

# Q-Reduct

## Quantum-Ready Erasure Codec for Extreme Storage Reduction

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GitHub: <https://github.com/Picyboo-Cybernetics/picyboo-public-qreduct>

## Abstract

Q-Reduct is a lossless, quantum-ready erasure codec that achieves file-size reduction by deliberately discarding payload bits and retaining a compact set of deterministic constraints that uniquely characterize the original. Decoding is posed as an oracle-search problem: given the stored constraints, find the erased bits that make every local and global check true. Classically, aggressive erasure makes decoding computationally infeasible; on a future quantum computer, amplitude-amplification (Grover-style) reduces the expected search cost from  $O(2^m)$  to  $O(2^{(m/2)})$  oracle calls, where  $m$  is the effective constraint strength.

**Keywords:** quantum decoding, Grover search, oracular reconstruction, erasure codec, Merkle verification, linear syndromes, storage reduction

**Projected benefit.** Under quantum decoding and suitable parameterization, the size reduction approaches the erased fraction  $e = d/k$  per chunk. With overhead amortized, reductions on the order of 80-90% (i.e., encoded size  $\leq 10\text{-}20\%$  of original) are mathematically achievable for large  $e$  (e.g.,  $e \approx 0.9$ ) provided the quantum oracle budget suffices to search the induced space and the constraint set enforces uniqueness. Classically, the same parameters are intentionally impractical; small, testable settings validate correctness but do not exceed top classical compressors on average data.

**Contributions.** We specify the format, constraints, oracle, and verification hierarchy; derive classical vs quantum complexity; give parameter guidance; provide reference pseudocode and a PHP skeleton; and outline a rigorous evaluation plan and a quantum implementation roadmap.

## 1. Motivation and Scope

Modern compressors are close to Shannon-style limits on many corpora. Surpassing them consistently and losslessly requires adding information (side-info/models) or trading compute for storage. Q-Reduct formalizes the latter: remove bits now, prove uniqueness by constraints, and shift the heavy work to the decoder. The approach is:

- **Lossless by specification.** If decoding succeeds, the output equals the original bit-for-bit.
- **Asymmetric.** Encoding is linear-time; decoding cost scales with the constraint budget, not with encoder effort.
- **Quantum-ready.** The decoding predicate is an explicit oracle suitable for amplitude amplification.

**Use cases.** Long-horizon archives expecting quantum resources; controlled pipelines willing to accept expensive, delayed decode; research platforms evaluating quantum advantage on real data paths.

**Non-goals.** Q-Reduct is not a universal, faster-than-zstd drop-in today; it is a storage primitive whose practical advantage manifests only with quantum search (or vast classical compute) at aggressive settings.

## 2. Model and Notation

- **File size:**  $N$  bytes
- **Chunk size:**  $k$  bytes (fixed; last chunk may be shorter)
- **Erasure per chunk:**  $d$  bytes removed; prefix kept:  $(k - d)$  bytes
- **Erasure fraction:**  $e = d/k$
- **Chunks:**  $C = \lceil N/k \rceil$
- **Candidate space per chunk:**  $|S| = 2^{(8d)}$
- **Constraints per chunk:**
  - Digest  $m$  bits:  $\text{dig}_i = \text{trunc}_m(H(\text{seed} \parallel \text{chunk}_i))$
  - Linear syndrome  $r$  bits:  $s_i = H_{\text{lin}} \cdot v_i$  over  $\text{GF}(2)$
  - Chain check  $t$  bits across neighbors
- **Global checks:** Merkle root over chunk digests; SHA-256 of the full original
- **Seed:** derived from a stable snapshot (e.g., filename hash, original size, original mtime) and/or a user passphrase

### 3. High-Level Architecture

#### Encoding.

Split the file into chunks of size  $k$ . For chunk  $i$ ,

store the prefix  $P_i \in \{0,1\}^{8(k-d)}$ .

Compute and store constraints:

$m$ -bit digest,  $r$ -bit linear syndrome, optional  $t$ -bit chain check to  $P_{i+1}$ .

