

# GPV SIGNATURES (HASH-THEN-SIGN SIGNATURES)

ADVANCED TOPICS IN CYBERSECURITY CRYPTOGRAPHY (7CCSMATC)

---

Martin R. Albrecht



# Falcon (signature scheme)

文 A 1 language ▾

Article Talk

Read Edit View history Tools ▾

From Wikipedia, the free encyclopedia

**Falcon** is a [post-quantum signature scheme](#) selected by the [NIST](#) at the fourth round of the [post-quantum standardisation](#) process. It was designed by Thomas Prest, Pierre-Alain Fouque, [Jeffrey Hoffstein](#), Paul Kirchner, Vadim Lyubashevsky, Thomas Pornin, Thomas Ricosset, Gregor Seiler, William Whyte, and Zhenfei Zhang. [\[1\]](#)[\[2\]](#)[\[3\]](#) It relies on the hash-and-sign technique over the [Gentry](#), Peikert, and [Vaikuntanathan](#) framework<sup>[4]</sup> over [NTRU lattices](#). The name *Falcon* is an acronym for ***Fast Fourier lattice-based compact signatures over NTRU***.

# OUTLINE

Lattices

q-ary Lattices

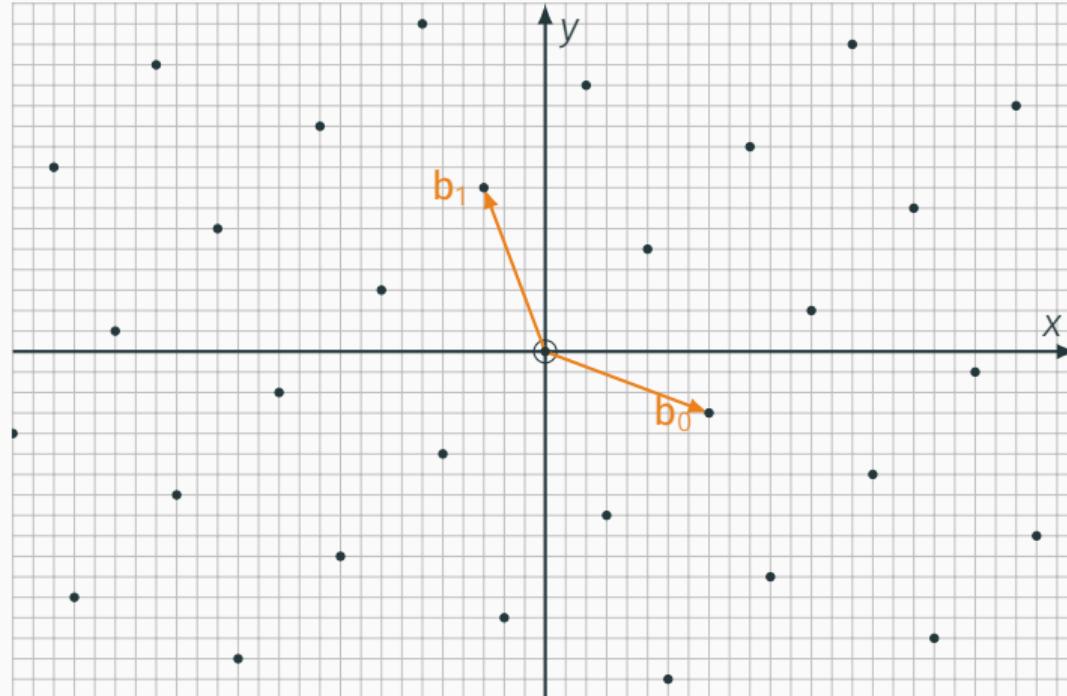
GPV Signatures

Security Proof

## LATTICES

---

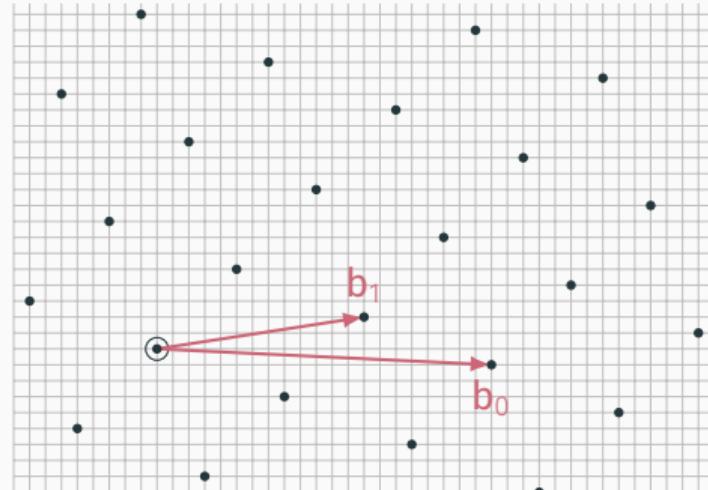
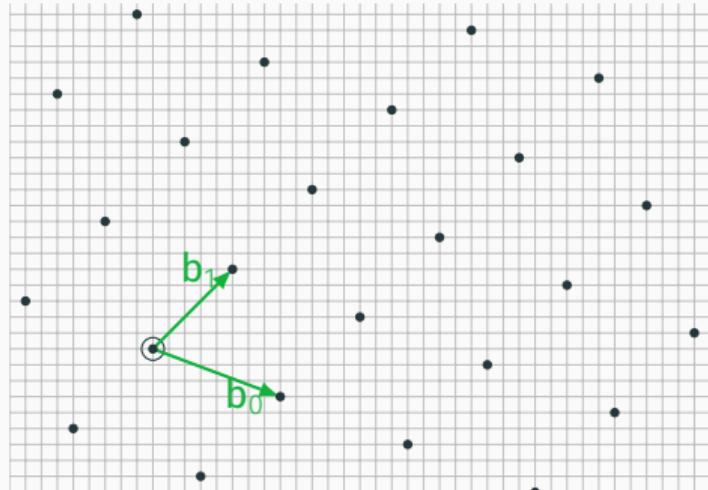
# LATTICES



A lattice  $\Lambda$  is a discrete subgroup of  $\mathbb{R}^d$ .

