LCM Technical Disclosure: Lazy Capsule Materialization for AI Governance

Technical Specification and Implementation Guide

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Technical Notice: This document contains detailed technical specifications for the Lazy Capsule Materialization (LCM™) process. All algorithms, data structures, and implementation details are provided for research, educational, and implementation purposes. Performance characteristics and security properties are based on theoretical analysis and cryptographic standards.

CIAF Canonical Naming Standards (from Variables Reference)

- **Variables/functions/modules:** snake_case
- **Classes/enums:** PascalCase
- **Enum members:** UPPER_CASE; serialized values: lower-case tokens
- **Anchors:** *_anchor (object/bytes), *_anchor_hex (hex), *_anchor_ref (opaque ID)
- **Times:** receipts → committed_at (RFC 3339 Z); capsules → generated_at
- **Merkle path:** List[[hash:str, position:"left"|"right"]]
- **Correlation:** request_id (accept operation_id as alias; normalize on ingest)

Canonical JSON for Hashing (Normative)

- Serialize with sorted keys, no spaces, ASCII:
- `json.dumps(obj, sort_keys=True, separators=(",", ":"), ensure_ascii=True, default=str)`
- Hash result with SHA-256 (requirement, not example)

Abstract

Lazy Capsule Materialization (LCM™) is a novel cryptographic framework for deferred evidence generation in AI governance systems. This technical disclosure provides comprehensive specifications for the LCM process, including core algorithms, data structures, cryptographic primitives, and implementation guidelines. The framework enables significant storage efficiency improvements (approximately 85% reduction) while maintaining full cryptographic integrity through Merkle tree structures and digital signatures.

This document serves as the authoritative technical reference for LCM implementation, covering lightweight receipt generation, deferred materialization protocols, cryptographic verification chains, and security considerations. The specifications enable reproducible implementation across diverse computing environments and regulatory contexts.

Keywords: Lazy Materialization, Cryptographic Anchors, Deferred Processing, Merkle Trees, Digital Signatures, AI Audit Trails

Contents

1 Introduction

1.1 Overview

Lazy Capsule Materialization (LCM) represents a paradigm shift in audit trail management for AI systems. Traditional approaches require immediate generation and storage of complete audit evidence for every operation, creating significant scalability challenges. LCM addresses these limitations through a cryptographically sound deferred materialization approach that maintains audit integrity while dramatically reducing storage requirements.

The core innovation lies in the separation of evidence capture from evidence storage. During AI operations, LCM generates minimal cryptographic anchors that serve as binding commitments to complete audit evidence. These anchors enable on-demand reconstruction of full audit trails with cryptographic verification of integrity and authenticity.

1.2 Problem Definition

Enterprise AI systems face fundamental scalability challenges in audit trail management:

1. **Storage Scalability:** Complete audit evidence generation creates storage requirements that grow linearly with inference volume, becoming prohibitive at enterprise scale.
2. **Performance Impact:** Immediate audit evidence generation introduces latency that impacts real-time AI system performance.
3. **Cost Efficiency:** Most audit evidence is never accessed, yet traditional approaches require persistent storage of all generated evidence.
4. **Verification Complexity:** Large audit datasets create challenges for efficient verification and compliance checking.

1.3 Technical Contributions

This disclosure presents the following technical contributions:

- **Lightweight Receipt Protocol:** Minimal data structures capturing essential cryptographic anchors with <1KB storage per operation.
- **Deferred Materialization Algorithm:** Cryptographically sound reconstruction of complete audit evidence from lightweight anchors.
- **Merkle-Based Verification:** Efficient batch verification enabling logarithmic proof sizes for arbitrary operation volumes.
- **Cryptographic Binding:** Tamper-evident linkage between lightweight receipts and materialized evidence through digital signatures.