Store a Merkle root over per-chunk digests and a global SHA-256 of the original.

#### Decoding.

For each chunk  $i$ , search for  $\text{tail}_i \in \{0,1\}^{8d}$  such that the oracle  $O_i$  (Section 6) returns true. Compose the recovered chunk  $C_i = P_i \parallel \text{tail}_i$ . Verify the global SHA-256. If all chunks succeed and the final hash matches, output is guaranteed equal to the original.

#### Design principles:

- **Locality.** Oracles are chunk-local to enable parallel search.
- **Composability.** Chain checks and a Merkle hierarchy prune cross-chunk combinations early.
- **Determinism.** No probabilistic reconstruction: constraints define a single valid original with overwhelming probability.

## 4. Format Specification

### 4.1. Header

- **magic** (4 B): "QRED"
- **version** (1 B)
- **params** (7 B total): k (uint16), d (uint8), m (uint8), r (uint8), t (uint8), flags (uint8)
- **orig\_size** (8 B)
- **global\_sha256** (32 B)
- **seed\_snapshot\_len** (1 B), **seed\_snapshot** ( $\leq 64$  B): compact snapshot and/or passphrase tag
- Optional **hmac** (32 B) if passphrase binding is enabled

**Flags.** bit0: passphrase used; bit1: chain enabled; bit2: syndrome enabled;  
bit3: merkle enabled.

### 4.2. Chunk record $i$

- **prefix\_i**:  $(k - d)$  bytes
- **digest\_i**:  $\lceil m/8 \rceil$  bytes
- **syndrome\_i**:  $\lceil r/8 \rceil$  bytes (optional)
- **chain\_i**:  $\lceil t/8 \rceil$  bytes (optional)

### 4.3. Trailer

- **merkle\_root** (if enabled)
- Optional auxiliary indices

## 5. Constraint Primitives

### Truncated digest $m$

- **Role:** probabilistic preimage check
- **Expected matches (per chunk):**  $E_m = 2^{(8d - m)}$
- **Cost:**  $\lceil m/8 \rceil$  bytes

### Linear syndrome $r$

- **Role:** algebraic pruning via  $s_i = H_{\text{lin}} \cdot v_i$ ,  $H_{\text{lin}} \in \{0,1\}^{(r \times 8k)}$
- Reduces the candidate set by a factor of  $2^r$  in expectation (keeps approximately  $1/2^r$ )
- Cheap to compute, easy to compose with digest
- **Cost:**  $\lceil r/8 \rceil$  bytes

### Chain check $t$

- **Role:** link neighbors to prevent cross-chunk combinatorics
- Example:  $\text{trunc\_t}(H(P_i \parallel P_{i+1}))$
- **Cost:**  $\lceil t/8 \rceil$  bytes

### Merkle hierarchy

- **Role:** hierarchical pruning and global integrity
- **Overhead:** compact (root only) if per-chunk digests are stored anyway



**Per-chunk net saving (bytes):**

$$\Delta_{\text{chunk}} \approx d - (m + r + t)/8$$

**Whole file net:**

$$\Delta_{\text{total}} \approx C \cdot \Delta_{\text{chunk}} - \text{header/trailer overhead}$$

Amortize per-chunk control bits by increasing  $k$  for the same fractional erasure  $e$ .

## 6. Decoding as an Oracle Problem

For chunk  $i$ , define the oracle  $O_i$  that tests a candidate tail:

**Input:**  $P_i$  (stored), candidate  $X \in \{0,1\}^{(8d)}$ , neighbor  $P_{i+1}$  if chain is enabled, seed.

**Construct:**  $C_i = P_i \parallel X$

**Return true iff:**

1.  $\text{trunc\_m}(H(\text{seed} \parallel C_i)) = \text{digest}_i$
2. If enabled,  $H_{\text{lin}} \cdot C_i = s_i$
3. If enabled,  $\text{trunc\_t}(H(P_i \parallel P_{i+1})) = \text{chain}_i$
4. (Optional during search) partial Merkle consistency holds

### Uniqueness condition

With independent constraints, the expected number of matches is

$$E[\text{matches}] \approx 2^{(8d - m - r_{\text{eff}} - t_{\text{eff}})} \leq 1$$

where  $r_{\text{eff}}$  and  $t_{\text{eff}}$  reflect the effective bits of pruning contributed by the syndrome and chain checks (bounded above by  $r$  and  $t$ ). Choose parameters so  $E \leq 1$  per chunk.

