V2: The Kyber PKE and KEM

Kyber and Dilithium

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August 2024

Kyber

- Kyber is a quantum-safe Key Encapsulation Mechanism (KEM).
- Standardized by NIST in FIPS 203, where it is called ML-KEM (Module-Lattice-based KEM).
- Kyber-KEM was designed by applying the Fujisaki-Okamoto transform to a public-key encryption scheme (Kyber-PKE).

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V2 outline

- V2a: Kyber-PKE (simplified)
- V2b: Optimizations
- V2c: Kyber-PKE (full scheme)
- V2d: Kyber-KEM

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V2a: Kyber-PKE (simplified)

1. Rounding
2. Domain parameters and key generation
3. Encryption and decryption
4. Security
5. Decryption doesn’t always work

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Notation

- Recall:
  - $R_q = \mathbb{Z}_q[x]/(x^n + 1)$.
  - S_η = set of polynomials in R_q with (mods q) coefficients in $[-\eta, \eta]$.
  - R_q^k, S_η^k
- The plaintext space is $\{0,1\}^n$.
  A plaintext $m \in \{0,1\}^n$ is associated with a polynomial in R_q with 0-1 coefficients.
  - Example: If $n = 5$ and $m = 10110$, then $m \leftrightarrow m(x) = 1 + x^2 + x^3$.
- $\lfloor x \rfloor$ is the largest integer $\leq x$, and $\lceil x \rceil$ is the smallest integer $\geq x$.
  - Example: $\lfloor 5.25 \rfloor = 5$ and $\lfloor -5.25 \rfloor = -6$, whereas $\lceil 5.25 \rceil = 6$ and $\lceil -5.25 \rceil = -5$.
- $\lceil x \rfloor$ denotes the closest integer to x, with ties broken upwards.
  - Example: $\lceil 13.3 \rfloor = 13$, $\lceil 13.5 \rfloor = 14$, $\lceil 13.7 \rfloor = 14$, $\lceil -13.5 \rfloor = -13$, and $\lceil -13.7 \rfloor = -14$.

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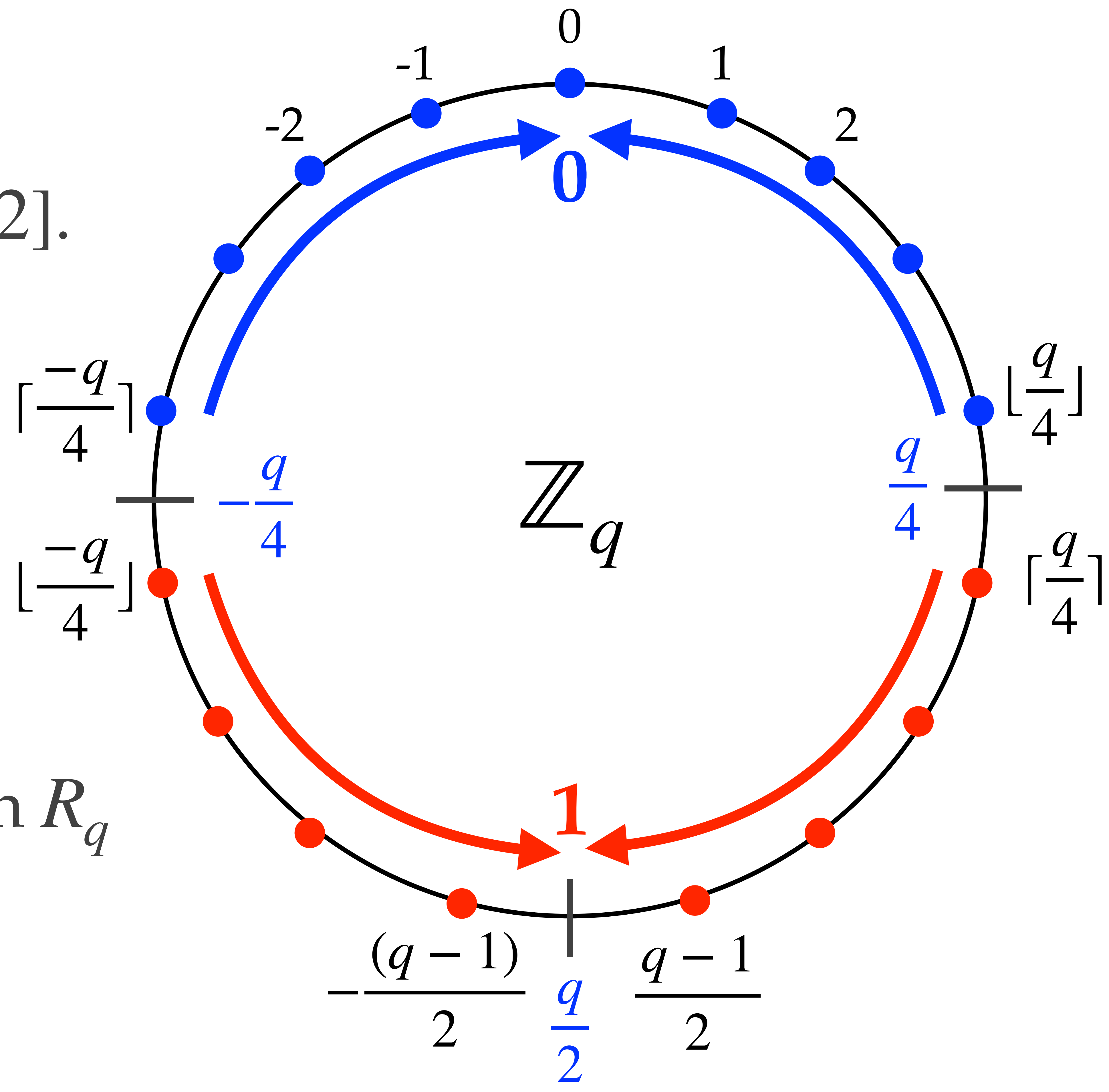
Rounding

- Let q be an odd prime, and let $x \in [0, q-1]$.
- Let $x' = x \text{ mods } q$; recall that $x' \in [-(q-1)/2, (q-1)/2]$.
- Then $\text{Round}_q(x) = \begin{cases} 0, & \text{if } -q/4 < x' < q/4, \\ 1, & \text{otherwise}. \end{cases}$
  - Example: Let $q = 3329$.
    Then $\text{Round}_q(x) = \begin{cases} 0, & \text{if } -832 \le x' \le 832, \\ 1, & \text{otherwise}. \end{cases}$
- The Round_q operation can be extended to polynomials in R_q by applying it to each coefficient of the polynomial.
  - Example: Let $q = 3329$. Then
    $\text{Round}_q(3000 + 1500x + 2010x^2 + 37x^3) = x + x^2$.



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Domain parameters and key generation

For concreteness, we'll use the ML-KEM-768 domain parameters:

- $q = 3329$
- $n = 256$
- $k = 3$
- $\eta_1 = 2$
- $\eta_2 = 2$

Kyber-PKE(s) key generation: Alice does:

1. Select $A \in_R R_q^{k \times k}$, $s \in_R S_{\eta_1}^k$, and $e \in_R S_{\eta_1}^k$.
2. Compute $t = As + e$.
3. Alice's encryption (public) key is (A, t); her decryption (private) key is s.