Picture credit: Léo Ducas

# LATTICE BASES



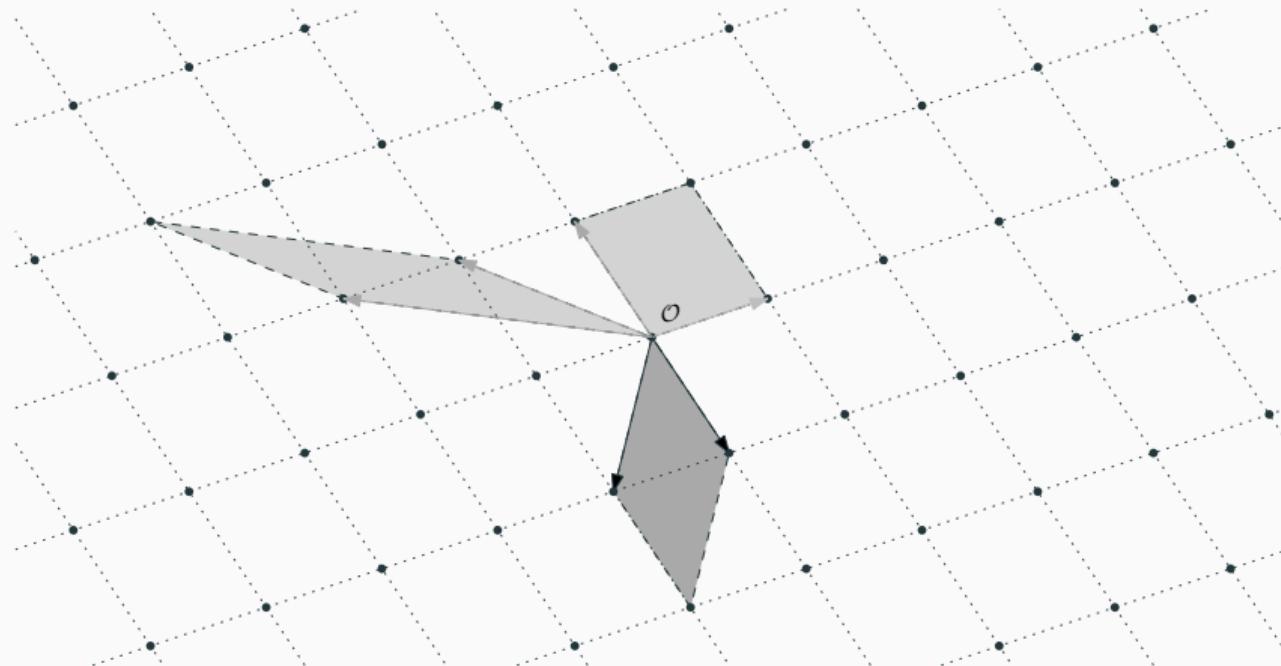
---

**G** → **B** : easy (compute Hermite Normal form);  
**B** → **G** : hard (BKZ, lattice sieve ...).

---

# LATTICE VOLUME I

The volume of a lattice is the volume of its fundamental domain.



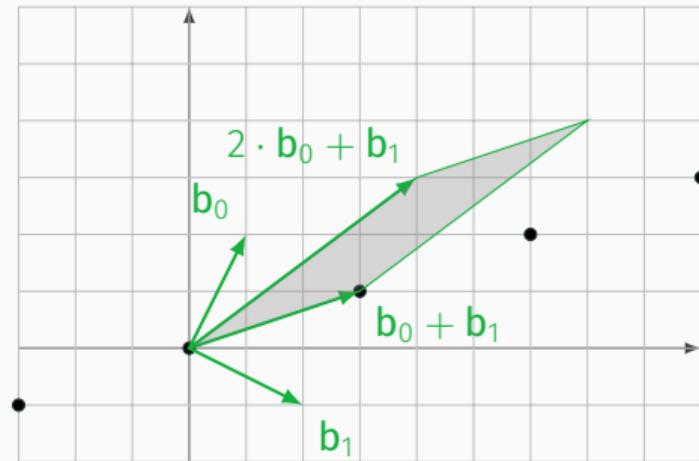
## LATTICE VOLUME II

For any two bases  $\mathbf{G}$ ,  $\mathbf{B}$  of the same lattice  $\Lambda$ :

$$\det(\mathbf{G} \cdot \mathbf{G}^T) = \det(\mathbf{B} \cdot \mathbf{B}^T).$$

We can therefore define:

$$\text{Vol}(\Lambda) = \sqrt{\det(\mathbf{B} \cdot \mathbf{B}^T)}.$$



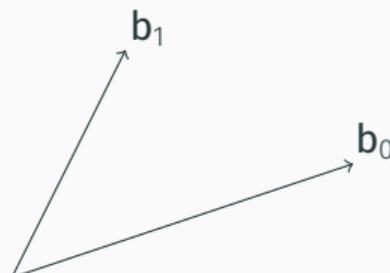
Picture credit: <https://tex.stackexchange.com/a/42559>

## LENGTH OF GRAM-SCHMIDT VECTORS

It will be useful to consider the lengths of the Gram–Schmidt vectors.

The vector  $\mathbf{b}_i^*$  is the orthogonal projection of  $\mathbf{b}_i$  to the space spanned by the vectors  $\mathbf{b}_0, \dots, \mathbf{b}_{i-1}$ .

Informally, this means taking out the contributions in the directions of previous vectors  $\mathbf{b}_0, \dots, \mathbf{b}_{i-1}$ .

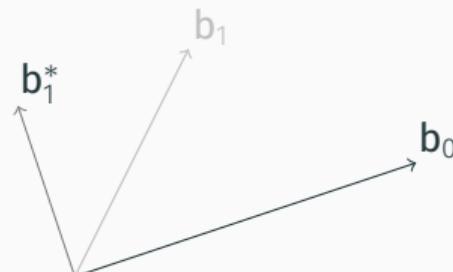


## LENGTH OF GRAM-SCHMIDT VECTORS

It will be useful to consider the lengths of the Gram–Schmidt vectors.

The vector  $\mathbf{b}_i^*$  is the orthogonal projection of  $\mathbf{b}_i$  to the space spanned by the vectors  $\mathbf{b}_0, \dots, \mathbf{b}_{i-1}$ .

Informally, this means taking out the contributions in the directions of previous vectors  $\mathbf{b}_0, \dots, \mathbf{b}_{i-1}$ .



## GRAM-SCHMIDT VECTORS AND LATTICE VOLUMES

Let  $\mathbf{B}^*$  be the Gram–Schmidt Orthogonalisation of  $\mathbf{B}$ . The matrix  $\mathbf{B}^*$  is **not** a basis for  $\Lambda$ , but

$$\text{Vol}(\Lambda) = \sqrt{\det(\mathbf{B}^* \cdot \mathbf{B}^{*T})} = \prod \| \mathbf{b}_i^* \| .$$

## “GOOD” BASES

Recall that, independently of the basis  $\mathbf{B}$  it hold that:

$$\text{vol}(\Lambda) = \prod \|\mathbf{b}_i^*\|.$$

Therefore, it is somehow equivalent that

- $\max_i \|\mathbf{b}_i^*\|$  is small
- $\min_i \|\mathbf{b}_i^*\|$  is large
- $\kappa(\mathbf{B}) = \min_i \|\mathbf{b}_i^*\| / \max_i \|\mathbf{b}_i^*\|$  is small

### Good Basis

$$\kappa(\mathbf{G}) = \text{poly}(d), \quad \forall i : \|\mathbf{g}_i^*\| = \text{poly}(d) \cdot \text{Vol}(\Lambda)^{1/d}.$$

### LLL-reduced Basis

$$\kappa(\mathbf{G}) \approx (1.04)^d, \quad \max_i \|\mathbf{g}_i^*\| \approx (1.02)^d \cdot \text{Vol}(\Lambda)^{1/d}.$$

