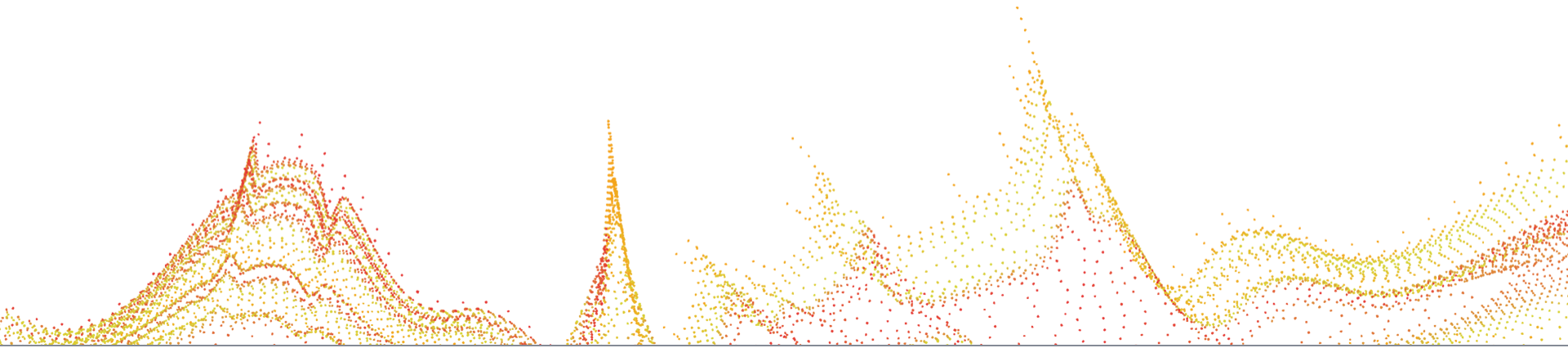
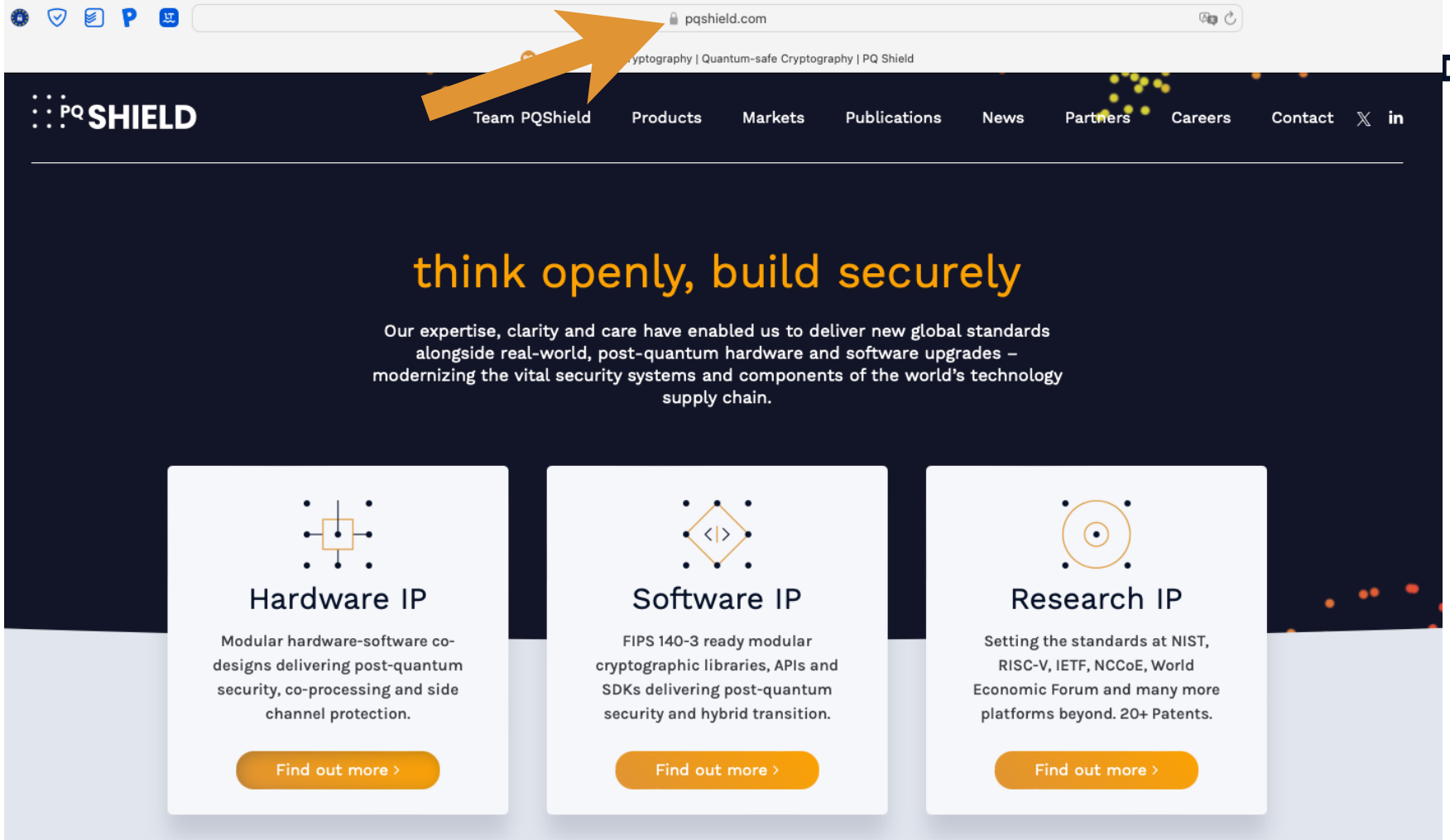
PQ SHIELD

Transport Layer Security

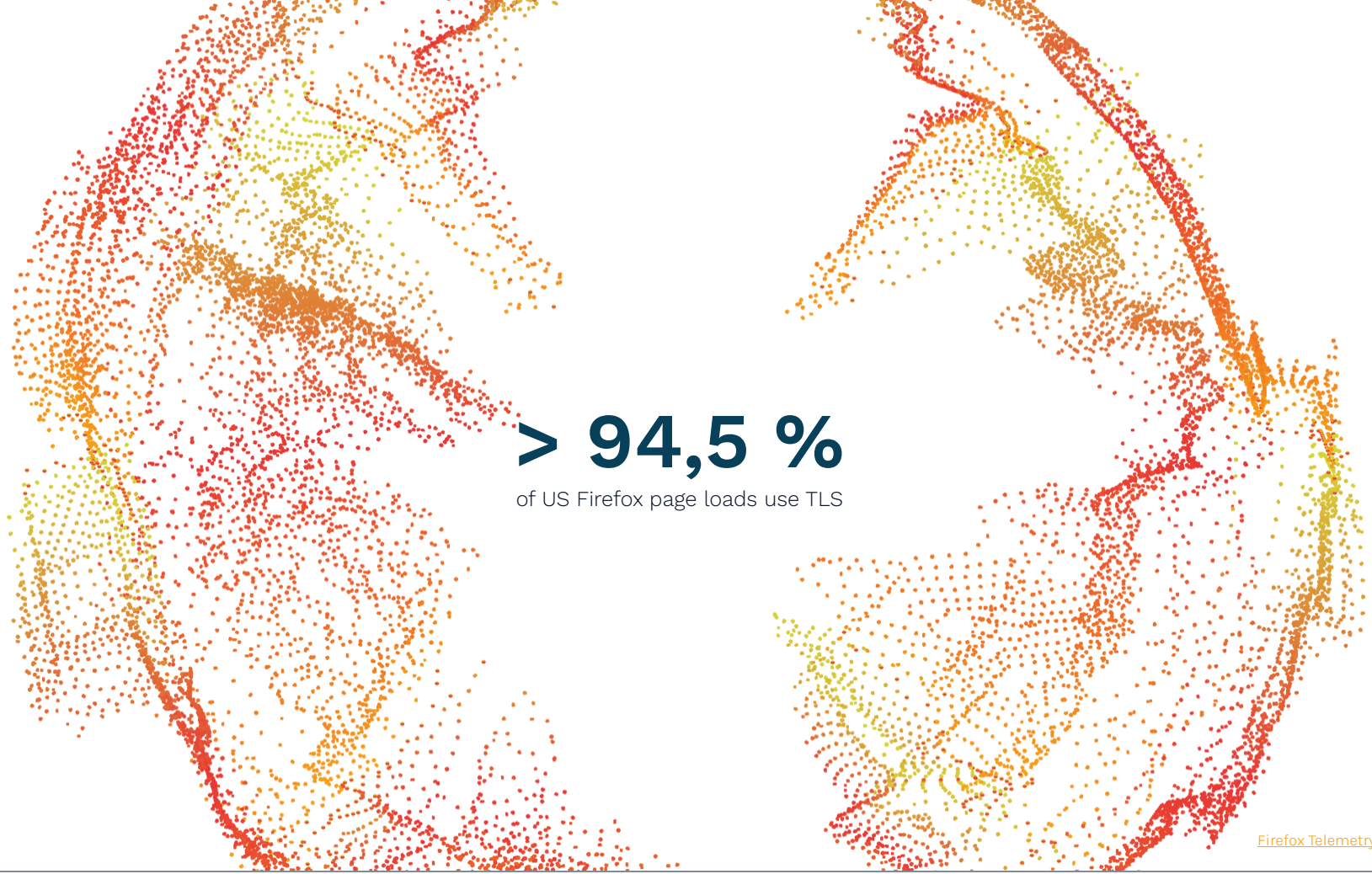
Thom Wiggers



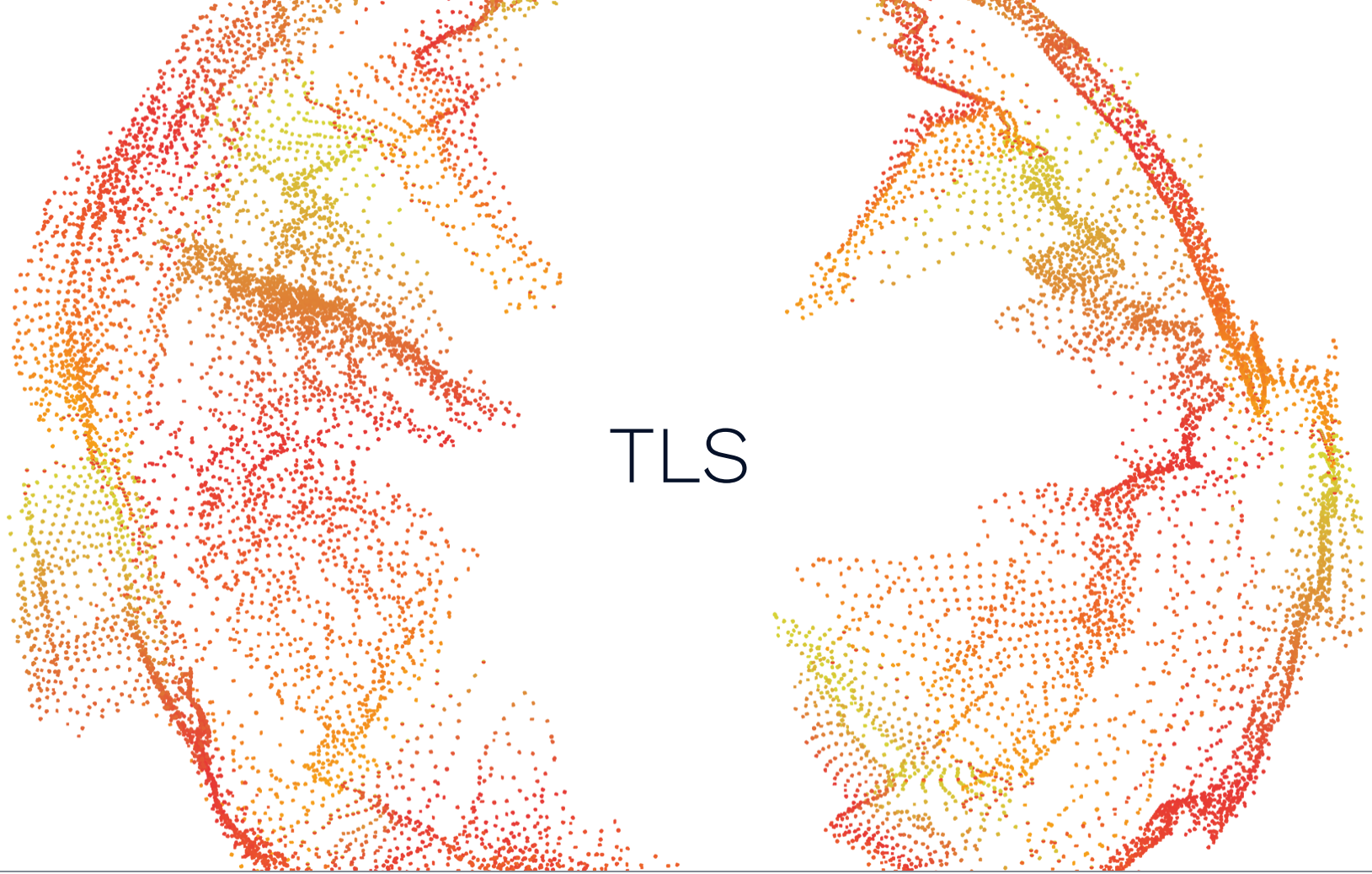


"TLS allows client/server applications to communicate over the Internet in a way that is designed to prevent eavesdropping, tampering, and message forgery."