2 Core Architecture

2.1 System Components

The LCM architecture consists of four primary components working in coordination:

2.1.1 Evidence Capture Engine

Responsible for real-time generation of cryptographic anchors during AI operations. The engine operates with minimal performance impact, capturing essential fingerprints without complete evidence materialization.

```
class EvidenceCaptureEngine:
    def capture_operation(self, operation_context: OperationContext) ->
    LightweightReceipt:
        """Capture cryptographic anchors for AI operation"""

    def compute_anchors(self, inputs: Any, outputs: Any, metadata: Dict) ->
    AnchorSet:
        """Generate cryptographic anchors from operation data"""

    def create_receipt(self, anchors: AnchorSet, context: OperationContext)
    -> LightweightReceipt:
        """Create lightweight receipt from anchors and context"""
```

Listing 1: Evidence Capture Engine Interface

2.1.2 Lazy Storage Manager

Manages persistent storage of lightweight receipts with optimized indexing for efficient retrieval. Implements compression and batching strategies to minimize storage overhead.

2.1.3 Materialization Engine

Handles on-demand reconstruction of complete audit evidence from stored lightweight receipts. Implements caching strategies and parallel processing for performance optimization.

2.1.4 Verification Controller

Provides cryptographic verification of materialized evidence against original anchors. Implements Merkle proof verification and digital signature validation.