Note: Computing s from (A, t) is an instance of MLWE.

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Encryption and decryption

Kyber-PKE(s) encryption: To encrypt a message $m \in \{0,1\}^n$ for Alice, Bob does:

1. Obtain an authentic copy of Alice's encryption key (A, t).
2. Select $r \in_R S_{\eta_1}^k$, $e_1 \in_R S_{\eta_2}^k$, and $e_2 \in_R S_{\eta_2}$.
3. Compute $u = A^T r + e_1$ and $v = t^T r + e_2 + \lceil \frac{q}{2} \rfloor m$.
4. Output $c = (u, v)$.

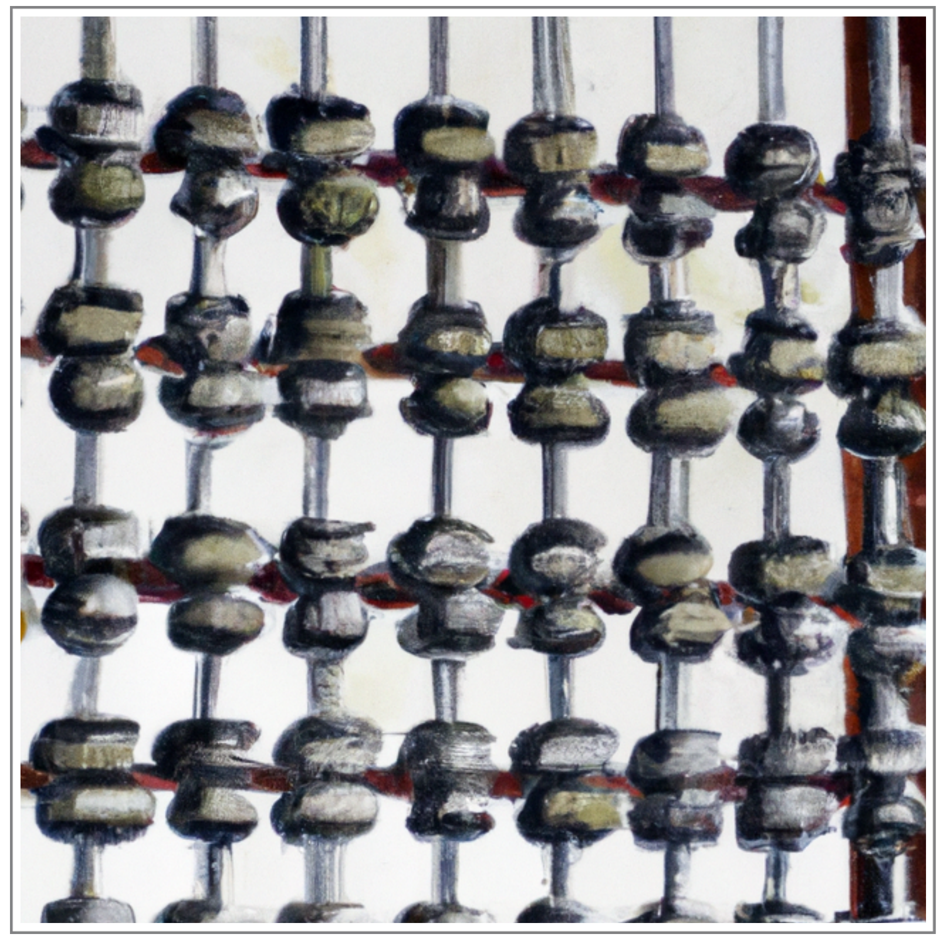
Note: $c \in R_q^k \times R_q$.

Kyber-PKE(s) decryption: To decrypt $c = (u, v)$, Alice does:

1. Compute $m = \text{Round}_q(v - s^T u)$.

Note: Alice uses her decryption key s.

Toy example: Kyber-PKE(s) (1)

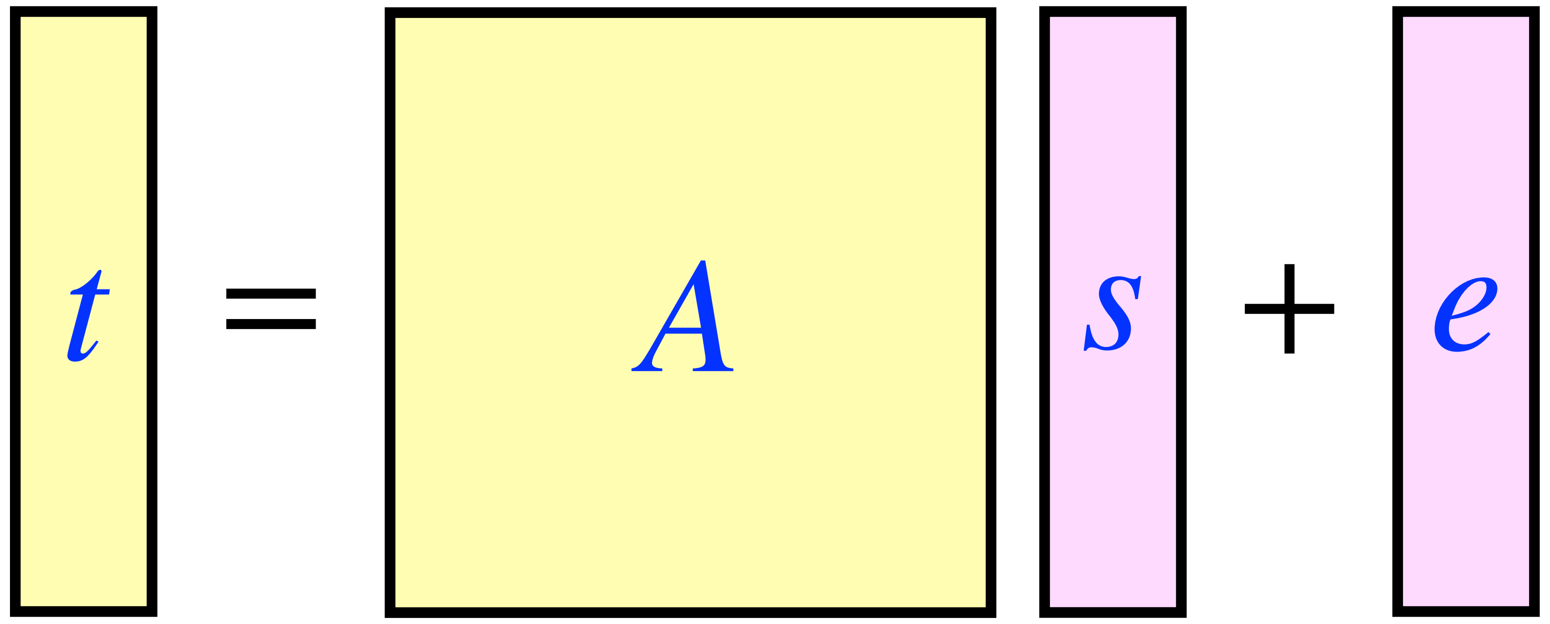


- **Domain parameters**: $q = 137,\ n = 4,\ k = 2,\ \eta_1 = 2,\ \eta_2 = 2.$
- **Key generation**: Alice selects:

$$A = \begin{bmatrix} 21 + 57x + 78x^2 + 43x^3 & 126 + 122x + 19x^2 + 125x^3 \\ 111 + 9x + 63x^2 + 33x^3 & 105 + 61x + 71x^2 + 64x^3 \end{bmatrix},$$

$$s = \begin{bmatrix} 1 + 2x - x^2 + 2x^3 \\ -x + 2x^3 \end{bmatrix},\quad e = \begin{bmatrix} 1 - x^2 + x^3 \\ -x + x^2 \end{bmatrix},$$ and computes

$$t = As + e = \begin{bmatrix} 55 + 96x + 123x^2 + 7x^3 \\ 32 + 27x + 127x^2 + 100x^3 \end{bmatrix}.$$



Alice's encryption key is (A, t); her decryption key is s.

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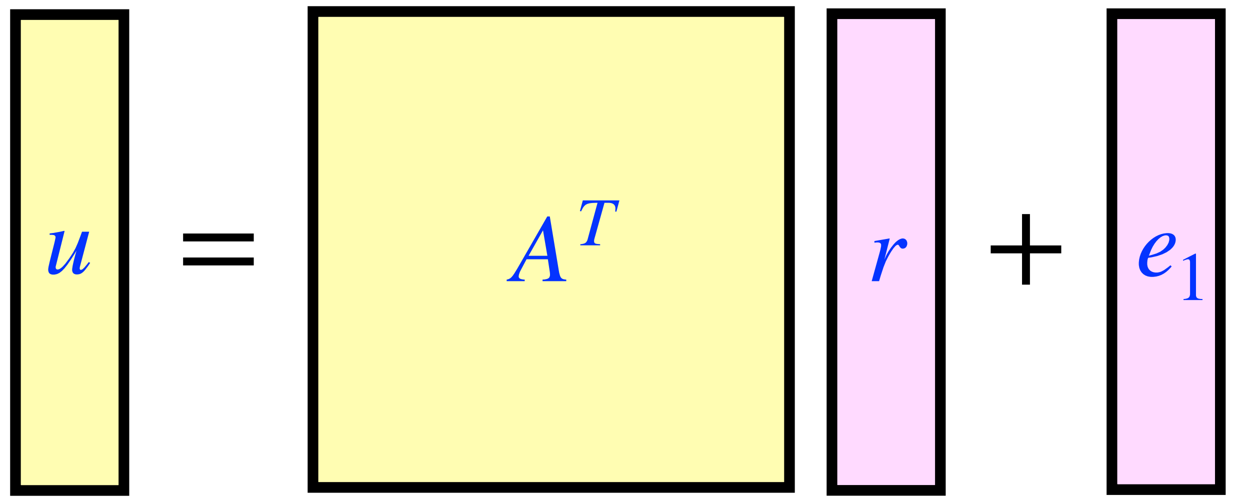
Toy example: Kyber-PKE(s) (2)

- Encryption: To encrypt the plaintext message $m = 0111 \leftrightarrow x + x^2 + x^3$, Bob selects

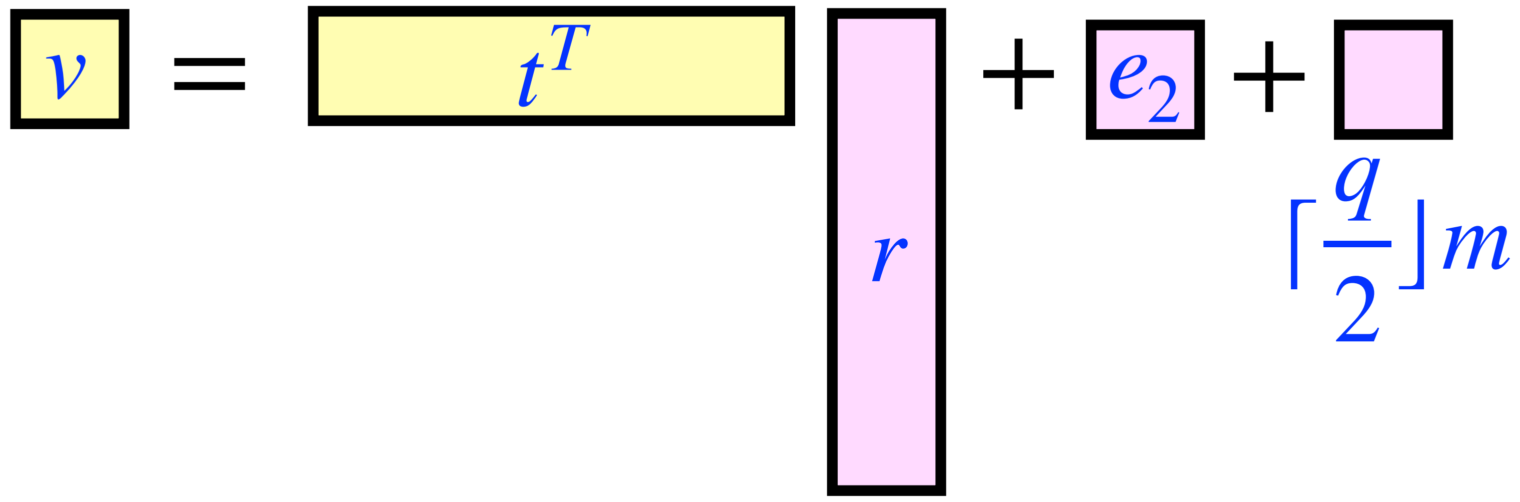
$$r = \begin{bmatrix} -2 + 2x + x^2 - x^3 \\ -1 + x + x^2 \end{bmatrix}, \quad e_1 = \begin{bmatrix} 1 - 2x^2 + x^3 \\ -1 + 2x - 2x^2 + x^3 \end{bmatrix}, \quad e_2 = 2 + 2x - x^2 + x^3,$$

and computes $u = A^T r + e_1 = \begin{bmatrix} 56 + 32x + 77x^2 + 9x^3 \\ 45 + 21x + 2x^2 + 127x^3 \end{bmatrix}$



and $v = t^T r + e_2 + 69m = 3 + 10x + 8x^2 + 123x^3$.
The ciphertext is $c = (u, v)$.

- Decryption: To decrypt $c = (u, v)$, Alice uses her decryption key s to compute $v - s^T u = 4 + 60x + 79x^2 + 66x^3$, and then rounds its coefficients to obtain $x + x^2 + x^3$, thereby recovering the plaintext $m = 0111$.



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Security

- Claim: Simplified Kyber-PKE(s) is indistinguishable against chosen-plaintext attack assuming that D-MLWE is intractable.
- Proof: The encryption operation can be written as: $\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} A^T \\ t^T \end{bmatrix} r + \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \lceil \frac{q}{2} \rfloor m \end{bmatrix}$.

