HAETAE

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February 27, 2024
2024 KpqC Winter Camp

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- Digital signature scheme
- Secure against quantum attacks!
  - based on **lattice hard problems** MLWE and MSIS
  - follows **Fiat-Shamir with aborts** framework, secure in QROM
- Simple but short!
  - simpler than Falcon[1] & shorter than Dilithium[1]
  - optimal rejection rate with simple rejection condition
- Design rationale
  - **Bimodal** rejection sampling
  - **Hyperball** distribution
- Candidate in *KpqC 2nd round & NIST PQC Additional Signatures*[2]

[1] NIST 2022 PQC signature standards
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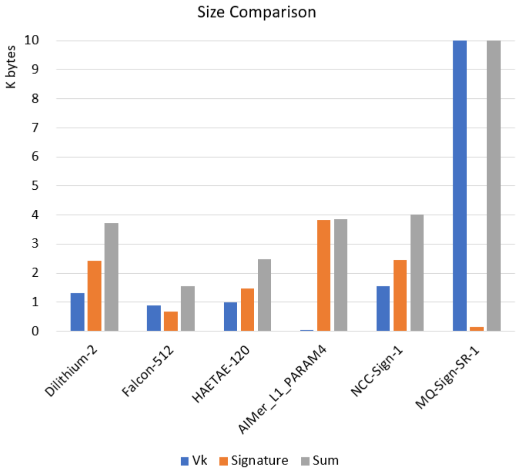
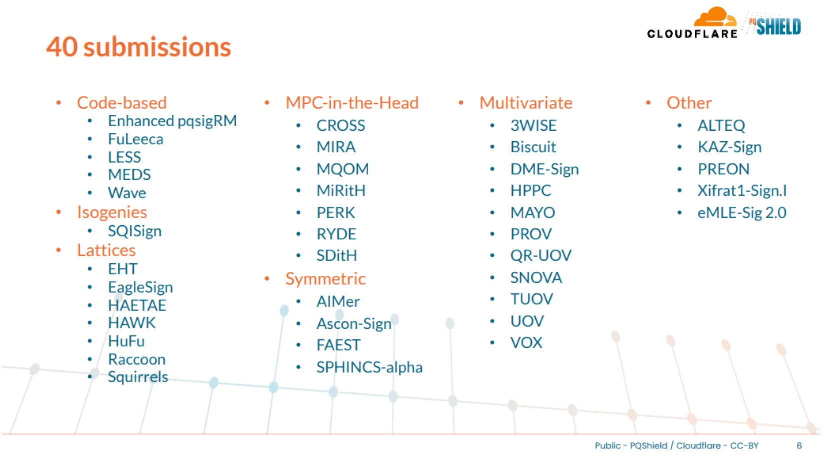


Figure: KpqC round 2, signature schemes

HAETAE



Slide from `https://datatracker.ietf.org/meeting/117/materials/slides-117-tls-new-post-quantum-signature-algorithms-on-the-horizon-00`

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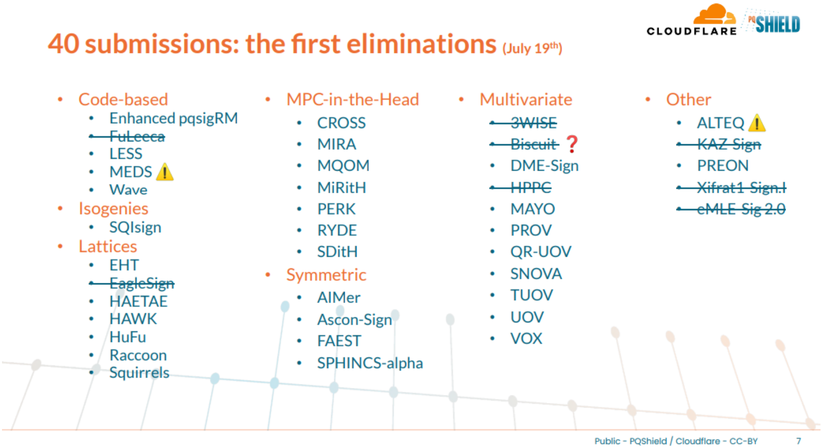

