POST-QUANTUM TLS

SUMMER SCHOOL IN POST-QUANTUM CRYPTOGRAPHY

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SPOILERS

- This talk is going to be mostly about *authentication*
- This talk is not going to touch *very much* the key exchange phase of protocols
- We will focus on TLS 1.3:
  - ≈ 20% of observed connections
  - ≈ 30% in the popular domain space

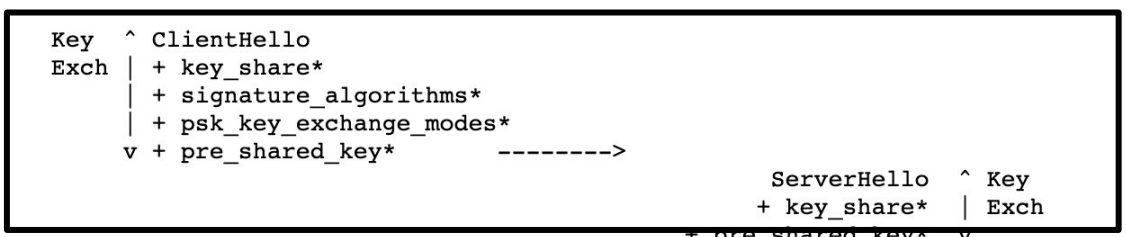
LET'S START BRIEFLY WITH TLS 1.3

TLS 1.3

- Two parts:
  - **A handshake protocol**
  - A record protocol

- Properties:
  - **Authentication** (certificates, password, pre-shared key)
    - Post-handshake authentication
  - Confidentiality
  - Integrity

Figure 1 below shows the basic full TLS handshake:




```
                                                  ServerHello  ^ Key
                                                 + key_share*  | Exch
                                            + pre_shared_key*  v
                                        {EncryptedExtensions}  ^  Server
                                        {CertificateRequest*}  v  Params
                                               {Certificate*}  ^
                                         {CertificateVerify*}  | Auth
                                                   {Finished}  v
                                <--------  [Application Data*]
     ^ {Certificate*}
Auth | {CertificateVerify*}
     v {Finished}               -------->
       [Application Data]       <-------->  [Application Data]
```

\+ Indicates noteworthy extensions sent in the previously noted message.

* Indicates optional or situation-dependent messages/extensions that are not always sent.

{} Indicates messages protected using keys derived from a [sender]_handshake_traffic_secret.

[] Indicates messages protected using keys derived from [sender]_application_traffic_secret_N.

Figure 1: Message Flow for Full TLS Handshake

From: https://datatracker.ietf.org/doc/html/rfc8446

KEY EXCHANGE

- (EC)DH -> target of quantum computers
- Quantum computer:
  - Break traffic that is transmitted at the moment
  - Break any traffic that was stored in the past

- The Key Exchange of TLS 1.3 gives:
  - Forward secrecy between sessions (except when PSK with early data is used)
  - Non-replayability (except when PSK with early data is used)
  - Downgrade protection

KEY EXCHANGE

- The Key Exchange of TLS 1.3 does not give:
  - Post-compromise security: https://ieeexplore.ieee.org/document/7536374
  - Privacy of data on the first message -> ClientHello -> https://datatracker.ietf.org/doc/draft-ietf-tls-esni/
    - Relies on DNS

PQ KEY EXCHANGE

- Should be as “easy” as swapping (EC)DH with KEMs
  - The first idea is to do it in a “hybrid” way: https://datatracker.ietf.org/doc/draft-stebila-tls-hybrid-design/ (FIPS compliant)
- New properties:
  - ECH -> HPKE (https://eprint.iacr.org/2020/243.pdf) should be easy to PQ

PQ KEY EXCHANGE

- What will be the problems we encounter in a migration?
  - Ossification: the tendency of middleboxes to write software that expects traffic to look and behave a certain way
  - Triggering of software bugs
  - Old devices
  - Settings for packets smaller than expected
- To avoid:
  - IP-level fragmentation (specially for the DTLS case)
  - DTLS-level fragmentation
  - Extra-round trips specially with stateless servers