  By the D-MLWE assumption, $\begin{bmatrix} A^T \\ t^T \end{bmatrix}$ is indistinguishable from random. Again by the D-MLWE assumption, $\begin{bmatrix} A^T \\ t^T \end{bmatrix} r + \begin{bmatrix} e_1 \\ e_2 \end{bmatrix} = \begin{bmatrix} A^T r + e_1 \\ t^T r + e_2 \end{bmatrix}$ is indistinguishable from random.

  Thus, from the adversary's perspective, v appears to be the sum of the random element $(t^T r + e_2)$ in R_q and the message polynomial $\lceil \frac{q}{2} \rfloor m$, so the adversary can learn nothing about m. $\square$

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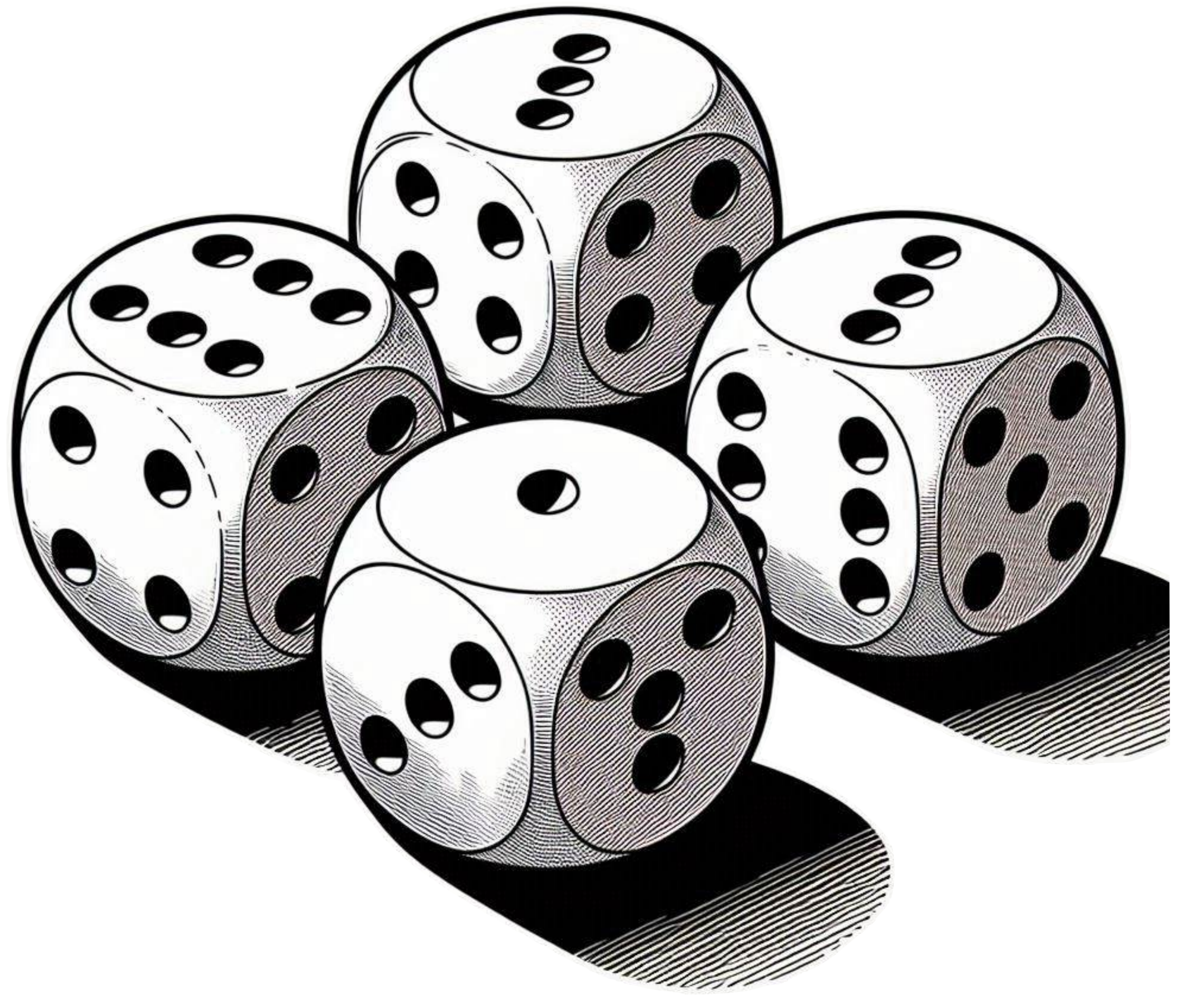
Decryption doesn't always work



- Question: Does decryption work? i.e., does $m = \text{Round}_q(v - s^T u)$?

- We have $v - s^T u = (t^T r + e_2 + \lceil q/2 \rfloor m) - s^T u$

$$= (s^T A^T + e^T) r + e_2 + \lceil q/2 \rfloor m - s^T (A^T r + e_1)$$
$$= s^T A^T r + e^T r + e_2 + \lceil q/2 \rfloor m - s^T A^T r - s^T e_1$$
$$= e^T r + e_2 - s^T e_1 + \lceil q/2 \rfloor m\,.$$

- Thus, $\text{Round}_q(v - s^T u) = m$ if each coefficient E_i of the error polynomial $E(x) = e^T r + e_2 - s^T e_1$ satisfies $-q/4 < E_i \text{ mods } q < q/4$, i.e., $\|E\|_\infty < q/4$.
- Now, $\|E_i\|_\infty \le kn\eta_1^2 + \eta_2 + kn\eta_1\eta_2$.
- For the ML-KEM-768 parameters ($q = 3329$, $n = 256$, $k = 3$, $\eta_1 = \eta_2 = 2$), we have $\|E_i\|_\infty \le 6146 \not< q/4$. Hence, *decryption is not guaranteed to succeed.*
- However, it can be shown that $\|E\|_\infty < q/4$ with probability extremely close to 1. Consequently, *decryption will almost certainly succeed.*

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V2b: Optimizations

1. Smaller public keys
2. Ciphertext compression
3. Central binomial distribution
4. Fast polynomial multiplication

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Encryption key and ciphertext sizes

- For concreteness, we'll consider the ML-KEM-768 parameters ($q = 3329, n = 256, k = 3, \eta_1 = 2, \eta_2 = 2$).
- The bitlength of an integer in $\mathbb{Z}_q$ is $\lceil \log_2 3329 \rceil = 12$ bits.
- Encryption key: The size of an encryption key (A, t) is $(9 \times 256 \times 12) + (3 \times 256 \times 12)$ bits, or 4,608 bytes.
- Ciphertext: The size of a ciphertext $c = (u, v)$ is $(3 \times 256 \times 12) + (256 \times 12)$ bits, or 1,536 bytes.