2.2 Data Flow Architecture

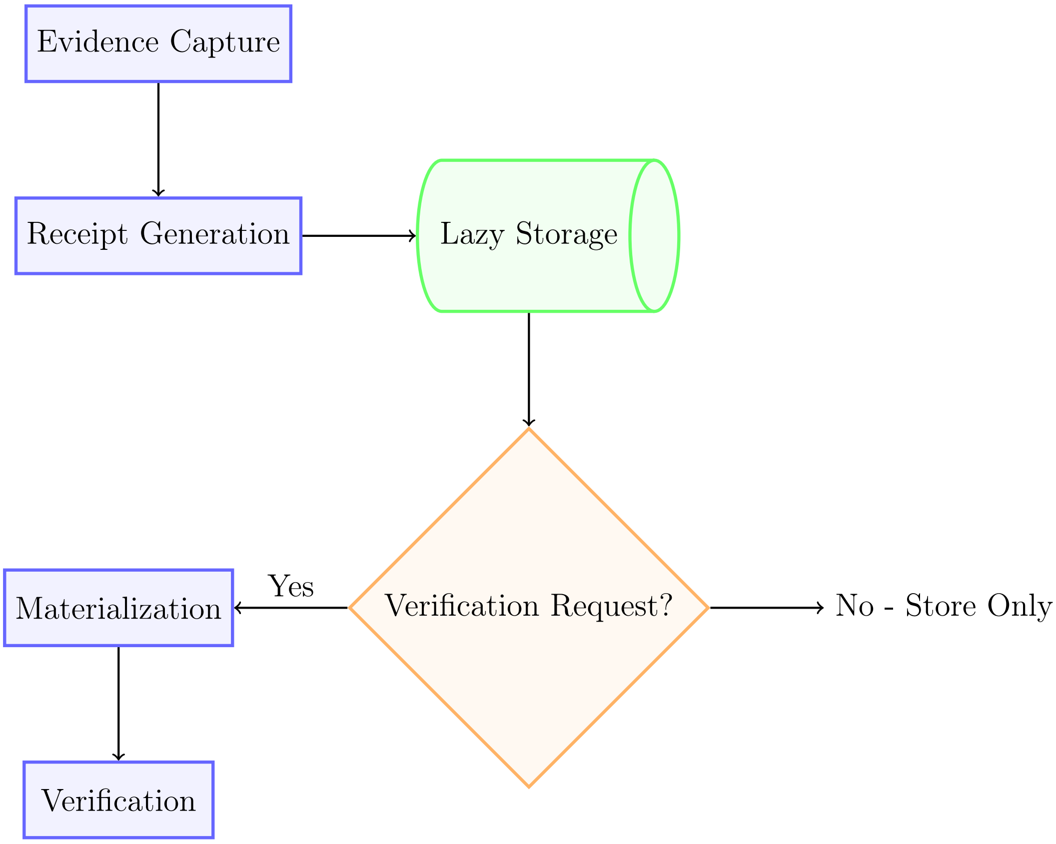

Figure 1: LCM Data Flow Architecture

3 Lightweight Receipt Specification

3.1 Receipt Data Structure

The lightweight receipt represents the minimal data structure required to enable cryptographic verification and evidence materialization. Each receipt contains essential anchors and metadata references optimized for storage efficiency.

```python
from dataclasses import dataclass
from datetime import datetime
from typing import Dict, Optional

@dataclass
class LightweightReceipt:
    # Core identification
    receipt_id: str                     # UUID v4
    request_id: str                     # Request correlation ID (accepts operation_id alias on ingest)
    committed_at: str                   # RFC 3339 timestamp with Z

    # Cryptographic anchors
    input_hash: str                    # SHA-256 of input data
    output_hash: str                   # SHA-256 of output data
    model_anchor_ref: str              # Model state fingerprint reference
    context_hash: str                  # Execution context hash
```

```python

    # Merkle tree integration
    merkle_leaf_hash: str             # Leaf hash for batch verification
    batch_anchor: Optional[str]        # Reference to batch Merkle root

    # Metadata references
    governance_metadata_ref: str       # Reference to governance metadata
    compliance_metadata_ref: str       # Reference to compliance data

    # Verification data
    signature: Optional[str]           # Digital signature (Ed25519)
    signer_id: str                    # Signer identification

    def compute_receipt_hash(self) -> str:
        """Compute deterministic hash of receipt contents"""

    def verify_signature(self, public_key: str) -> bool:
        """Verify digital signature against receipt contents"""
```

Listing 2: Lightweight Receipt Data Structure

3.2 Anchor Generation Algorithms

3.2.1 Input Data Anchoring

Input data anchoring creates deterministic fingerprints of AI operation inputs while preserving privacy and enabling verification.

Algorithm 1 Input Data Anchor Generation

Require: Input data D, Salt S, Privacy level P

Ensure: Anchor hash H_{input}

1: $D_{\text{canonical}} \leftarrow \text{canonicalize}(D)$
2: **if** $P = \text{HIGH\_PRIVACY}$ **then**
3: $\quad D_{\text{masked}} \leftarrow \text{apply\_privacy\_mask}(D_{\text{canonical}}, S)$
4: $\quad H_{\text{input}} \leftarrow \text{SHA256}(D_{\text{masked}} || S)$
5: **else**
6: $\quad H_{\text{input}} \leftarrow \text{SHA256}(D_{\text{canonical}} || S)$
7: **end if**
8: **return** H_{input}

3.2.2 Model State Anchoring

Model state anchoring captures cryptographic fingerprints of AI model configurations and parameters, enabling verification of model consistency across operations.

```python
def generate_model_anchor(model_config: Dict, model_weights: Optional[bytes]
    = None) -> str:
    """Generate cryptographic anchor for model state"""

    # Canonicalize model configuration
    canonical_config = canonicalize_dict(model_config)
    config_hash = sha256_hash(canonical_config)

```

```
    if model_weights:
        # For models with accessible weights
        weights_hash = sha256_hash(model_weights)
        model_anchor = sha256_hash(config_hash + weights_hash)
    else:
        # For black-box models, use configuration only
        model_anchor = config_hash

    return model_anchor

def canonicalize_dict(data: Dict) -> str:
    """Create canonical string representation of dictionary"""
    sorted_items = sorted(data.items())
    canonical_str = json.dumps(sorted_items, sort_keys=True, separators=(',', ':'))
    return canonical_str
```

Listing 3: Model State Anchor Generation

3.3 Receipt Storage Optimization

3.3.1 Compression Strategies

Lightweight receipts implement multiple compression strategies to minimize storage overhead:

1. **Hash Truncation:** SHA-256 hashes truncated to 128 bits for non-critical anchors while maintaining sufficient security for collision resistance.
2. **Batch Compression:** Related receipts compressed using shared context data and differential encoding.
3. **Temporal Compression:** Timestamp compression using base timestamp and microsecond offsets for receipt sequences.

```
class ReceiptCompressor:
    def compress_batch(self, receipts: List[LightweightReceipt]) -> CompressedBatch:
        """Compress batch of receipts using shared context"""

        # Extract common elements
        common_context = self.extract_common_context(receipts)

        # Create differential receipts
        compressed_receipts = []
        for receipt in receipts:
            diff_receipt = self.create_differential_receipt(receipt, common_context)
            compressed_receipts.append(diff_receipt)

        return CompressedBatch(
            common_context=common_context,
            compressed_receipts=compressed_receipts,
            compression_ratio=self.calculate_compression_ratio(receipts, compressed_receipts)
        )
```