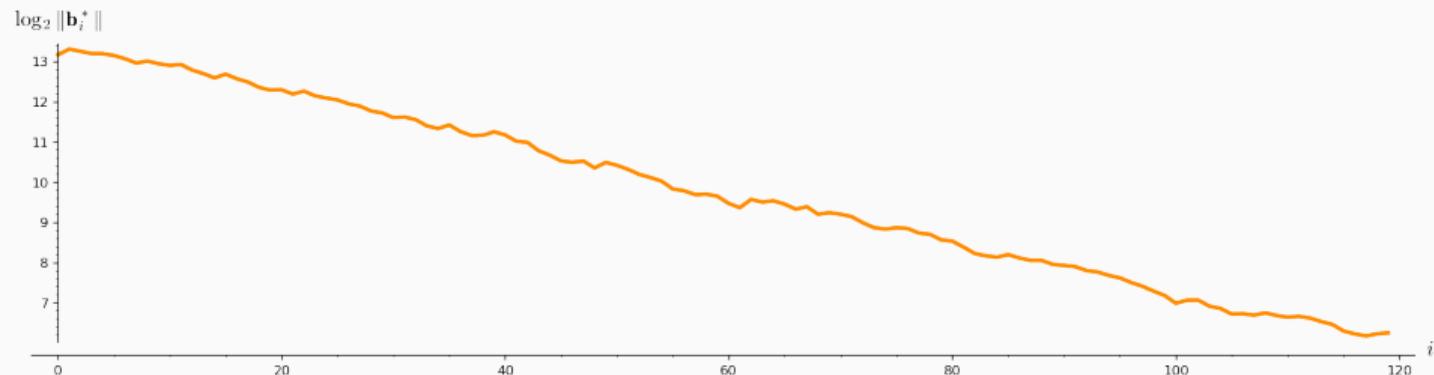
## EXAMPLE GRAM-SCHMIDT “SHAPE”

```
A = IntegerMatrix.random(120, "qary", k=60, bits=20)[::-1]
M = GS0.Mat(A, update=True)
line([(i,log(r_, 2)/2) for i, r_ in enumerate(M.r())]), **plot_kwds)
```



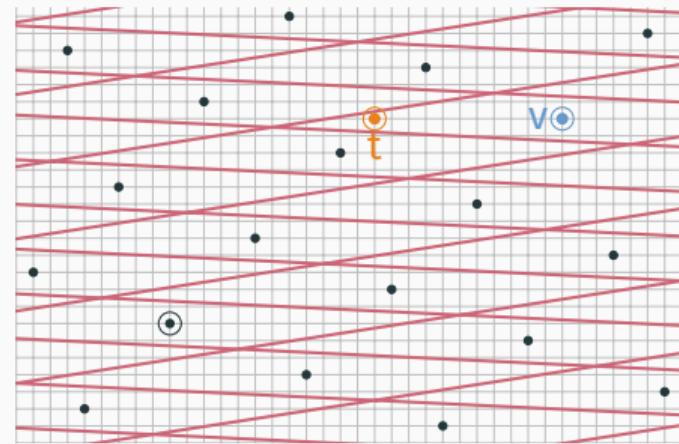
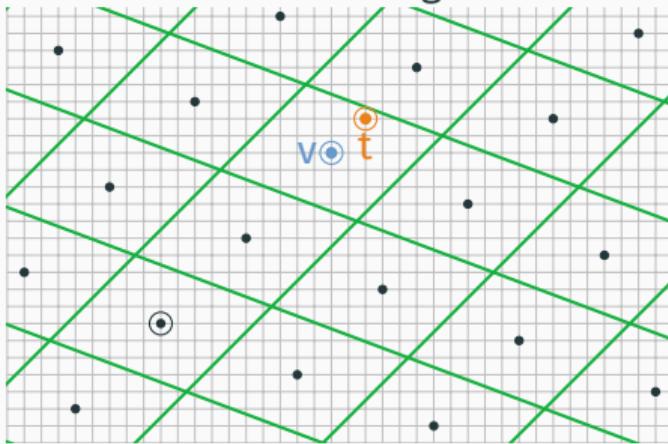
## EXAMPLE GRAM-SCHMIDT “SHAPE” AFTER LLL

```
A = LLL.reduction(A)
M = GS0.Mat(A, update=True)
line([(i,log(r_, 2)/2) for i, r_ in enumerate(M.r())], **plot_kwds)
```



# BASES AND FUNDAMENTAL DOMAINS

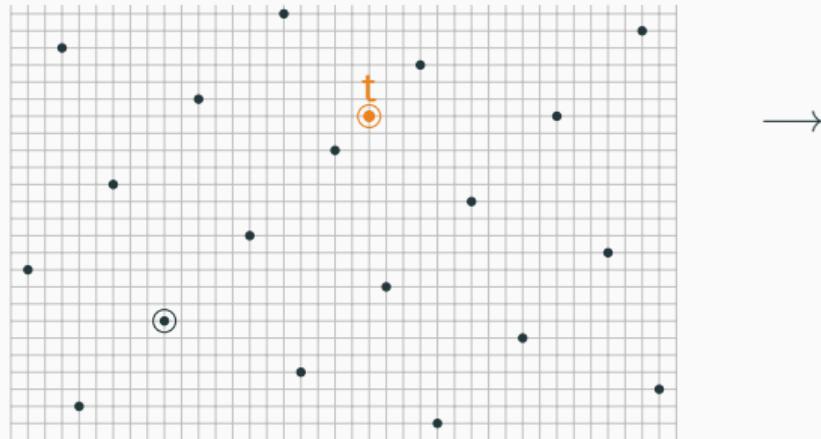
Each basis defines a **tiling**.



Round'off Algorithm [Lenstra, Babai]:

Given a target  $t$ , find  $v \in \Lambda$  at the center the tile.

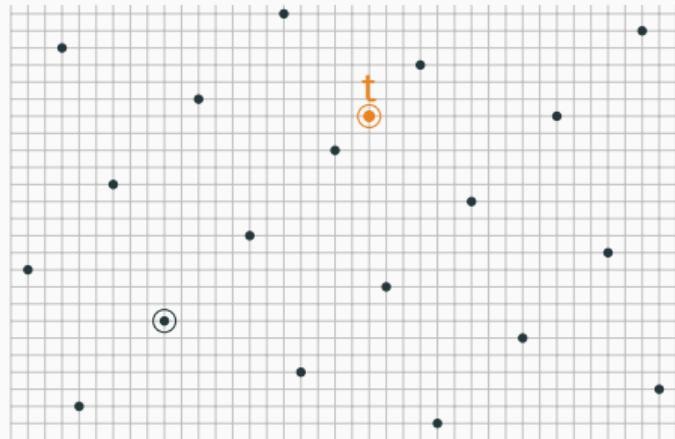
# ROUND OFF ALGORITHM



Round Off Algorithm  
[Lenstra,Babai]:

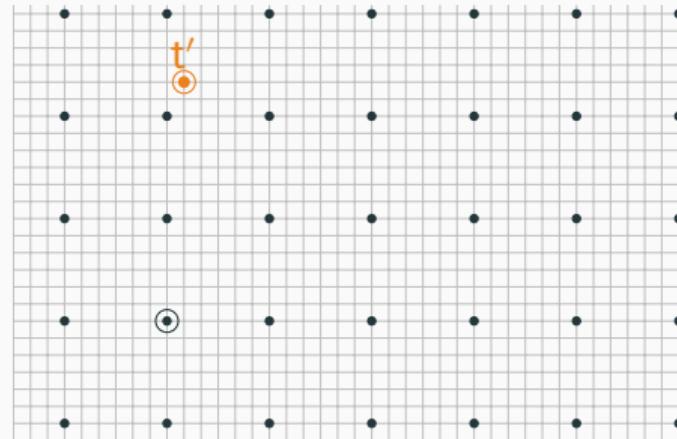
Credit: Léo Ducas

# ROUND OFF ALGORITHM



$$\cdot \mathbf{B}^{-1}$$

→

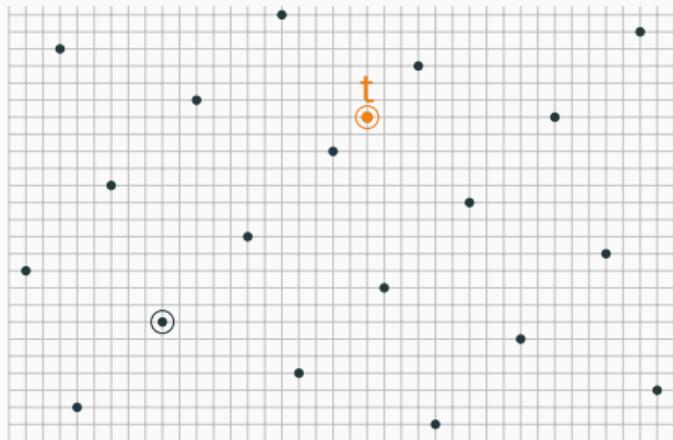


Round Off Algorithm  
[Lenstra,Babai]:

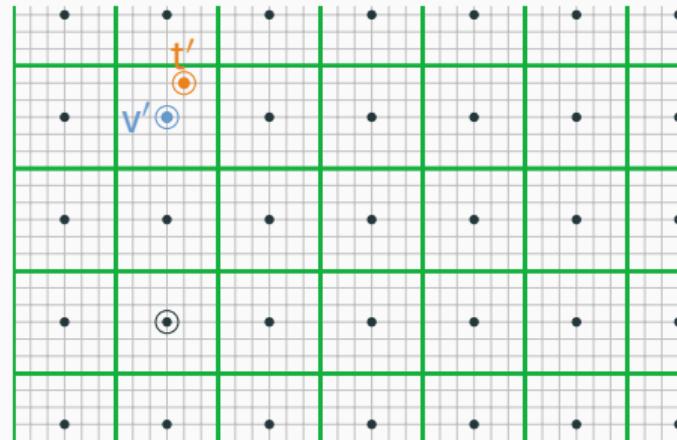
- Use  $\mathbf{B}$  to switch to the lattice  $\mathbb{Z}^d$      $\mathbf{t}' = \mathbf{B}^{-1} \cdot \mathbf{t}$

Credit: Léo Ducas

# ROUND OFF ALGORITHM



$$\cdot \mathbf{B}^{-1}$$
  
 $\longrightarrow$

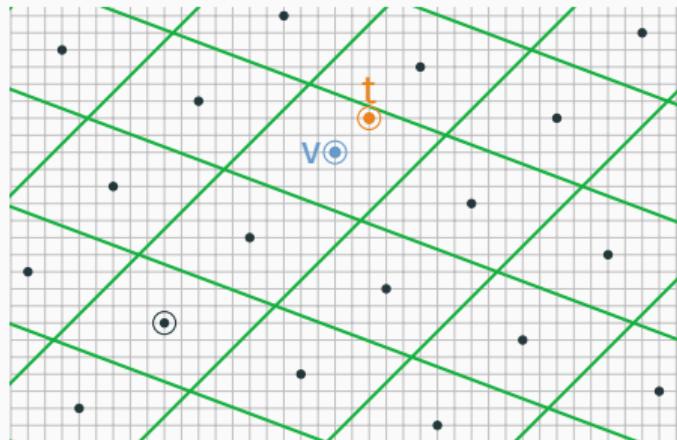


Round Off Algorithm  
[Lenstra,Babai]:

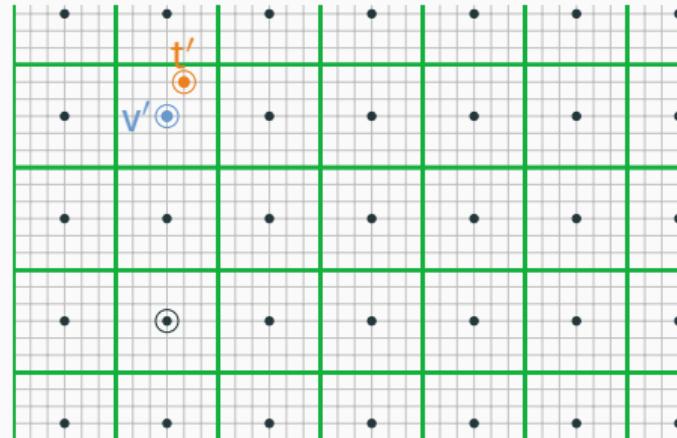
Credit: Léo Ducas

- Use  $\mathbf{B}$  to switch to the lattice  $\mathbb{Z}^d$      $\mathbf{t}' = \mathbf{B}^{-1} \cdot \mathbf{t}$
- Round each coordinate     $\mathbf{v}' = \lfloor \mathbf{t}' \rfloor$

# ROUND OFF ALGORITHM



$$\cdot B^{-1} \rightarrow$$
  
$$\leftarrow \cdot B$$



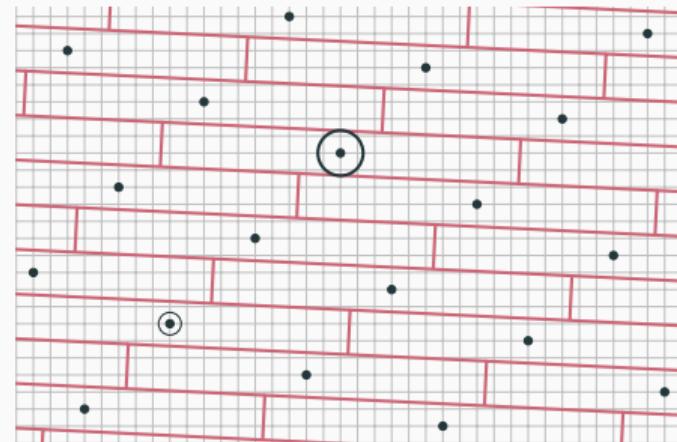
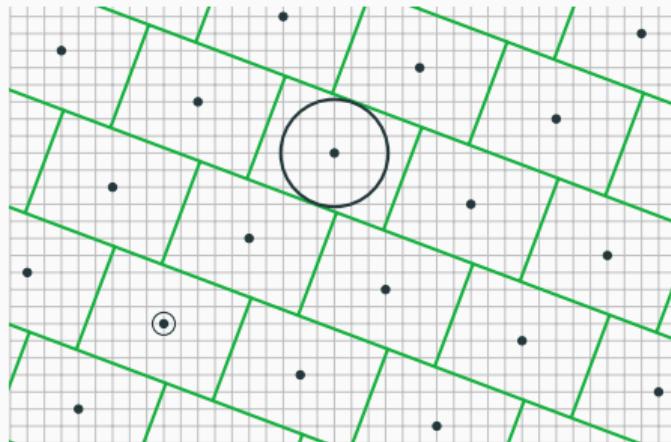
Round Off Algorithm  
[Lenstra,Babai]:

Credit: Léo Ducas

- Use  $B$  to switch to the lattice  $\mathbb{Z}^d$      $t' = B^{-1} \cdot t$
- Round each coordinate     $v' = \lfloor t' \rfloor$
- Switch back to  $\Lambda$      $v = B \cdot v'$

## NEAREST-PLANE ALGORITHM

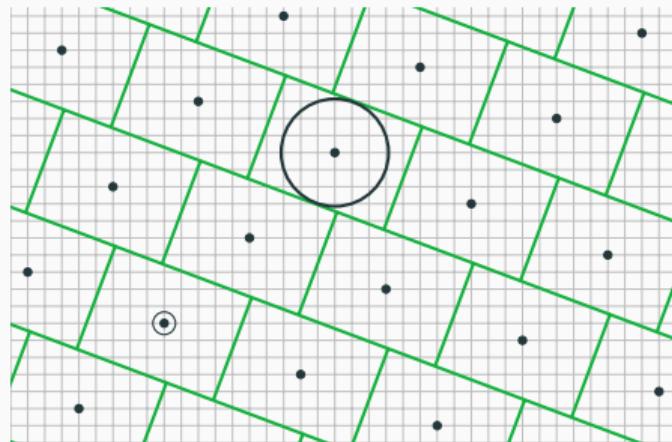
There is a better algorithm (Nearest Plane) based on Gram–Schmidt Orthogonalisation:



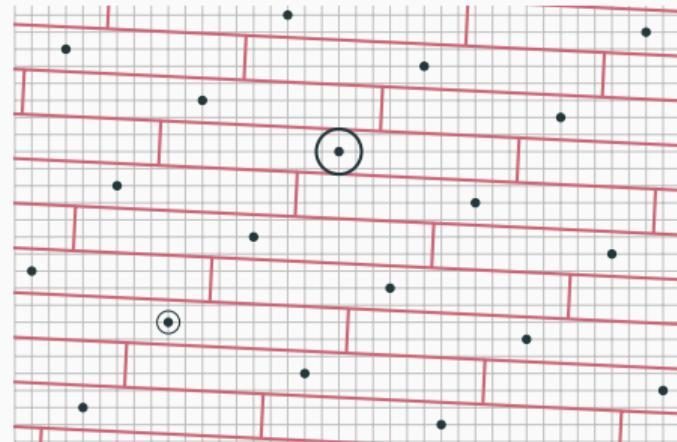
- Worst-case distance:  $\frac{1}{2} \sqrt{\sum \|b_i^*\|^2}$
- Correct decoding of  $t = v + e$  for  $v \in \Lambda$  if  $\|e\| \leq \min \|b_i^*\|$

# TRAPDOORS FROM LATTICES ?

Good basis **G**: can solve Approx-CVP / BDD.



Bad basis **B**: solving CVP is hard.

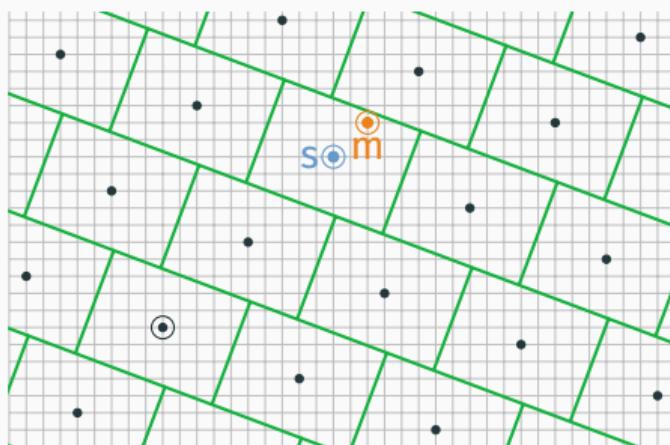


Can we use this as a trapdoor?

# SIGNATURES

Sign:

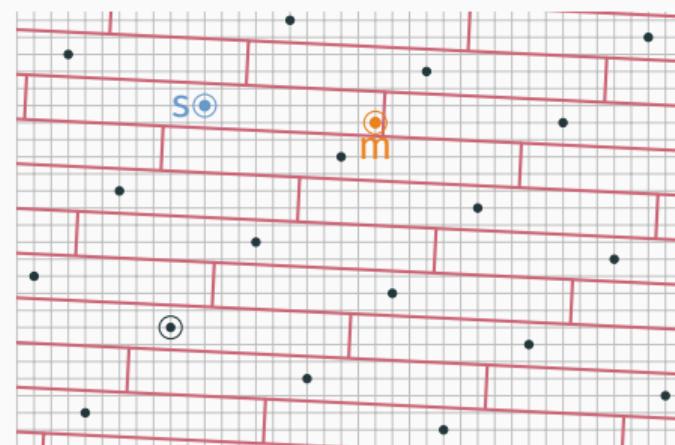
1. Hash message to a random vector  $\mathbf{m}$ .
2. Apply Nearest Plane with a good basis  $\mathbf{G}$ : find  $\mathbf{s} \in \Lambda$  close to  $\mathbf{m}$ .



Credit: Léo Ducas

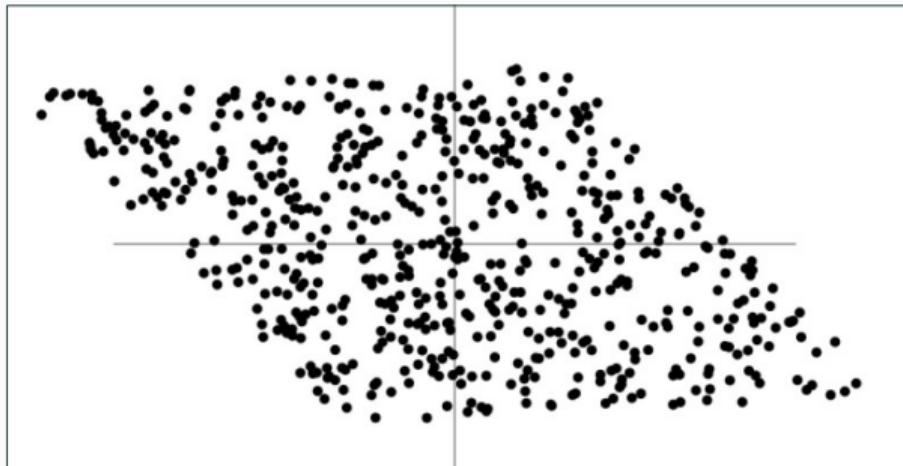
Verify:

1. Check that  $\mathbf{s} \in \Lambda$  using the bad basis  $\mathbf{B}$
2. Check that  $\mathbf{m}$  is close to  $\mathbf{s}$ .



## A STATISTICAL ATTACK

The difference  $s - m$  is always inside the parallelepiped spanned by the good basis  $G$  or its Gram–Schmidt Orthogonalisation  $G^*$ :



- Each signatures ( $s, m$ ) leaks information about  $G$ .
- Learning a parallelepiped from few signatures [NR06]
- Total break of original GGH and NTRUSign schemes

The distribution of  $s - m$  can be made **independent** of  $G$  by randomising the above algorithms:

### Seminal Work

Craig Gentry, Chris Peikert, and Vinod Vaikuntanathan. **Trapdoors for hard lattices and new cryptographic constructions.** In: *40th ACM STOC*. ed. by Richard E. Ladner and Cynthia Dwork. ACM Press, May 2008, pp. 197–206. DOI: [10.1145/1374376.1374407](https://doi.org/10.1145/1374376.1374407)

## Q-ARY LATTICES

---

## CONSTRUCTION OF $q$ -ARY LATTICES (PRIMAL / CONSTRUCTION A)

- Let  $q$  be a prime integer<sup>1</sup> and  $n < m$  two positive integers.
- The matrix  $\mathbf{A} \in \mathbb{Z}_q^{m \times n}$  spans the  $q$ -ary lattice:

$$\Lambda_q(\mathbf{A}) := \{\mathbf{x} \in \mathbb{Z}^m \mid \exists \mathbf{y} \in \mathbb{Z}_q^n, \mathbf{x} \equiv \mathbf{A} \cdot \mathbf{y} \pmod{q}\} = \mathbf{A} \cdot \mathbb{Z}_q^n + q\mathbb{Z}^m$$

### Lattice Parameters

Assuming  $\mathbf{A}$  is full-rank:

- $\dim(\Lambda_q(\mathbf{A})) = m$
- $\text{Vol}(\Lambda_q(\mathbf{A})) = q^{m-n}$

---

<sup>1</sup>for simplicity

## EXAMPLE

```
q = 19; n = 3; m = 7; A = random_matrix(GF(q), n, m)
B = A.lift().stack(q * identity_matrix(m)); B.T
```

```
[1      4 19]
[ 3  5      19]
[15 3 17      19]
[ 2  7      19]
[14 7      19]
[ 9 8 15      19]
[15 1 11      19]
```

```
B.echelon_form()[:B.rank()].T
```

```
[ 1
[   1
[     1
[18 14 17 19
[ 1 4 2 19
[ 2 17 6 19
[ 5 7 14 19]
```

**Row-Based:** SageMath's convention is "row based", i.e. it considers combinations of rows not columns. The literature on lattices favours column-based notation, i.e. combinations of columns. I transposed the output to make it consistent with the slide before.