RFC 8446: The Transport Layer Security (TLS) Protocol Version 1.3

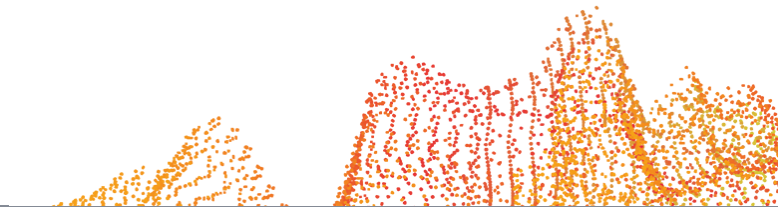


Firefox Telemetry, 2024-04-23



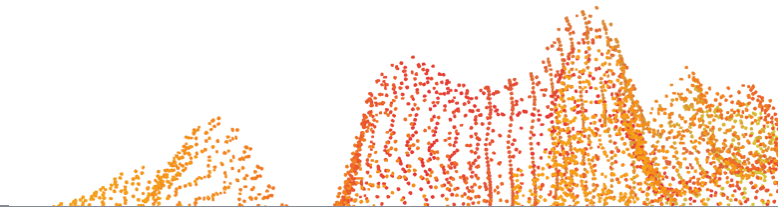
Imagine it’s 1997

1. You want to set up a web shop
2. You need to process credit card information
    a. If bad guys obtain a credit card number…
3. You are advertising in newspapers
    a. You can hardly distribute key material beforehand



TLS Handshake Requirements

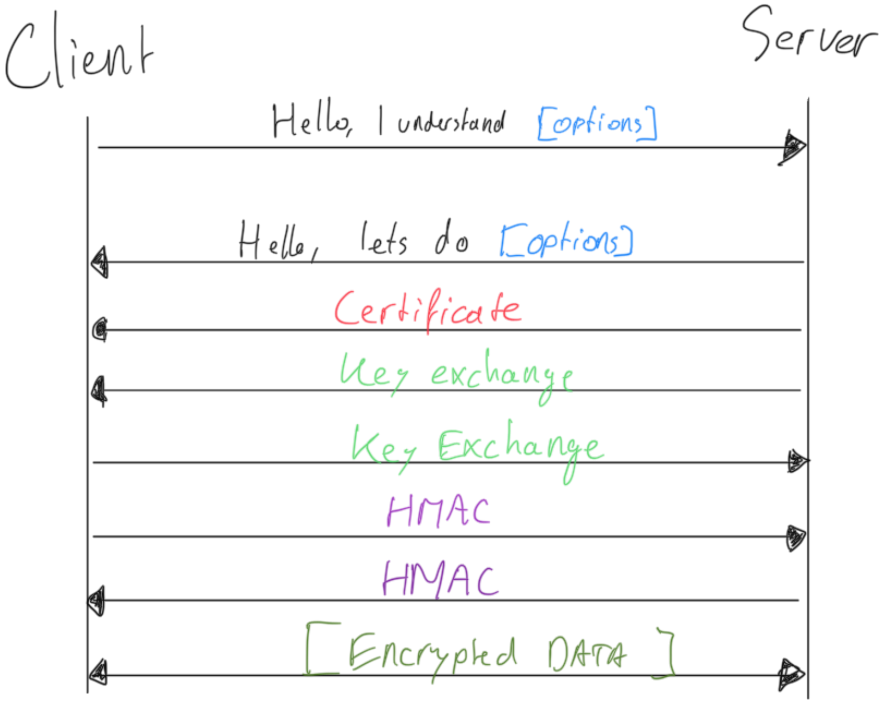
- Set up a shared secret key for encrypting application traffic
- Transmit the identity and key material during the protocol handshake
  - Don’t require prior knowledge of the server
- Be secure



TLS Version history

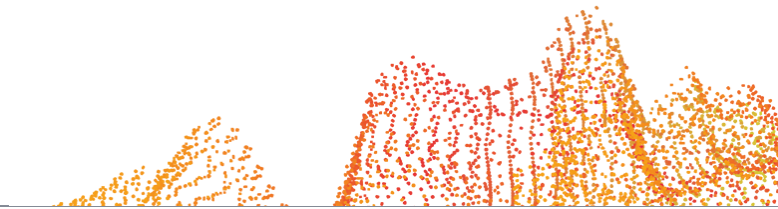
- 1995: SSL 2.0 (“Secure Sockets Layer”) ☠️ (insecure)
- 1996: SSL 3.0 update ☠️ (insecure)
  - Already fixes many problems in 2.0
- 1999: TLS 1.0 🔥 (deprecated)
- 2006: TLS 1.1 🔥 (deprecated)
- 2008: TLS 1.2 (okay with the right config)
- 2018: TLS 1.3

TLS 1.2 and earlier



TLS 1.2 problems

- Too many round-trips
- Certificates are sent in the clear
  - Everybody can see you're connecting to wggrs.nl
  - Especially problematic for client authentication
- A lot of legacy cryptography and patches against attacks

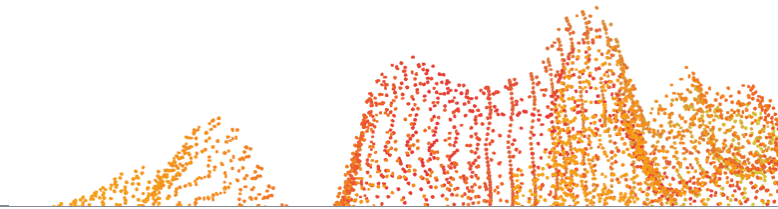


Attacks on TLS (subset)

- 1998, 2006: **Bleichenbacher** breaks RSA encryption and RSA signatures using errors as side-channel
- 2011: **BEAST**: breaks SSL 3.0 and TLS 1.0 (nobody was using TLS 1.1 (2006) or 1.2 (2008)…)
  - avoid attack by using RC4 (but since 2013 RC4 is considered ☠️…)
- 2012/2013: **CRIME / BREACH**: compression in TLS is bad
- 2013: **Lucky Thirteen**: timing attack on encrypt-then-MAC
- 2014: **POODLE**: destroys SSL 3.0
- 2014: Bleichenbacher again (**BERserk**): signature forgery
- 2015/2016: **FREAK / Logjam**: implementation flaws downgrade to EXPORT cryptography
- 2016: **DROWN**: use the server's SSLv2 support to break SSLv3/TLS 1.{0,1,2}
- 2018: **ROBOT**: Bleichenbacher's 1998 attack is still valid on many TLS 1.2 implementations
- 2023: **Everlasting ROBOT**: Bleichenbacher's 1998 attack is still, still valid on many TLS 1.2 implementations

Common Themes

- Attacks on old versions of TLS remain valid for decades
  - XP, Vista, Android <5 never supported TLS 1.1, 1.2
- Many attacks are possible because legacy algorithms are never turned off by servers
  - FREAK/Logjam: 512-bit RSA/Diffie-Hellman (‘Export’ crypto)
- Setting up TLS servers is a massive headache
  - So many ciphersuites, key exchange groups, …



Description
TLS_NULL_WITH_NULL_NULL
TLS_RSA_WITH_NULL_MD5
TLS_RSA_WITH_NULL_SHA
TLS_RSA_EXPORT_WITH_RC4_40_MD5
TLS_RSA_WITH_RC4_128_MD5
TLS_RSA_WITH_RC4_128_SHA
TLS_RSA_EXPORT_WITH_RC2_CBC_40_MD5
TLS_RSA_WITH_IDEA_CBC_SHA
TLS_RSA_EXPORT_WITH_DES40_CBC_SHA
TLS_RSA_WITH_DES_CBC_SHA
TLS_RSA_WITH_3DES_EDE_CBC_SHA
TLS_DH_DSS_EXPORT_WITH_DES40_CBC_SHA
TLS_DH_DSS_WITH_DES_CBC_SHA
TLS_DH_DSS_WITH_3DES_EDE_CBC_SHA
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TLS_DH_anon_WITH_RC4_128_MD5
TLS_DH_anon_EXPORT_WITH_DES40_CBC_SHA
TLS_DH_anon_WITH_DES_CBC_SHA
TLS_DH_anon_WITH_3DES_EDE_CBC_SHA
Reserved to avoid conflicts with SSLv3
TLS_KRB5_WITH_DES_CBC_SHA
TLS_KRB5_WITH_3DES_EDE_CBC_SHA
TLS_KRB5_WITH_RC4_128_SHA
TLS_KRB5_WITH_IDEA_CBC_SHA
TLS_KRB5_WITH_DES_CBC_MD5
TLS_KRB5_WITH_3DES_EDE_CBC_MD5
TLS_KRB5_WITH_RC4_128_MD5
TLS_KRB5_WITH_IDEA_CBC_MD5
TLS_KRB5_EXPORT_WITH_DES_CBC_40_SHA
TLS_KRB5_EXPORT_WITH_RC2_CBC_40_SHA
TLS_KRB5_EXPORT_WITH_RC4_40_SHA
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TLS_KRB5_EXPORT_WITH_RC2_CBC_40_MD5
TLS_KRB5_EXPORT_WITH_RC4_40_MD5

TLS_RSA_WITH_CAMELLIA_256_CBC_SHA
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TLS_PSK_WITH_AES_128_CCM_8
TLS_PSK_WITH_AES_256_CCM_8
TLS_PSK_DHE_WITH_AES_128_CCM_8

PQ SHIELD

Ciphersuites in TLS

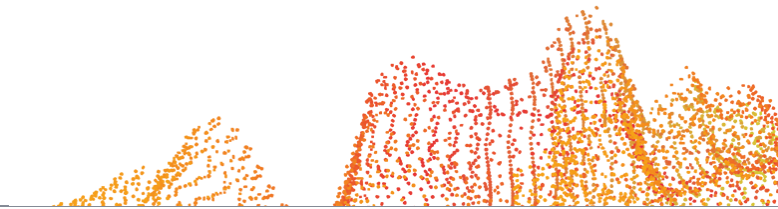
This isn't even all of them!

Room for improvement

- TLS 1.2 is not very robust against attacks
- TLS 1.2 leaks server and user identities in the handshake
- TLS 1.2 is not super efficient in the handshake

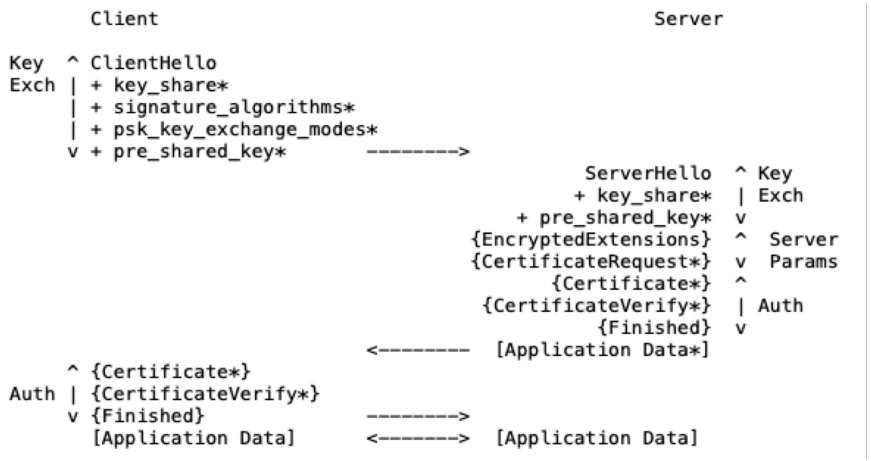
TLS 1.3 wishlist

- Secure handshake
  - More privacy
  - Only forward secret key exchanges
  - Get rid of MD5, SHA1, 3DES, EXPORT, NULL, …
- Simplify parameters
- More robust cryptography
- Faster, 1-RTT protocol
- 0-RTT resumption



TLS 1.3: RFC 8446

- Move key exchange into the first two messages
- Encrypt everything afterwards
- Be done as soon as possible



TLS 1.3 full handshake

- Key exchange via ECDH
  - Only ephemeral key exchange
- Server authentication: Signature
- Handshake authentication: HMAC-SHA256
  - “Key confirmation”
- AEAD: Only AES-GCM or ChaCha20-Poly1305