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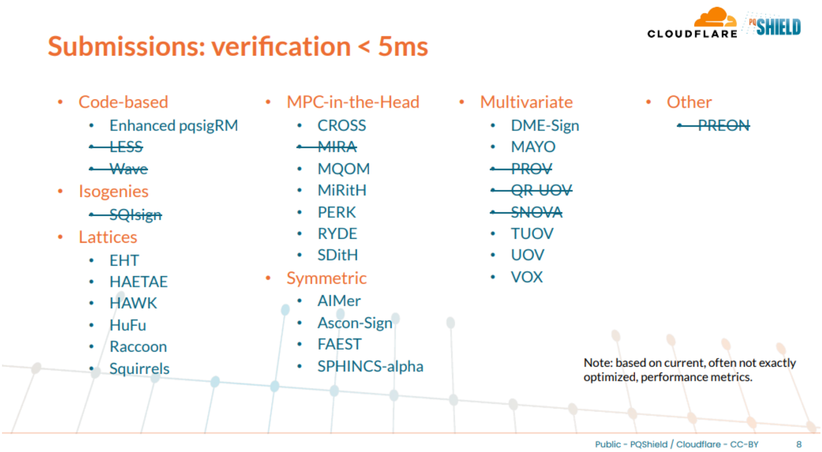

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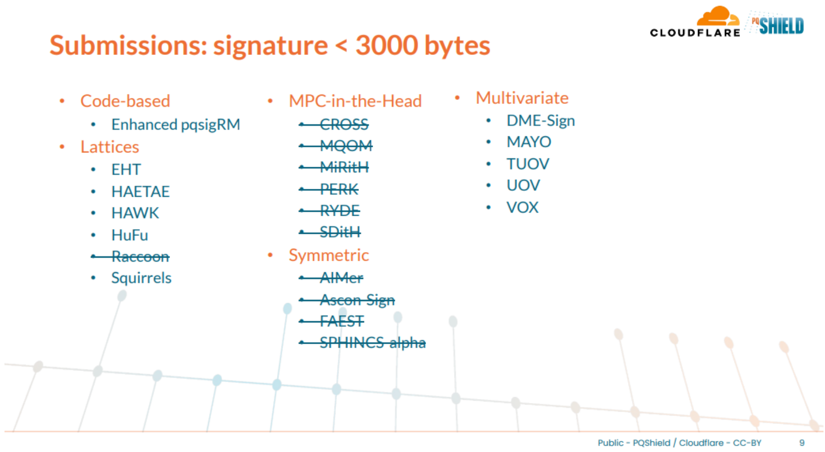

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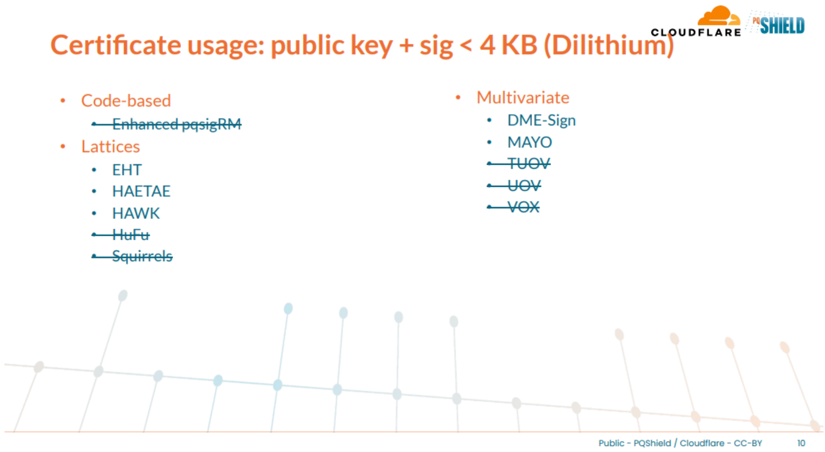

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1. Brief Introduction to HAETAE

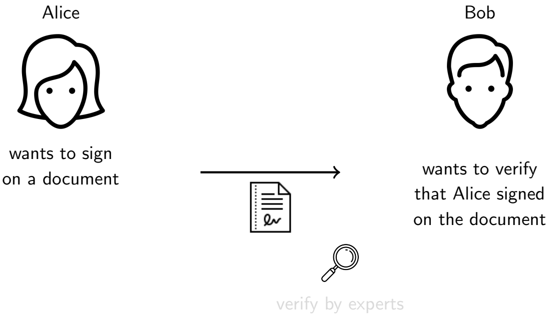
2. Preliminaries:
   - Digital signatures
   - Lattice hard problems
   - Lattice-based signatures
     - Bimodal rejection sampling

3. HAETAE:
   - Hyperball bimodal rejection sampling
   - Comparison to SotA lattice signatures

4. Changes after Round 1

Digital signatures

Conventional signatures:



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Digital signatures

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Digital signatures

Conventional signatures:

Alice

wants to sign
on a document

Bob

wants to verify
that Alice signed
on the document

verify by experts

Digital signatures:

(sk, vk) $\leftarrow$ KeyGen and broadcast vk

Alice (knows sk)

signature $\sigma \leftarrow \mathsf{Sign}(\mathsf{sk}, m)$

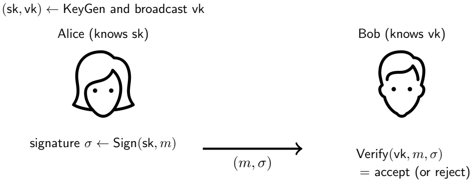
$$\xrightarrow[(m,\sigma)]{}$$

Bob (knows vk)

$\mathsf{Verify}(\mathsf{vk}, m, \sigma)$
$=$ accept (or reject)

Digital signatures

Digital signatures:



Anyone (who can access vk) can verify that (m, σ) is from Alice or not!