PQ KEY EXCHANGE

- Notes on DTLS and QUIC:
  - Use UDP
  - UDP datagrams MUST NOT be fragmented at the IP layer
  - QUIC assumes a minimum IP packet size of at least 1280 bytes: the IPv6 minimum size and is also supported by most modern IPv4 networks

https://datatracker.ietf.org/doc/html/rfc9000

CERTIFICATE-BASED AUTHENTICATION

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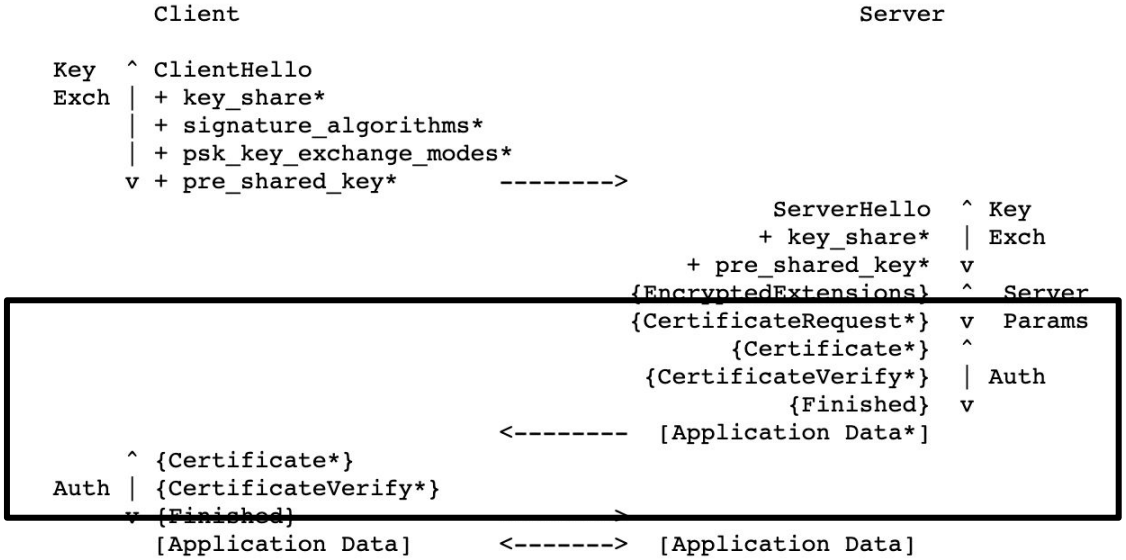

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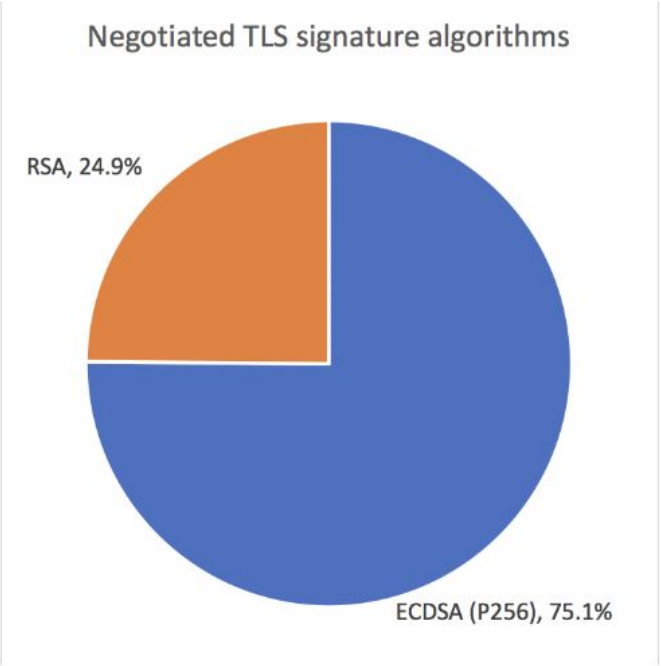
SIGNATURES