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Smaller encryption keys

- Idea: Generate A from a random (and public) 256-bit seed ρ.
- The polynomials in A can be generated by first selecting $\rho \in_R \{0,1\}^{256}$, and then generating the coefficients of the polynomials by hashing ρ with a counter.
- The encryption key is (ρ, t) instead of (A, t).
- Anyone who knows ρ can generate A.
- The encryption key size is now $256 + (3 \times 256 \times 12)$ bits, or 1,184 bytes (a substantial reduction from 4,608 bytes).

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Compression

- Idea: Discard the "low order" bits of the coefficients of all polynomials in the ciphertext $c = (u, v)$.
- Let $1 \leq d \leq \lfloor \log_2 q \rfloor$, and define:
  - For $x \in [0, q-1]$, $\text{Compress}_q(x, d) = \lceil (2^d/q) \cdot x \rfloor \bmod 2^d$.
  - For $y \in [0, 2^d - 1]$, $\text{Decompress}_q(y, d) = \lceil (q/2^d) \cdot y \rfloor \bmod q$.
- Fact: Let $x \in [0, q-1]$ and $x' = \text{Decompress}_q(\text{Compress}_q(x, d), d)$. Then $\|x' - x\|_\infty \leq \lceil q/2^{d+1} \rfloor$.
- The functions Compress and Decompress extend in the natural way to polynomials in R_q and polynomial vectors in R_q^k.

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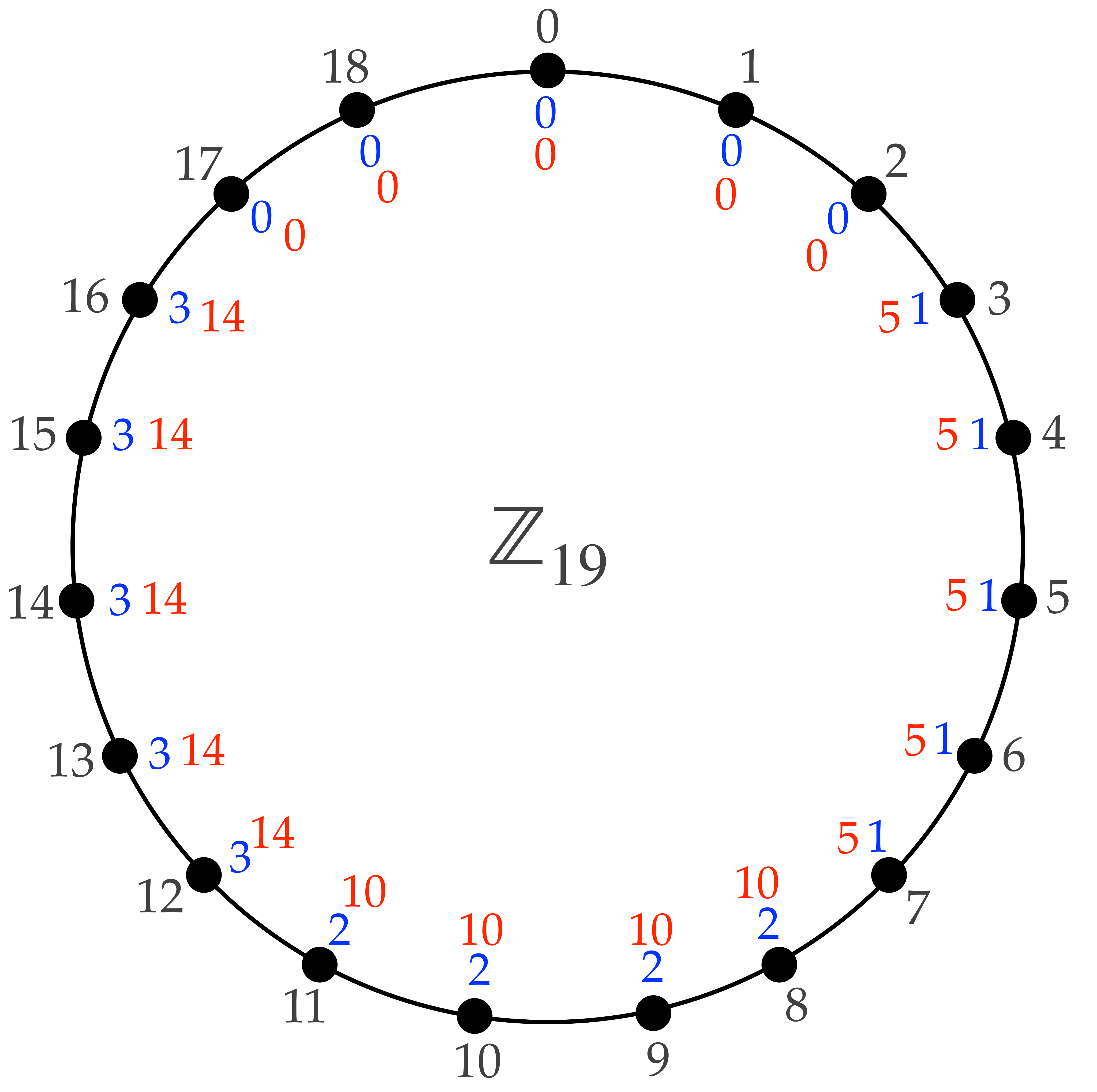
Examples: compression and decompression (1)

- Let $q = 19$ and $d = 2$.
- Let $x \in [0, 18]$.
- Let $y = \text{Compress}_{19}(x, 2)$.
- Let $x' = \text{Decompress}(y, 2)$.
- Then $\|x' - x\|_\infty \le 2$.



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Examples: compression and decompression (2)

- Let $q = 3329$, $d = 10$, $x \in [0, q-1]$.
- Let $x' = \text{Decompress}_q(\text{Compress}_q(x, d), d)$.
- Then $|(x - x') \text{ mods } q| \leq 2$.
- Example:
  - $\text{Compress}_q(223 + 1438x + 3280x^2 + 798x^3, 10) = 69 + 442x + 1009x^2 + 245x^3$.
  - $\text{Decompress}_q(69 + 442x + 1009x^2 + 245x^3, 10) = 224 + 1437x + 3280x^2 + 796x^3$.
  - The error polynomial is $-1 + x + 2x^3$.

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Examples: compression and decompression (3)

- Let $q = 3329$, $d = 4$, $x \in [0, q-1]$.
- Let $x' = \text{Decompress}_q(\text{Compress}_q(x, d), d)$.
- Then $|(x - x') \text{ mods } q| \leq 104$.
- Example:
  - $\text{Compress}_q(223 + 1438x + 3280x^2 + 798x^3, 4) = 1 + 7x + 4x^3$.
  - $\text{Decompress}_q(1 + 7x + 4x^3, 4) = 208 + 1456x + 832x^3$.
  - The error polynomial is $15 - 18x - 49x^2 - 34x^3$.