Correctness: Verify(vk, m, Sign(sk, m)) = accept

Unforgeability: No one but Alice can make a new signature.

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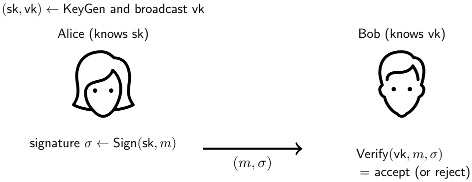

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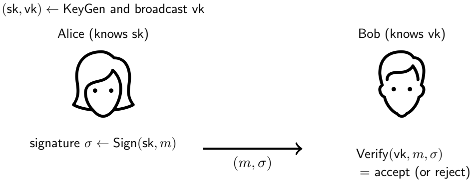

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Lattice hard problems

Lattice-based cryptography is ... are currently important candidates for post-quantum cryptography.

- *Wikipedia* -

Lattice-based cryptography bases its security on lattice hard problems, which have strong theoretical backgrounds:

- SVP and GapSVP$_\lambda$: NP-hard! [Ajt96, HR07]
- Worst-case to average-case **reductions** [Ajt96]
- Useful hard problems: NTRU, LWE, SIS, MLWE, MSIS, etc

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Lattice hard problems

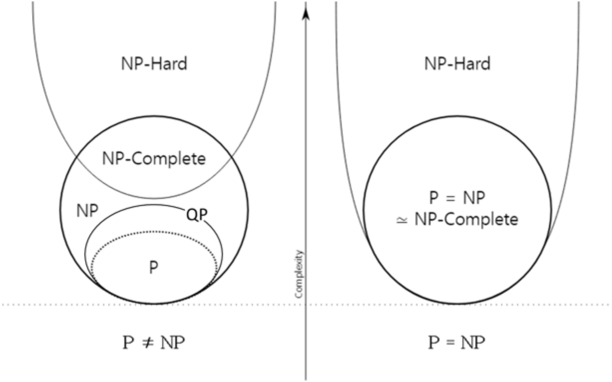
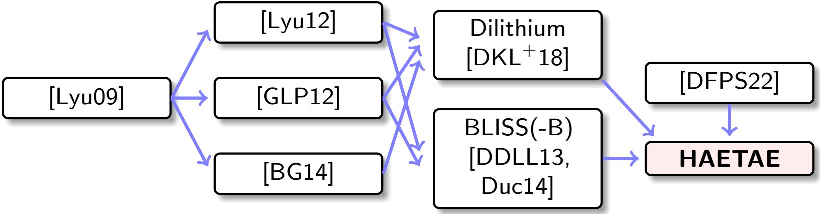


Figure: Category of hard problems when P≠NP and P=NP.

No proofs for Quantum Poly (QP), but is believed to be separated to NP-Hard problems.

Lattice-based signatures

Fiat-Shamir with abort



Hash-and-Sign

Lattice-based signatures

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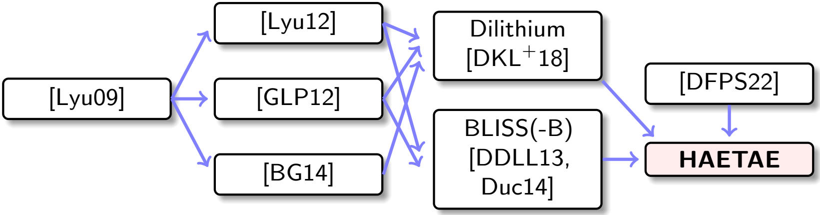

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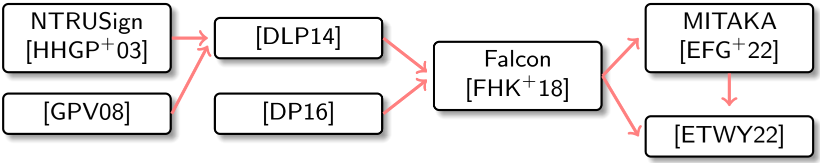


Lattice-based signatures

Fiat-Shamir with abort:

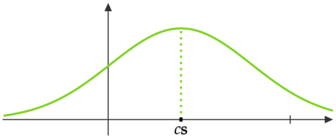
For secret $\mathbf{s}$, random $\mathbf{y}$, c, signature $\sigma = (c, \mathbf{z} = \mathbf{y} + c\mathbf{s})$

$$\left(\boxed{8}, \begin{bmatrix} 9 \\ -9 \\ 6 \\ 2 \\ 1 \\ 11 \\ 8 \\ -9 \end{bmatrix} = \begin{bmatrix} 1 \\ -1 \\ -2 \\ 2 \\ 1 \\ 3 \\ 0 \\ -1 \end{bmatrix} + \boxed{8} \begin{bmatrix} 1 \\ -1 \\ 1 \\ 0 \\ 0 \\ 1 \\ 1 \\ -1 \end{bmatrix} \right)$$

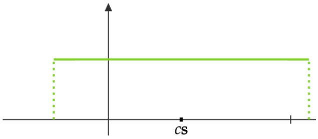
Lattice-based signatures

Leakage from $(c, \mathbf{z} = \mathbf{y} + c\mathbf{s})$?

(High-level) With ∞ pairs of $(c, \mathbf{z} = \mathbf{y} + c\mathbf{s})$, we may collect $\mathbf{z}$ for same c:



($y \leftarrow \mathcal{N}(0, \sigma^2)$)



($y \leftarrow U[-a, a]$)

$\Rightarrow$ Recover $\mathbf{s}$ from $c\mathbf{s}$.

How to make it safe?

$$(c, \mathbf{z} = \mathbf{y} + c\mathbf{z}) \xrightarrow[\text{Rejection Sampling}]{\text{several trials}} \sigma = (c, \mathbf{z} = \mathbf{y} + c\mathbf{z})$$

not safe safe

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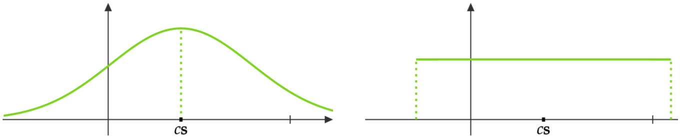

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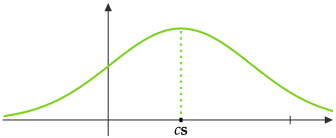

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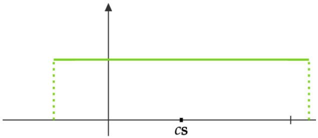

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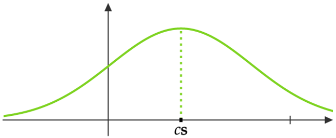

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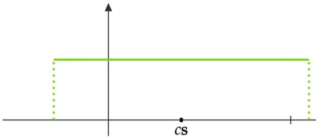

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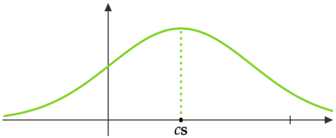

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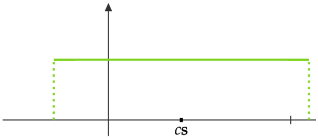

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$$\underset{\text{not safe}}{(c, \mathbf{z} = \mathbf{y} + c\mathbf{z})} \xrightarrow[\text{Rejection Sampling}]{\text{several trials}} \underset{\text{safe}}{\sigma = (c, \mathbf{z} = \mathbf{y} + c\mathbf{z})}$$

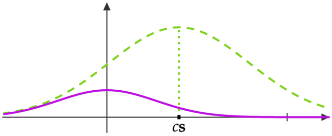
Rejection sampling

Rejection sampling

$$D_{\text{source}} = \{(c, \mathbf{z})\} \xrightarrow[\text{prob. } p(c,\mathbf{z})]{\text{reject with}} D_{\text{target}}$$

distribution of $(c, \mathbf{z})$, possibly leak $\mathbf{s}$

new distribution, independent of $\mathbf{s}$



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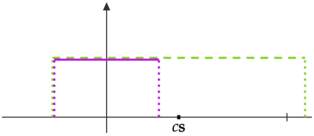

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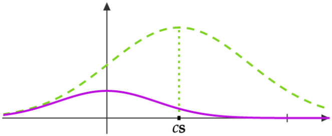

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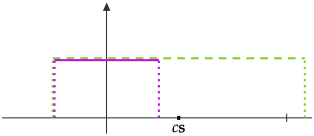


$$y \leftarrow U[-a, a]$$

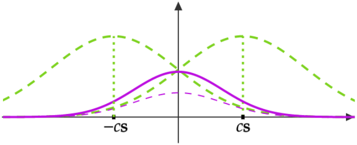
Bimodal rejection sampling

Run-time $\propto M$ ($\approx$ green area / purple area).

