

# RFC-029: Compression and Deduplication

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**Implementation:** Proposed

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## Abstract

This RFC specifies compression and deduplication for the Library of Cyberspace: how vaults reduce storage requirements while maintaining content-addressability, integrity verification, and efficient retrieval. Compression is transparent to the content-addressing layer.

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## Motivation

Storage efficiency matters for preservation:

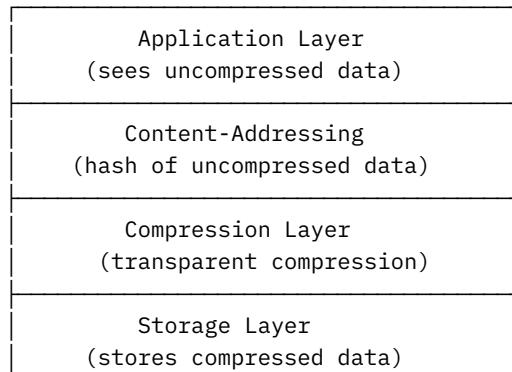
- **Cost** - Less storage means more preservation per dollar
- **Bandwidth** - Compressed transfers are faster
- **Redundancy** - More copies fit in same space
- **Longevity** - Smaller archives survive longer

But compression must not compromise:

- **Integrity** - Hashes must remain valid
  - **Addressability** - Content addressing still works
  - **Deduplication** - Identical content stored once
  - **Accessibility** - Data remains retrievable
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## Compression Model

### Layered Architecture



## Compression Metadata

```
(define (compress-object data algorithm)
  (let* ((compressed (compress algorithm data))
         (ratio (/ (bytevector-length compressed)
                   (bytevector-length data))))
    `(compressed-object
      (algorithm ,algorithm)
      (original-size ,(bytevector-length data))
      (compressed-size ,(bytevector-length compressed)))
    (ratio ,ratio)
    (data ,compressed))))  
  
;; Stored in soup  
(soup-object  
  (hash "sha256:original-content-hash...")  
  (compression  
    (algorithm zstd)  
    (level 3)  
    (original-size 1048576)  
    (compressed-size 524288)  
    (ratio 0.5)))
```

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## Compression Algorithms

### Supported Algorithms

```
(define compression-algorithms
  `((zstd . ((extension . "zst")
              (levels . (1 3 9 19))
              (default-level . 3)
              (dictionary . #t)))
    (lz4 . ((extension . "lz4")
              (levels . (1 9))
              (default-level . 1)
              (dictionary . #f)))
    (gzip . ((extension . "gz")
              (levels . (1 6 9))
              (default-level . 6)
              (dictionary . #f)))
    (none . ((extension . #f)
              (levels . ()))
              (default-level . #f)))
```

```
(dictionary . #f))))
```

## Algorithm Selection

```
(define (select-compression-algorithm content-type size)
  "Select best algorithm for content"
  (cond
    ;; Already compressed formats
    ((member content-type '("image/jpeg" "image/png" "video/mp4"
                           "application/zip" "application/gzip"))
     'none)
    ;; Small objects - overhead not worth it
    ((< size 1024)
     'none)
    ;; Text and code - zstd with dictionary
    ((member content-type '("text/plain" "text/html" "application/json"
                           "application/javascript" "text/x-scheme"))
     'zstd)
    ;; Binary data - lz4 for speed
    ((string-prefix? "application/" content-type)
     'lz4)
    ;; Default
    (else 'zstd)))
```

## Zstd Dictionaries

```
; Train dictionary on sample data
(define (train-dictionary samples dict-size)
  "Train zstd dictionary from sample data"
  (zstd-train-dictionary samples dict-size))

;; Content-type specific dictionaries
(define dictionaries
  `((scheme . ,(load-dictionary "scheme.dict"))
    (json . ,(load-dictionary "json.dict"))
    (markdown . ,(load-dictionary "markdown.dict"))))

(define (compress-with-dictionary data content-type)
  (let ((dict (assoc-ref dictionaries content-type)))
    (if dict
        (zstd-compress-with-dict data dict)
        (zstd-compress data))))
```

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## Compression Operations

### Transparent Compression

```
(define (cas-put-compressed data)
  "Store data with transparent compression"
  (let* ((hash (content-hash data)) ; Hash uncompressed
         (algorithm (select-compression-algorithm
                     (detect-content-type data)
                     (bytevector-length data))))
    (stored (if (eq? algorithm 'none)
                data
                (compress algorithm data))))
  ;; Store compressed, index by uncompressed hash
  (storage-put hash stored)
  ;; Record compression metadata
  (soup-put hash
    compression: `((algorithm . ,algorithm)
                  (original-size . ,(bytevector-length data))
                  (compressed-size . ,(bytevector-length stored))))
  hash))

(define (cas-get-decompressed hash)
  "Retrieve and decompress data"
  (let* ((stored (storage-get hash))
         (meta (soup-get hash))
         (algorithm (assoc-ref (assoc-ref meta 'compression) 'algorithm)))
    (if (or (not algorithm) (eq? algorithm 'none))
        stored
        (decompress algorithm stored))))
```