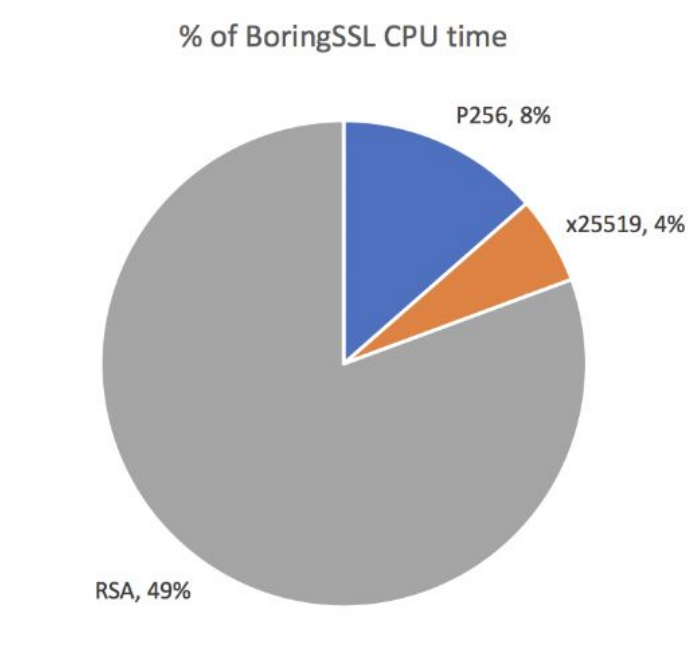
- **Authentication:** Assurance that you are talking with the correct party
  - Party signs with the private key
  - Peer (or anyone) verifies with the public key
- Server-only authentication or mutual (both server and client) authentication
- Need to verify the used public key

Scheme Name	Problem	Public key size (bytes)	Signature size (bytes)
RSA-2048	Factoring	272	256
Ed25519	Elliptic curve discrete logarithm	32	64
Dilithium2	Lattice-based (MLWE/MSIS)	1312	2420
Falcon-512	Lattice-based (NTRU)	897	666
Picnic (L1- FS)	Hash + Block Cipher	32	34032 (max)
Rainbow-I-Classic	Multi-variate equations	161,600	66
XMSS	Hash-based	32	979
SPHINCS+	Hash-based	32	7856
SQISign (6983)	Isogeny-based	64	204
MAYO	Multivariate Quadratic	830	420

SIGNATURE ALGORITHMS

Scheme Name	Signing (cycles)	Verification (cycles)	On
Dilithium2	2348703	529106	Intel Core-i7 6600U (Skylake) CPU
SQISign	6,673 million cycles	82 million cycles	Intel Core i7-6700 clocked at 3.40 GHz with turbo-boost deactivated
MAYO	2.50 million cycles	1.3 million cycles	Intel i5-8400H CPU





‘How expensive is crypto anyway?’ (2017):
https://blog.cloudflare.com/how-expensive-is-crypto-anyway/
Profiled server in CF Frankfurt data center: 2 Xeon Silver 4116 processors

- Latests results of:
  - SQSign: De Feo, Leroux, Wesolowski, ‘New algorithms for the Deuring correspondence: SQISign twice as fast‘, De Feo https://eprint.iacr.org/2022/234.pdf
  - XMSS: Kampanakis, Fluhrer, ‘LMS vs XMSS: Comparison of two Hash-Based Signature Standards’: https://eprint.iacr.org/2017/349.pdf
  - Breaking Rainbow: Beullens, ‘Breaking Rainbow Takes a Weekend on a Laptop’: https://eprint.iacr.org/2022/214.pdf

TLS SIGNATURES

- “CertificateVerify: A signature over the entire handshake using the private key corresponding to the public key in the Certificate message.” - RFC8446
  - Public key in the end-entity Certificate
  - Certificate is the whole Certificate Chain