## CONSTRUCTION OF $q$ -ARY LATTICES (DUAL / PARITY-CHECK)

- Let  $q$  be a prime integer<sup>2</sup> and  $n < m$  two positive integers.
- The matrix  $\mathbf{A} \in \mathbb{Z}_q^{n \times m}$  is the parity-check of the lattice:

$$\Lambda_q^\perp(\mathbf{A}) := \{\mathbf{x} \in \mathbb{Z}^m \mid \mathbf{A} \cdot \mathbf{x} \equiv 0 \pmod{q}\} = \ker(\mathbf{x} \mapsto \mathbf{A} \cdot \mathbf{x} \pmod{q})$$

### Lattice parameters

Assuming  $\mathbf{A}$  is full-rank:

- $\dim(\Lambda_q^\perp(\mathbf{A})) = m$
- $\text{Vol}(\Lambda_q^\perp(\mathbf{A})) = q^n$

---

<sup>2</sup>for simplicity

## EXAMPLE

```
q = 19; n = 3; m = 7; A = random_matrix(GF(q), n, m)
K = A.right_kernel().basis_matrix()
B = K.lift().stack(q * identity_matrix(m)); B.T
```

```
[ 1          19          ]
[   1          19          ]
[     1          19          ]
[       1          19          ]
[13  1  1 16          19          ]
[12 15  1 11          19          ]
[12 12  4  2          19]
```

```
B.echelon_form()[:B.rank()].T
```

```
[ 1          ]
[   1          ]
[     1          ]
[       1          ]
[13  1  1 16 19]
[12 15  1 11 19]
[12 12  4  2 19]
```

# THE SHORT INTEGER SOLUTION PROBLEM (SIS)

## Definition (SIS Assumption)

Given a random matrix  $\mathbf{A} \in \mathbb{Z}_q^{n \times m}$ , finding a small non-zero  $\mathbf{x} \in \mathbb{Z}^m$  such that  $\mathbf{A} \cdot \mathbf{x} \equiv \mathbf{0} \pmod{q}$  is hard.<sup>3</sup>

## Lattice Formulation

Solving Approx-SVP in  $\Lambda_q^\perp(\mathbf{A})$  is hard.

In [Ajt98], Ajtai established that if solving SIS is easy then solving Approx-SVP for any lattice is also easy.

---

<sup>3</sup>Also on a quantum computer!

# A SIMPLE APPLICATION OF SIS

Consider the function:

$$f_A : \{0,1\}^m \rightarrow \mathbb{Z}_q^n, \quad x \mapsto A \cdot x \bmod q$$

## SIS $\Rightarrow$ Collision Resistant Hashing and One-Way Function

- Finding collisions is as hard as SIS<sup>4</sup> (take the difference)

Moreover, if  $m \gg n \log q$ :

- $f_A$  is highly surjective (many pre-images for any image)
- Finding pre-images is hard (show it!)

---

<sup>4</sup>Collisions must exist when  $m > n \log q$ .

## GPV SIGNATURES

---

# OUTLINE

**KeyGen** generate a random (looking) matrix  $\mathbf{A}$  together with a short basis  $\text{td}$  for the lattice  $\Lambda_q^\perp(\mathbf{A}) := \{\mathbf{x} \in \mathbb{Z}^m \mid \mathbf{A} \cdot \mathbf{x} \equiv 0 \pmod{q}\}$ .

**Sign** Compute  $H(m)$ .

Find an arbitrary, not-necessarily short, preimage  $\mathbf{u}: \mathbf{A} \cdot \mathbf{u} \equiv H(m) \pmod{q}$ .

Use the trapdoor  $\text{td}$  to solve Approx-CVP for  $\mathbf{u}$  on  $\Lambda_q^\perp(\mathbf{A})$ , call it  $\mathbf{z}$ . By construction  $\mathbf{A} \cdot \mathbf{z} \equiv 0 \pmod{q}$ .

Output  $\mathbf{y} := \mathbf{u} - \mathbf{z}$ . By construction  $\|\mathbf{y}\|$  is small.

**Verify** Check that  $\mathbf{A} \cdot \mathbf{y} \equiv H(m) \pmod{q}$  and that  $\|\mathbf{y}\|$  is small.

# SCHEME

KeyGen( $1^\lambda$ )

---

$\mathbf{A}, \text{td} \leftarrow \$ \text{TrapGen}(1^n, 1^m, q, \beta)$

return  $\text{vk} := \mathbf{A}$ ,  $\text{sk} := \text{td}$

Sign( $m, \text{sk}$ )

---

$\mathbf{r} \leftarrow \$ \{0, 1\}^\lambda$

$\mathbf{y} \leftarrow \$ \text{SampPre}(\text{td}, H(m, \mathbf{r}), \beta')$

return  $\sigma := (\mathbf{y}, \mathbf{r})$

Verify( $\text{vk}, \sigma, m$ )

---

return  $\|\mathbf{y}\| \stackrel{?}{\leq} \beta' \wedge H(m, \mathbf{r}) \stackrel{?}{\equiv} \mathbf{A} \cdot \mathbf{y}$

- $(\mathbf{A}, \text{td}) \leftarrow \text{TrapGen}(1^n, 1^m, q, \beta)$  takes dimensions  $n, m \in \mathbb{N}$ , a modulus  $q \in \mathbb{N}$  and a norm bound  $\beta \in \mathbb{R}$  and generates a matrix  $\mathbf{A} \in \mathbb{Z}_q^{n \times m}$  and a trapdoor  $\text{td}$ .

*When  $\ell > 2m \log q$ , the distribution of  $\mathbf{A}$  is within  $\text{negl}(\lambda)$  statistical distance to the uniform distribution on  $\mathbb{Z}_q^{n \times m}$ .*

- $\mathbf{u} \leftarrow \text{SampD}(1^n, 1^m, \beta')$  outputs an element in  $\mathbf{u} \in \mathbb{Z}^m$  with norm bound  $\beta' \geq \beta$ .
- $\mathbf{v} := \mathbf{A} \cdot \mathbf{u} \bmod q$  is within  $\text{negl}(\lambda)$  statistical distance to the uniform distribution on  $\mathbb{Z}_q^n$ .
- $\mathbf{u} \leftarrow \text{SampPre}(\text{td}, \mathbf{v}, \beta')$  takes a trapdoor  $\text{td}$ , a vector  $\mathbf{v} \in \mathbb{Z}_q^n$  and a norm bound  $\beta' \geq \beta$  and samples  $\mathbf{u} \in \mathbb{Z}^\ell$  satisfying  $\mathbf{A} \cdot \mathbf{u} \equiv \mathbf{v} \bmod q$  and  $\|\mathbf{u}\| \leq \beta'$ .  
 $\mathbf{u}$  is within  $\text{negl}(\lambda)$  statistical distance to  
 $\mathbf{u} \leftarrow \text{SampD}(1^n, 1^m, \mathcal{R}, \beta')$  conditioned on  $\mathbf{v} \equiv \mathbf{A} \cdot \mathbf{u} \bmod q$ .

