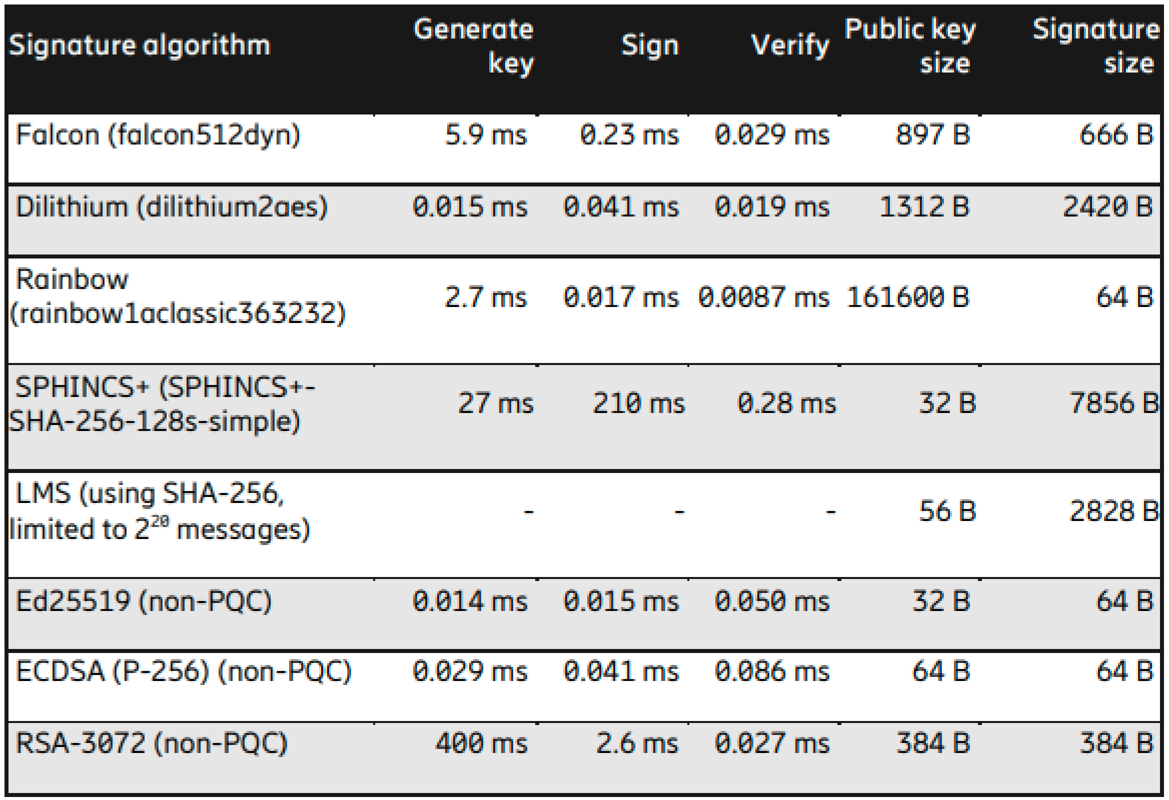


KEM algorithm	Generate key	Encaps.	Decaps.	Public key size	Encaps. size
NTRU (ntruhps2048509)	0.048 ms	0.0073 ms	0.012 ms	699 B	699 B
Kyber (kyber512)	0.0070 ms	0.011 ms	0.0084 ms	800 B	768 B
SABER (lightsaber2)	0.012 ms	0.016 ms	0.016 ms	672 B	736 B
Classic McEliece (mceliece348864)	14 ms	0.011 ms	0.036 ms	261120 B	128 B
SIKE (SIKEp434_compressed)	3.0 ms	4.4 ms	3.3 ms	197 B	236 B
ECDH (X25519) (non-PQC)	0.038 ms	0.044 ms	0.044 ms	32 B	32 B
ECDH (P-256) (non-PQC)	0.074 ms	0.18 ms	0.18 ms	32-64 B	32-64 B
RSA-3072 (non-PQC)	400 ms	0.027 ms	2.6 ms	384 B	384 B

Table 1: Single-core median performance on Intel Xeon E-2124 3.3 GHz of some of the NIST PQC KEM algorithm candidates (and some current non-PQC alternatives) at NIST PQC security level 1. Source: r24000, supercop-20210604 at [107]. The measurements for RSA-3072 are estimated by taking the measurements for verify and sign from Table 1 as encapsulate and decapsulate, respectively. The measurements for SIKE are for a different platform: Intel Core i7-6700 3.4 GHz [108].

