Hash-based Signature, the Round-3 Candidate: SPHINCS+

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Post-quantum cryptography forum
14 January 2022

Public-key signatures

- Prerequisite: Alice has a private key  and public key .
- Prerequisite: Everyone knows  as belonging to Alice.
- Alice signs messages using . Other people verify using .

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- Security goals: Integrity and authenticity.
- Nobody can produce signatures valid under  without .
- Modifications to signed message get caught.


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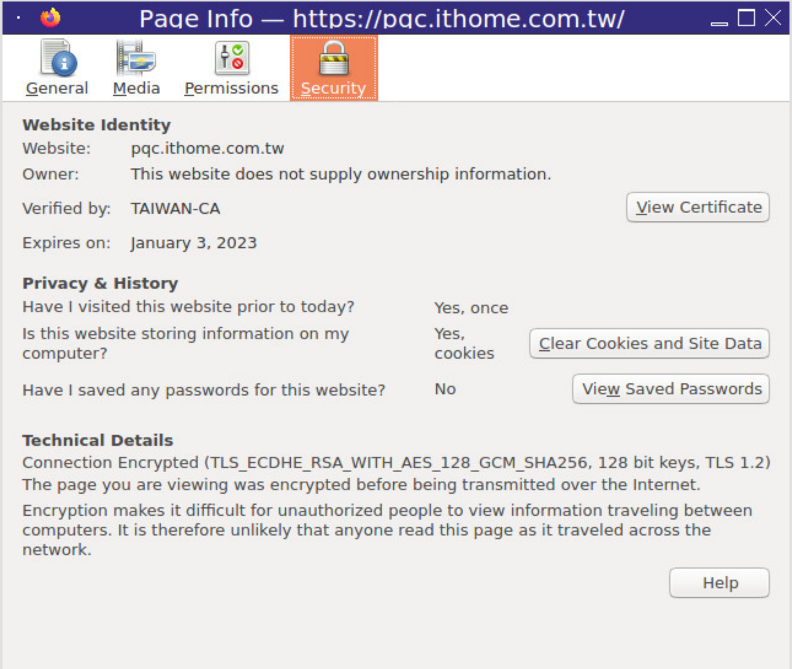
More Information



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*.ithome.com.tw | TWCA Secure SSL Certification Authority | TWCA Global Root CA

Subject Name

Country	TW
State/Province	Taiwan
Locality	Taipei
Organization	ITHOME PUBLICATIONS INC.
Organizational Unit	SYSTEM
Common Name	*.ithome.com.tw

Issuer Name

Country	TW
Organization	TAIWAN-CA
Organizational Unit	Secure SSL Sub-CA
Common Name	TWCA Secure SSL Certification Authority

Validity

Not Before	Thu, 16 Dec 2021 08:43:55 GMT
Not After	Tue, 03 Jan 2023 15:59:59 GMT

Subject Alt Names

DNS Name	*.ithome.com.tw
DNS Name	ithome.com.tw

Public Key Info

Algorithm	RSA
Key Size	2048
Exponent	65537
Modulus	C5:16:B9:74:75:83:F5:F4:37:6A:5F:27:A2:1B:6D:F9:AB:C5:8B:DC:D...

Miscellaneous

Serial Number	47:E5:00:00:00:04:EA:15:4A:58:85:C3:B1:2D:1A:51
Signature Algorithm	SHA-256 with RSA Encryption

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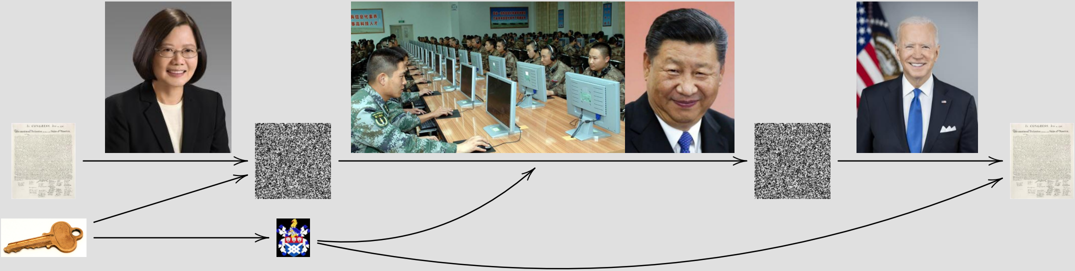
Signature Algorithm	SHA-256 with RSA Encryption
Version	3
Download	PEM (cert) PEM (chain)