## SECURITY PROOF

---

## EUF-CMA IN THE ROM

EUF-CMA	S( $m$ )	H( $m$ )
$\mathcal{Q}, \mathcal{H} \leftarrow \emptyset, \emptyset;$	$\sigma \leftarrow_{\$} \Sigma.\text{Sign}(\text{sk}, m)$	<b>if</b> $m \notin \mathcal{H}$ <b>then</b>
$\text{vk}, \text{sk} \leftarrow_{\$} \Sigma.\text{KeyGen}(1^\lambda);$	$\mathcal{Q} \leftarrow \mathcal{Q} \cup \{(m, \sigma)\}$	$\mathcal{H}[m] \leftarrow_{\$} \{0, 1\}^\lambda$
$(m^*, \sigma^*) \leftarrow_{\$} \mathcal{A}^{S, H}(\text{vk});$	<b>return</b> $\sigma$	<b>return</b> $\mathcal{H}[m]$
$b_0 := (m^*, \cdot) \notin \mathcal{Q}$		
$b_1 := \Sigma.\text{Verify}(\text{vk}, \sigma^*, m^*) = 1$		
<b>return</b> $b_0 \wedge b_1$		

$$\text{Adv}_{\mathcal{A}, \Sigma}^{\text{euf-cma}}(\lambda) := \Pr[\text{EUF-CMA}_{\Sigma}^{\mathcal{A}}(\lambda) \Rightarrow 1]$$

# INLINE GPV SIGNATURES

Game <sub>0</sub>	S(m)	H(m, r)
$\mathcal{Q}, \mathcal{H} \leftarrow \emptyset, \emptyset;$	$r \leftarrow \$ \{0, 1\}^\lambda$	
$A, \text{td} \leftarrow \$ \text{TrapGen}(\dots)$	$y \leftarrow \$ \text{SampPre}(\text{td}, H(m, r), \beta')$	$\text{if } (m, r) \notin \mathcal{H} \text{ then}$
$(m^*, (y^*, r^*)) \leftarrow \mathcal{A}^{S, H}(\text{vk});$	$\sigma := (y, r)$	$\mathcal{H}[m, r] \leftarrow \$ \mathbb{Z}_q^n$
$b_0 := (m^*, \cdot) \notin \mathcal{Q}$	$\mathcal{Q} \leftarrow \mathcal{Q} \cup \{(m, \sigma)\}$	$\text{return } \mathcal{H}[m, r]$
$b_1 := \ y^*\  \leq \beta'$		
$b_2 := H(m^*, r^*) \equiv A \cdot y^*$	$\text{return } \sigma$	
<b>return</b> $b_0 \wedge b_1 \wedge b_2$		

## CHANGING THE RO

Game <sub>1</sub>	S(m)	H(m, r)
$\mathcal{Q}, \mathcal{H}, \mathcal{P} \leftarrow \emptyset, \emptyset, \emptyset;$	$r \leftarrow \$_{\{0,1\}^\lambda}$	<b>if</b> $(m, r) \notin \mathcal{H}$ <b>then</b>
$A, td \leftarrow \$ \text{TrapGen}(\dots)$	$y \leftarrow \$ \text{SampPre}(td, H(m, r), \beta')$	$y \leftarrow \$ \text{SampD}(\dots, \beta')$
$(m^*, (y^*, r^*)) \leftarrow \mathcal{A}^{S, H}(vk);$	$\sigma := (y, r)$	$t := A \cdot y \bmod q$
$b_0 := (m^*, \cdot) \notin \mathcal{Q}$	$\mathcal{Q} \leftarrow \mathcal{Q} \cup \{(m, \sigma)\}$	$\mathcal{H}[m, r] \leftarrow t$
$b_1 := \ y^*\  \leq \beta'$	<b>return</b> $\sigma$	$\mathcal{P}[m, r] \leftarrow y$
$b_2 := H(m^*, r^*) \equiv A \cdot y^*$		<b>return</b> $\mathcal{H}[m, r]$
$b_0 \wedge b_1 \wedge b_2$		

By a Leftover Hash Lemma the distributions of Game<sub>0</sub> and Game<sub>1</sub> are statistically close.

# BOOKKEEPING

Game <sub>2</sub>	$S(m)$	$H(m, r)$
$\mathcal{Q}, \mathcal{H}, \mathcal{P} \leftarrow \emptyset, \emptyset, \emptyset;$	$r \leftarrow \$ \{0, 1\}^\lambda$	<b>if</b> $(m, r) \notin \mathcal{H}$ <b>then</b>
$\text{bad} \leftarrow \text{false}$	<b>if</b> $(m, r) \in \mathcal{H}$ <b>then</b>	$y \leftarrow \$ \text{SampD}(\dots, \beta')$
$A, \text{td} \leftarrow \$ \text{TrapGen}(\dots)$	$\text{bad} \leftarrow \text{true}$	$t := A \cdot y \bmod q$
$(m^*, (y^*, r^*)) \leftarrow \mathcal{A}^{S, H}(\text{vk});$	$y \leftarrow \$ \text{SampPre}(\text{td}, H(m, r), \beta')$	$\mathcal{H}[m, r] \leftarrow t$
$b_0 := (m^*, \cdot) \notin \mathcal{Q}$	$\sigma := (y, r)$	$\mathcal{P}[m, r] \leftarrow y$
$b_1 := \ y^*\  \leq \beta'$	$\mathcal{Q} \leftarrow \mathcal{Q} \cup \{(m, \sigma)\}$	<b>return</b> $\mathcal{H}[m, r]$
$b_2 := H(m^*, r^*) \equiv A \cdot y^*$	<b>return</b> $\sigma$	
$b_0 \wedge b_1 \wedge b_2$		

No change in behaviour.

## Avoid Collisions

Game <sub>3</sub>	$S(m)$	$H(m, r)$
$\mathcal{Q}, \mathcal{H}, \mathcal{P} \leftarrow \emptyset, \emptyset, \emptyset;$	$r \leftarrow \$ \{0, 1\}^\lambda$	$\text{if } (m, r) \notin \mathcal{H} \text{ then}$
$\text{bad} \leftarrow \text{false}$	$\text{if } (m, r) \in \mathcal{H} \text{ then}$	$y \leftarrow \$ \text{SampD}(\dots, \beta')$
$A, td \leftarrow \$ \text{TrapGen}(\dots)$	$\text{bad} \leftarrow \text{true}$	$t := A \cdot y \bmod q$
$(m^*, (y^*, r^*)) \leftarrow \mathcal{A}^{S, H}(vk);$	<b>abort</b>	$\mathcal{H}[m, r] \leftarrow t$
$b_0 := (m^*, \cdot) \notin \mathcal{Q}$	$y \leftarrow \$ \text{SampPre}(td, H(m, r), \beta')$	$\mathcal{P}[m, r] \leftarrow y$
$b_1 := \ y^*\  \leq \beta'$	$\sigma := (y, r)$	<b>return</b> $\mathcal{H}[m, r]$
$b_2 := H(m^*, r^*) \equiv A \cdot y^*$	$\mathcal{Q} \leftarrow \mathcal{Q} \cup \{(m, \sigma)\}$	
$b_0 \wedge b_1 \wedge b_2$	<b>return</b> $\sigma$	

Apply Fundamental Lemma of Game Playing with  $\Pr[\text{bad}] \approx |\mathcal{Q}|/2^{\lambda/2}$ .