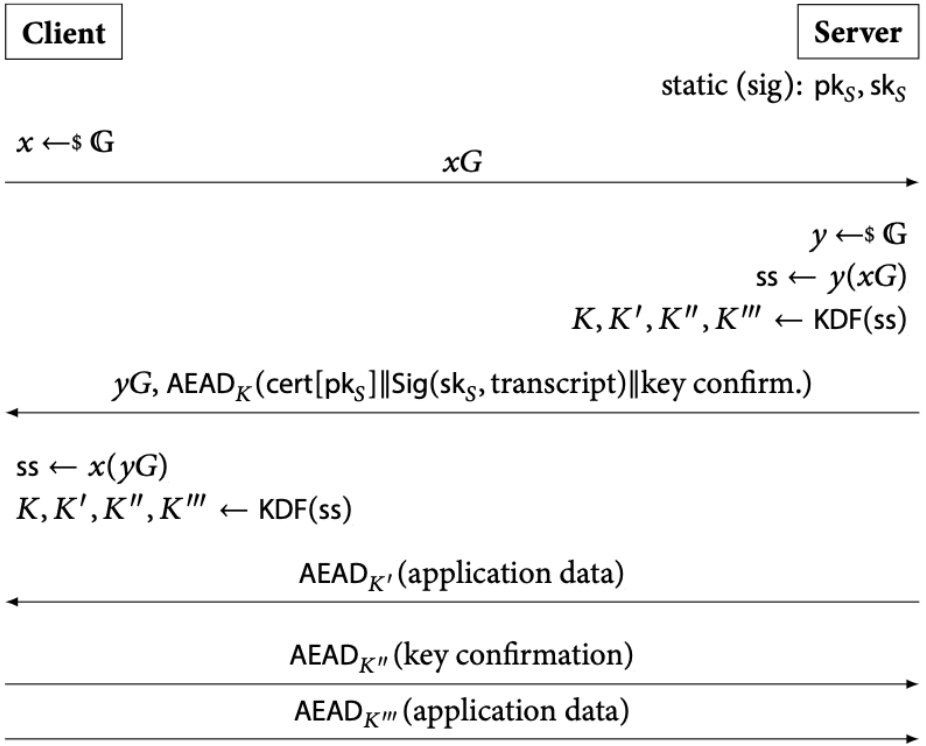
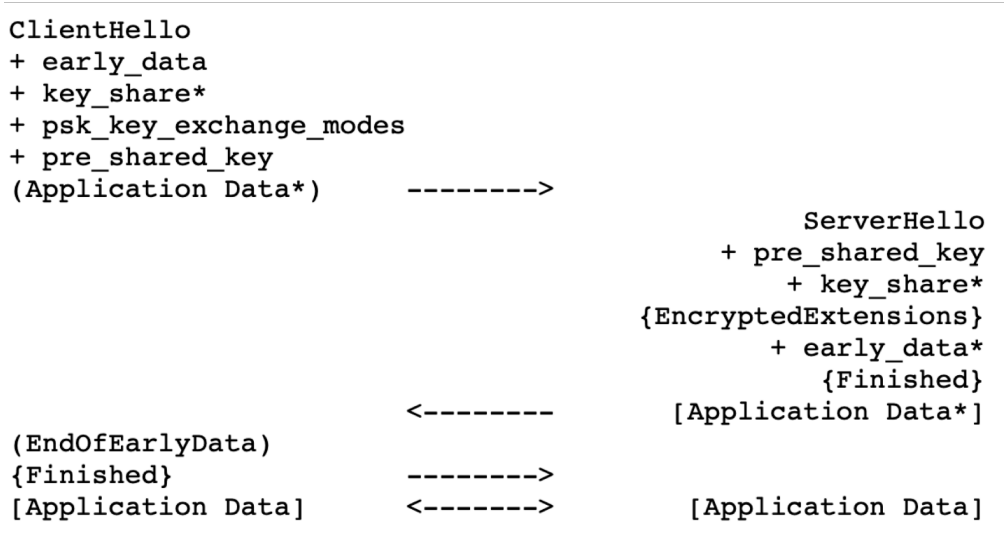


Figure 3.1: High-level overview of the TLS 1.3 handshake.

TLS 1.3 Resumption and 0-RTT

- If you have a pre-shared key, you can do a bunch of stuff faster!
- Use PSK to compute traffic secret
- Ephemeral key exchange optional
- No certificates
- Use PSK to encrypt “Early Data”



0-RTT caveats

IMPORTANT NOTE: The security properties for 0-RTT data are weaker than those for other kinds of TLS data. Specifically:

1. This data is **not forward secret**, as it is encrypted solely under keys derived using the offered PSK.
2. There are **no guarantees of non-replay** between connections. Protection against replay for ordinary TLS 1.3 1-RTT data is provided via the server's Random value, but 0-RTT data does not depend on the ServerHello and therefore has weaker guarantees. This is especially relevant if the data is authenticated either with TLS client authentication or inside the application protocol. The same warnings apply to any use of the early_exporter_master_secret.

0-RTT data cannot be duplicated within a connection (i.e., the server will not process the same data twice for the same connection), and an attacker will not be able to make 0-RTT data appear to be 1-RTT data (because it is protected with different keys). Appendix E.5 contains a description of potential attacks, and Section 8 describes mechanisms which the server can use to limit the impact of replay.

RFC 8446 page 18

Why 0-RTT?

- Siri requests
- GET requests on websites*
- Other stateless stuff

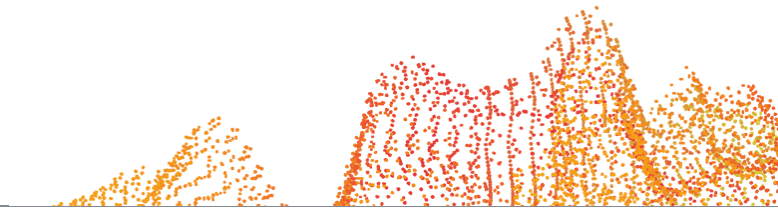
But are you sure your application is completely robust to replays?

```
GET /?query=INSERT into payments (to, amount)
                          VALUES (“Thom”, 1000);
```

TLS 1.3 standardization

- Strong collaboration with academics for protocol evaluation
  - Proofs on pen/paper, and using tools like ProVerif, Tamarin
- Academic results influenced protocol design
- But TLS working group gonna TLS working group
  - State machines are still only in the appendix

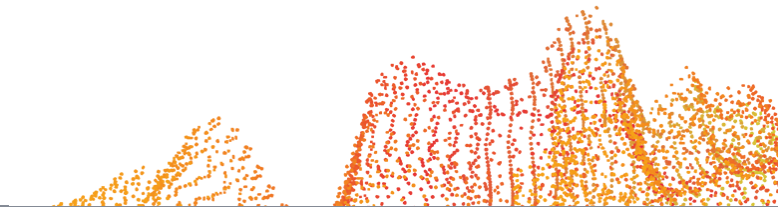
Much less ad-hoc design: design-break-patch-release process instead of design-release-break-patch



TLS 1.3 wishlist

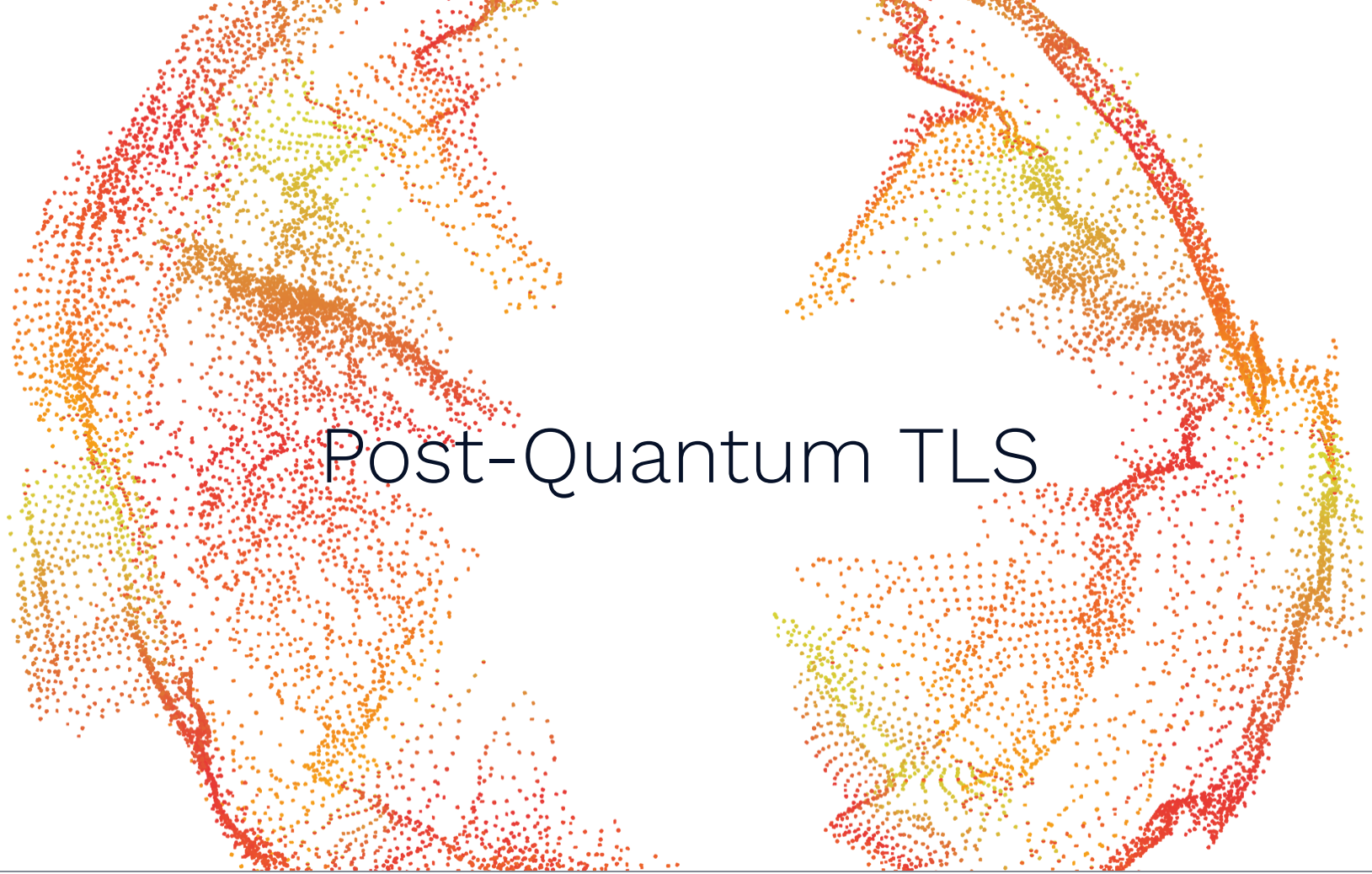
- ✓ Secure handshake
  - ✓ More privacy
  - ✓ Only forward secret key exchanges
  - ✓ Get rid of MD5, SHA1, 3DES, EXPORT, NULL, …
- ✓ Simplify parameters
- ✓ More robust cryptography
- ✓ Faster, 1-RTT protocol
- ✓ 0-RTT resumption

❑ Post-quantum?

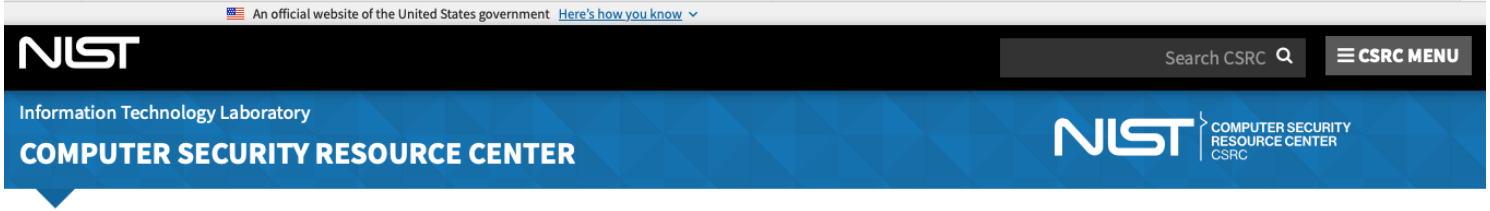


Server Name Indication: the remaining privacy problem

- TLS 1.3 encrypts the ServerCertificate and ClientCertificate messages
- But, Client includes the domain that they want to talk to in ClientHello in **plain text**!
- This allows CDNs / "virtual hosts" to serve many sites off of one IP address
- Problem: no keys established beforehand to encrypt the hostname
- Current proposed solution: put HPKE (RFC9180) keys in DNS so that server name can be encrypted (ECH: Encrypted Client Hello, WIP)
    - Post-Quantum challenges: DNS has significant size restrictions; adds additional ciphertext
- Only a real solution when many names map to the same IP (i.e. big-enough anonymity set implies CDN)
- ECH KEM keys are not useful for server (host) authentication (due to anonymity set)



Post-Quantum TLS



SHIELD

PROJECTS

Post-Quantum Cryptography PQC

Overview

Public comments are available for Draft FIPS 203, Draft FIPS 204 and Draft FIPS 205, which specify algorithms derived from CRYSTALS-Dilithium, CRYSTALS-KYBER and SPHINCS+. The public comment period closed November 22, 2023.

PQC Seminars
Next Talk: April 23, 2024

4th Round KEMs

Additional Digital Signature Schemes - Round 1 Submissions

PQC License Summary & Excerpts

Background

NIST initiated a process to solicit, evaluate, and standardize one or more quantum-resistant public-key cryptographic algorithms. **Full details can be found in the Post-Quantum Cryptography Standardization page.**

In recent years, there has been a substantial amount of research on quantum computers – machines that exploit quantum

PROJECT LINKS

- **Overview**
- **FAQs**
- **News & Updates**
- **Events**
- **Publications**
- **Presentations**

ADDITIONAL PAGES

- **Post-Quantum Cryptography Standardization**
  - Call for Proposals
  - Example Files
  - Round 1 Submissions
  - Round 2 Submissions
  - Round 3 Submissions
    - *Round 3 Seminars*
- **Round 4 Submissions**
- **Selected Algorithms 2022**

TLS 1.3

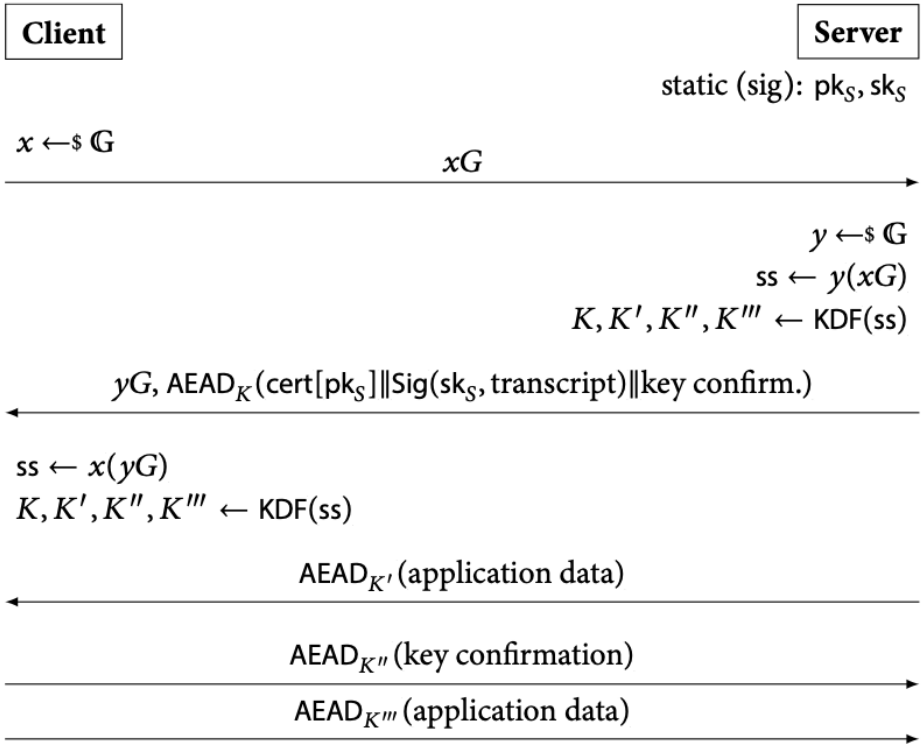


Figure 3.1: High-level overview of the TLS 1.3 handshake.