From: https://arxiv.org/pdf/2112.00399.pdf

BUSTED



Signature algorithm	Generate key	Sign	Verify	Public key size	Signature size
Falcon (falcon512dyn)	5.9 ms	0.23 ms	0.029 ms	897 B	666 B
Dilithium (dilithium2aes)	0.015 ms	0.041 ms	0.019 ms	1312 B	2420 B
Rainbow (rainbow1aclassic363232)	2.7 ms	0.017 ms	0.0087 ms	161600 B	64 B
SPHINCS+ (SPHINCS+-SHA-256-128s-simple)	27 ms	210 ms	0.28 ms	32 B	7856 B
LMS (using SHA-256, limited to 2^{28} messages)	-	-	-	56 B	2828 B
Ed25519 (non-PQC)	0.014 ms	0.015 ms	0.050 ms	32 B	64 B
ECDSA (P-256) (non-PQC)	0.029 ms	0.041 ms	0.086 ms	64 B	64 B
RSA-3072 (non-PQC)	400 ms	2.6 ms	0.027 ms	384 B	384 B

Table 2: Single-core median performance on Intel Xeon E-2124 3.3 GHz of some of NIST PQC signature algorithm candidates (and some current non-PQC alternatives) at NIST PQC security level 1 (Dilithium is at that submission's smallest suggested parameter set – at level 2). Source: r24000, supercop-20210604 at [103]. The measurements for SPHINCS are for a separate platform: Intel XeonE3-1220 3.1 GHz in Table 6 of [106]. LMS is a stateful hash-based signature scheme (see Section 4.4), these schemes have slow key generation, while signing and verification takes at most a few milliseconds on a comparable platform to those used by the other algorithms in the table.

From: https://arxiv.org/pdf/2112.00399.pdf

PQC not a “drop-in” replacement

- As you can see from the size/performance numbers, PQC algs don’t satisfy the same size/CPU requirements met by classic public key algs
- Size/CPU impact varies from alg to alg and application to application:
  - BIG public keys or sigs – bad for DNSSEC, X.509 sizes
  - Bigger KEM outputs – not great but maybe ok if e.g. TLS ClientHello still fits in one packet
  - CPU performance for finalists seems ok, not true for all candidate algs though
- We still need more time to be more confident in these algorithms

Kyber aka ML-KEM (1)

- Based on module learning with errors (MLWE) problem
  - Can be stated a different ways, e.g. the shortest vector problem (SVP):
  - What x,y,z makes x(a,b,c)+y(d,e,f)+z(i,j,k) closest to (but !=) (0,0,0) ?
  - If you could solve that 3-D problem in 256 dimensions, you could break Kyber
  - As usual, there may be easier ways to break Kyber, we don’t know
- Variants: Kyber512, Kyber768, Kyber1024
- Kyber512
  - similar security level to AES128 (if a CRQC exists)
  - public key: 800 octets, encap: 768 octets

Kyber (2)

- Arithmetic deals with vectors and matrices of polynomials over a ring:
  - R_q is $Z_q [X]/(X^n +1)$ for $n = 256$, $q = 3329$
- Secret vector **s** is an element of R_q^2 and error vector **e** another element of R_q^2
- Secret and (all) error vectors are “small” (think of ‘em as vectors of polynomials with small coefficients)
- We use a matrix **A** from R_q^{2x2}
- Public key is **A** and $\mathbf{t} = \mathbf{As} + \mathbf{e}$

Kyber (3)