### Batch Compression

```
(define (compress-batch objects)
  "Compress multiple objects efficiently"
  ;; Group by content type for dictionary efficiency
  (let ((groups (group-by detect-content-type objects)))
    (append-map
      (lambda (group)
        (let ((content-type (car group))
              (items (cdr group)))
          (map (lambda (obj)
                  (compress-with-dictionary obj content-type))
               items)))
    groups)))
```

## Recompression

```
(define (recompress-object hash new-algorithm new-level)
  "Recompress object with different settings"
  (let* ((data (cas-get-decompressed hash))
         (new-compressed (compress new-algorithm data new-level)))
    (storage-put hash new-compressed)
    (soup-update hash
      compression: `((algorithm . ,new-algorithm)
                     (level . ,new-level)
                     (original-size . ,(bytevector-length data))
                     (compressed-size . ,(bytevector-length new-compressed))))
    (audit-append action: 'recompressed
                  hash: hash
                  algorithm: new-algorithm)))
```

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## Deduplication

### Content-Based Deduplication

```
; Content addressing provides automatic deduplication
(define (store-deduplicated data)
  (let ((hash (content-hash data)))
    (if (cas-exists? hash)
        (begin
          ;; Increment reference count
          (soup-update hash ref-count: (+ 1 (soup-ref-count hash)))
          (audit-append action: 'deduplicated hash: hash)
          hash)
        (cas-put data))))
```

### Block-Level Deduplication

```
; Split large objects into blocks
(define *block-size* 65536) ; 64KB

(define (chunk-object data)
  "Split object into content-defined chunks"
  (let ((chunks '())
        (pos 0))
    (while (< pos (bytevector-length data))
      (let ((boundary (find-chunk-boundary data pos)))
        (set! chunks (cons (subbytevector data pos boundary) chunks))
        (set! pos boundary)))
    (reverse chunks)))
```

```

;; Content-defined chunking (Rabin fingerprint)
(define (find-chunk-boundary data start)
  "Find chunk boundary using rolling hash"
  (let ((min-size 4096)
        (max-size 131072)
        (mask #x1FFF)) ; Average 8KB chunks
    (let loop ((pos (+ start min-size)))
      (cond
        ((>= pos (min (+ start max-size) (bytevector-length data)))
         pos)
        ((= (bitwise-and (rabin-hash data pos) mask) 0)
         pos)
        (else (loop (+ pos 1)))))))

```

## Chunk Storage

```

(define (store-chunked data)
  "Store large object as deduplicated chunks"
  (let* ((chunks (chunk-object data))
         (chunk-hashes (map (lambda (chunk)
                               (store-deduplicated chunk))
                           chunks)))
    ;; Store manifest
    (let ((manifest `(chunked-object
                      (chunks ,chunk-hashes)
                      (total-size ,(bytevector-length data))
                      (chunk-count ,(length chunks))))))
      (cas-put (serialize manifest)))))

(define (retrieve-chunked manifest-hash)
  "Reassemble chunked object"
  (let* ((manifest (deserialize (cas-get manifest-hash)))
         (chunks (map cas-get (assoc-ref manifest 'chunks))))
    (bytevector-concatenate chunks)))

```

## Deduplication Statistics

```

(define (deduplication-stats)
  "Calculate deduplication effectiveness"
  (let* ((objects (soup-query type: 'any))
         (logical-size (sum (map soup-original-size objects)))
         (physical-size (sum (map soup-compressed-size
                                   (delete-duplicates objects hash=?)))))
    `((logical-size . ,logical-size)
      (physical-size . ,physical-size)))

```

```
(dedup-ratio . ,(/ logical-size physical-size))
(space-saved . ,(- logical-size physical-size))))
```