## 7. Complexity: Classical vs Quantum

Let  $m_{\text{eff}} = m + r_{\text{eff}} + t_{\text{eff}}$ .

**Classical (random-oracle model):** expected oracle calls to find a preimage that passes all checks scale as

$$T_{\text{classical}} = \Theta(2^{m_{\text{eff}}})$$

Even if  $E \approx 1$ , finding the solution typically costs exponential time in  $m_{\text{eff}}$ .

**Quantum (Grover / amplitude amplification):**

$$T_{\text{quantum}} = \Theta(2^{m_{\text{eff}}/2})$$

given a coherent oracle  $U_O$  implementing the joint predicate. This is the core speedup that makes large  $d$  feasible.

### Implication

To erase a fraction  $e = d/k$  and keep uniqueness with negligible false positives, pick  $m_{\text{eff}} \approx 8d$ . Then

- $T_{\text{classical}} \approx 2^{(8d)}$
- $T_{\text{quantum}} \approx 2^{(4d)}$

For  $d = 12$  bytes,  $T_{\text{classical}} \sim 2^{96}$  (impossible), while  $T_{\text{quantum}} \sim 2^{48}$  oracle calls (still enormous, but a roadmap target for future QC at scale). In practice, choose  $d$  to match the oracle budget.

## 8. Projected Storage Reduction

Let  $e = d/k$ . Per chunk:

$$\text{size\_stored} = (k - d) + (m + r + t)/8$$

Fractional size:

$$\rho = \text{size\_stored}/k = 1 - e + (m + r + t)/(8k)$$

For fixed  $(m, r, t)$  and growing  $k$ , overhead amortizes. Under quantum decoding, we select large  $d$  (large  $e$ ) and modest  $(m, r, t)$  that still enforce uniqueness, yielding:

$$\rho \approx 1 - e \implies \text{reduction} \approx e$$

### Example (headline)

Choose  $e = 0.90$  (erase 90% of each chunk),  $k = 1$  MiB,  $(m, r, t) = (64, 16, 16)$  bits.

Overhead  $(m + r + t)/8 = 12$  B per chunk  $\implies \rho \approx 0.10 + 12/2^{20} \approx 0.10001$ .

The encoded file is ~10% of the original, i.e., ~90% reduction, contingent on a quantum decoder capable of handling  $m_{\text{eff}} \approx 96$  bits of oracle strength per chunk (and thus  $T_{\text{quantum}} \sim 2^{48}$  coherent oracle evaluations).

Classically infeasible by design.

**Today's regime.** With small  $d$  chosen so classical brute force terminates,  $\rho$  is near 1 once  $(m, r, t)$  are counted; practical reductions beyond top compressors are not expected on average data.

## 9. Parameter Guidance

- **Chunk size  $k$ .** Larger  $k$  better amortizes overhead; increases working-set and I/O.  
Typical quantum-target:  $k \in [256 \text{ KiB}, 4 \text{ MiB}]$ .
- **Erasure  $d$ .** Drives savings. Classical tests:  $d \in \{2, 3, 4\}$  bytes.  
Quantum-target:  $d$  into tens or hundreds of bytes (or more),  
bounded by search budget.
- **Digest  $m$ .** Dominant determinant of search cost.  
For uniqueness, start from  $m \approx 8d - \delta$  and add syndrome/chain to close the gap.
- **Syndrome  $r$ .** Cheap pruning. Sparse random or LDPC-like  $H_{\text{lin}}$  works well;  
typical  $r \in \{8, 16, 32\}$ .
- **Chain  $t$ .** Helps kill cross-chunk ambiguity;  $t \in \{0, 8, 16\}$  suffices.
- **Seeds.** Prefer a stored snapshot (24-64 B). Optional passphrase can be added;  
neither is used for secrecy unless HMAC is enabled.