- Encrypt message m (< 256 bits) as a polynomial with one message bit per coefficient
- Random “small” vector **r** in R_q^2 and error vectors $\mathbf{e_1}$, $\mathbf{e_2}$ also in $\mathbf{R_q^2}$
- $\mathbf{u} = \mathbf{Ar} + \mathbf{e_1}$
- $\mathbf{v = tr + e_2 + [q/2]m}$
- Ciphertext is **u**,**v**
- In real alg, there’s a compression thing going on and a number of the values are represented differently

Kyber (4)

- To decrypt calculate **v** – **su**
  $= (As + e)r + e_2 + [q/2]m - s(Ar + e_1)$
  $= Asr + er + e_2 + [q/2]m - Asr - se_1$
  $= [q/2]m + er + e_2 - se_1$
- Other than [q/2]m all terms are “small” and since each m coefficient is 0 or 1 result has coefficients that are either close to 0 in which case the relevant message bit was zero, or close to [q/2] in which case the relevant message bit was 1
- These slides describe the Kyber public key encryption alg, the KEM is a little different

Kyber (5)

- Algebra needed for Kyber: https://words.filippo.io/dispatches/kyber-math/
- “Simplified” explainations: https://crypto.stackexchange.com/questions/103754/kyber-and-dilithium-explained-to-primary-school-students
- Another simplification: https://medium.com/@krisinfosec/post-quantum-cryptography-38bcbad95284

Stateful Hash-Based Signatures

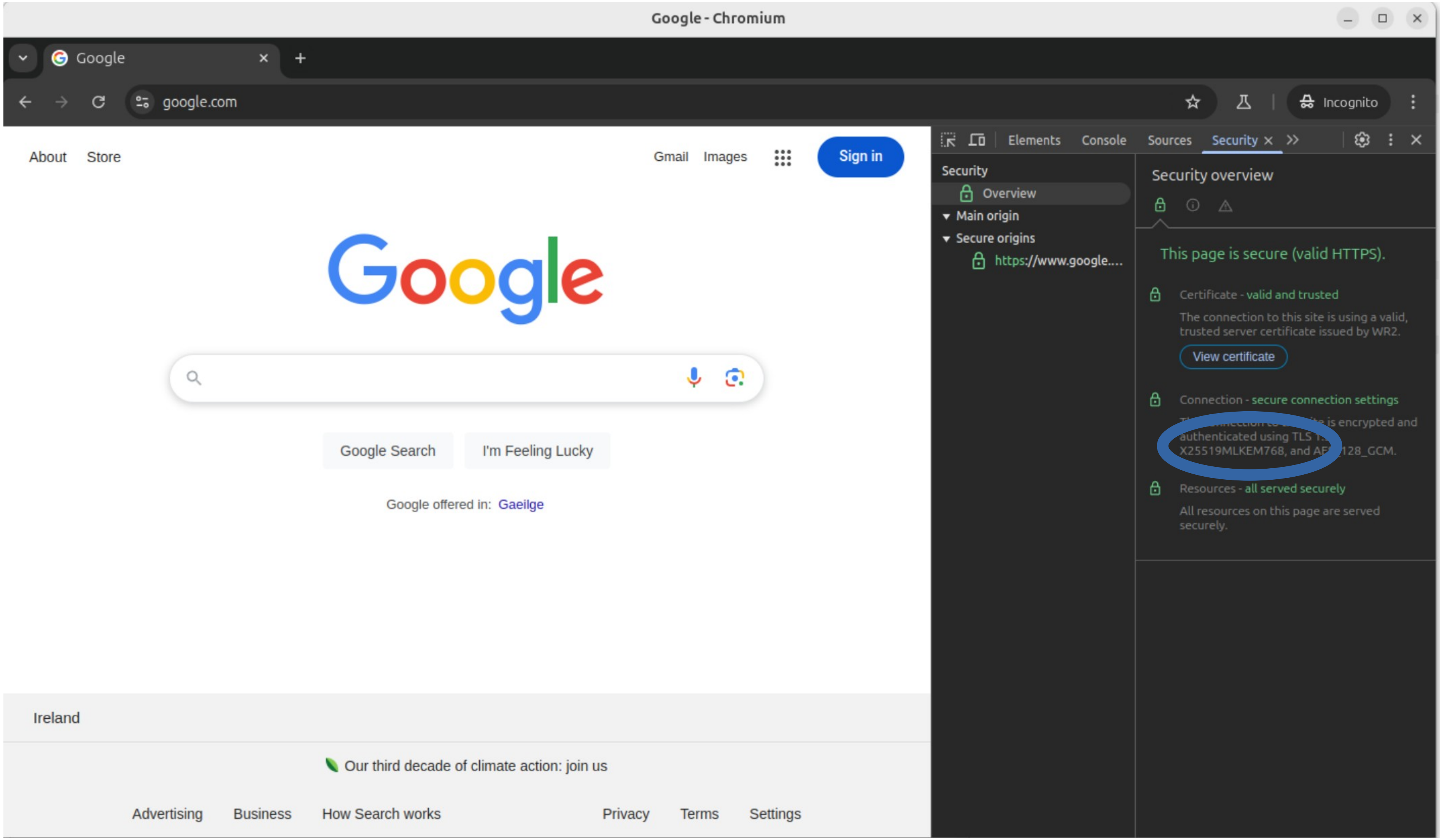
- These are **stateful** signature schemes which means that the private state (i.e. the value of the private key) changes with every signature operation
- Yes, they are quantum resistant, so worth having, esp. for things like software-signing where we won't need many signatures and sizes aren't a big deal
- **BUT they need a different cryptographic API** as private keys have a fixed, limited number of uses allowed, (maybe 2^10 or 2^20) and if you go over that limit, you lose all security (signatures could be forged)
- Also, **if you EVER re-use a private key value you're hosed**, so you need to be very very careful e.g. about reboots, forking, and state maintenance
- Two algorithms standardised: XMSS (RFC 8391 and LMS (RFC 8554)
- You can't just replace Ed25519 with XMSS or LMS without changes to applications/systems