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## Delta Compression

### Version Deltas

```
(define (store-delta base-hash new-data)
  "Store object as delta from base"
  (let* ((base-data (cas-get base-hash))
         (delta (compute-delta base-data new-data))
         (new-hash (content-hash new-data)))
    (if (< (bytevector-length delta)
            (* 0.5 (bytevector-length new-data)))
        ;; Delta is worthwhile
        (begin
          (storage-put new-hash delta)
          (soup-put new-hash
                    delta: `((base . ,base-hash)
                               (type . xdelta)))
          new-hash)
        ;; Store full object
        (cas-put new-data)))))

(define (retrieve-delta hash)
  "Reconstruct object from delta"
  (let ((meta (soup-get hash)))
    (if (assoc-ref meta 'delta)
        (let* ((base-hash (assoc-ref (assoc-ref meta 'delta) 'base))
               (base-data (cas-get base-hash))
               (delta (storage-get hash)))
          (apply-delta base-data delta)
          (storage-get hash)))
        (storage-get hash))))
```

### Delta Chains

```
;; Limit delta chain depth
(define *max-delta-depth* 10

(define (delta-chain-depth hash)
  "Calculate depth of delta chain"
  (let ((meta (soup-get hash)))
    (if (assoc-ref meta 'delta)
        (+ 1 (delta-chain-depth (assoc-ref (assoc-ref meta 'delta) 'base)))
        0)))
```

```
(define (should-store-delta? base-hash)
  "Check if delta storage is appropriate"
  (< (delta-chain-depth base-hash) *max-delta-depth*))
```

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## Archive Compression

### Sealed Archive Format

```
;; RFC-018 integration
(define (create-compressed-archive objects)
  "Create compressed sealed archive"
  (let* ((serialized (serialize-objects objects))
         (compressed (zstd-compress serialized 19)) ; Max compression
         (encrypted (age-encrypt compressed recipients)))
    (cas-put encrypted)))
```

### Streaming Compression

```
(define (stream-compress input-port output-port algorithm)
  "Stream compression for large files"
  (let ((ctx (compression-context-create algorithm)))
    (let loop ()
      (let ((chunk (read-bytevector *chunk-size* input-port)))
        (unless (eof-object? chunk)
          (write-bytevector (compress-chunk ctx chunk) output-port)
          (loop))))
    (write-bytevector (compress-finish ctx) output-port)))
```

---

## Performance Optimization

### Compression Cache

```
(define compression-cache (make-lru-cache 1000))

(define (cached-decompress hash)
  "Cache decompressed data for frequent access"
  (or (lru-get compression-cache hash)
      (let ((data (cas-get-decompressed hash)))
        (lru-put! compression-cache hash data)
        data)))
```

## Parallel Compression

```
(define (parallel-compress objects num-threads)
  "Compress multiple objects in parallel"
  (let ((work-queue (make-channel))
        (results (make-channel)))
    ;; Start workers
    (do ((i 0 (+ i 1)))
        ((= i num-threads))
      (thread-start!
       (make-thread
        (lambda ()
          (let loop ()
            (let ((obj (channel-get! work-queue)))
              (when obj
                (channel-put! results (compress-object obj))
                (loop)))))))
    ;; Queue work
    (for-each (lambda (obj) (channel-put! work-queue obj)) objects)
    ;; Collect results
    (map (lambda (_) (channel-get! results)) objects)))
```

## Adaptive Compression

```
(define (adaptive-compress data)
  "Select compression based on content analysis"
  (let* ((sample (subbytevector data 0 (min 4096 (bytevector-length data))))
         (entropy (calculate-entropy sample)))
    (cond
     ;; High entropy - already compressed or encrypted
     ((> entropy 7.9) 'none)
     ;; Low entropy - highly compressible
     ((< entropy 4.0) (values 'zstd 19))
     ;; Medium entropy - balanced
     (else (values 'zstd 3)))))
```

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## Integrity

### Verification

```
(define (verify-compressed-object hash)
  "Verify compressed object integrity"
  (let* ((stored (storage-get hash))
         (meta (soup-get hash))
         (decompressed (decompress (assoc-ref meta 'algorithm) stored)))
```

```
(computed-hash (content-hash decompressed)))
(equal? hash computed-hash)))
```

## Corruption Recovery

```
(define (recover-compressed hash)
  "Attempt to recover corrupted compressed object"
  ;; Try partial decompression
  (let ((partial (decompress-partial hash)))
    (when partial
      (audit-append action: 'partial-recovery hash: hash)
      partial))

  ;; Fetch from replica
  (let ((replica-data (fetch-from-replica hash)))
    (when replica-data
      (storage-put hash replica-data)
      replica-data)))
```

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## References

1. Zstandard - Facebook's compression algorithm
  2. Content-Defined Chunking - Restic blog
  3. RFC-018: Sealed Archive Format
  4. RFC-020: Content-Addressed Storage
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## Changelog

- 2026-01-07 - Initial draft
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**Implementation Status:** Draft **Dependencies:** cas, zstd, soup **Integration:** Storage layer, archive creation, replication