**Rule of thumb.** Positive net saving per chunk requires  $d > (m + r + t)/8$  or amortization of control bits across larger  $k$ .

## 10. Security, Robustness, and Portability

- **Integrity.** Global SHA-256 and Merkle ensure deterministic acceptance or failure; no silent corruption.
- **Tamper binding (optional).** HMAC over header with passphrase.
- **Portability.** Include a compact seed snapshot; do not rely on live file system metadata.
- **Adversarial inputs.** Parameterize  $m_{\text{eff}}$  to keep  $E \leq 1$  with wide safety margins; randomize  $H_{\text{lin}}$  per file if desired.

## 11. Pseudocode (Reference)

### 11.1 Encoder

**function QRED\_Encode**(bytes data, uint16 k, uint8 d, uint8 m, uint8 r, uint8 t, Seed seed):

  N = len(data)

  C = ceil(N / k)

  header = build\_header(k,d,m,r,t,N, sha256(data), seed.snapshot)

  out.write(header)

  digests = []

  prefixes = []

  syndromes = []

  chains = []

  for i in 0..C-1:

    chunk = data[i\*k : min((i+1)\*k, N)]

    if len(chunk) < d: error("chunk shorter than d")

    prefix = chunk[0 : len(chunk)-d]

    full = chunk

    dig\_i = trunc\_m( sha256(seed || full), m )

    syn\_i = trunc\_r( linear\_syndrome(H\_lin, full), r )

    prefixes.append(prefix); digests.append(dig\_i); syndromes.append(syn\_i)

  for i in 0..C-1:

    next\_prefix = (i+1<C) ? prefixes[i+1] : EMPTY

    chain\_i = (t>0) ? trunc\_t( sha256(prefixes[i] || next\_prefix), t ) : EMPTY

    chains.append(chain\_i)

  for i in 0..C-1:

    out.write(prefixes[i])

    out.write(digests[i])

    if r>0: out.write(syndromes[i])

    if t>0: out.write(chains[i])

  if merkle\_enabled:

    root = merkle\_root(digests)

    out.write(root)

## 11.2 Oracle and Decoder (classical brute, per chunk)

**function Oracle\_Test**(prefix, candidate\_tail, digest, syndrome, chain, next\_prefix, seed, m,r,t):

```

    full = prefix || candidate_tail
    if trunc_m(sha256(seed || full), m) != digest: return FALSE
    if r>0 and trunc_r(linear_syndrome(H_lin, full), r) != syndrome: return FALSE
    if t>0:
        if trunc_t(sha256(prefix || next_prefix), t) != chain: return FALSE
    return TRUE

```

**function QRED\_Decompile**(stream in):

```

    header = parse_header(in)
    k,d,m,r,t = header.params
    out = empty_buffer()
    chunks = []
    for i in 0..C-1:
        prefix = in.read(k-d for full chunks; last chunk sized)
        digest = in.read(ceil(m/8))
        syndrome = (r>0) ? in.read(ceil(r/8)) : EMPTY
        chain    = (t>0) ? in.read(ceil(t/8)) : EMPTY
        next_prefix = peek_next_prefix(in) // or deferred check
        found = FALSE
        for x in 0 .. 2^(8*d)-1:
            tail = int_to_bytes(x, d)
            if Oracle_Test(prefix, tail, digest, syndrome, chain, next_prefix, header.seed, m,r,t):
                chunks.append(prefix || tail)
                found = TRUE
                break
        if not found: error("no candidate for chunk " + i)
    data = concat(chunks)
    if sha256(data) != header.global_sha256: error("global hash mismatch")
    return data