TLS 1.3 AND THE PKI

- The signatures could be:
  - two signatures in the certificate chain
  - **one handshake signature**
  - one Online Certificate Status Protocol (OCSP) staple for revocation state
  - two SCTs used for certificate transparency

- **Online** signatures:
  - Signature of the handshake: signing and verifying
- **Semi-online** signatures (signed at different moments, and verified by different parties)
  - Signature(s) of the certificate chain: offline signing and online (offline) verifying
  - OSCP staple: offline signing and online (offline) verifying
    - Online (i.e. OCSP and CRL) checks are not, generally, performed by major browsers
    - Underlying system certificate library performs the checks
  - SCT: offline signing and online (offline) verifying
    - Depends on browsers policy:
      - Google Chrome requires CT log inclusion
      - Safari requires a varying number of SCTs (https://support.apple.com/en-gb/HT205280)
      - Firefox or Brave do not check or require the use of CT logs (https://bugzilla.mozilla.org/show_bug.cgi?id=1281469)

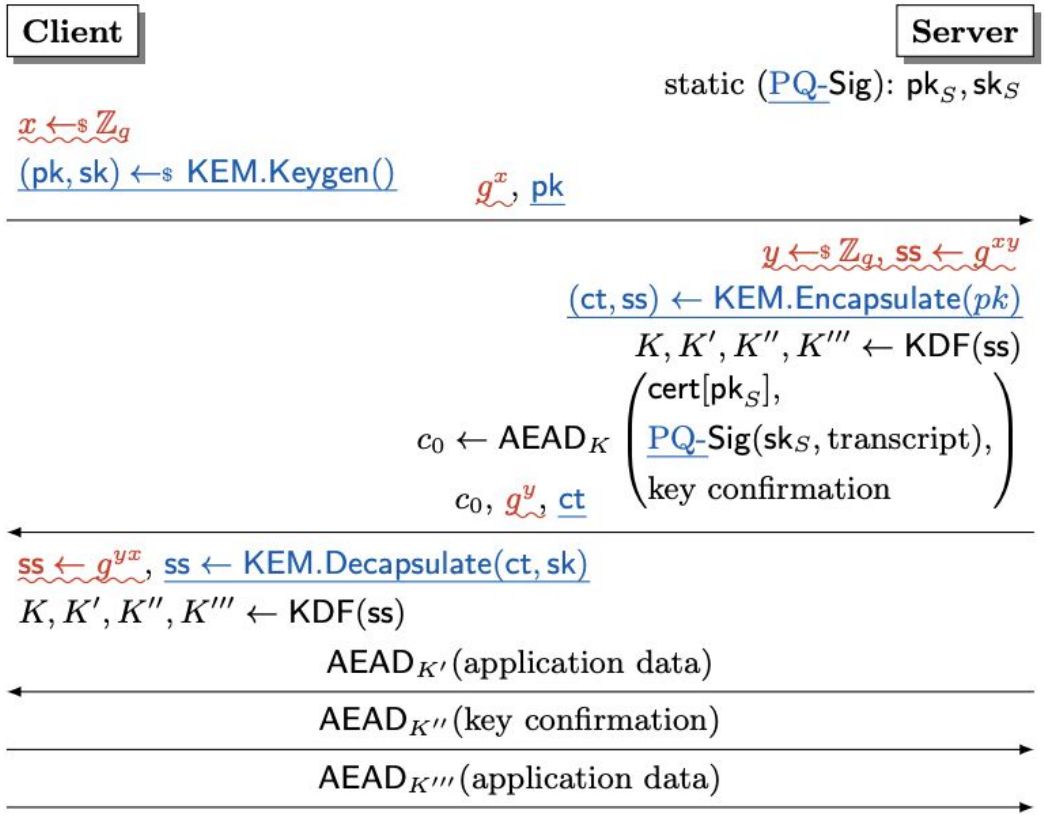


Fig. 1. Comparison between TLS 1.3 handshake (black and red) and PQTLS (black and blue). Note that both protocols require the same number of rounds and messages.