To decrease M, [DDLL13] uses

$$\mathbf{z} = \mathbf{y} + (-1)^b c\mathbf{s}$$

instead of $\mathbf{z} = \mathbf{y} + c\mathbf{s}$:



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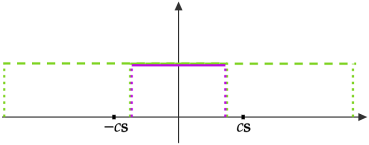

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Note, no change for the uniform case.

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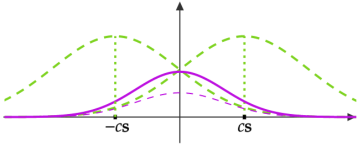

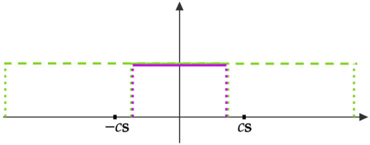

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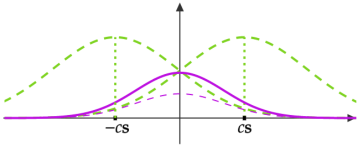

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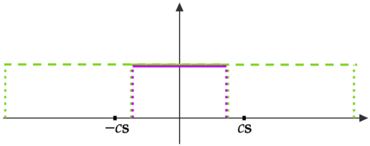

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Bimodal rejection sampling

However, this makes "secure" implementation[3] much harder. It is basically due to "reject with probability a (transcendental) function of sk."

For e.g., for ≈120 bits security[4][5],

[3] an implementation secure against physical attacks (side-channel attacks)

[4] core-SVP hardness

[5] size= |sig| + |vk|

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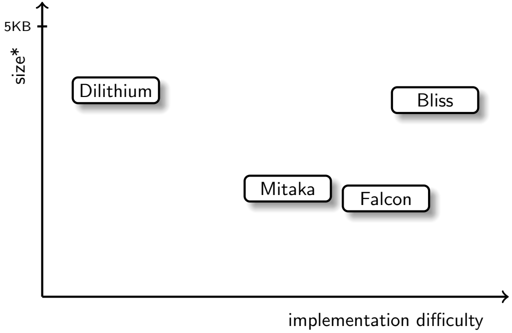

[3] an implementation secure against physical attacks (side-channel attacks)
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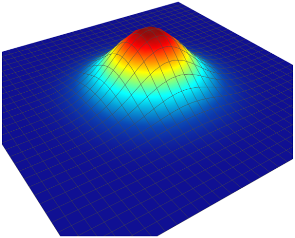
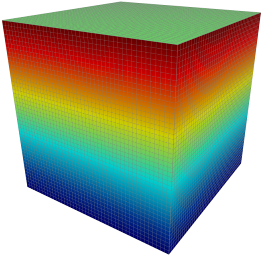
Hyperball bimodal rejection sampling

Previously, the randomness $\mathbf{y}$ was chosen from either discrete Gaussian or uniform hypercube[6].



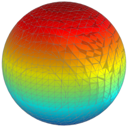


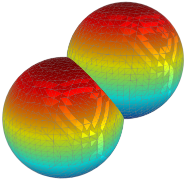
[6] The vectors $\mathbf{y}$ and $\mathbf{z}$ are high-dimensional vectors, so uniform in an interval is indeed a uniform hypercube.

Hyperball bimodal rejection sampling

We, instead, use **uniform hyperball** distribution for sampling $\mathbf{y}$ [DFPS22];

- to exploit optimal M,
- to reduce signature and verification key sizes,





based on the **bimodal approach** [DDLL13].

Hyperball bimodal rejection sampling

We, instead, use **uniform hyperball** distribution for sampling $\mathbf{y}$ [DFPS22];

- to exploit optimal M,
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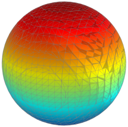
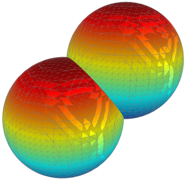


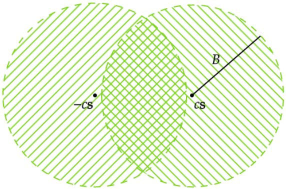


based on the **bimodal approach** [DDLL13].