Post-Quantum

TLS 1.3

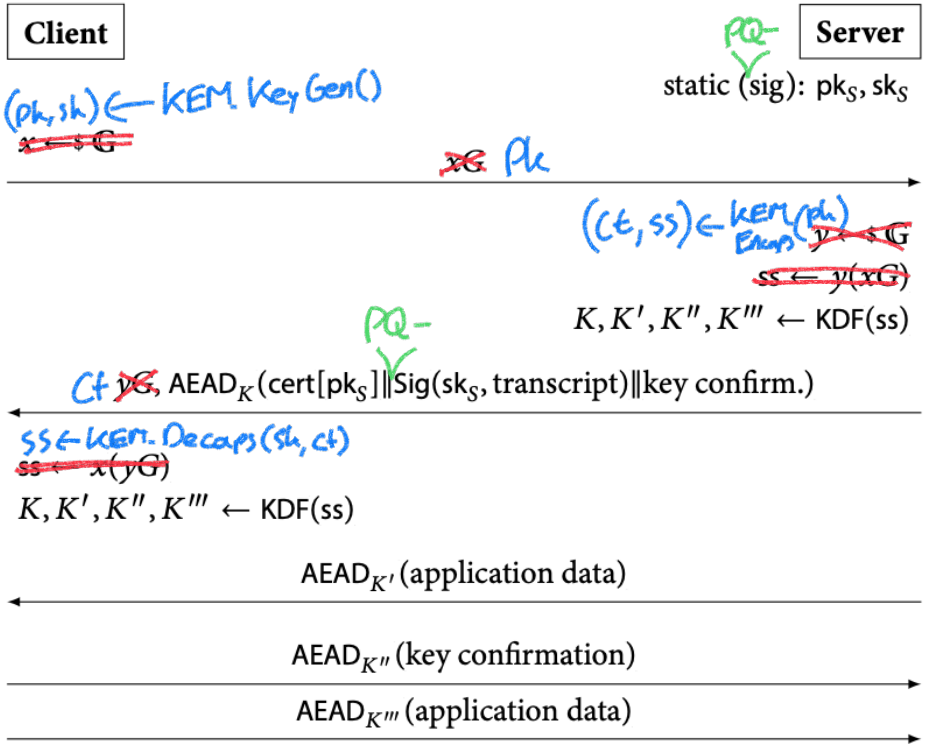


Figure 3.1: High-level overview of the TLS 1.3 handshake.

(AES-128 is fine btw)

Post-Quantum KEMs

Operation	Description
$(pk, sk) \leftarrow \text{KEM-KeyGen}()$	Generates a public/private key pair.
$(K, ct) \leftarrow \text{KEM-Encaps}(pk)$	Generates shared key K and encapsulates it to public key pk as ct.
$K \leftarrow \text{KEM-Decaps}(ct, sk)$	Decapsulates ct using sk to obtain K

	Public key	Ciphertext
ML-KEM 512	800 b	768 b
ML-KEM 768	1184 b	1088b
ML-KEM 1024	1568 b	1568 b

Post-Quantum Signatures: NIST Standards

	Public key	Signature
ML-DSA 44	1312 b	2420 b
ML-DSA 65	1952 b	3309 b
ML-DSA 87	2592 b	4627 b

Formerly Dilithium

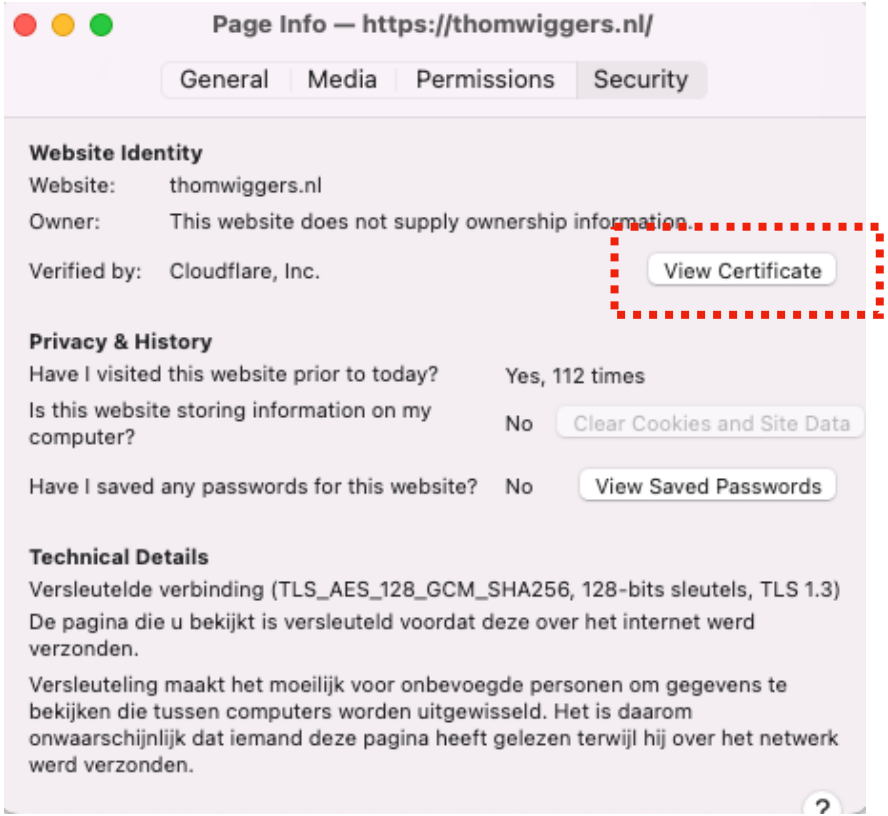
	Public key	Signature
Falcon-512	897 b	666 b
Falcon-1024	1793 b	1280 b

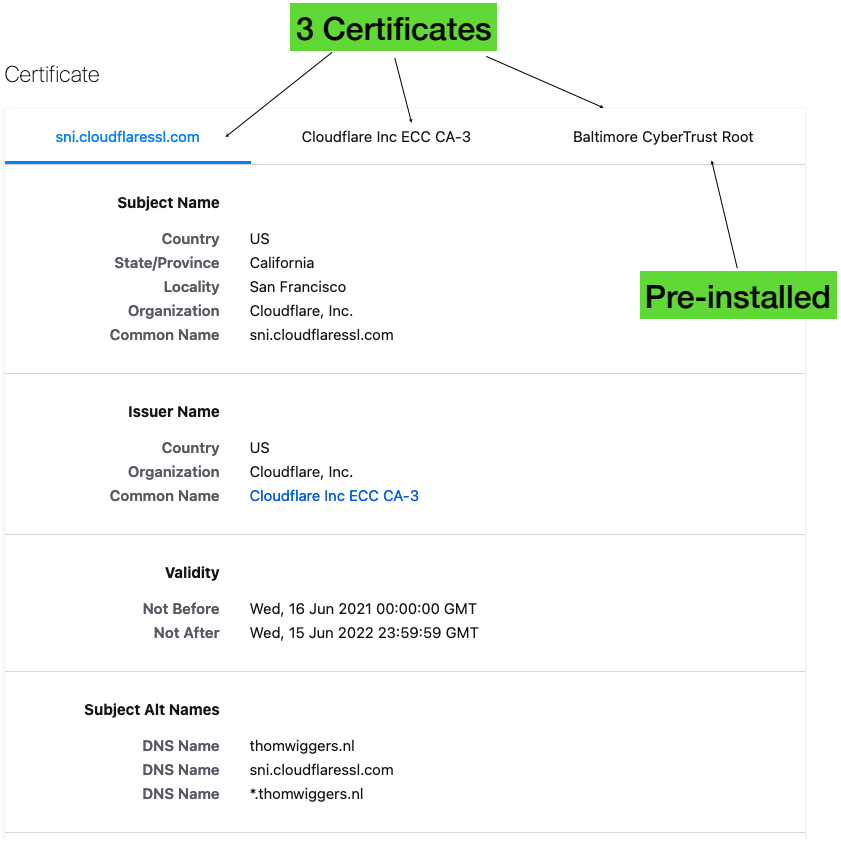
⚠ Falcon *signing* uses 64-bit floats: side-channel issues

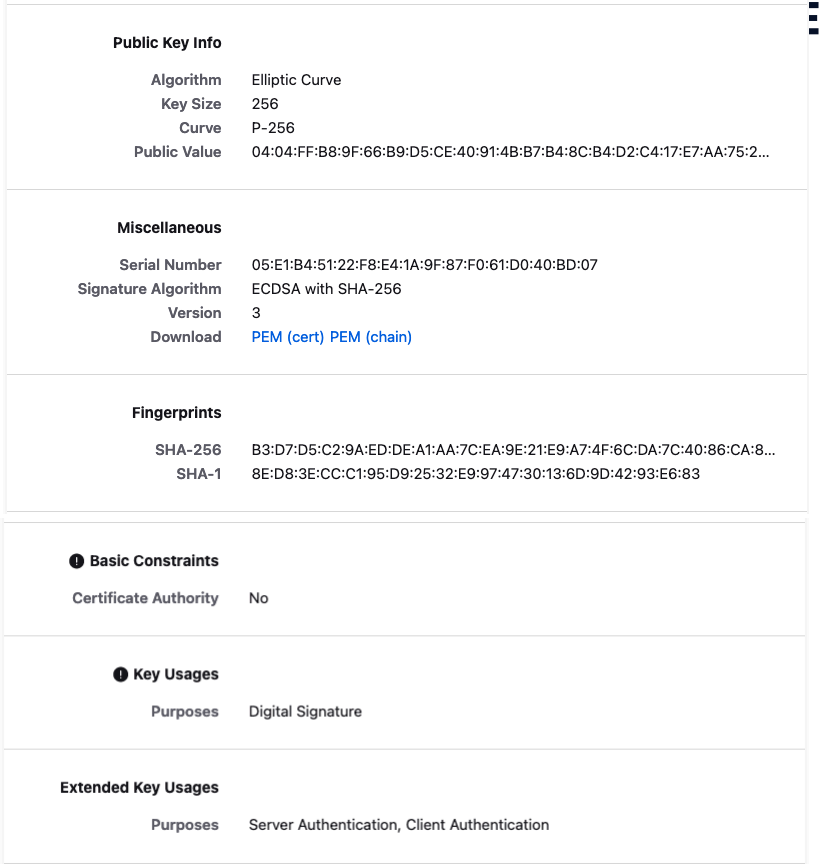
SLH-DSA	Public Key	Signature
128s	32 b	7856 b
128f	32 b	17088 b
192s	48 b	16224 b
192f	48 b	35664 b
256s	64 b	29792 b
256f	64 b	49856 b

Formerly known as SPHINCS+

Muhammad Mahdi Karim/www.micro2macro.net
GFDL 1.2 Source



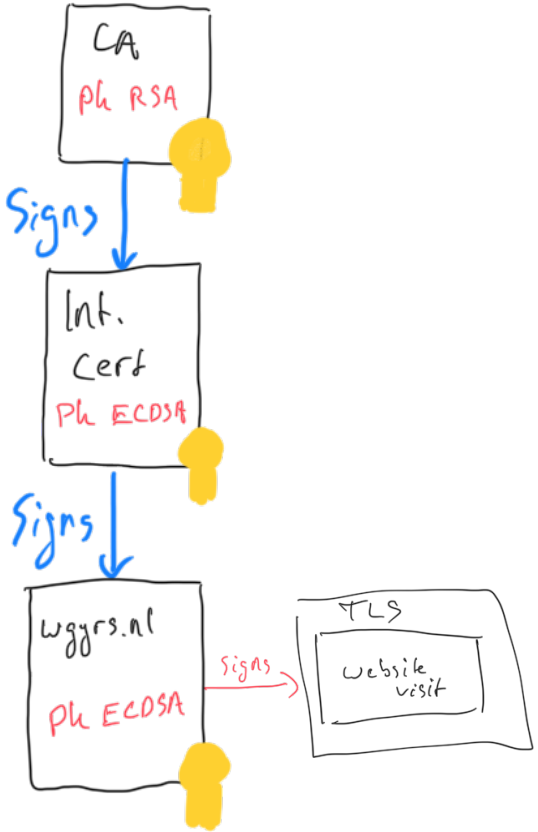




handshake signature
+ leaf certificate public key + intermediate certificate signature
+ root signature on intermediate
= 3 signatures and 2 public keys