Ciphertext compression

- The ciphertext components u and v are replaced by $c_1 = \text{Compress}_q(u, d_u)$ and $c_2 = \text{Compress}_q(v, d_v)$.
- The ML-KEM-768 parameters ($q = 3329$, $n = 256$, $k = 3$, $\eta_1 = 2$, $\eta_2 = 2$) have $d_u = 10$ and $d_v = 4$.
- So, the size of the compressed ciphertext is $3 \times 256 \times 10 + 256 \times 4$ bits, or 1,088 bytes (a significant reduction from 1,536 bytes).

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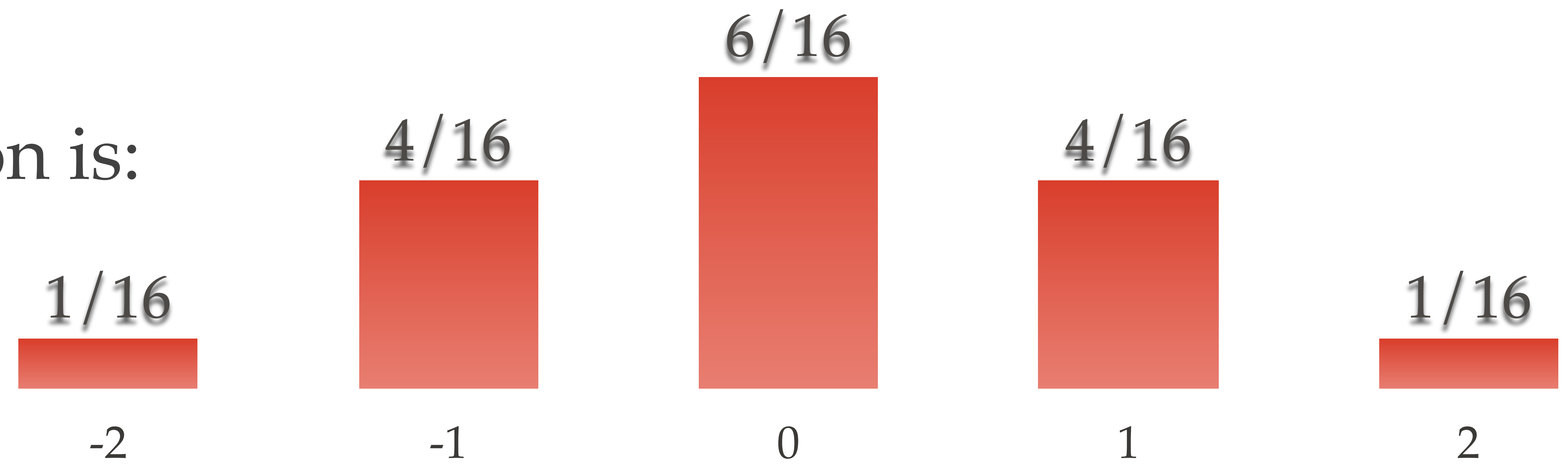
Central binomial distribution

- Idea: A polynomial can be selected uniformly at random from S_η by selecting each of its coefficients uniformly at random from $[-\eta, \eta]$. To simplify this, the coefficients c are drawn instead according to a central binomial distribution (CBD) as follows.
- Select η pairs of bits (a_i, b_i) (with $1 \leq i \leq \eta$) uniformly at random, and output $c = \sum_{i=1}^{\eta} (a_i - b_i)$. Note that $c \in [-\eta, \eta]$.
- In fact, for each $j \in [-\eta, \eta]$, $\Pr(c = j) = \binom{2\eta}{\eta + j} / 2^{2\eta}$; this is the CBD.
- Example: For $\eta = 2$, the central binomial distribution is:



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Fast polynomial multiplication

- The computation times for encryption and decryption is dominated by the time to multiply polynomials in $R_q = \mathbb{Z}_{3329}[x]/(x^{256}+1)$.
- The multiplication can be sped up considerably by using the Number-Theoretic Transform (NTT), which will be covered in V4.

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V2c: Kyber-PKE (full)

1. Domain parameters and key generation
2. Encryption and decryption
3. Decryption doesn’t always work
4. Security

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Domain parameters and key generation

For concreteness, we'll use the ML-KEM-768 domain parameters:

- $q = 3329$
- $n = 256$
- $k = 3$
- $\eta_1 = 2$ and $\eta_2 = 2$
- $d_u = 10$ and $d_v = 4$

Kyber-PKE key generation: Alice does:

1. Select $\rho \in_R \{0,1\}^{256}$ and compute $A = \text{Expand}(\rho)$, where $A \in R_q^{k\times k}$.
2. Select $s \in_{CBD} S_{\eta_1}^k$ and $e \in_{CBD} S_{\eta_1}^k$.
3. Compute $t = As + e$.
4. Alice's encryption (public) key is (ρ, t); her decryption (private) key is s.

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Encryption and decryption

Kyber-PKE encryption: To encrypt a message $m \in \{0,1\}^n$ for Alice, Bob does:

1. Obtain an authentic copy of Alice's encryption key (ρ, t) and compute $A = \text{Expand}(\rho)$.
2. Select $r \in_{CBD} S_{\eta_1}^k$, $e_1 \in_{CBD} S_{\eta_2}^k$, and $e_2 \in_{CBD} S_{\eta_2}$.
3. Compute $u = A^T r + e_1$ and $v = t^T r + e_2 + \lceil \frac{q}{2} \rfloor m$.
4. Compute $c_1 = \text{Compress}_q(u, d_u)$ and
   $c_2 = \text{Compress}_q(v, d_v)$.
5. Output $c = (c_1, c_2)$.

Kyber-PKE decryption: To decrypt $c = (c_1, c_2)$, Alice does:

1. Compute
   $u' = \text{Decompress}_q(c_1, d_u)$ and
   $v' = \text{Decompress}_q(c_2, d_v)$.
2. Compute
   $m = \text{Round}_q(v' - s^T u')$.