SPHINCS+ Stateless HBS

- SPHINCS+ (aka SLH-DSA) is internally similar to stateful hash based signatures like XMSS
- Statelessness achieved by selecting from many private signing values using an r-subset resilient selection function
  - Basically, select the set of private values to use based on the hash of the to-be-signed thing (and some randomness), thereby not re-using private values too often
- As the private key doesn't change it's ok to sign 2^64 messages without significant loss of security (sign more and security degrades)
- A nice description: https://er4hn.info/blog/2023.12.16-sphincs_plus-step-by-step/

Embed PQ KEMs with classic ECDH (hybrid approach)

- TLS, SSH, IPsec and other “classic” key exchanges will be extended to allow mixing in of PQ key exchanges **in addition** to the classic DH exchange
- Bottom line: it’s OK to do this now, and if your data is long-term sensitive definitely start now, if you’re not sure, then do it anyway
- Draft specification for TLS: https://datatracker.ietf.org/doc/draft-ietf-tls-hybrid-design/
- Chrome does this already, using X25519MLKEM768



Security overview

This page is secure (valid HTTPS).

Certificate - valid and trusted

The connection to this site is using a valid, trusted server certificate issued by WR2.

Connection - secure connection settings

The connection to this site is encrypted and authenticated using TLS 1.3, X25519MLKEM768, and AES_128_GCM.

Resources - all served securely

All resources on this page are served securely.

Quantum Key Distribution

- QKD: **Directly** exchange photons between endpoints e.g. (over a single-hop fibre or RF link); accumulate key bits based on received photon state (e.g. polarisation)
  - Claims made this is “unbreakable… because <physics>”
  - (At least) Saturation attacks exist against real implementations
    - https://www.nature.com/articles/s41598-021-87574-4
- Requires (classic) authentication of eventual key bits selected
    - https://www.ietf.org/proceedings/99/slides/slides-99-saag-post-quantum-cryptography-01.pdf
      - Slides 12-18
- By definition, QKD requires no intermediaries hence has scaling problems
- Still could be useful for specific links used for specific purposes
- But: be aware of marketing hype

Top Level Message

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- Hybrid cryptographic solutions (using both “classic” algorithms and post-quantum algorithms) will be deployed at scale in the next few years
  - Some are already deployed