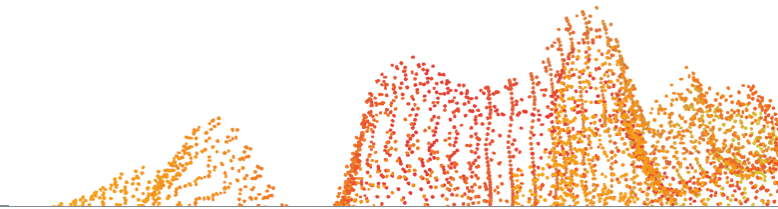
Public Key Infrastructure

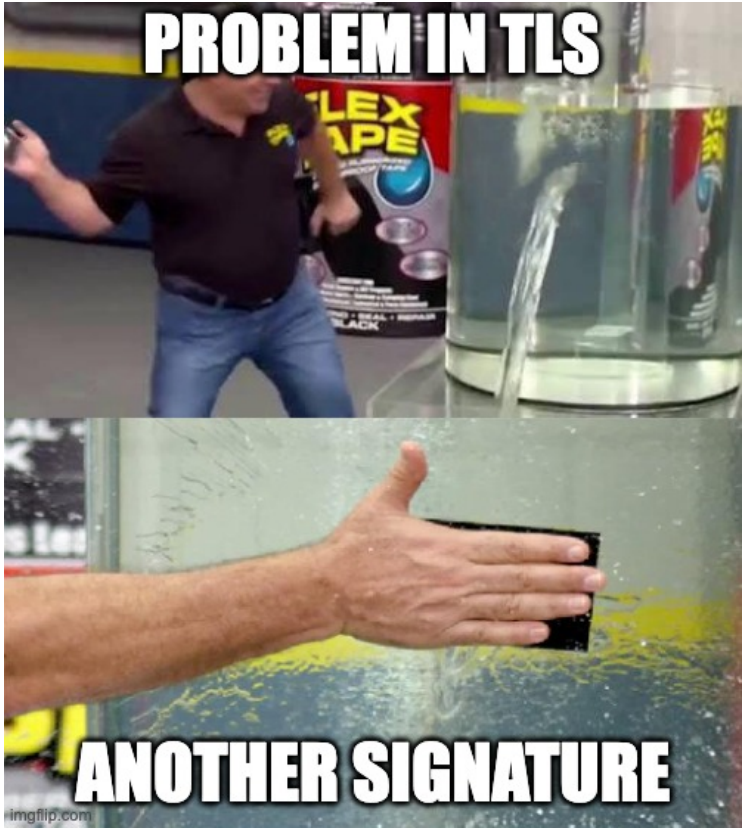
- Certificate Authorities (CA)
- Become a trusted CA by:
  - spending 💰💰 on audits
  - convince vendors to install your certificate
- Vendors trust CAs to check if I own wggrs.nl
- Intermediate CA certs make key management easier
  - (offline master signing key, etc)



Aside: PKI open problems

- Certificate issuance
- Certificate Revocation
  - Certificate Revocation Lists (CRL)
  - Online Certificate Status Protocol (OCSP)
- Any trusted CA can issue a certificate for anyone
  - Famously abused by Iran(?) to attack Gmail in DigiNotar.nl hack
  - “Certificate Transparency” (CT)





Slap another signature on it

Online Certificate Status Protocol

Authority Info (AIA)

Location	http://ocsp.digicert.com
Method	Online Certificate Status Protocol (OCSP)
Location	http://cacerts.digicert.com/CloudflareIncECCCA-3.crt
Method	CA Issuers

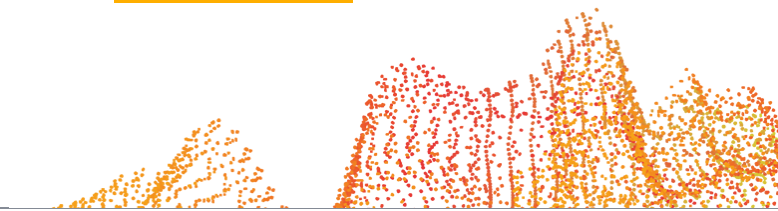
+= 1 signature

Certificate Transparency

Embedded SCTs

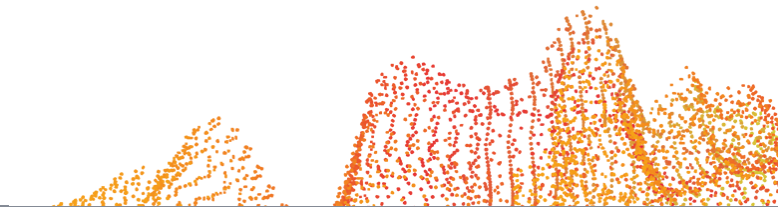
Log ID	29:79:BE:F0:9E:39:39:21:F0:56:73:9F:63:A5:77:E5:BE:57:7D:9C:60:0A:F8:...
Name	Google "Argon2022"
Signature Algorithm	SHA-256 ECDSA
Version	1
Timestamp	Wed, 16 Jun 2021 17:11:33 GMT
Log ID	22:45:45:07:59:55:24:56:96:3F:A1:2F:F1:F7:6D:86:E0:23:26:63:AD:C0:4B...
Name	DigiCert Yeti2022
Signature Algorithm	SHA-256 ECDSA
Version	1
Timestamp	Wed, 16 Jun 2021 17:11:33 GMT
Log ID	51:A3:B0:F5:FD:01:79:9C:56:6D:B8:37:78:8F:0C:A4:7A:CC:1B:27:CB:F7:9E...
Name	DigiCert Nessie2022
Signature Algorithm	SHA-256 ECDSA
Version	1
Timestamp	Wed, 16 Jun 2021 17:11:33 GMT

+= 3 signatures



Certificate Transparency

- Chrome, Safari require all certificates to be submitted to at least 2 certificate transparency logs
- Log is a Merkle tree of hostnames and hashes of included certificates
  - No privacy! You can search this using https://crt.sh
- Auditing, etc, are part of the design
- SCT proofs in certificates are promises of inclusion within 24 hours for deployment reasons
- CT logs typically only accept certificates from trusted issuers
- Running Certificate Transparency Logs is extremely hard and expensive
  - Only 6 log operators: Cloudflare, Digicert, Google, Sectigo, Let's Encrypt, and TrustAsia



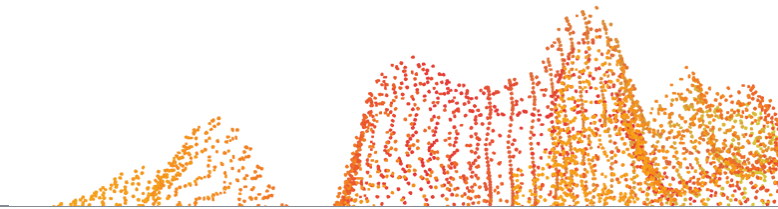
Summarising

- Typical **web** TLS handshake:
  - ephemeral key exchange
  - handshake signature
  - leaf certificate:
    pk
    + signature by intermediate CA crt
    + OCSP staple
    + 3x SCT
  - intermediate CA certificate:
    pk + signature by root CA
  - root certificate (preinstalled)

1 online keygen+key exchange

1 online signing operation

6 offline signatures



PQ Performance

Impact of PQ

- ~~Kyber~~ML-KEM key exchange: ~1.5kB
- ML-DSA-44: 18 kB of certificates!!
- Falcon-512: ~5 kB

Note: TCP congestion control

On connection establishment, TCP will allow you to send some amount of data before acknowledgement from the other side.

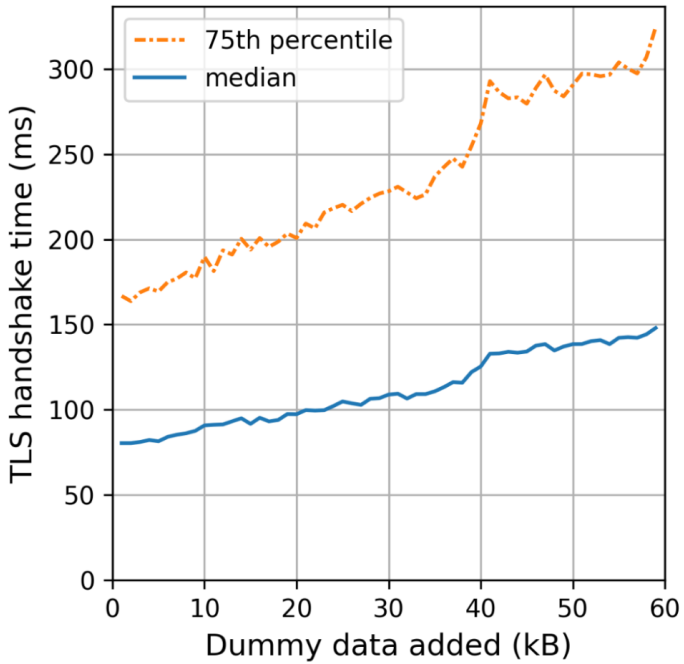
This window (and thus available connection bandwidth) scales as the connection is proven reliable when receiving TCP ACKs.

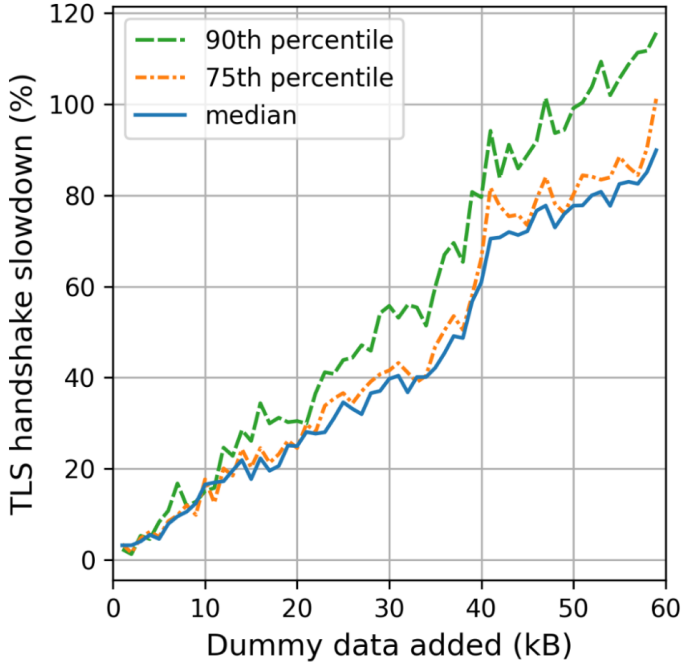
The default initial window on Linux is 10 packets, so **if you send more than ~15 kB of data, you're stuck waiting for an extra round-trip!**

Even without congestion control, more bytes = more slowlier

sizes per https://blog.cloudflare.com/sizing-up-post-quantum-signatures/

Cloudflare live internet experiment: More data results in slowdown





Bas Westerbaan, https://blog.cloudflare.com/sizing-up-post-quantum-signatures/. **Cloudflare has a 30 MSS = ~40kb congestion window**

Combining different algorithms

- handshake signature
- leaf certificate:
  pk
  + signature by intermediate CA crt
  + OCSP staple
  + 3x SCT
- intermediate CA certificate:
  pk
  + signature by root CA
- root certificate (preinstalled)

Robust against side-channels, pk+sig small

ML-DSA

Signature-verification only, pk+sig small

Falcon

Signature-verification only, signature small

UOV? (Signatures on-ramp)

Note: using multiple algorithms also has cost!

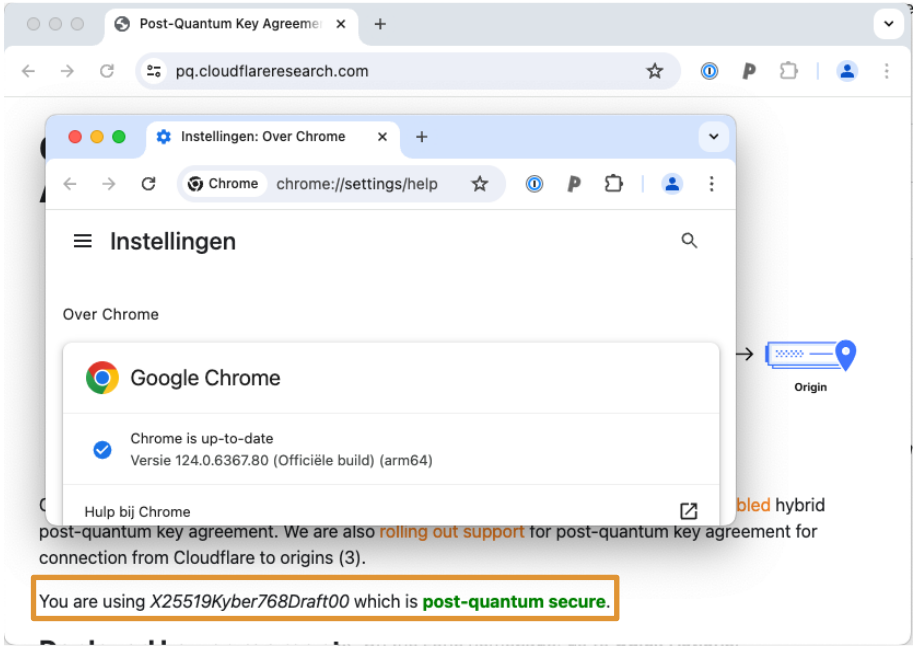
Table 11.1: Instantiations at NIST level I of unilaterally authenticated post-quantum TLS handshakes and the sizes of the public-key cryptography elements in bytes.