Fingerprints

SHA-256	BB:D8:99:8A:7B:9A:06:FE:81:A1:F2:18:92:1D:93:CB:62:1F:42:BE:36...
SHA-1	8E:E3:DA:17:00:DD:4F:7C:89:1A:33:E3:C2:9C:C1:ED:C4:3F:87:6B

Post-quantum public-key signatures: hash-based



- Only one prerequisite: a good hash function, e.g. SHA3-512, ...
  Hash functions map long strings to fixed-length strings.
  $H : \{0,1\}^* \to \{0,1\}^n$.

  Signature schemes use hash functions in handling  .

- Old idea: 1979 Lamport one-time signatures;
  1979 Merkle extends to more signatures.

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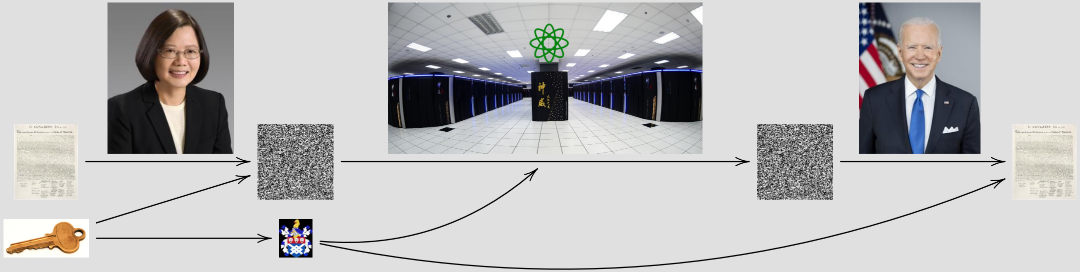

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  Signature schemes use hash functions in handling .
- Quantum computers affect the hardness only marginally (Grover, not Shor).
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One-time signatures (Lamport and Winternitz)

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Lamport signs m via $H(m) = (h_0, h_1, \ldots, h_{255})$.
Private key: 256×2 bit strings $\mathbf{s} = (s_{0,0}, s_{0,1}, s_{1,0}, s_{1,1}, \ldots, s_{255,0}, s_{255,1})$,
public key: $\mathbf{p} = (H(s_{0,0}), H(s_{0,1}), H(s_{1,0}), H(s_{1,1}), \ldots, H(s_{255,0}), H(s_{255,1}))$.
To sign m reveal $s_{0,h_0}, s_{1,h_1}, \ldots, s_{255,h_{255}}$.

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for short public key at expense of longer signature.

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Winternitz achieves short public keys and signatures costing more calls to H.

On the fast track: stateful hash-based signatures

- CFRG has published 2 RFCs: RFC 8391 and RFC 8554

IETF Datatracker Groups Documents Meetings Other User

```
Internet Research Task Force (IRTF)                          A. Huelsing
Request for Comments: 8391                                 TU Eindhoven
Category: Informational                                        D. Butin
ISSN: 2070-1721                                            TU Darmstadt
                                                              S. Gazdag
                                                             genua GmbH
                                                            J. Rijneveld
                                                      Radboud University
                                                             A. Mohaisen
                                         University of Central Florida
                                                                May 2018

               XMSS: eXtended Merkle Signature Scheme
```