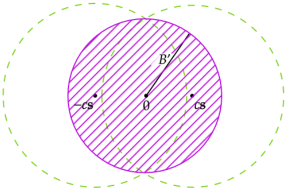
Hyperball bimodal rejection sampling

We reject $(c, \mathbf{z}) \sim D_\mathsf{s}$ (with p.d.f. p_s) to a target distribution D_t (with p.d.f. p_t), where

- p_s: uniform in hyperballs of radii B centered at $\pm c\mathbf{s}$
  - union of two large balls
- p_t: uniform in a smaller hyperball of radii B' centered at zero
  - a smaller ball in the middle



p_s



p_t

Hyperball bimodal rejection sampling

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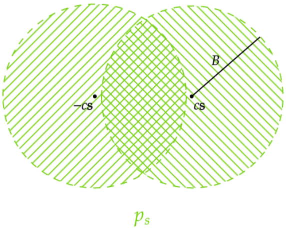

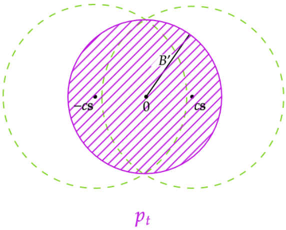

Hyperball bimodal rejection sampling

- $p_{\mathsf{s}}(\mathbf{x}) = \frac{1}{2\cdot\mathsf{vol}(\mathcal{B}(B))} \cdot \chi_{\|\mathbf{z}-c\mathbf{s}\|<B} + \frac{1}{2\cdot\mathsf{vol}(\mathcal{B}(B))} \cdot \chi_{\|\mathbf{z}+c\mathbf{s}\|<B}$,
- $p_{\mathsf{t}}(\mathbf{x}) = \frac{1}{\mathsf{vol}(\mathcal{B}(B))} \cdot \chi_{\|\mathbf{z}\|<B'}$.

$$\Rightarrow p(\mathbf{x}) = \frac{p_{\mathsf{t}}(\mathbf{x})}{M \cdot p_{\mathsf{s}}(\mathbf{x})} = \frac{\chi_{\|\mathbf{z}\|<B'}}{\chi_{\|\mathbf{z}-c\mathbf{s}\|<B} + \chi_{\|\mathbf{z}+c\mathbf{s}\|<B}}$$

$$= \begin{cases} 0 & \text{if } \mathbf{z} \notin \mathcal{B}(B'), \\ 1/2 & \text{if } \mathbf{z} \in \mathcal{B}(B') \cap \mathcal{B}(B, c\mathbf{s}) \cap \mathcal{B}(B, -c\mathbf{s}), \\ 1 & \text{if } \mathbf{z} \in \mathcal{B}(B') \setminus (\mathcal{B}(B, c\mathbf{s}) \cap \mathcal{B}(B, -c\mathbf{s})), \end{cases}$$

for some $M > 0$.

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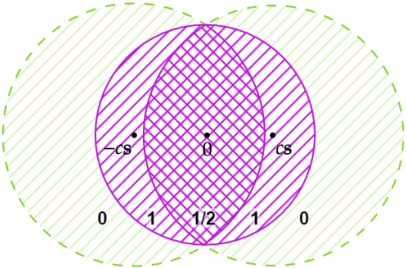
Hyperball bimodal rejection sampling

That is, we return $\mathbf{x} = (c, \mathbf{z})$ with probability

- 0: if $\|\mathbf{z}\| \geq B'$,
- 1/2: else if $\|\mathbf{z} - c\mathbf{s}\| < B$ and $\|\mathbf{z} + c\mathbf{s}\| < B$,
- 1: otherwise.



1. Brief Introduction to HAETAE

2. Preliminaries:
   - Digital signatures
   - Lattice hard problems
   - Lattice-based signatures
     - Bimodal rejection sampling

3. HAETAE:
   - Hyperball bimodal rejection sampling
   - Comparison to SotA lattice signatures

4. Changes after Round 1

Comparison to SotA lattice signatures.

For 120-bit classical security. Sizes are in bytes.

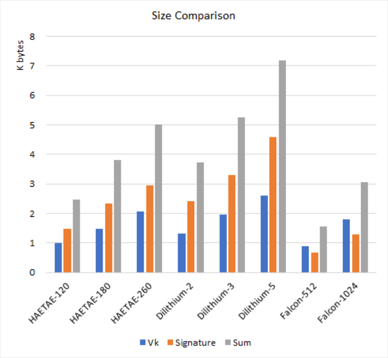
Scheme	sig	vk	KeyGen	Sign	
				sampling	rejection
Dilithium-2	2420	1312	fast	Hypercube	$\|\cdot\|_\infty < B$
Bliss-1024[7]	1700	1792	fast	dGaussian at 0	reject with prob. f(sk, Sig)
HAETAE120	1468	1056	fast	dHyperball at 0	$\|\cdot\|_2 < B$
Mitaka-512[8]	713	896	slow	dGaussian at 0 & intGaussian at $H(m)$	none
Falcon-512	666	897	slow	dGaussian at $H(m)$	none

Table: Comparison between different lattice-based signature schemes.