		Leaf certificate			Int. CA certificate			Offline
Experiment	**Key Exchange**	**Handshake auth.**	**Int. CA signature**		**Int. CA public key**	**Root CA signature**		**Root CA public key**
handle	pk+ct	pk+sig	sig	**Sum**	pk	sig	**Sum**	pk
Pre-quantum	X25519	RSA-2048	RSA-2048	848	RSA-2048	RSA-2048	1 376	RSA-2048
errr	64	528	256		272	256		272
Primary	Kyber-512	Dilithium2	Dilithium2	7 720	Dilithium2	Dilithium2	11 452	Dilithium2
KDDD	1568	3732	2420		1312	2420		1312
Falcon	Kyber-512	Falcon-512	Falcon-512	3 797	Falcon-512	Falcon-512	5 360	Falcon-512
KFFF	1568	1563	666		897	666		897
Falcon offline	Kyber-512	Dilithium2	Falcon-512	5 966	Falcon-512	Falcon-512	7 529	Falcon-512
KDFF	1568	3732	666		897	666		897

Src: Post-Quantum TLS, Thom Wiggers. PhD thesis. https://wggrs.nl/p/thesis/

Excludes OCSP and SCTs!

By the way: Chrome 124.0



Severe performance impact

- Kyber-768 “only” adds 2.3 kB to the handshake
- Google notes this already slows down handshakes by 4%
- Google observes a significant impact on lower-quality internet connections
  - This is why they’re only enabling this on Chrome Desktop right now

- We need something better than just replacing signatures

https://dadrian.io/blog/posts/pqc-signatures-2024/
https://blog.chromium.org/2024/05/advancing-our-amazing-bet-on-asymmetric.html

Not just speed

- Larger Hello messages can lead to fragmentation
- Not all implementations are prepared to deal with fragmented packets
- Especially middle boxes affected

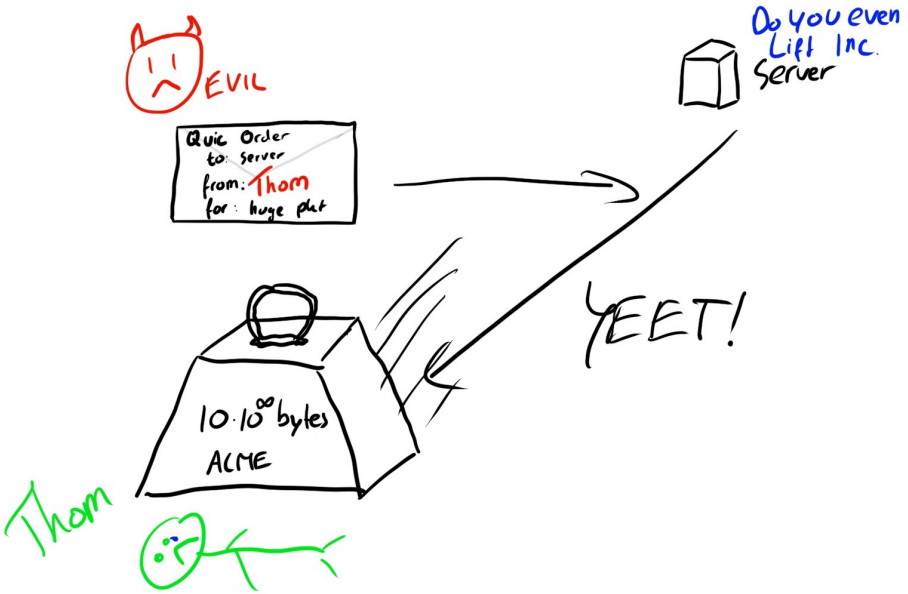
Product	Status	Discovered	Via	Patched	Links
Vercel	✅	2023-08-15	Chrome Beta	2023-08-23	Twitter
ZScalar	✅	2023-08-17	Chrome Beta	2023-09-28	
Cisco		2024-04-23	Chrome 124	Unknown	Cisco Bug
Envoy	✅	2024-04-29	Chrome 124	n/a (config-only)	Github

Table last updated 2024-05-13

https://tldr.fail

More problems with sizes

- Variant protocols DTLS and QUIC are based on UDP: no TCP SYN/ACK sequence
- ClientHello message received by server could be spoofed, so QUIC allows sending back at most 3x the ClientHello size (avoids DoS amplification)
- Sending back 18kB of ML-DSA requires the client to pad its ClientHello message with ~5kB



Avoiding the costs of certificates

- Certificates are already very large, PQ makes this much worse
- We have multiple signatures that prove validity in each certificate:
  - Signature on certificate itself
  - OCSP staple that proves that certificate is currently valid
  - Certificate Transparency log inclusion proves that certificate was from a trusted issuer

Can we do things in a smarter way?

Avoiding the costs of certificates

- Certificates are very large, PQ makes this much worse
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Can we do things in a smarter way?

Now is the time for redesigning the PKI

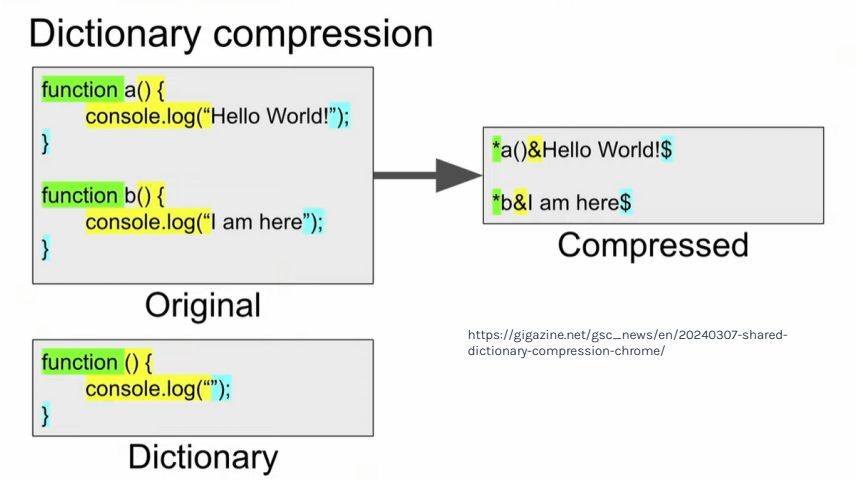
Abridged Compression for WebPKI Certificates

- Browser vendors control the root certificates that are included
- Step 1: Just ship the intermediate certificates as well
  - Client indicates to the server it has version N of the intermediate certificates list
  - Server omits intermediate certificate if present in list version N
  - Immediate savings: 1 certificate including 1 public key + 1 signature

https://datatracker.ietf.org/doc/draft-ietf-tls-cert-abridge/

Abridged Compression for WebPKI Certificates

- Certificates contain many common strings
  - policy urls, CA names, CT urls, extensions …
  - RFC 8879 already specifies certificate compression using zlib, brotli, zstd
- Step 2: Instead of applying compression algorithm directly, pre-train a compression dictionary based on sample certificates from all issuers
- Ship compression dictionary in browser



https://datatracker.ietf.org/doc/draft-ietf-tls-cert-abridge/

Abridged Certificate Compression for TLS

- Step 3: compress certificates before sending using the pre-trained dictionary (if client up-to-date)

- Shipping compression dictionary out-of-band massively improves compression results
- Gain ~3000 bytes, i.e. space for 1 ML-DSA
- Remember that public keys and signatures themselves don't compress at all
- Security analysis very easy: just uncompress and you have the same TLS handshake

Scheme	Storage Footprint	p5	p50	p95
Original	0	2308	4032	5609
TLS Cert Compression	0	1619	3243	3821
Intermediate Suppression and TLS Cert Compression	0	1020	1445	3303
This Draft	65336	661	1060	1437
This Draft with opaque trained dictionary	3000	562	931	1454
Hypothetical Optimal Compression	0	377	742	1075

https://datatracker.ietf.org/doc/draft-ietf-tls-cert-abridge/

Merkle Tree Certificates

What if we build the PKI on Certificate Transparency's ideas, combined with OCSP?

- Step 1: CA builds a Merkle Tree of all its currently valid certificates
- Step 2: Browsers collect and validate Merkle Tree heads and push them to clients
- Step 3: Webserver replaces its certificate chain by public key + merkle tree authentication path
- Step 4: Repeat every hour

This achieves authentication of the server public key in ~1000 bytes!

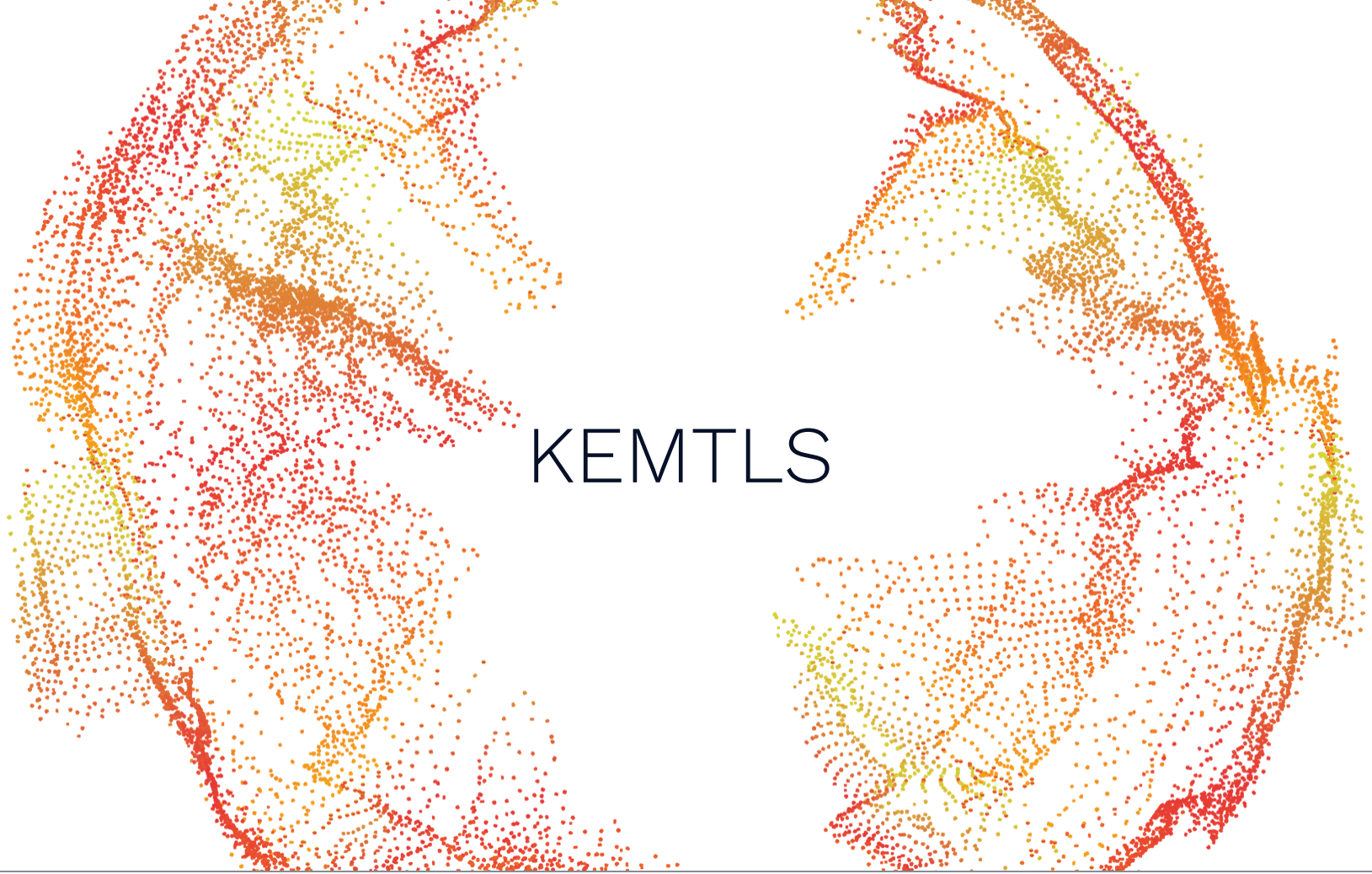
But is only a solution if you can keep your clients constantly up-to-date…