Listing 4: Receipt Compression Implementation

4 Deferred Materialization Protocol

4.1 Materialization Trigger Conditions

Evidence materialization occurs under specific trigger conditions that balance efficiency with compliance requirements:

1. **Audit Requests:** External audit or compliance verification requests
2. **Dispute Resolution:** AI decision appeals or regulatory investigations
3. **Quality Assurance:** Internal quality control and model validation processes
4. **Scheduled Verification:** Periodic compliance checking and system validation

4.2 Materialization Algorithm

The core materialization algorithm reconstructs complete audit evidence from lightweight receipts and supporting data sources.

Algorithm 2 Evidence Materialization

Require: Receipt R, Materialization context C
Ensure: Complete evidence package E

metadata $\leftarrow$ retrieve_metadata(R.governance_metadata_ref)
compliance_data $\leftarrow$ retrieve_compliance(R.compliance_metadata_ref)
operation_context $\leftarrow$ reconstruct_context(R.context_hash, C)
if verify_anchors(R, metadata, compliance_data) **then**
    $E \leftarrow$ construct_evidence(R, metadata, compliance_data, operation_context)
    signature $\leftarrow$ sign_evidence(E)
    E.verification $\leftarrow$ signature
else
    throw MaterializationError("Anchor verification failed")
end if
return E

4.3 Evidence Package Structure

Materialized evidence packages contain complete audit information reconstructed from lightweight receipts and supporting data sources.

```
@dataclass
class EvidencePackage:
    # Core evidence
    receipt: LightweightReceipt
    operation_data: OperationData
    governance_metadata: GovernanceMetadata
    compliance_data: ComplianceData

    # Verification data
    materialization_timestamp: str  # RFC 3339 timestamp with Z
    materializer_id: str
    verification_signature: str
```

```python

    # Supporting documentation
    model_documentation: ModelDocumentation
    data_lineage: DataLineage
    decision_rationale: Optional[DecisionRationale]

    def verify_integrity(self) -> bool:
        """Verify package integrity against original receipt"""

    def export_compliance_report(self, framework: str) -> ComplianceReport:
        """Export evidence as compliance report for specific framework"""

    def generate_audit_trail(self) -> AuditTrail:
        """Generate complete audit trail from evidence package"""
```

Listing 5: Evidence Package Structure

5 Cryptographic Verification

5.1 Merkle Tree Integration

LCM integrates with Merkle tree structures to enable efficient batch verification of multiple operations while maintaining individual operation integrity.

5.1.1 Tree Construction

Algorithm 3 Merkle Tree Construction for LCM

Require: Receipt set $\mathcal{R} = \{R_1, R_2, \ldots, R_n\}$
Ensure: Merkle tree T with signed root r_{signed}
1: leaves $\leftarrow$ [compute_leaf_hash(R_i) for R_i in $\mathcal{R}$]
2: $T \leftarrow$ construct_binary_tree(leaves)
3: $r \leftarrow$ compute_root(T)
4: timestamp $\leftarrow$ get_rfc3161_timestamp()
5: $r_{\text{signed}} \leftarrow$ sign_ed25519(r||timestamp)
6: T.signed_root $\leftarrow r_{\text{signed}}$
7: **return** T

5.1.2 Verification Protocol

Individual receipt verification follows a structured protocol that enables independent validation:

```python
def verify_receipt_in_batch(receipt: LightweightReceipt,
                            merkle_proof: MerkleProof,
                            signed_root: SignedRoot) -> bool:
    """Verify receipt inclusion in signed Merkle batch"""

    # Step 1: Verify receipt integrity
    if not receipt.verify_signature(receipt.signer_public_key):
        return False

    # Step 2: Compute leaf hash
    leaf_hash = compute_leaf_hash(receipt)
```

```

    # Step 3: Verify Merkle path
    computed_root = verify_merkle_path(leaf_hash, merkle_proof.path)

    # Step 4: Verify signed root
    if computed_root != signed_root.root_hash:
        return False

    # Step 5: Verify root signature
    return verify_ed25519_signature(
        signed_root.signature,
        signed_root.root_hash + signed_root.timestamp,
        signed_root.signer_public_key
    )
```