IETF Datatracker Groups Documents Meetings Other User

```
Internet Research Task Force (IRTF)                           D. McGrew
Request for Comments: 8554                                     M. Curcio
Category: Informational                                       S. Fluhrer
ISSN: 2070-1721                                            Cisco Systems
                                                              April 2019

               Leighton-Micali Hash-Based Signatures
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- ISO SC27 JTC1 WG2 is working on standard for stateful hash-based signatures.

Merkle's (e.g.) 8-time signature system

Hash 8 one-time public keys into a single Merkle public key P_{15}.

$$P_{15} = H(P_{13}, P_{14})$$

$$P_{13} = H(P_9, P_{10}) \qquad P_{14} = H(P_{11}, P_{12})$$

$$P_9 = H(P_1, P_2) \quad P_{10} = H(P_3, P_4) \quad P_{11} = H(P_5, P_6) \quad P_{12} = H(P_7, P_8)$$

$$S_1 \to P_1 \quad S_2 \to P_2 \quad S_3 \to P_3 \quad S_4 \to P_4 \quad S_5 \to P_5 \quad S_6 \to P_6 \quad S_7 \to P_7 \quad S_8 \to P_8$$

$S_i \to P_i$ can be Lamport or Winternitz one-time signature system.
Each such pair (S_i, P_i) may be used only once.

Signature in 8-time Merkle hash tree

Signature of first message: $(\texttt{sign}(m, S_1), P_1, P_2, P_{10}, P_{14})$.

$$\begin{tikzcd}
\boxed{P_{15} = H(P_{13}, P_{14})} & & & & & & & \\
P_{13} = H(P_9, P_{10}) \arrow[u] & & & & \boxed{P_{14} = H(P_{11}, P_{12})} \arrow[ullll] & & & \\
P_9 = H(P_1, P_2) \arrow[u] & & \boxed{P_{10} = H(P_3, P_4)} \arrow[ull] & & P_{11} = H(P_5, P_6) \arrow[u] & & P_{12} = H(P_7, P_8) \arrow[ull] & \\
\boxed{P_1} \arrow[u] & \boxed{P_2} \arrow[ul] & P_3 \arrow[u] & P_4 \arrow[ul] & P_5 \arrow[u] & P_6 \arrow[ul] & P_7 \arrow[u] & P_8 \arrow[ul] \\
\boxed{S_1} \arrow[u] & S_2 \arrow[u] & S_3 \arrow[u] & S_4 \arrow[u] & S_5 \arrow[u] & S_6 \arrow[u] & S_7 \arrow[u] & S_8 \arrow[u]
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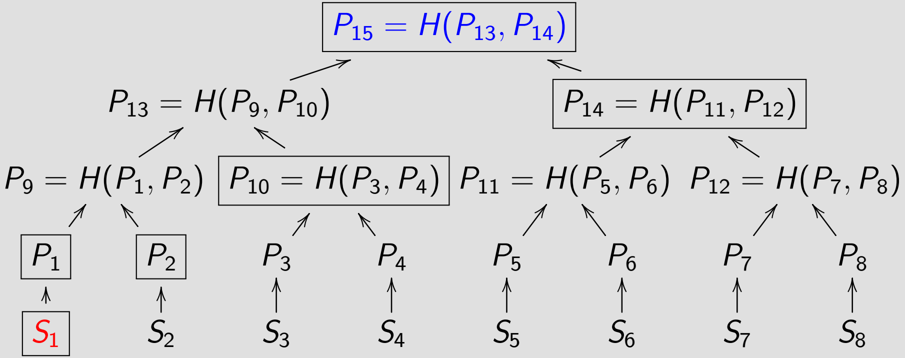


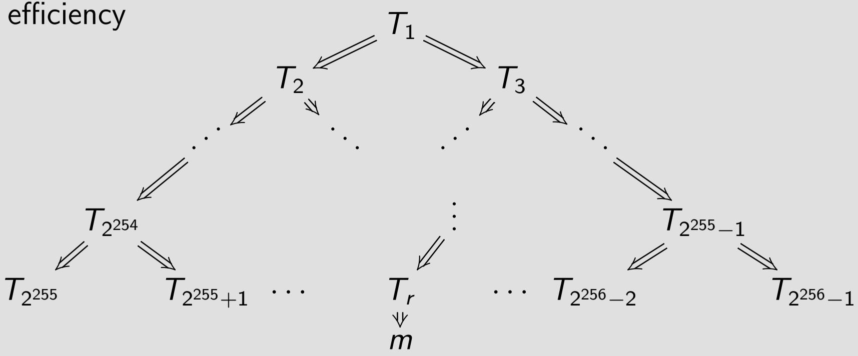
Verify signature $\texttt{sign}(m, S_1)$ with public key P_1 (provided in signature).
Link P_1 against public key P_{15} by computing $P'_9 = H(P_1, P_2)$, $P'_{13} = H(P'_9, P_{10})$, and comparing $H(P'_{13}, P_{14})$ with P_{15}. Reject if $H(P'_{13}, P_{14}) \neq P_{15}$.