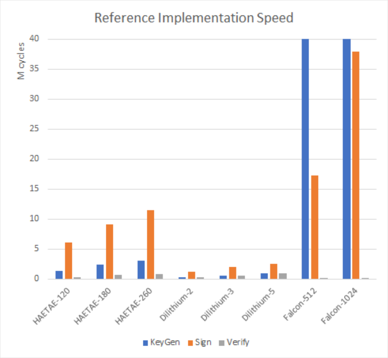
[7] modified Bliss (to ≥ 120 bit-security) in Dilithium paper.

[8] Mitaka-512 has 102 bits of security

Numbers - Updated Reference Implementation

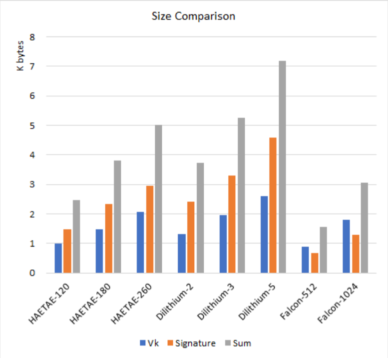


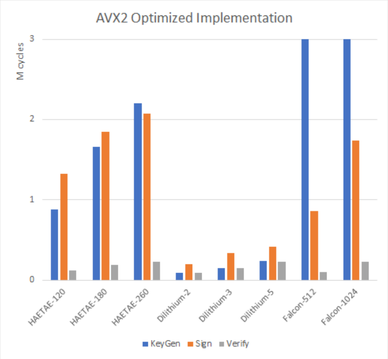
Size



Performance

Numbers - AVX2 optimized Implementation



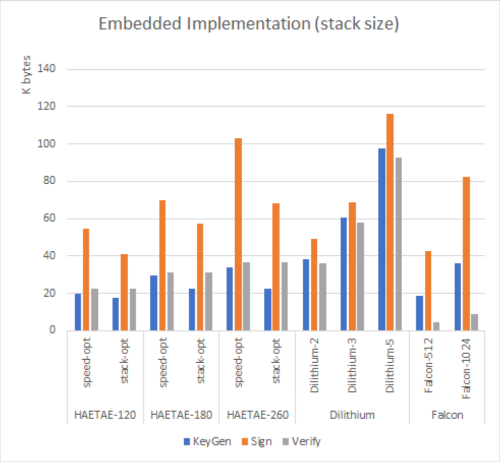


Size

Performance

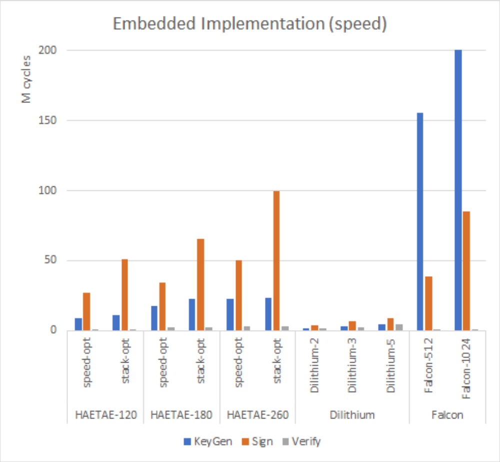
Numbers - Embedded Implementation on Cortex-M4

Stack-size of HAETAE and others on Cortex-M4.



Numbers - Embedded Implementation on Cortex-M4

Speed of HAETAE and others on Cortex-M4.



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May, 2023 (v1.0)

- spec: missing parts inclusion, min-entropy analysis
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- implementation: fixed-point, constant-time

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which can be efficiently checked.

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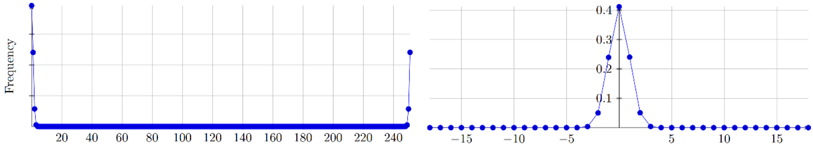

(a) h Coefficient values **(b)** HB($\mathbf{z_1}$) Coefficient values

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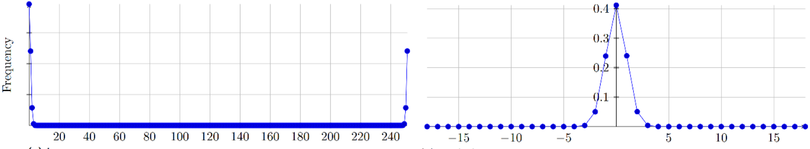

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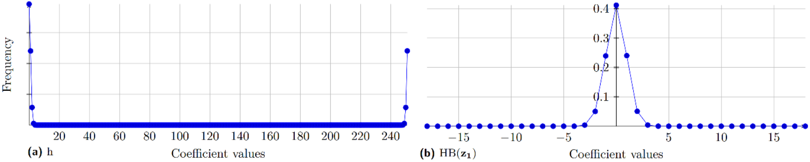

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Thanks!