## FAKE SIGNATURES

Game <sub>4</sub>	S(m)	H(m, r)
$\mathcal{Q}, \mathcal{H}, \mathcal{P} \leftarrow \emptyset, \emptyset, \emptyset;$	$r \leftarrow_{\$} \{0,1\}^\lambda$	<b>if</b> $(m, r) \notin \mathcal{H}$ <b>then</b>
$\text{bad} \leftarrow \text{false}$	<b>if</b> $(m, r) \in \mathcal{H}$ <b>then</b>	$y \leftarrow_{\$} \text{SampD}(\dots, \beta')$
$A, \text{td} \leftarrow \$ \text{TrapGen}(\dots)$	$\text{bad} \leftarrow \text{true}$	$t := A \cdot y \bmod q$
$(m^*, (y^*, r^*)) \leftarrow \mathcal{A}^{S,H}(vk);$	<b>abort</b>	$\mathcal{H}[m, r] \leftarrow t$
$b_0 := (m^*, \cdot) \notin \mathcal{Q}$	$H(m, r)$	$\mathcal{P}[m, r] \leftarrow y$
$b_1 := \ y^*\  \leq \beta'$	$y \leftarrow \mathcal{P}[m, r]$	<b>return</b> $\mathcal{H}[m, r]$
$b_2 := H(m^*, r^*) \equiv A \cdot y^*$	$\sigma := (y, r)$	
$b_0 \wedge b_1 \wedge b_2$	$\mathcal{Q} \leftarrow \mathcal{Q} \cup \{(m, \sigma)\}$	
		<b>return</b> $\sigma$

Use SampPre  $\approx$  SampD.

## THROW AWAY TRAPDOOR

Game <sub>5</sub>	S(m)	H(m, r)
$\mathcal{Q}, \mathcal{H}, \mathcal{P} \leftarrow \emptyset, \emptyset, \emptyset;$	$r \leftarrow \$_{\{0,1\}^\lambda}$	<b>if</b> $(m, r) \notin \mathcal{H}$ <b>then</b>
$\text{bad} \leftarrow \text{false}$	<b>if</b> $(m, r) \in \mathcal{H}$ <b>then</b>	$y \leftarrow \$_{\text{SampD}(\dots, \beta')}$
$A \leftarrow \$_{\mathbb{Z}_q^{n \times 2n \lceil \log q \rceil}}$	$\text{bad} \leftarrow \text{true}$	$t := A \cdot y \bmod q$
$(m^*, (y^*, r^*)) \leftarrow \mathcal{A}^{S, H}(\text{vk})$	<b>abort</b>	$\mathcal{H}[m, r] \leftarrow t$
$b_0 := (m^*, \cdot) \notin \mathcal{Q}$	$H(m, r)$	$\mathcal{P}[m, r] \leftarrow y$
$b_1 := \ y^*\  \leq \beta'$	$y \leftarrow \mathcal{P}[m, r]$	<b>return</b> $\mathcal{H}[m, r]$
$b_2 := H(m^*, r^*) \equiv A \cdot y^*$	$\sigma := (y, r)$	
$b_0 \wedge b_1 \wedge b_2$	$\mathcal{Q} \leftarrow \mathcal{Q} \cup \{(m, \sigma)\}$	
		<b>return</b> $\sigma$

Use that TrapGen produces pseudorandom A.

## Invoke SIS

We turn an adversary  $\mathcal{A}$  that wins Game<sub>5</sub> into an adversary that breaks SIS for  $A$ .

- The adversary outputs  $(m^*, (y^*, r^*))$  s.t.  $H(m^*, r^*) \equiv A \cdot y^*$  and  $\|y^*\| \leq \beta'$ .
- If  $\mathcal{A}$  has not called  $H(m^*, r^*)$  before producing its forgery,  $t := H(m^*, r^*)$  is unknown and (close to) uniformly random: it succeeds with probability  $1/q^n < 2^{-\lambda}$ .
- If  $\mathcal{A}$  has called  $H(m^*, r^*)$  then  $y \leftarrow \mathcal{P}[m^*, r^*]$  with  $\|y\| \leq \beta'$  and **with high probability**  $y \neq y^*$ .

$$H(m^*, r^*) \equiv A \cdot y^* \equiv A \cdot y \quad \Rightarrow \quad 0 \equiv A \cdot (y^* - y) \text{ and } \|y^* - y\| \leq 2\beta'$$

## THE ROLE OF $r$

If the signing algorithm did not sample a fresh  $r$  for each signature, then

- Game<sub>3</sub> would output new, fresh  $y$  on each call, but
- Game<sub>4</sub> would output the same  $y$  on each call.

which is easy to distinguish by just calling the signing algorithm twice.

### Corresponding Attack

Without  $r$ , when  $\mathcal{A}$  calls the signing oracle twice on the same  $m$ , it would get two different preimages  $y_0, y_1$  for  $H(m)$ :

$$H(m) \equiv A \cdot y_0 \equiv A \cdot y_1 \quad \Rightarrow \quad 0 \equiv A \cdot (y_0 - y_1) \text{ and } \|y_0 - y_1\| \leq 2\beta'.$$

- This solves SIS, which is supposed to be hard for our security proof to work.

## THE ROLE OF $r$

If the signing algorithm did not sample a fresh  $r$  for each signature, then

- Game<sub>3</sub> would output new, fresh  $y$  on each call, but
- Game<sub>4</sub> would output the same  $y$  on each call.

which is easy to distinguish by just calling the signing algorithm twice.

### Corresponding Attack

Without  $r$ , when  $\mathcal{A}$  calls the signing oracle twice on the same  $m$ , it would get two different preimages  $y_0, y_1$  for  $H(m)$ :

$$H(m) \equiv A \cdot y_0 \equiv A \cdot y_1 \quad \Rightarrow \quad 0 \equiv A \cdot (y_0 - y_1) \text{ and } \|y_0 - y_1\| \leq 2\beta'.$$

- This solves SIS, which is supposed to be hard for our security proof to work.
- This gives a short vector in  $\Lambda_q^\perp(A)$ , such short vectors make up our trapdoor!

FIN

IN THE RANDOM ORACLE MODEL WE  
CAN CHOOSE WHAT THE HASH  
FUNCTION OUTPUTS.

## REFERENCES I

- [Ajt98] Miklós Ajtai. **The Shortest Vector Problem in L<sub>2</sub> is NP-hard for Randomized Reductions (Extended Abstract)**. In: *30th ACM STOC*. ACM Press, May 1998, pp. 10–19. DOI: [10.1145/276698.276705](https://doi.org/10.1145/276698.276705).
- [GPV08] Craig Gentry, Chris Peikert, and Vinod Vaikuntanathan. **Trapdoors for hard lattices and new cryptographic constructions**. In: *40th ACM STOC*. Ed. by Richard E. Ladner and Cynthia Dwork. ACM Press, May 2008, pp. 197–206. DOI: [10.1145/1374376.1374407](https://doi.org/10.1145/1374376.1374407).
- [NR06] Phong Q. Nguyen and Oded Regev. **Learning a Parallelepiped: Cryptanalysis of GGH and NTRU Signatures**. In: *EUROCRYPT 2006*. Ed. by Serge Vaudenay. Vol. 4004. LNCS. Springer, Berlin, Heidelberg, 2006, pp. 271–288. DOI: [10.1007/11761679\\_17](https://doi.org/10.1007/11761679_17).