```



## 12. Implementation Appendix (PHP Skeleton)

**Purpose:** reference only; not optimized; no quantum paths; suitable for small-d classical validation.

```
<?php
```

```
function sha256bin(string $b): string { return hash('sha256', $b, true); }
```

```
function trunc_bits(string $bin, int $bits): string {
```

```
    $bytes = intval($bits + 7, 8);
```

```
    $t = substr($bin, 0, $bytes);
```

```
    $excess = $bytes * 8 - $bits;
```

```
    if ($excess > 0) {
```

```
        $last = ord($t[$bytes - 1]) >> $excess;
```

```
        $t[$bytes - 1] = chr($last);
```

```
    }
```

```
    return $t;
```

```
}
```

```
function lin_syndrome(string $chunk, int $rBits): string {
```

```
    // demo: XOR-of-bytes folded into 32-bit, then truncate
```

```
    $x = 0;
```

```
    $n = strlen($chunk);
```

```
    for ($i = 0; $i < $n; $i++) $x ^= ord($chunk[$i]);
```

```
    $raw = pack('N', $x);
```

```
    $len = intval($rBits + 7, 8);
```

```
    return substr($raw, 0, $len);
```

```
}
```

```
function qred_encode(string $inPath, string $outPath, int $k=4096, int $d=3,  
    int $m=24, int $r=8, int $t=8, string $seed=""): void {
```

```
    $data = file_get_contents($inPath);
```

```
    $N = strlen($data);
```

```
    $fh = fopen($outPath, 'wb');
```

```
    fwrite($fh, "QRED"); fwrite($fh, chr(1));
```

```
    // params
```

```
    fwrite($fh, pack('n', $k)); fwrite($fh, chr($d)); fwrite($fh, chr($m));
```

```
    fwrite($fh, chr($r)); fwrite($fh, chr($t)); fwrite($fh, chr(0));
```

```
    fwrite($fh, pack('J', $N)); fwrite($fh, sha256bin($data));
```

```

$snap = ""; fwrite($fh, chr(strlen($snap))); // seed snapshot len
if ($snap !== "") fwrite($fh, $snap);

$mBytes = intdiv($m + 7, 8); $rBytes = intdiv($r + 7, 8);
$tBytes = intdiv($t + 7, 8);
$prefixes = $digests = $syndromes = $chains = [];
$C = intdiv($N + $k - 1, $k);

for ($i=0,$soff=0; $i<$C; $i++, $soff+=$k) {
    $chunk = substr($data, $soff, min($k, $N - $soff));
    if (strlen($chunk) <= $d) throw new RuntimeException("chunk shorter than d");
    $prefix = substr($chunk, 0, strlen($chunk) - $d);
    $digest = trunc_bits(sha256bin($seed . $chunk), $m);
    $syn = ($r>0) ? trunc_bits(lin_syndrome($chunk, $r), $r) : "";
    $prefixes[] = $prefix; $digests[] = $digest; $syndromes[] = $syn;
}
for ($i=0; $i<$C; $i++) {
    $next_prefix = ($i+1<$C) ? $prefixes[$i+1] : "";
    $chain = ($t>0) ? trunc_bits(sha256bin($prefixes[$i] . $next_prefix), $t) : "";
    $chains[] = $chain;
}
for ($i=0; $i<$C; $i++) {
    fwrite($fh, $prefixes[$i]);
    fwrite($fh, $digests[$i]);
    if ($r>0) fwrite($fh, $syndromes[$i]);
    if ($t>0) fwrite($fh, $chains[$i]);
}
fclose($fh);
}

```

```

function qred_decode(string $inPath, string $outPath): void {
    $f = fopen($inPath, 'rb');
    if (fread($f,4)!="QRED") throw new RuntimeException("bad magic");
    $ver = ord(fread($f,1));
    $k = unpack('n', fread($f,2))[1]; $d=ord(fread($f,1)); $m=ord(fread($f,1));
    $r=ord(fread($f,1)); $t=ord(fread($f,1)); $flags=ord(fread($f,1));
    $N = unpack('J', fread($f,8))[1]; $sha = fread($f,32);
    $snapLen = ord(fread($f,1)); $seed = ($snapLen>0) ? fread($f,$snapLen) : "";
    $mBytes = intdiv($m+7,8); $rBytes = intdiv($r+7,8); $tBytes = intdiv($t+7,8);