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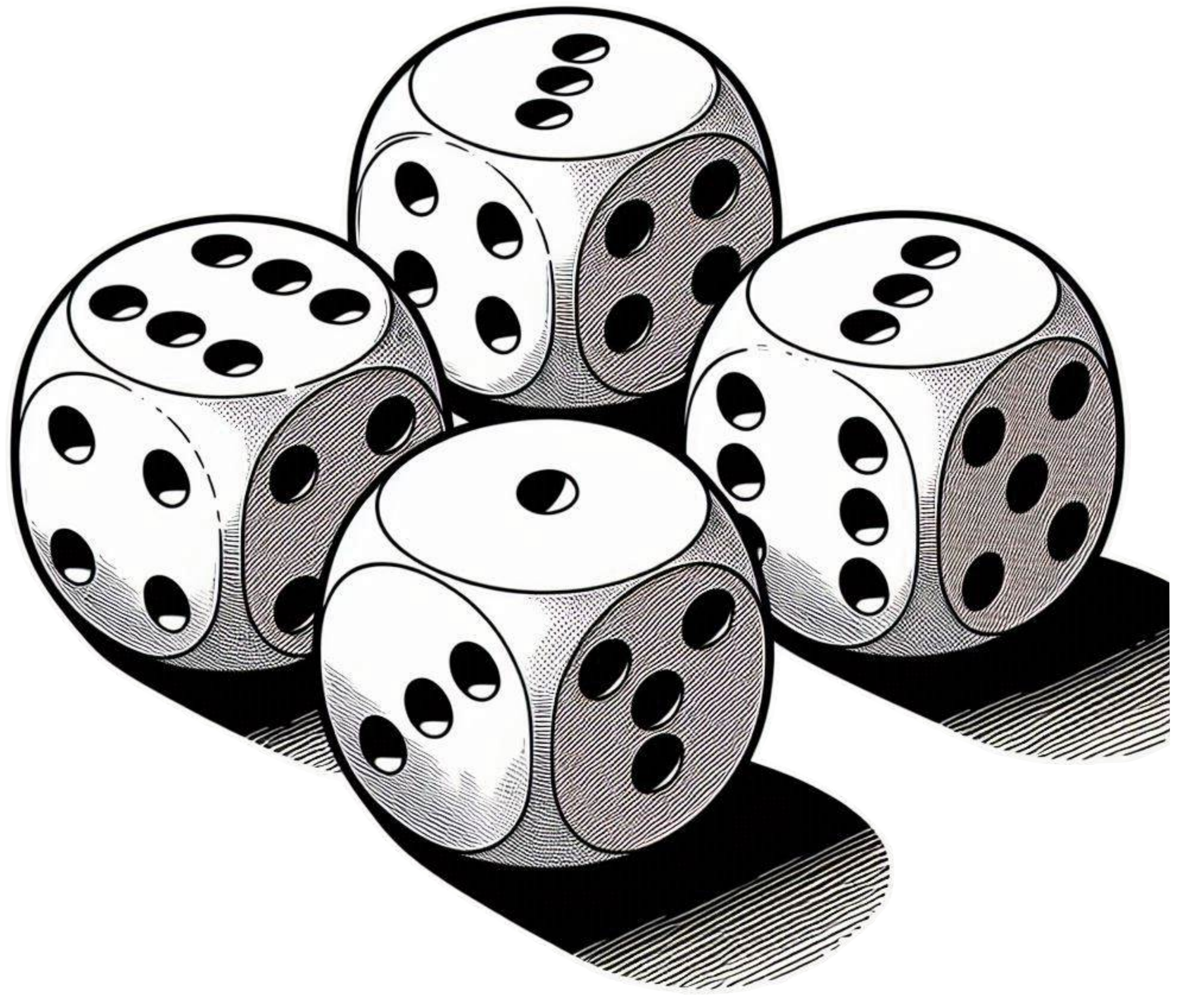
Decryption doesn't always work



- Question: Does decryption work? i.e., does $m = \text{Round}_q(v' - s^T u')$?
- Let $u' = u + e_u$ and $v' = v + e_v$.

- We have $v' - s^T u' = (v + e_v) - s^T(u + e_u)$

$$= v - s^T u + e_v - s^T e_u$$

$$= e^T r + e_2 - s^T e_1 + e_v - s^T e_u + \lceil q/2 \rfloor m\,.$$

- Thus, $\text{Round}_q(v' - s^T u') = m$ if each coefficient E_i of the error polynomial $E(x) = e^T r + e_2 - s^T e_1 + e_v - s^T e_u$ satisfies $-q/4 < E_i \text{ mods } q < q/4$, i.e., $\|E\|_\infty < q/4$.
- For the ML-KEM-768 parameters $|E_i| \not< q/4$ and hence *decryption is not guaranteed to succeed*.
- However, it can be shown that $\|E\|_\infty < q/4$ with probability extremely close to 1. Consequently, *decryption will almost certainly succeed*.

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Security

- Ciphertext compression doesn't affect the security of Kyber-PKE. Consequently, the following claim holds:

- Claim: Kyber-PKE is indistinguishable against chosen-plaintext attack assuming that D-MLWE is intractable.

- Note: Kyber-PKE is *not* intended for stand-alone use.

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V2d: Kyber-KEM

1. Key encapsulation mechanisms
2. Kyber-KEM
3. Parameter sets
4. Omitted details

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Key encapsulation mechanisms

- A key encapsulation mechanism (KEM) allows two parties to establish a shared secret key.
- A KEM is comprised of three algorithms:
  1. Key generation: Each user, say Alice, uses this algorithm to generate an encapsulation key *ek* (public key) and a decapsulation key *dk* (the private key).
  2. Encapsulation: Bob uses Alice's encapsulation key *ek* to generate a secret key K and ciphertext c, and sends c to Alice.
  3. Decapsulation: Alice uses her decapsulation key *dk* to recover K from the ciphertext c.

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Kyber-KEM

- Kyber-KEM is derived by applying (a slight modification) of the "Fujisaki-Okamoto" (FO) transform to Kyber-PKE.
- The FO transform is a generic method for converting a public-key encryption scheme that is secure against chosen-plaintext attacks to one that is secure against chosen-ciphertext attacks.
- The transform uses three hash functions: $G : \{0,1\}^* \longrightarrow \{0,1\}^{512}$, $H : \{0,1\}^* \longrightarrow \{0,1\}^{256}$, and $J : \{0,1\}^* \longrightarrow \{0,1\}^{256}$.

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Fujisaki-Okamoto transform

- Encapsulation: Kyber-PKE is used to encrypt a randomly selected $m \in \{0,1\}^{256}$.
  - Derandomization: m and the encapsulation key ek are hashed to produce a random seed R and the secret key K. The random polynomials r, e_1 and e_2 needed for encryption are derived from R.
- Decapsulation: The intended recipient decrypts the Kyber-PKE ciphertext c to recover m', and then hashes m' and ek to obtain R' and K'. She then re-encrypts m' (using R') and compares the resulting ciphertext c' with c.
  - If $c = c'$, she accepts K'; otherwise, she outputs a random key $\overline{K}$ (which is independent of K) obtained by hashing c and a secret z.
- Kyber-KEM has plaintext awareness, i.e., decapsulation will produce K (and not $\overline{K}$) only if the entity who performed the encapsulation already knows K.
  - This provides resistance to chosen-ciphertext attacks.

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Domain parameters and key generation

For concreteness, we'll use the ML-KEM-768 domain parameters:

- $q = 3329$
- $n = 256$
- $k = 3$
- $\eta_1 = 2$ and $\eta_2 = 2$
- $d_u = 10$ and $d_v = 4$

Kyber-KEM key generation: Alice does:

1. Use the Kyber-PKE key generation algorithm to select a Kyber-PKE encryption key (ρ, t) and decryption key s.
2. Select $z \in_R \{0,1\}^{256}$.
3. Alice's encapsulation key is $ek = (\rho, t)$; her decapsulation key is $dk = (s, ek, H(ek), z)$.

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Encapsulation and decapsulation

Kyber-KEM encapsulation: To establish a shared secret key with Alice, Bob does:

1. Obtain an authentic copy of Alice's encapsulation key ek.
2. Select $m \in_R \{0,1\}^{256}$.
3. Compute $h = H(ek)$ and $(K, R) = G(m, h)$, where $K, R \in \{0,1\}^{256}$.
4. Use the Kyber-PKE encryption algorithm to encrypt m with encryption key ek, and using R to generate the random quantities needed; call the resulting ciphertext c.
5. Output the secret key K and ciphertext c.