TLS 1.3 HANDSHAKE SIGNATURE

- How much will adding PQ signatures slow connections?
  - Initial study by Westerbaan: https://blog.cloudflare.com/sizing-up-post-quantum-signatures/
  - Missing many verifications and edge cases
- “Online” signature: created every time a TLS connection is made

- If the computational times of PQ signatures is slower and their sizes bigger, can we use KEMs for authentication?
  - Enter KEMTLS or AuthKEM

KEM-BASED AUTHENTICATION

- a.k.a KEMTLS or AuthKEM: abstraction of Diffie–Hellman key exchange
- KEM-based authentication is not new: Signal, OTR, Wireguard, OPTLS (first version of TLS 1.3)
- Interactive but not publicly verifiable
- Smaller trusted code base and usage of only one algorithm
- Downside: in TLS 1.3, it increases the number of rounds depending on which peer authenticates:
  - No extra round trips required until client starts sending application data for server-only authentication (half-round trip added)
  - Full round-trip added for mutual authentication

KEMTLS

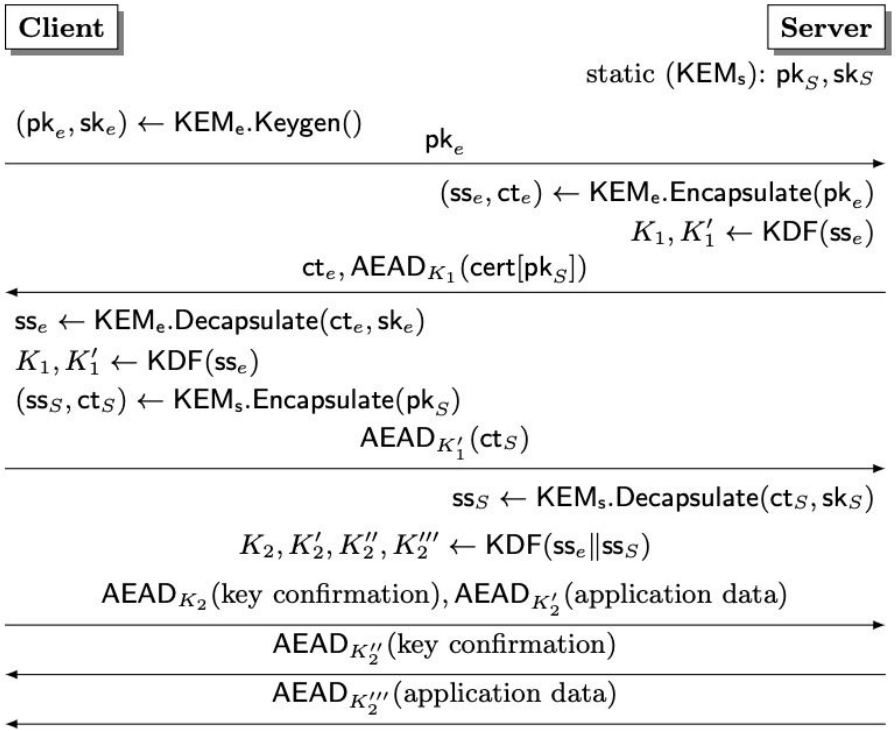


Fig. 2. Overview of KEMTLS with server-only authentication.

