

# ATLAS: A Cognitive Memory Architecture for Resource-Constrained Edge Computing

## 1. Architectural Philosophy and Constraint Analysis

### 1.1 The "Edge-Native" Cognitive Paradigm

The design of ATLAS represents a fundamental divergence from the prevailing "cloud-native" AI architectures that dominate current research. In typical enterprise deployments, AI agents rely on a microservices ecosystem: a containerized vector database (e.g., Milvus, Weaviate), a dedicated graph database (Neo4j), and massive orchestration layers, all assuming an abundance of RAM and horizontal scalability. However, the constraints imposed on ATLAS—specifically the 16GB total RAM (with only 4-6GB effective usability due to Windows 11 and WSL2 overhead), a mobile RTX 3050 Ti with 4GB VRAM, and a strict prohibition on Docker containers—mandate a radical rethinking of memory systems. We must shift from a distributed systems mindset to a "monolithic modular" kernel architecture, where memory is not merely a storage medium but a scarce, contended resource requiring active arbitration.

This report posits that the optimal architecture for such a constrained environment functions less like a web service and more like an operating system's memory manager.<sup>1</sup> In this paradigm, the "Memory" of the AI is not a passive repository but an active hierarchical system of caches, working memory, and archival storage, managed directly within the application's process space to eliminate the serialization overhead of Inter-Process Communication (IPC). The rejection of Docker is particularly significant; while containers provide isolation, on Windows/WSL2 they introduce a virtualization penalty and a fixed memory tax that ATLAS cannot afford. Instead, the architecture must rely on Python virtual environments and static binaries, running "bare metal" on the WSL2 instance.<sup>3</sup>

### 1.2 Hardware-Aware Resource budgeting

The critical bottleneck in the ATLAS system is not the compute capability of the CPU, but the "effective available RAM" and the VRAM ceiling. Windows 11 is a resource-heavy operating system, often reserving 4-6GB for background processes, telemetry, and the GUI stack. WSL2, operating as a utility VM, dynamically allocates memory but can trigger aggressive paging (swapping) when pressure mounts. For a real-time voice agent, swapping is catastrophic; the latency introduced by disk I/O during a vector search or graph traversal destroys the illusion of intelligence.

Therefore, the resource allocation strategy must be strictly compartmentalized:

1. **VRAM (4GB RTX 3050 Ti):** This resource is insufficient for running decent-quality quantized Large Language Models (LLMs) like Llama-3-8B locally with sufficient context. However, it is vastly oversized for embedding models. A quantized all-MiniLM-L6-v2 model consumes less than 100MB of VRAM.<sup>5</sup> Consequently, the GPU must be strictly dedicated to the *embedding* and *reranking* pipeline. This ensures that vector generation is instantaneous (<5ms), leaving the CPU free for logic.
2. **System RAM (4-6GB Usable):** This must house the application logic, the SQLite page cache, and the active context window processing. The architecture must strictly avoid loading entire datasets into memory (e.g., no Pandas DataFrames of the whole history). Streaming cursors and lazy-loading iterators are mandatory.<sup>6</sup>
3. **Disk (NVMe SSD):** With high sequential read speeds, the SSD serves as the backing store for SQLite. The database configuration must be tuned (WAL mode, memory-mapped I/O) to treat the disk as extended RAM.<sup>7</sup>

### 1.3 The "Hierarchical Latency" Model

Just as modern CPUs utilize L1, L2, and L3 caches to mask latency, ATLAS implements a tiered memory architecture defined by retrieval speed and information density:

- **Tier 1: Core Memory (Context Window):** Resides in the System Prompt. This is the "L1 Cache"—instant access by the LLM, but extremely expensive (\$/token) and limited in size.
- **Tier 2: Short-Term Episodic (RAM-Mapped):** Resides in sqlite-vec virtual tables. Fast retrieval via vector similarity, representing the "working memory" of the immediate conversation.
- **Tier 3: Long-Term Semantic (Disk-Backed):** Resides in standard SQLite tables with full-text search indices. This represents the vast repository of consolidated facts.
- **Tier 4: Archival (Cold Storage):** Resides in compressed JSON/Parquet flat files. This is the "tape backup," accessible only via explicit, slow retrieval processes.<sup>9</sup>

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## 2. SQLite-Based Memory Architectures

### 2.1 The Vector Extension Landscape: sqlite-vss vs. sqlite-vec

The foundational decision for the ATLAS persistence layer is the choice of vector search engine. Historically, sqlite-vss (Vector Similarity Search) was the standard recommendation for SQLite. However, a rigorous analysis of the current landscape reveals that sqlite-vss is no longer in active development, suffers from complex compilation requirements involving the FAISS library, and has known stability issues on Windows/WSL environments.<sup>1</sup>

The superior alternative, and the specific recommendation for ATLAS, is **sqlite-vec**.

- **Architecture:** sqlite-vec is a "no-dependency" C-extension. It does not link against heavy external libraries like FAISS or HNSWLIB, making it incredibly lightweight and portable—crucial for the "No Docker" constraint.<sup>2</sup>

- **Quantization:** It supports native int8 and binary vector quantization. For a memory-constrained environment, int8 quantization reduces the storage footprint by 4x compared to float32 (from ~1500 bytes to ~384 bytes per vector) with negligible loss in retrieval recall for semantic tasks.<sup>12</sup>
- **Integration:** It utilizes SQLite's virtual table mechanism (vec0), allowing vector operations to be mixed with standard SQL filters in a single query plan, a feature often poorly implemented in external vector databases.<sup>12</sup>

## 2.2 Optimal Schema Design

The database schema must support three distinct memory types: **Episodic** (the raw stream of consciousness), **Semantic** (consolidated facts), and **Core** (the user profile and prime directives). A "Single Database, Hybrid Storage" approach is recommended to minimize file handle overhead and simplify ACID transactions.