Kyber-KEM decapsulation: To recover the secret key K from c using $dk = (s, ek, H(ek), z)$, Alice does:

1. Use the Kyber-PKE decryption algorithm to decrypt c using decryption key s; call the resulting plaintext m'.
2. Compute $(K', R') = G(m', H(ek))$.
3. Compute $\overline{K} = J(z, c)$.
4. Use the Kyber-PKE encryption algorithm to encrypt m' with encryption key ek, and using R' to generate the random quantities needed; call the resulting ciphertext c'.
5. If $c \neq c'$ then return($\overline{K}$).
6. Return(K').

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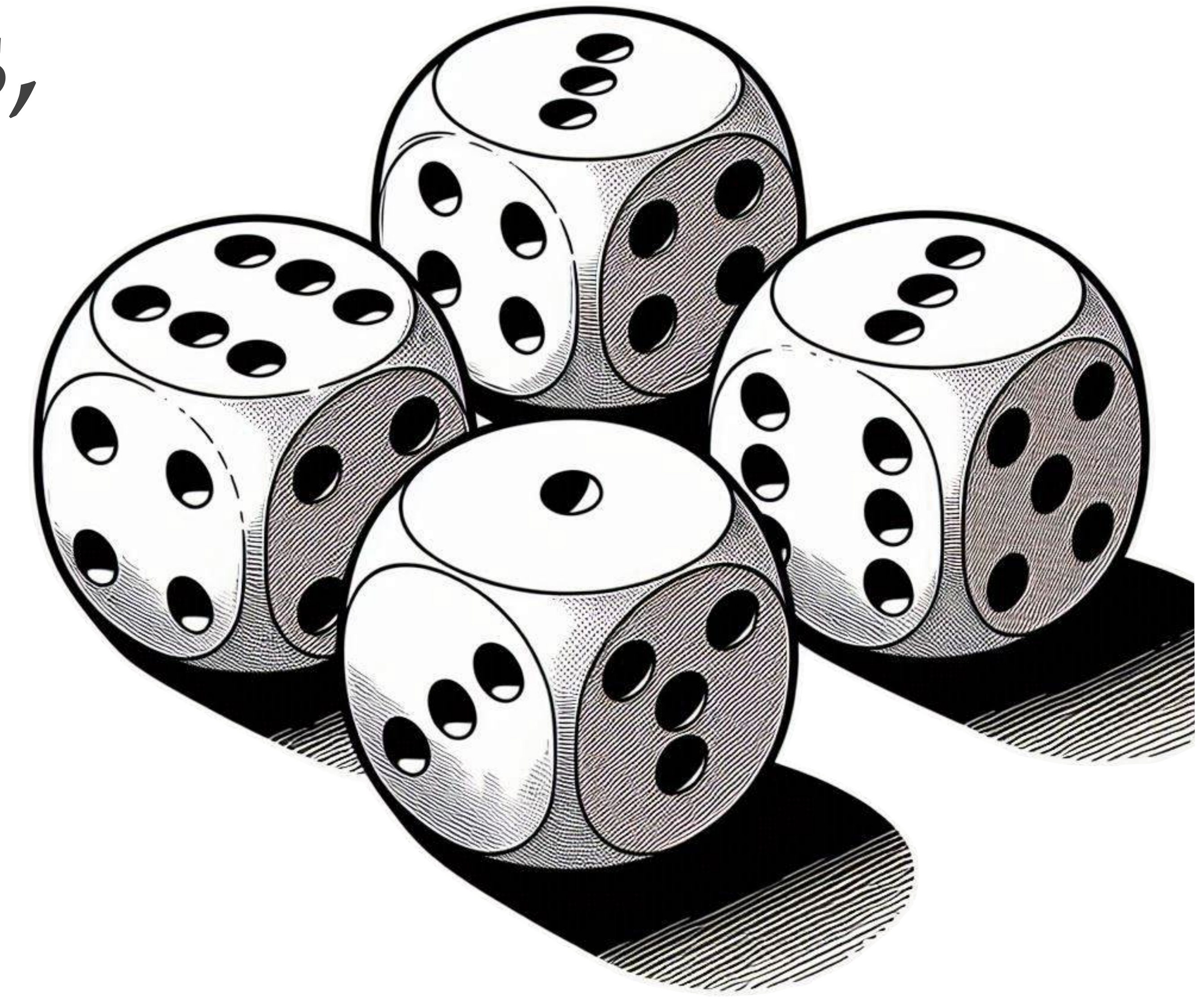
Decapsulation failure

- Decapsulation fails when $c \neq c'$, whereby the key $\overline{K}$ that is outputted is (almost certainly) different from the key K that was encapsulated.
- This can occur even if the communicating parties, Alice and Bob, behave honestly since there is a (very small) probability that there is a failure in the underlying Kyber-PKE (whereby $m' \neq m$).



- It can be shown that the decapsulation failure rate is negligible.

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Security

- Kyber-KEM is indistinguishable against chosen-ciphertext attacks assuming that D-MLWE is intractable, and G, H, J are random functions.
- Kyber-KEM is also indistinguishable against a chosen-ciphertext attack by a quantum adversary who is able to make both classical queries and quantum queries (in superposition) to G, H and J.

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Parameter sets

	Security category	q	n	k	η_1	η_2	d_u	d_v	encaps. key size (bytes)	ciphertext size (bytes)	decapsulation failure rate
ML-KEM-512	1	3329	256	2	3	2	10	4	800	768	$< 2^{-139}$
ML-KEM-768	3	3329	256	3	2	2	10	4	1184	1088	$< 2^{-164}$
ML-KEM-1024	5	3329	256	4	2	2	11	5	1568	1568	$< 2^{-174}$

Categories 1, 3, 5: Fastest known attacks require at least as much resources as needed for exhaustive key search on, respectively, a 128-bit, 192-bit, and 256-bit block cipher.

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Omitted details

FIPS PUB 202

FEDERAL INFORMATION PROCESSING STANDARDS PUBLICATION

SHA-3 Standard: Permutation-Based Hash and Extendable-Output Functions

- Formatting for bit strings and byte strings.
- Hash functions:
  - G is SHA3-512, H is SHA3-256, J is SHAKE256 (see FIPS 202).
- eXtendable Output Function (XOF) used to generate A.
  - SHAKE128 is used.
- PseudoRandom Function (PRF) used to generate s, e, r, e_1, e_2.
  - SHAKE256 is used.
- Number-Theoretic Transform (NTT)
  - for fast polynomial multiplication in $R_q = \mathbb{Z}_{3329}[x]/(x^{256}+1)$ (see V4b).

References

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Algorithm Specifications And Supporting Documentation
(version 3.0)

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October 1, 2020

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NIST
Information Technology Laboratory
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FIPS 203

Federal Information Processing Standards Publication

Module-Lattice-Based Key-Encapsulation Mechanism Standard