Check http://kpqc.cryptolab.co.kr/haetae!

Check https://github.com/mupq/pqm4 for the *embedded code*!

Any question?

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HAETAE description (high-level)

KeyGen(1^λ)

1: $\mathbf{A}_{\text{gen}} \leftarrow \mathcal{R}_q^{k\times(\ell-1)}$ and $(\mathbf{s}_{\text{gen}}, \mathbf{e}_{\text{gen}}) \leftarrow S_\eta^{\ell-1} \times S_\eta^k$
2: $\mathbf{b} = \mathbf{A}_{\text{gen}} \cdot \mathbf{s}_{\text{gen}} + \mathbf{e}_{\text{gen}} \in \mathcal{R}_q^k$
3: $\mathbf{A} = (-2\mathbf{b} + q\mathbf{j} \,|\, 2\mathbf{A}_{\text{gen}} \,|\, 2\mathbf{Id}_k) \bmod 2q$ and write $\mathbf{A} = (\mathbf{A}_1 \,|\, 2\mathbf{Id}_k)$
4: $\mathbf{s} = (1, \mathbf{s}_{\text{gen}}, \mathbf{e}_{\text{gen}})$
5: if $\sigma_{\max}(\mathrm{rot}(\mathbf{s}_{\text{gen}})) > \gamma$, then restart
6: Return $\mathsf{sk} = \mathbf{s}$, $\mathsf{vk} = \mathbf{A}$

Sign(sk, M)

1: $\mathbf{y} \leftarrow U(\mathcal{B}_{(1/N)\mathcal{R},(k+\ell)}(B))$
2: $c = H(\mathrm{HighBits}_{2q}^{\mathrm{hint}}(\mathbf{A}\lfloor\mathbf{y}\rceil, \alpha), \mathrm{LSB}(\lfloor y_0 \rceil), M) \in \mathcal{R}_2$
3: $\mathbf{z} = (\mathbf{z}_1, \mathbf{z}_2) = \mathbf{y} + (-1)^b c \cdot \mathbf{s}$ for $b \leftarrow U(\{0,1\})$
4: $\mathbf{h} = \mathrm{HighBits}_{2q}^{\mathrm{hint}}(\mathbf{A}\lfloor\mathbf{z}\rceil - qc\mathbf{j}, \alpha) - \mathrm{HighBits}_{2q}^{\mathrm{hint}}(\mathbf{A}_1\lfloor\mathbf{z}_1\rceil - qc\mathbf{j}, \alpha) \bmod^{+} \frac{2(q-1)}{\alpha}$
5: if $\|\mathbf{z}\|_2 \geq B'$, then restart
6: if $\|2\mathbf{z} - \mathbf{y}\|_2 < B$, then restart with probability $1/2$
7: Return $\sigma = (\mathrm{Encode}(\mathrm{HighBits}(\lfloor\mathbf{z}_1\rceil, a)), \mathrm{LowBits}(\lfloor\mathbf{z}_1\rceil, a), \mathrm{Encode}(\mathbf{h}), c)$

Verify$(\mathsf{vk}, M, \sigma = (x, \mathbf{v}, h, c))$

1: $\tilde{\mathbf{z}}_1 = \mathrm{Decode}(x) \cdot a + \mathbf{v}$ and $\tilde{\mathbf{h}} = \mathrm{Decode}(h)$
2: $\mathbf{w} = \tilde{\mathbf{h}} + \mathrm{HighBits}_{2q}^{\mathrm{hint}}(\mathbf{A}_1\tilde{\mathbf{z}}_1 - qc\mathbf{j}, \alpha) \bmod^{+} \frac{2(q-1)}{\alpha}$
3: $w' = \mathrm{LSB}(\tilde{z}_0 - c)$
4: $\tilde{\mathbf{z}}_2 = \left[\mathbf{w} \cdot \alpha + w'\mathbf{j} - (\mathbf{A}_1\tilde{z}_1 - qc\mathbf{j})\right]/2 \bmod^{\pm} q$
5: $\tilde{\mathbf{z}} = (\tilde{\mathbf{z}}_1, \tilde{\mathbf{z}}_2)$
6: Return $(\, c = H(\mathbf{w}, w', M) \,) \wedge (\, \|\tilde{\mathbf{z}}\| < B'' \,)$