```

```

$C = intdiv($N + $k - 1, $k);
$out = "";
for ($i=0; $i<$C; $i++) {
    $lastSize = ($i<$C-1) ? $k : ($N - $k*($C-1));
    $prefixLen = $lastSize - $d;
    $prefix = fread($f, $prefixLen);
    $digest = fread($f, $mBytes);
    $syn = ($r>0)? fread($f, $rBytes):"";
    $chain = ($t>0)? fread($f, $tBytes):"";
    // Peek next prefix for chain check
    $pos = ftell($f);
    $next_prefix = "";
    if ($i<$C-1) {
        $nextSize = ($i+1<$C-1) ? $k : ($N - $k*($C-1));
        $next_prefix = fread($f, $nextSize - $d);
    }
    fseek($f, $pos);
    $found = null;
    $space = 1 << (8*$d);
    for ($x=0; $x<$space; $x++) {
        $tail = "";
        for ($b=$d-1; $b>=0; $b--) $tail = chr(($x >> (8*$b)) & 0xFF) . $tail;
        $full = $prefix . $tail;
        if (trunc_bits(sha256bin($seed.$full), $m) !== $digest) continue;
        if ($r>0 && trunc_bits(lin_syndrome($full,$r), $r) !== $syn) continue;
        if ($t>0) {
            if (trunc_bits(sha256bin($prefix.$next_prefix), $t) !== $chain) continue;
        }
        $found = $full; break;
    }
    if ($found===null) throw new RuntimeException("no candidate in chunk $i");
    $out .= $found;
}
fclose($f);
if (sha256bin($out) !== $sha) throw new RuntimeException("global hash mismatch");
file_put_contents($outPath, $out);
}

```

**Notes.** This skeleton keeps the critical ideas compact. Real implementations should stream I/O, validate bounds, and add Merkle verification and error handling.

### 13. Evaluation Plan

**Datasets.** Text/JSON/logs (structured), uncompressed binaries, already-compressed (control), random (control).

**Baselines.** zstd-19, brotli-11, paq/paq8.

**Parameters.**  $k \in \{1 \text{ KiB}, 4 \text{ KiB}, 64 \text{ KiB}\}$ ,  $d \in \{2, 3, 4, 6\}$ ,  $m \approx 8d$ ,  $r \in \{8, 16\}$ ,  $t \in \{0, 8\}$ .

**Metrics.** Encoded size ratio  $\rho$ ; classical decode attempts per chunk; wall-clock decode time; false-match rate; pass/fail on hash.

**Success criteria (classical lab).** Deterministic correctness on small  $d$ ; empirical match to predicted costs; no silent failures.

**Quantum roadmap validation.** Map the oracle to a reversible circuit; estimate gate counts for SHA-256 truncation and linear checks; extrapolate feasible  $(d, m_{\text{eff}})$  with assumed quantum resources.

## 14. Quantum Implementation Roadmap

**Oracle unitary  $U_O$ .** Build a coherent predicate for (digest, syndrome, chain).

- SHA-256 reversible circuits are known in literature; use truncation by discarding high bits.
- Linear syndromes are Clifford-friendly.

**Amplitude amplification.** Standard Grover iterations; per-chunk search in superposition space  $|x\rangle$ ,  $x \in \{0,1\}^{(8d)}$ .

**Data access.** Seed and stored constants are classical; embed as control parameters.

Prefix and neighbor prefixes are classical inputs loaded to quantum ancillas.

**Parallelization.** Run per-chunk searches in parallel across quantum processors; or pipeline chunks.

**Resource estimation.** For target  $d$  and  $m_{\text{eff}}$ , estimate  $2^{(m_{\text{eff}}/2)}$  oracle calls; compute depth  $\times$  calls; incorporate error-correction overheads.