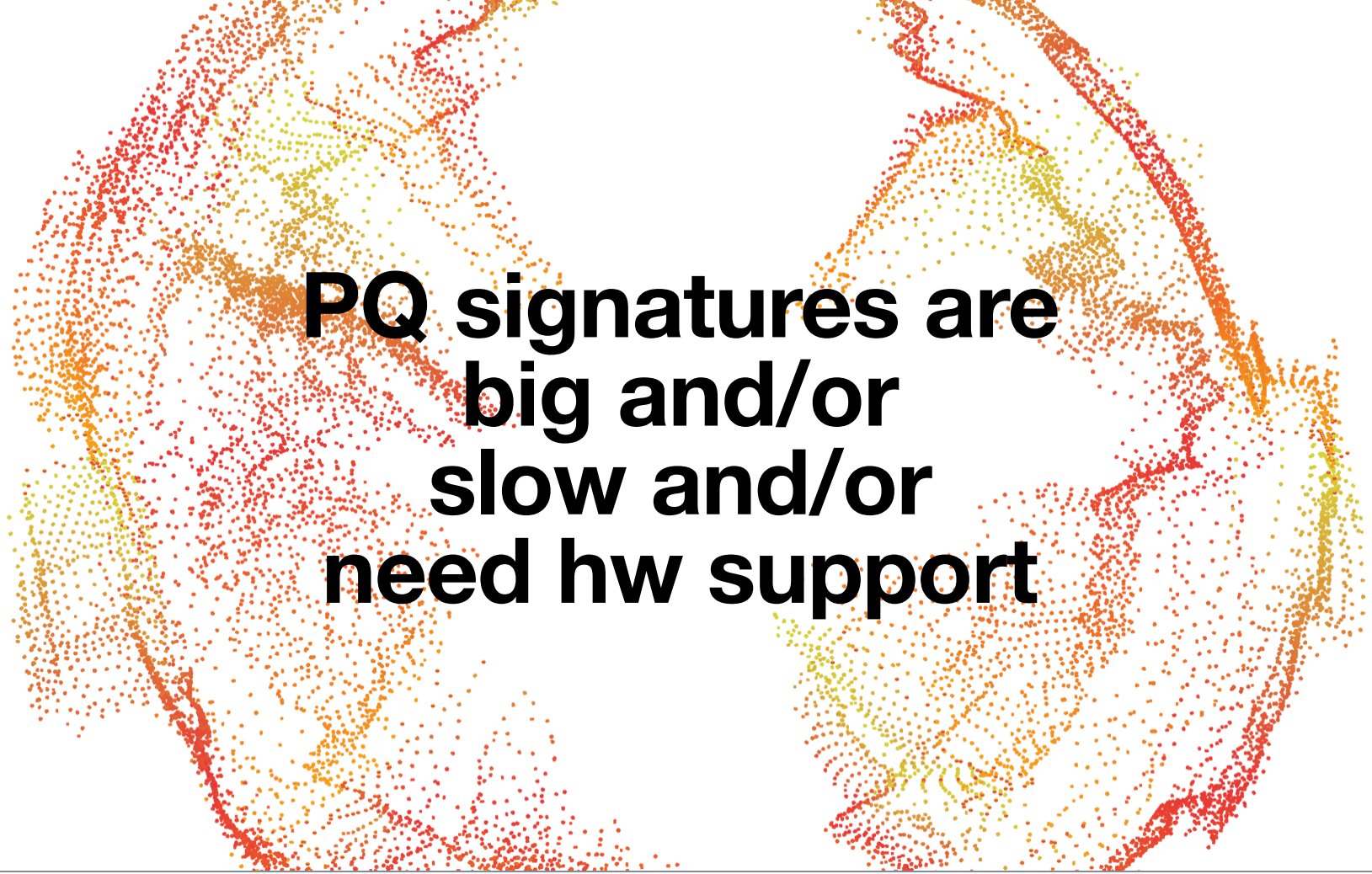
https://datatracker.ietf.org/doc/draft-davidben-tls-merkle-tree-certs/

Merkle Tree Certificates

- Big changes necessary to every part of the ecosystem
  - Short-lived certificates
  - Webserver must continuously fetch the latest authentication paths
  - Clients must keep downloading currently valid tree heads
  - Automated certificate provisioning such as ACME [RFC8555] should help with this
- New trust model makes security analysis more complicated

- Both MTC and Abridged Compression designed for big deployments and publicly trusted CAs
  - What about IoT? What about ABN AMRO's internal stuff?





Use key exchange for authentication

Authentication

Explicit authentication:

Alice receives assurance that she really is talking to Bob

- Signed Diffie-Hellman
- SIGMA
- TLS 1.3

Implicit authentication:

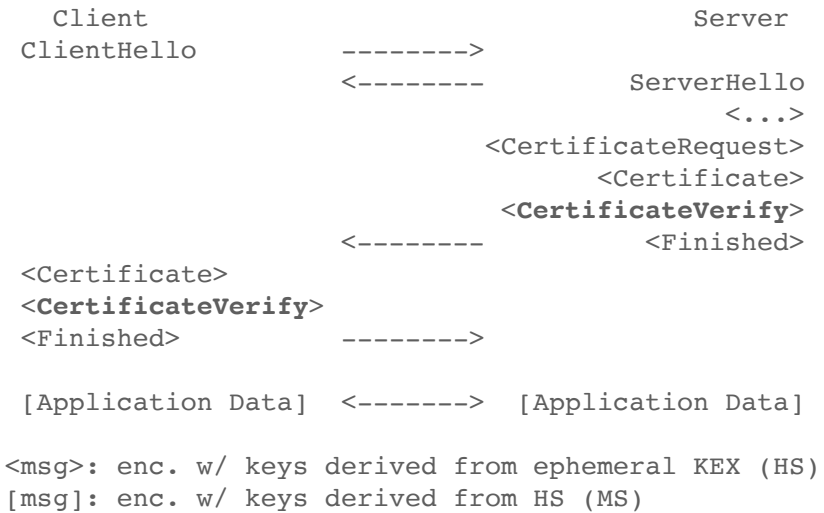
Alice is assured that only Bob would be able to compute the shared secret

- Signal
- Wireguard
- Noise framework

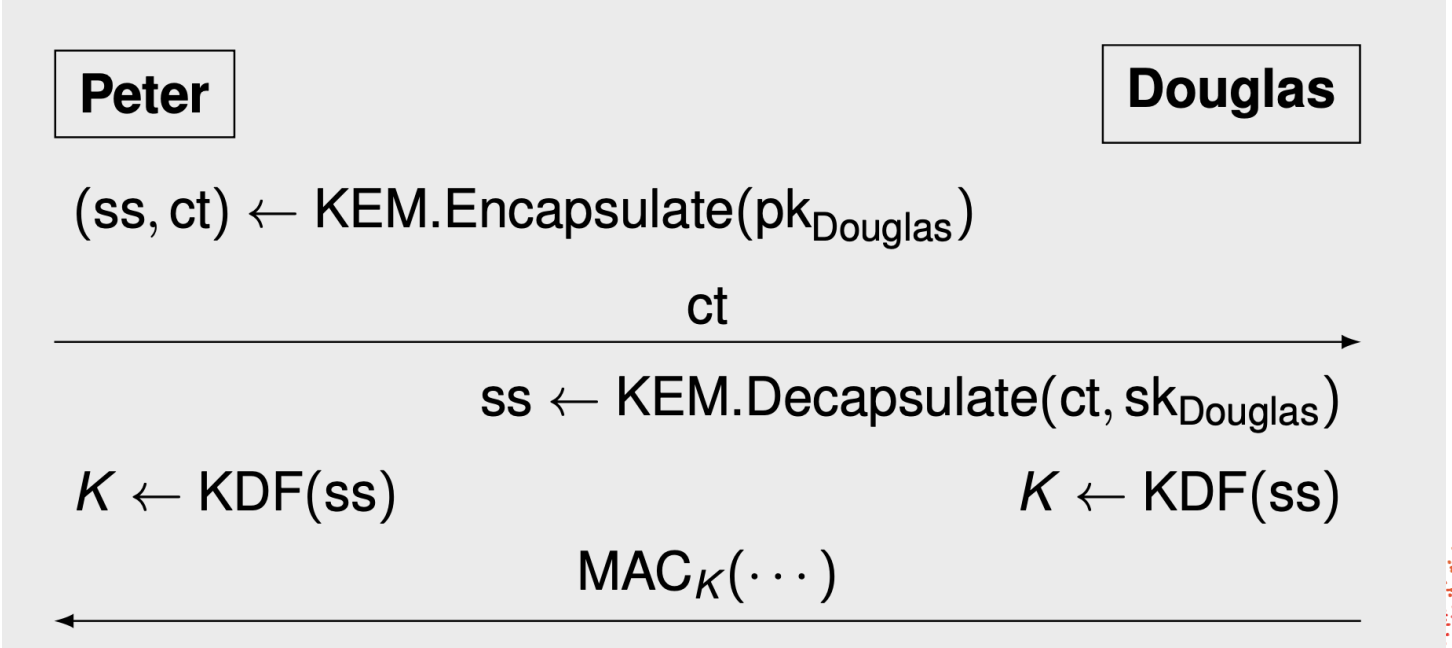
Can always use MAC to confirm key

TLS handshake authentication

- Signatures allow us to authenticate immediately!



Authenticated Key Exchange via KEM

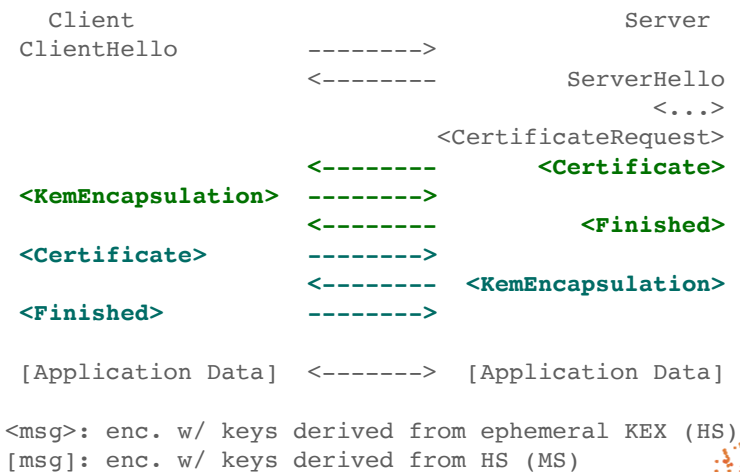


Note that this protocol assumes that we have already exchanged the public keys!

TLS authentication via KEM

- Signatures allow us to authenticate immediately!
- KEMs require interactivity

- Exercise for the reader: see how Diffie–Hellman's non-interactive key exchange property would have allowed us to do this more efficiently
  (See OPTLS by Krawczyk and Wee)

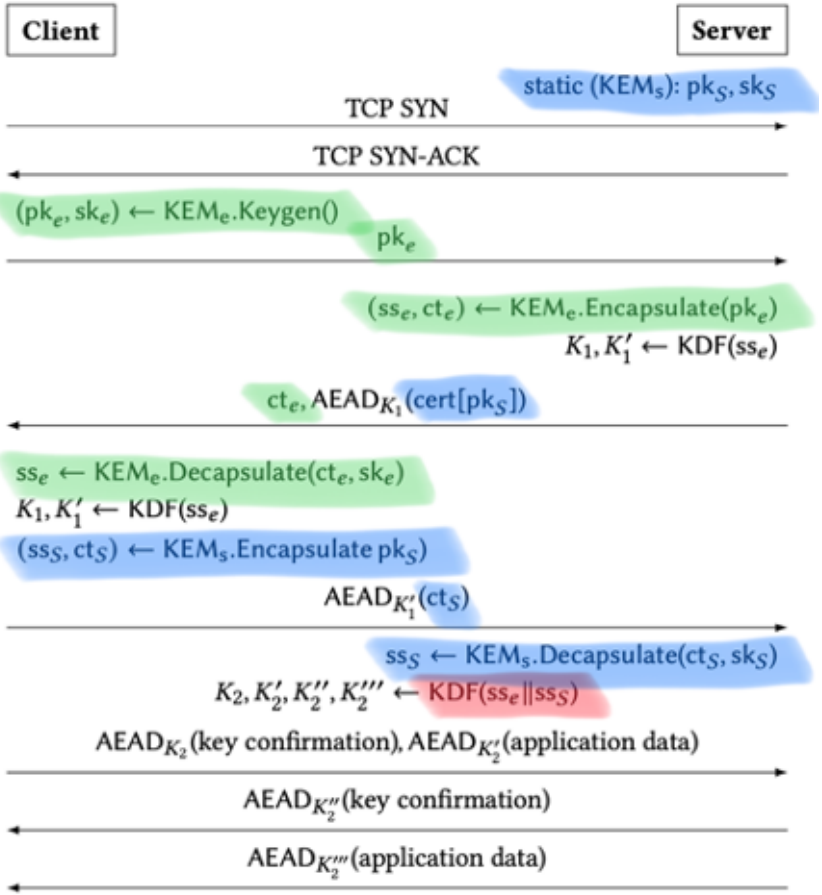


KEMTLS

KEM for
ephemeral key exchange

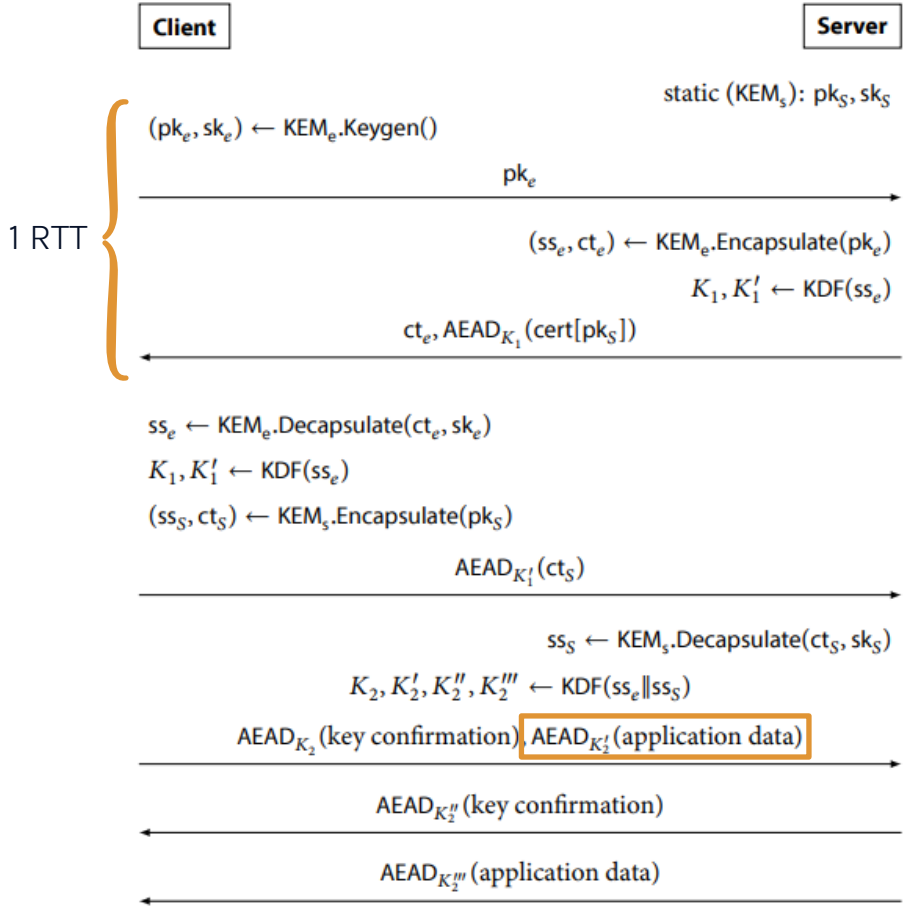
KEM for
server-to-client
authenticated key exchange

Combine shared secrets



KEMTLS

- What can a server send to a client, before the client has said what they wanted?
- Use implicitly authenticated key to encrypt application message (request) to server before receiving Server's Finished message
- Avoid 2-RTT protocol
- Client can send HTTP request in same place as in TLS 1.3



Sizes of KEMTLS

Table 13.1: Instantiations at NIST level I of unilaterally authenticated KEMTLS handshakes and the sizes of the public-key cryptography elements in bytes.