Huge trees (1987 Goldreich), keys on demand (Levin)

Signer chooses random $r \in \{2^{255}, 2^{255}+1, \ldots, 2^{256}-1\}$, uses one-time public key T_r to sign m; uses one-time public key T_i to sign (T_{2i}, T_{2i+1}) on path to T_1.

Generates ith secret key deterministically as $H_k(i)$ where k is master secret.

Important for efficiency



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$$
\begin{tikzcd}
 & & & T_1 \arrow[dl, Rightarrow] \arrow[dr, Rightarrow] & & & \\
 & & T_2 \arrow[dl, Rightarrow] \arrow[d, Rightarrow] & & T_3 \arrow[d, Rightarrow] \arrow[dr, Rightarrow] & & \\
 & \iddots \arrow[d, Rightarrow] & \ddots & & \iddots & \ddots \arrow[d, Rightarrow] & \\
 & T_{2^{254}} \arrow[dl, Rightarrow] \arrow[d, Rightarrow] & & \vdots \arrow[d, Rightarrow] & & T_{2^{255}-1} \arrow[d, Rightarrow] \arrow[dr, Rightarrow] & \\
T_{2^{255}} & T_{2^{255}+1} & \cdots & T_r \arrow[d, Rightarrow] & \cdots & T_{2^{256}-2} & T_{2^{256}-1} \\
 & & & m & & &
\end{tikzcd}
$$

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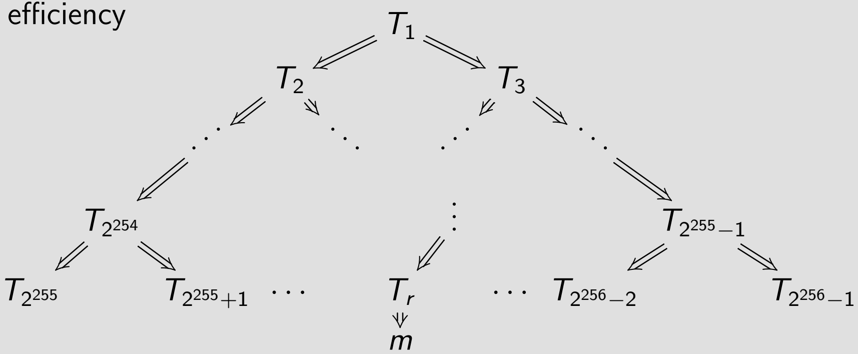

T_i for small i gets used repeatedly (each time an m falls in that sub-tree) but $H_k(i)$ being deterministic means it signs the same value, so no break.

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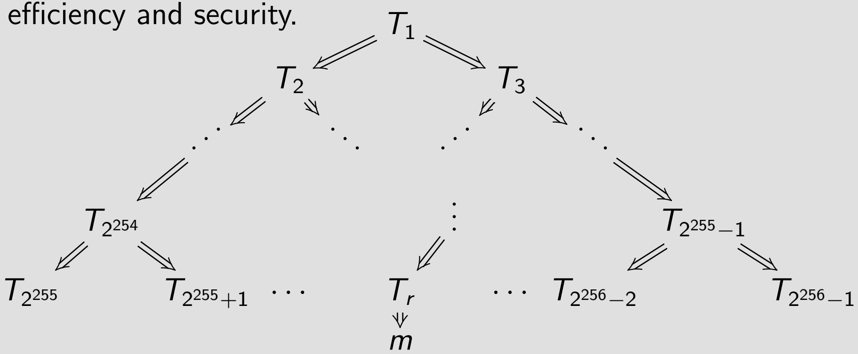
Generates ith secret key deterministically as $H_k(i)$ where k is master secret.
Important for efficiency and security.



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NIST submission SPHINCS+

- Post-quantum signature based on hash functions.
- Requires only a secure hash function, no further assumptions.
- Based on ideas of Lamport (1979) and Merkle (1979).
- Developed starting from SPHINCS with
  - improve multi-signature,
  - smaller keys,
  - Option for shorter signatures (30kB instead of 41kB) if "only" 2^{50} messages signed.
- Three versions (using different hash functions)
  - SPHINCS+-SHA3 (with SHAKE256),
  - SPHINCS+-SHA2 (with SHA-256),
  - SPHINCS+-Haraka (with Haraka, a hash function for short inputs).

More info at `https://sphincs.org/`.

See also my course page for more detailed videos and slides.