**Hybrid pruning.** Classical prefilters (e.g., linear checks) can be pushed ahead to lower oracle load.

## 15. Limitations and Risks

- **Impossibility bounds.** This is not a universal better-than-entropy compressor; it trades compute for storage and relies on constraints, not magic.
- **Classical practicality.** Aggressive settings are intentionally infeasible today.
- **Quantum uncertainty.** Timelines and practical oracle costs are uncertain; resource estimates must be revisited.
- **Portability.** If seed snapshots or passphrases are lost, decoding fails by design.
- **Adversarial inputs.** Choose conservative  $m_{\text{eff}}$  and randomized matrices to bound worst-case collisions.

## 16. Conclusion

Q-Reduct reframes lossless storage as compute-for-storage exchange with an explicit quantum decoding advantage. By erasing a large fraction of payload and storing compact constraints, we shift complexity to a search oracle. Classically, only small  $d$  is testable; under quantum decoding, projected reductions track the erasure fraction, enabling on the order of 80-90% size reduction for high  $e$  with sufficient quantum resources and properly tuned constraints. The specification, pseudocode, PHP skeleton, and evaluation plan provided here support immediate laboratory validation and future quantum mapping.

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## Appendix A — Symbols at a Glance

Symbol	Definition
$N$	Original size (bytes)
$k$	Chunk size (bytes)
$d$	Bytes erased per chunk
$e$	Erasure fraction = $d/k$
$m, r, t$	Digest, syndrome, chain bits
$C$	Chunk count = $\lceil N/k \rceil$
$\Delta_{\text{chunk}}$	Net saving per chunk = $d - (m+r+t)/8$
$E$	Expected matches $\approx 2^{(8d - m - r_{\text{eff}} - t_{\text{eff}})}$
$m_{\text{eff}}$	Effective constraint strength = $m + r_{\text{eff}} + t_{\text{eff}}$
$T_{\text{classical}}$	Classical complexity = $\Theta(2^{m_{\text{eff}}})$
$T_{\text{quantum}}$	Quantum complexity = $\Theta(2^{(m_{\text{eff}}/2)})$
$\rho$	Fractional size = $\text{size}_{\text{stored}}/k$

## Appendix B — Parameter Tables (examples)

**Per-chunk net saving (bytes):**  $\Delta_{\text{chunk}} = d - (m+r+t)/8$

**Note on notation:** In mathematical formulas we use  $\parallel$  for concatenation;  
in pseudocode and implementation we use  $||$ .

### Classical-testable parameters (small d)

k (Bytes)	k (KiB)	d (Bytes)	e = d/k	m	r	t	$\Delta_{\text{chunk}}$ (B)	$\rho$	Reduction
4,096	4	3	0.000732	24	8	8	-2	$\approx 1.00049$	-0.049%
65,536	64	6	0.000092	48	16	16	-4	$\approx 1.00006$	-0.006%

### Quantum-target regime (90% headline example)

k (Bytes)	k (KiB)	d (Bytes)	e = d/k	m	r	t	$\Delta_{\text{chunk}}$ (B)	$\rho$	Reduction
1,048,576	1	943,718	0.90	64	16	16	943,706	$\approx$ 0.10001	$\approx 90.0\%$

In the quantum regime:  $e \approx 0.9$ , overhead  $(m+r+t)/8 \ll k$ , enabling dramatic reduction with quantum oracle budget.

## Appendix C — Pseudocode: Merkle and Syndrome Construction

**function merkle\_root**(list digests):

```
    level = digests
    while len(level) > 1:
        next = []
        for j in 0..step2(len(level)):
            a = level[j]
            b = (j+1<len(level)) ? level[j+1] : level[j]
            next.append( sha256(a || b) )
        level = next
    return level[0]
```

**function random\_sparse\_Hlin**(r, bitsPerChunk, density):

```
    // return r x bitsPerChunk binary matrix with given sparsity
```

## Appendix D — Implementation Checklist

- Streaming encoder/decoder; bounds checks; endian consistency
- Stable seed snapshot; optional passphrase; deterministic seed derivation
- Robust header validation; versioning
- Optional Merkle root; chunk digests already present
- Unit tests: oracle truth table; collision statistics; chunk independence
- Benchmarks: per-chunk oracle cost; end-to-end decode time; corpus ratios
- Security: HMAC option; tamper detection; controlled failure semantics