KEMTLS

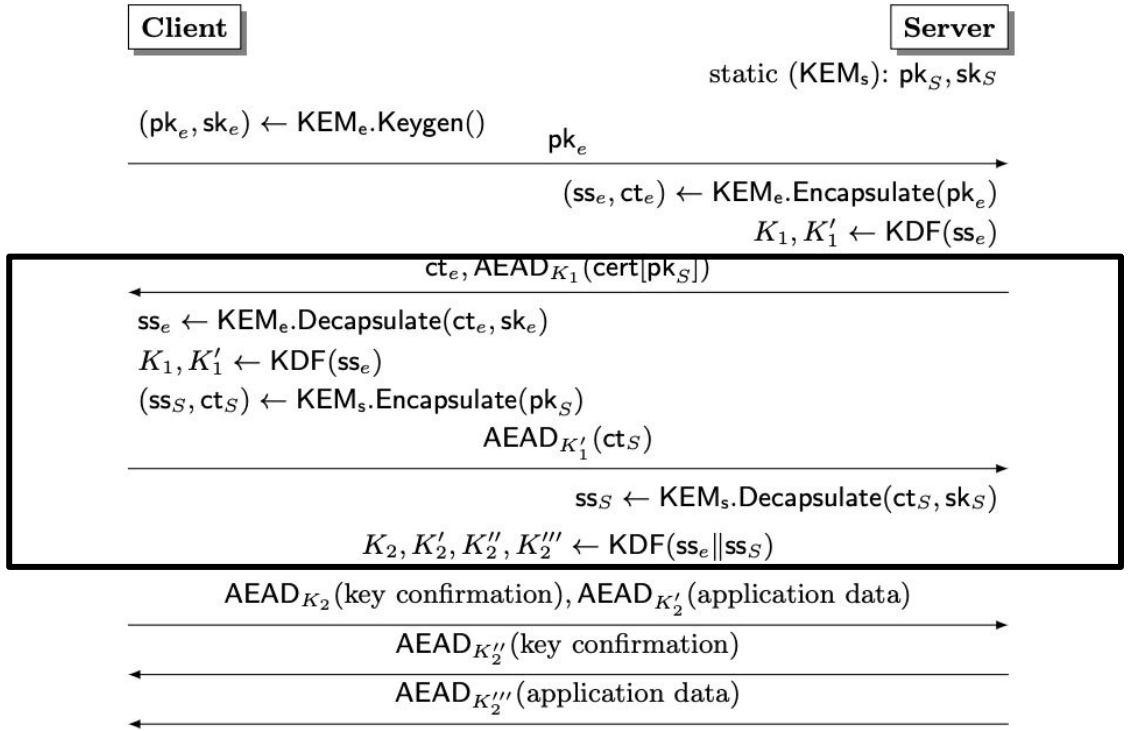


Fig. 2. Overview of KEMTLS with server-only authentication.

- Peter Schwabe, Douglas Stebila, Thom Wiggers
- ACM CCS 2020: https://eprint.iacr.org/2020/534
- ESORICS 2021: https://eprint.iacr.org/2021/779
- Sofía Celi, Peter Schwabe, Douglas Stebila, Nick Sullivan, Thom Wiggers: https://datatracker.ietf.org/doc/html/draft-celi-wiggers-tls-authkem-01
- Measuring and Implementing KEMTLS: https://eprint.iacr.org/2021/1019.pdf

- Comparison:

Table 3. Average time in 10^{-3} seconds of messages for mutual authentication. Note that timings are measured per-client and per-server: each one has its own timer. The 'KEX' label refers to the Key Exchange and the 'Auth' label refers to authentication.

Handshake	KEX	Auth	Handshake Flight					
			1st	2nd	3rd	4th	5th	6th
TLS 1.3	X25519	Ed25519	0.113	0.420	111.358	121.349		
TLS 1.3+DC	X25519	Ed25519	0.148	0.546	129.638	178.90		
TLS 1.3+DC	X25519	Ed448	0.154	0.221	137.131	192.283		
PQTLS	Kyber512	Dilithium3	0.125	1.326	231.232	191.187		
PQTLS	SIKEp434	Dilithium4	3.324	7.294	459.888	216.077		
KEMTLS	Kyber512	Kyber512	0.244	0.303	231.752	175.490	375.202	346.308
KEMTLS	SIKEp434	SIKEp434	2.450	6.206	431.445	228.414	510.591	436.301

Variants:

- Number of round trips can be decreased if key is cached/pinned/embedded or out-of-band (using DNS)
  - 1 RTT
  - Bandwidth save

Security/Privacy properties:

- All the properties of TLS 1.3:
  - Key indistinguishability
  - Achieves explicit authentication at different points (retroactive explicit authentication)
  - Achieves downgrade resilience at different points
  - Forward secrecy
- **Privacy:** can KEMTLS-PDK be used with ECH?
- **Deniability**: a form of offline deniability is achieved
- Properties verified by pen-and-proof and formal verification using the Tamarin prover (to appear)
  - Modelled following the TLS 1.3 Tamarin model
  - Modelled following a multi-stage key exchange model

Comments:

- What is more important?
  - Round-trips
    - TLS 1.2 and two-round-trip overhead: caused latency
  - Longer handshake messages
  - Longer computations times

THE PKI

- **Certificate Chain:** root Certificate signed by the Certificate Authority (CA), *n* number of intermediate certificates, and an end-entity (leaf) certificate
- Each certificate in the chain is signed by the entity identified by the next certificate in the chain (this could be malformed as intermediate deprecated certificates can be present, or misordered)
- “Offline” signing: it does not happen at the handshake phase
- Checks the signature of end-entity certificate, and keeps checking certificates until the root certificate, stored in a trust store (OS or browser)

THE PKI

- Intermediate certificates:
  - Have to be included in the certificate chain
  - They can be reduced: can be cached: https://datatracker.ietf.org/doc/html/rfc7924
    - Proposal to use it more for the post-quantum case
  - Can we omit some certificates? Can we make the ‘intermediates’ the ‘trust-anchor’?: https://mailarchive.ietf.org/arch/msg/tls/0xn2DKFCGFqGX8Z1dqIfpVuCIts/

THE PKI

- Certificate Transparency:
  - Issued certificates are placed in public logs
  - Issue a signed certificate timestamp (SCT): a promise to include the certificate in the log within some delay
  - SCTs are presented with the certificate to the client: check that the SCTs are valid and other policies. Check inclusion in the log
    - Privacy violation
  - Designated auditors and monitors check that logs are append-only, globally consistent and that logs do not contain any inconsistencies or misissued certificates

THE PKI

- Certificate Revocation:
  - Online Certificate Status Protocol (OCSP):
    - Privacy violation when checking with the log directly
  - OCSP Stapling: the holder of the certificate staples the check
  - CRL and CRLite
    - Huge databases

THE PQ PKI

- Many problems:
  - Two many signatures to verify
  - Few signatures to create
  - Many public keys to transmit
  - Several privacy violations
  - Two databases to append to, and to check to

THE FUTURE OF THE PKI: PQ AND PRIVATE

- Upcoming work:
  - List the challenges of migrating the PKI to PQ
  - Propose solutions:
    - VOPRFs or PIR to prevent privacy violations (some are not PQ)
    - Shorten chains -> proofs of chains
      - Use Cinderella-like certificates: https://ieeexplore.ieee.org/document/7546505

THE FUTURE OF THE PKI: PQ AND PRIVATE

TLS is complex:

- No real studies on migrating the PKI to PQ
- Middle boxes in the way will be slow to update
  - Chrome stopped their experimentation due to this
  - It will inevitably cause latency, especially on the 95% tails.
  - Challenges on the corner-cases: tails or process-intensive operations
- What about QUIC?
- What about DTLS?
- What about password-based authentication?

- User studies:
  - How slow is ‘too slow’ for users?

THE FUTURE OF THE PKI: PQ AND PRIVATE

"Instead of looking at substituting algorithms, we can look at the properties and how to make them happen in a post-quantum way."

THE FUTURE OF DNSSEC

- The scenario is DNSSEC is more dim:
  - Avoid fragmentation at all costs
  - Avoid using TCP
  - No load on verification
  - No Round-3 finalist public key fits in a DNS datagram

THE FUTURE OF DNSSEC

- Rethink DNSSEC:
  - What operational challenges are there?
  - How much do DNS attacks occur in the wild?
  - Ongoing work

THE FUTURE

- Find more of these open questions: https://sofiaceli.com/thoughts/Taxonomy.pdf

- Join the slack for discussion! https://join.slack.com/t/post-quantumfuture/shared_invite/zt-16gd8po13-~i0ReTJKn3J_F6AZXlJSBA

THANK YOU!

@claucece