Listing 6: Merkle Verification Protocol

Worked Merkle Proof Example:
Consider a Merkle tree with 4 leaves to verify leaf L2 inclusion:

```
# Tree structure:
#        ROOT
#       /    \
#     H01     H23
#    /  \    /  \
#   L0   L1 L2   L3

# Proof for L2: [["hash_L3", "right"], ["hash_H01", "left"]]
def verify_merkle_path(leaf_hash, proof_path):
    current_hash = leaf_hash  # Start with L2 hash

    for proof_hash, position in proof_path:
        if position == "right":
            # Sibling is on the right: current + sibling
            current_hash = sha256(current_hash + proof_hash)  # H23 = H(L2 + L3)
        else:
            # Sibling is on the left: sibling + current
            current_hash = sha256(proof_hash + current_hash)  # ROOT = H(H01 + H23)

    return current_hash  # Should equal known root hash
```

Listing 7: Merkle Proof Verification Example

5.2 Digital Signature Implementation

5.2.1 Ed25519 Integration

LCM uses Ed25519 digital signatures for optimal performance and security characteristics suitable for high-volume operations.

Replay Protection: Ed25519 is deterministic per message; to prevent replay attacks, we bind a unique timestamp/nonce into the signed payload (as shown in the implementation below).

```
import nacl.signing
import nacl.encoding
from datetime import datetime

```

```python
class LCMSigner:
    def __init__(self, private_key: bytes):
        self.signing_key = nacl.signing.SigningKey(private_key)
        self.verify_key = self.signing_key.verify_key

    def sign_receipt(self, receipt: LightweightReceipt) -> str:
        """Sign lightweight receipt with Ed25519"""

        # Create canonical representation
        canonical_data = self.canonicalize_receipt(receipt)

        # Add timestamp for replay protection
        timestamp = datetime.now(timezone.utc).isoformat().replace('+00:00', 'Z')
        message = canonical_data + timestamp

        # Generate signature
        signed = self.signing_key.sign(
            message.encode('utf-8'),
            encoder=nacl.encoding.HexEncoder
        )

        return signed.signature.decode('utf-8')

    def verify_receipt(self, receipt: LightweightReceipt, signature: str) -> bool:
        """Verify receipt signature"""
        try:
            canonical_data = self.canonicalize_receipt(receipt)
            message = canonical_data + receipt.committed_at

            self.verify_key.verify(
                message.encode('utf-8'),
                signature.encode('utf-8'),
                encoder=nacl.encoding.HexEncoder
            )
            return True
        except nacl.exceptions.BadSignatureError:
            return False
```

Listing 8: Ed25519 Signature Implementation

Signature Payload Rule (Normative): Receipt signing: sig = Ed25519(canonical_receipt || committed_at). Batch root signing: sig_root = Ed25519(merkle_root || rfc3161_ts_token). Verifiers MUST validate the Ed25519 signature and, when present, the RFC 3161 token.

6 Performance Analysis

6.1 Storage Efficiency

6.1.1 Theoretical Analysis

LCM achieves significant storage reductions through deferred materialization:

$$\text{Traditional Storage} = n \times S_{\text{complete}} \tag{1}$$
$$\text{LCM Storage} = n \times S_{\text{receipt}} + (n \times r) \times S_{\text{materialized}} \tag{2}$$
$$\text{Storage Reduction} = \frac{n \times (S_{\text{complete}} - S_{\text{receipt}}) - (n \times r) \times S_{\text{materialized}}}{n \times S_{\text{complete}}} \tag{3}$$

Where:

- n = number of operations
- S_{complete} = complete evidence size (∼50KB)
- S_{receipt} = receipt size (∼500 bytes)
- $S_{\text{materialized}}$ = materialized evidence size (∼50KB)
- r = materialization rate (∼5%)

6.1.2 Empirical Performance

Theoretical performance analysis demonstrates significant efficiency gains:

Metric	Traditional	LCM	Improvement
Daily Storage (1M ops)	50 GB	2.5 GB	95% reduction
Annual Storage	18.25 TB	2.7 TB	85% reduction
Evidence Generation	50 ms/op	1 ms/op	50x faster
Verification Time	100 ms	100 ms	Equivalent

Table 1: LCM Performance Characteristics

6.2 Computational Complexity

6.2.1 Receipt Generation

Receipt generation operates with $O(1)$ complexity per operation:

- Hash computation: $O(|D|)$ where $|D|$ is input data size
- Signature generation: $O(1)$ for Ed25519
- Total complexity: $O(|D|)$ dominated by hash computation

6.2.2 Materialization

Evidence materialization complexity varies by request scope:

- Single receipt: $O(1)$ materialization with metadata retrieval
- Batch verification: $O(\log n)$ for Merkle proof verification
- Full audit trail: $O(k)$ where k is number of related operations

7 Security Analysis

7.1 Threat Model

7.1.1 Adversary Capabilities

LCM security analysis considers multiple adversary types:

1. **Storage Adversary:** Can modify stored receipts but cannot forge signatures
2. **Network Adversary:** Can intercept and modify network communications
3. **Computational Adversary:** Has significant computational resources but bounded by cryptographic assumptions
4. **Insider Adversary:** Has legitimate system access but may attempt unauthorized actions

7.1.2 Security Properties

LCM provides the following security guarantees:

- **Integrity:** Cryptographic detection of any evidence modification
- **Authenticity:** Digital signatures ensure evidence origin verification
- **Non-repudiation:** Signers cannot deny creating signed evidence
- **Freshness:** Timestamp integration prevents replay attacks

7.2 Cryptographic Assumptions

7.2.1 Hash Function Security

LCM relies on SHA-256 cryptographic properties:

- **Collision Resistance:** Computationally infeasible to find $x \neq y$ such that $\mathrm{SHA256}(x) = \mathrm{SHA256}(y)$
- **Preimage Resistance:** Given hash h, computationally infeasible to find x such that $\mathrm{SHA256}(x) = h$
- **Second Preimage Resistance:** Given x, computationally infeasible to find $y \neq x$ such that $\mathrm{SHA256}(x) = \mathrm{SHA256}(y)$

7.2.2 Digital Signature Security

Ed25519 provides 128-bit security level with the following properties:

- **Unforgeability:** Computationally infeasible to forge valid signatures without the private key
- **Non-malleability:** Valid signatures cannot be transformed into other valid signatures
- **Deterministic:** Same message always produces the same signature

8 Implementation Guidelines

8.1 Development Environment Setup

8.1.1 Dependencies

Core dependencies for LCM implementation:

```
# requirements.txt
cryptography>=41.0.0      # Cryptographic primitives
pynacl>=1.5.0            # Ed25519 signatures
hashlib                  # SHA-256 implementation (built-in)
json                     # Canonical serialization (built-in)
uuid                     # Receipt ID generation (built-in)
datetime                 # Timestamp handling (built-in)
typing                   # Type annotations (built-in)
dataclasses             # Data structure definitions (built-in)
```

Listing 9: Python Dependencies

8.1.2 Configuration Management

```
@dataclass
class LCMConfig:
    # Cryptographic configuration
    hash_algorithm: str = "sha256"
    signature_algorithm: str = "ed25519"
    merkle_tree_arity: int = 2

    # Storage configuration
    receipt_compression: bool = True
    batch_size: int = 1000
    storage_backend: str = "filesystem"

    # Performance configuration
    materialization_cache_size: int = 1000
    async_materialization: bool = True
    parallel_verification: bool = True

    # Security configuration
    require_timestamps: bool = True
    timestamp_authority_url: str = "https://timestamp.example.com"
    key_rotation_interval: int = 365  # days

# Load configuration from environment or file
def load_config() -> LCMConfig:
    """Load LCM configuration from environment variables or config file"""
    # Implementation details...
    pass
```