		Leaf certificate			Int. CA certificate			Offline
Experiment	**Key Exchange**	**Handshake auth.**	**Int. CA signature**		**Int. CA public key**	**Root CA signature**		**Root CA public key**
handle	pk+ct	pk+ct	sig	**Sum**	pk	sig	**Sum**	pk
Primary	Kyber-512	Kyber-512	Dilithium2	5 556	Dilithium2	Dilithium2	9 288	Dilithium2
KKDD	1568	1568	2420		1312	2420		1312
Falcon	Kyber-512	Kyber-512	Falcon-512	3 802	Falcon-512	Falcon-512	5 365	Falcon-512
KKFF	1568	1568	666		897	666		897
SPHINCS$^+$-f	Kyber-512	Kyber-512	SPHINCS$^+$-128f	20 224	SPHINCS$^+$-128f	SPHINCS$^+$-128f	37 344	SPHINCS$^+$-128f
KKSfSf	1568	1568	17 088		32	17 088		32
SPHINCS$^+$-s	Kyber-512	Kyber-512	SPHINCS$^+$-128s	10 992	SPHINCS$^+$-128s	SPHINCS$^+$-128s	18 880	SPHINCS$^+$-128s
KKSsSs	1568	1568	7856		32	7856		32
Hash-based CA	Kyber-512	Kyber-512	XMSS$_s^{MT}$-I	4 115	XMSS$_s^{MT}$-I	XMSS$_s^{MT}$-I	5 126	XMSS$_s^{MT}$-I
KKXX	1568	1568	979		32	979		32

Table excludes OCSP, SCT

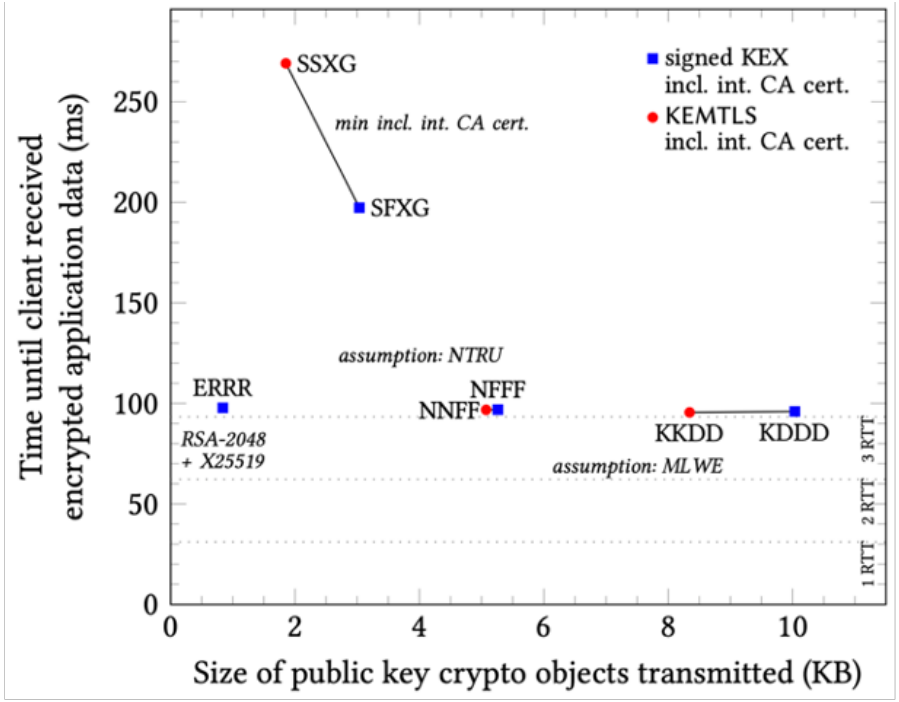
Table 13.5: Comparison of handshake size and time until the client receives a response from the server (30.9 ms, 1000 Mbps), between unilaterally authenticated post-quantum TLS 1.3 and KEMTLS instances at NIST level I.

Experiment		**Handshake size (bytes)**				**Time until response (ms)**			
		No int.	**Δ%**	**With int.**	**Δ%**	**No int.**	**Δ%**	**With int.**	**Δ%**
TLS	KDDD	7720	−28.0 %	11 452	−18.9 %	94.8	−0.4 %	95.0	−0.3 %
KEMTLS	KKDD	5556		9288		94.4		94.8	
TLS	KFFF	3797	+0.1 %	5360	+0.1 %	95.8	−1.3 %	96.1	−1.2 %
KEMTLS	KKFF	3802		5365		94.5		94.9	
TLS	KDFF	5966	−36.3 %	7529	−28.7 %	94.8	−0.3 %	95.2	−0.3 %
KEMTLS	KKFF	3802		5365		94.5		94.9	
TLS	KSsSsSs	17 312	−36.5 %	25 200	−25.1 %	197.7	−52.0 %	198.0	−36.2 %
KEMTLS	KKSsSs	10 992		18 880		94.9		126.4	

Signed KEX versus KEMTLS

Labels ABCD:
A = ephemeral KEM
B = leaf certificate
C = intermediate CA
D = root CA

Algorithms: (all level 1)
Dilithium,
ECDH X25519,
Falcon,
GeMSS,
Kyber,
NTRU,
RSA-2048,
SIKE,
XMSS'

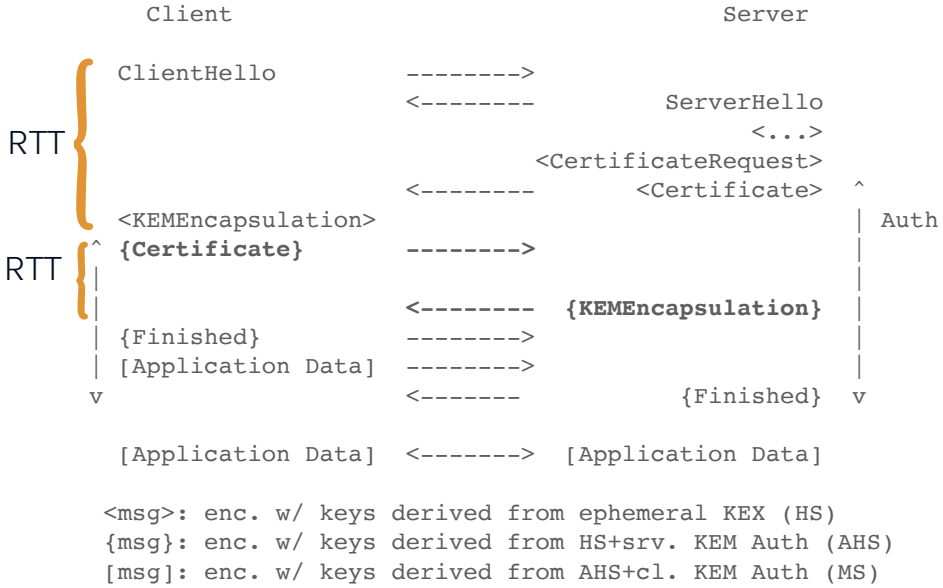


Rustls client/server with some AVX2 implementations. Emulated network: latency 31.1 ms, bandwidth 1000 Mbps, 0% packet loss. Average of 100000 iterations.

Slightly dated slide borrowed from Douglas Stebila

KEMTLS client auth

- Unfortunately, no nice tricks exist for the client certificate …
- **Full extra round-trip** in KEMTLS
- Also: we need an extra “authenticated” handshake traffic secret to protect the client certificate



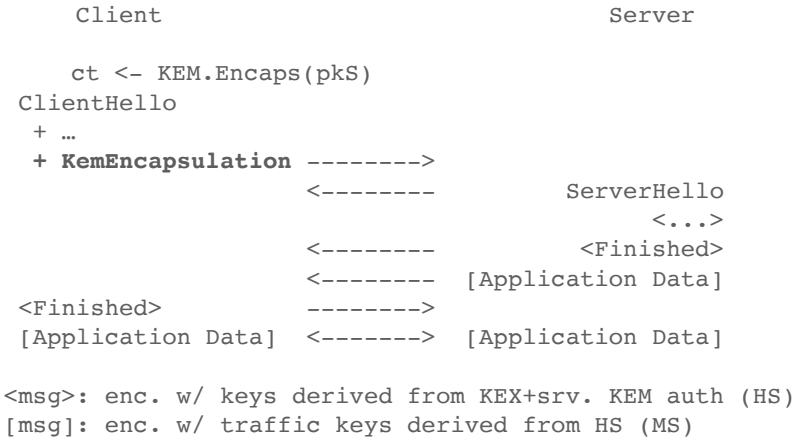
KEMTLS-PDK

- The client often knows the server:
  - It's the 10th time you refreshed the front page of Reddit in the past 5 minutes
  - You've been doom-scrolling /r/wallstreetbets 📉 for two hours already
  - Or the client is a too-cheap IoT security camera ~~spying on you for China~~ checking firmware updates from the same server every day

➡️ The client reasonably might know the server's long-term key

KEMTLS-PDK

- Use server's long-term (certificate) public key to encaps *before ClientHello*
- Send the ciphertext *with ClientHello*
- Don't transmit certificates anymore
- Save even more bytes



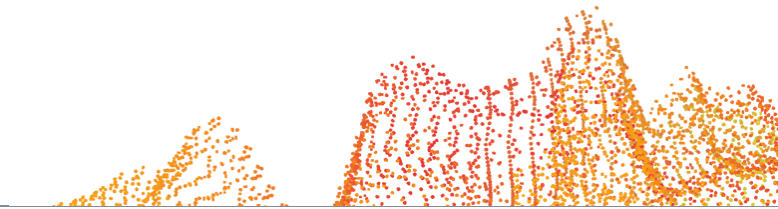
KEMTLS-PDK

- We now have an implicitly authenticated key already before we sent the ClientHello message!
- Use this to also encrypt and send over the client's certificate
- Or 0-RTT?

- ! No replay protection
- ! No forward secrecy

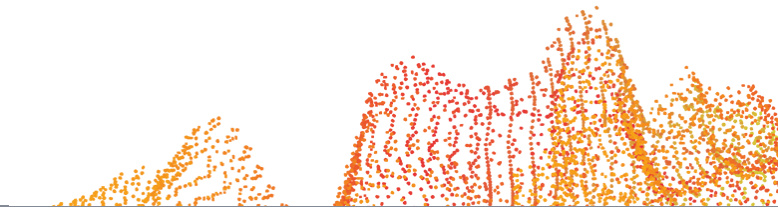
TLS ecosystem challenges

- Datagram TLS
- Use of TLS handshake in other protocols
  - e.g. QUIC
- Application-specific behaviour
  - e.g. HTTP3 SETTINGS frame not server-authenticated
- PKI involving KEM public keys
- Long tail of implementations
- …



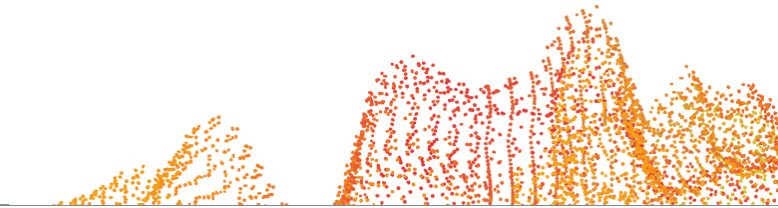
Standardizing KEMTLS

- Authentication bits from KEMTLS have been submitted to the TLS working group at the Internet Engineering Task Force (IETF) (aka the RFC people)
  - https://datatracker.ietf.org/doc/draft-celi-wiggers-tls-authkem/
  - https://datatracker.ietf.org/doc/draft-wiggers-tls-authkem-psk/
  - https://wggrs.nl/docs/authkem-abridged/



Transitioning to PQ

- The transition to post-quantum means:
  - KEMs are less flexible than Diffie—Hellman
    - No non-interactive key exchange
  - PQ is bigger than ECC we got used to
  - Post-Quantum Signatures are big
- **Big changes to surrounding ecosystems might be necessary**
- KEMTLS really explores **new tradeoffs**
  - Signing and key exchange are not the same operations anymore
  - Transitioning to PQ is an opportunity to reconsider some established protocols!



Internship / thesis opportunities

- PQShield has experts in cryptographic software, hardware design, side-channel analysis, cryptanalysis, cryptographic primitive design, secure messaging, and so on
- We publish many research papers in top-tier conferences each year
- We can host research/thesis projects, and might also be able to help with your project ideas

Example:

- Apples-to-apples comparison of hardware implementations of classical and post-quantum cryptography

Reach out to thom.wiggers@PQShield.com