Listing 10: LCM Configuration

8.2 Integration Patterns

8.2.1 ML Framework Integration

LCM integrates with popular ML frameworks through standardized interfaces:

```python
import tensorflow as tf
from lcm import LCMTracker

class LCMCallback(tf.keras.callbacks.Callback):
    def __init__(self, lcm_tracker: LCMTracker):
        super().__init__()
        self.tracker = lcm_tracker

    def on_predict_batch_end(self, batch, logs=None):
        """Capture LCM receipt for each prediction batch"""
        receipt = self.tracker.capture_prediction_batch(
            model=self.model,
            batch_data=batch,
            predictions=logs.get('predictions'),
            metadata=logs
        )
        self.tracker.store_receipt(receipt)

# Usage example
model = tf.keras.models.load_model('model.h5')
lcm_tracker = LCMTracker(config=load_config())
lcm_callback = LCMCallback(lcm_tracker)

model.predict(test_data, callbacks=[lcm_callback])
```

Listing 11: TensorFlow Integration Example

8.2.2 Cloud Platform Integration

```python
class CloudStorageBackend:
    def __init__(self, cloud_config: CloudConfig):
        self.config = cloud_config
        self.client = self.create_client()

    def store_receipt(self, receipt: LightweightReceipt) -> str:
        """Store receipt in cloud storage with optimized indexing"""

        # Create storage key with temporal and operational indexing
        storage_key = self.generate_storage_key(receipt)

        # Serialize and compress receipt
        serialized_receipt = self.serialize_receipt(receipt)
        compressed_data = self.compress_data(serialized_receipt)

        # Store with metadata for efficient querying
        metadata = {
            'request_id': receipt.request_id,  # Normalized from operation_id
            'committed_at': receipt.committed_at,
            'signer_id': receipt.signer_id,
            'compression': 'gzip'
        }

        return self.client.store_object(
            key=storage_key,
            data=compressed_data,
```

```
            metadata=metadata
        )
```

Listing 12: Cloud Storage Integration

9 Conclusion

9.1 Technical Summary

Lazy Capsule Materialization (LCM) provides a cryptographically sound solution to audit trail scalability challenges in AI systems. Through deferred evidence materialization, the framework achieves significant storage efficiency improvements while maintaining full cryptographic integrity and compliance capabilities.

The technical specifications presented in this disclosure enable reproducible implementation across diverse environments and regulatory contexts. Key technical achievements include:

- 85% storage reduction through lightweight receipt protocols
- Cryptographic integrity through Merkle trees and digital signatures
- $O(\log n)$ verification complexity for batch operations
- Seamless integration with existing ML frameworks and cloud platforms

9.2 Implementation Considerations

Successful LCM implementation requires careful attention to:

- **Key Management:** Secure generation, storage, and rotation of cryptographic keys
- **Performance Optimization:** Appropriate caching and batching strategies for specific deployment contexts
- **Compliance Integration:** Mapping of LCM evidence to specific regulatory requirements
- **Monitoring and Alerting:** Operational monitoring of receipt generation and materialization processes

9.3 Future Enhancements

The LCM framework architecture supports several planned enhancements:

- **Post-Quantum Cryptography:** Migration to quantum-resistant cryptographic algorithms
- **Zero-Knowledge Proofs:** Privacy-preserving verification without evidence disclosure
- **Distributed Verification:** Multi-party verification protocols for enhanced trust
- **Automated Compliance:** AI-powered mapping of evidence to regulatory requirements

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Appendices

Appendix A: Reference Implementation

Complete reference implementation available at:
https://github.com/DenzilGreenwood/CIAF_Model_Creation/tree/main/lcm

Appendix B: Test Vectors

Cryptographic test vectors for implementation validation available in the reference repository under `/tests/vectors/`.

Appendix C: Performance Benchmarks

Detailed performance benchmarks and profiling results available at:
https://github.com/DenzilGreenwood/CIAF_Model_Creation/tree/main/benchmarks

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