### 2.2.1 Core Memory: The "Bio" Table

Core memory contains highly salient, rarely changing facts about the user and the agent's persona. This table is small enough to be aggressively cached.

SQL

```
CREATE TABLE core_memory (
  id INTEGER PRIMARY KEY AUTOINCREMENT,
  category TEXT NOT NULL CHECK(length(category) < 50), -- e.g., 'user_profile', 'agent_persona',
  'active_goal'
  content TEXT NOT NULL,
  last_updated DATETIME DEFAULT CURRENT_TIMESTAMP,
  is_active BOOLEAN DEFAULT 1,
  -- JSON Constraints ensure data integrity without external validation code
  metadata JSON CHECK(json_valid(metadata))
);

-- Index for rapid retrieval during context construction
CREATE INDEX idx_core_category ON core_memory(category) WHERE is_active = 1;
```

### 2.2.2 Episodic Memory: The Write-Ahead Log

This table acts as the raw log of interactions. It requires a "Shadow Table" pattern. Storing the raw vector embedding in the same table as the text content (content) causes "bloat" in the database page cache. When performing standard SQL queries (e.g., filtering by date), the

engine might load pages containing heavy vectors, pushing useful text data out of the cache. Therefore, vectors are stored in a dedicated virtual table (vec\_episodic), linked by rowid.

## SQL

-- 1. Main Content Table

```
CREATE TABLE episodic_memory (  
  id INTEGER PRIMARY KEY AUTOINCREMENT,  
  role TEXT CHECK(role IN ('user', 'assistant', 'system')),  
  content TEXT NOT NULL,  
  timestamp DATETIME DEFAULT CURRENT_TIMESTAMP,  
  session_id TEXT,  
  token_count INTEGER,  
  -- Analysis metadata: sentiment, keywords, entities extracted  
  analysis JSON  
);
```

-- 2. Full-Text Search Virtual Table (FTS5)

-- Trigram tokenizer is superior for fuzzy matching in natural language queries

```
CREATE VIRTUAL TABLE episodic_fts USING fts5(  
  content,  
  content='episodic_memory',  
  content_rowid='id',  
  tokenize='trigram'  
);
```

-- 3. Vector Search Virtual Table (sqlite-vec)

-- Dimensions: 384 (for all-MiniLM-L6-v2)

-- Type: float32 (Use int8 here if RAM < 4GB is strictly enforced)

```
CREATE VIRTUAL TABLE vec_episodic USING vec0(  
  embedding float  
);
```

-- 4. Triggers to maintain FTS consistency automatically

```
CREATE TRIGGER episodic_ai AFTER INSERT ON episodic_memory BEGIN  
  INSERT INTO episodic_fts(rowid, content) VALUES (new.id, new.content);  
END;  
CREATE TRIGGER episodic_ad AFTER DELETE ON episodic_memory BEGIN  
  INSERT INTO episodic_fts(episodic_fts, rowid, content) VALUES('delete', old.id, old.content);  
END;
```

-- [Note](#): Embeddings are inserted manually by the application layer after generation to allow batching.

### 2.2.3 Semantic Memory: The Knowledge Graph Nodes

Semantic memory represents consolidated knowledge. It requires a schema that supports both vector similarity (finding related concepts) and graph-like traversal (connecting concepts).

SQL

```
CREATE TABLE semantic_memory (  
  id INTEGER PRIMARY KEY AUTOINCREMENT,  
  concept TEXT NOT NULL,  
  description TEXT,  
  -- Provenance: Link back to the episode(s) that generated this fact  
  source_episode_ids JSON,  
  last_recalled DATETIME,  
  recall_count INTEGER DEFAULT 0,  
  -- Spaced Repetition Parameters (SuperMemo-2/FSRS)  
  stability REAL DEFAULT 0,  
  difficulty REAL DEFAULT 0  
);
```

```
CREATE VIRTUAL TABLE vec_semantic USING vec0(  
  embedding float  
);
```

```
-- Relationship Table for Graph Traversal (The "Edges")  
CREATE TABLE semantic_edges (  
  source_id INTEGER,  
  target_id INTEGER,  
  relation_type TEXT,  
  weight REAL DEFAULT 1.0,  
  FOREIGN KEY(source_id) REFERENCES semantic_memory(id),  
  FOREIGN KEY(target_id) REFERENCES semantic_memory(id),  
  PRIMARY KEY(source_id, target_id, relation_type)  
) WITHOUT ROWID; -- Optimization for index-only tables
```

## 2.3 Efficient Similarity Search Without Vector Databases

The "No Docker" constraint precludes running dedicated vector databases like Qdrant.

However, for datasets under 100,000 records (typical for a personal agent), "Brute Force" search is often superior to Approximate Nearest Neighbor (ANN) indexing in terms of recall and setup complexity.

The "Brute Force" Advantage:

With sqlite-vec, a full table scan of 100,000 quantized vectors on a modern CPU (like the i7/i9 likely paired with a 3050 Ti) takes less than 20-50ms.<sup>2</sup> Building an HNSW index (Hierarchical Navigable Small World) graph consumes significant additional RAM (often 1.5x the raw vector size) to maintain the graph connections. By avoiding HNSW and relying on optimized brute force (SIMD-accelerated), ATLAS saves crucial RAM at the cost of a few milliseconds of latency—an acceptable trade-off.

Hybrid Search Query Pattern (FTS + Vector):

The most robust retrieval combines semantic understanding (Vector) with precise keyword matching (FTS5). This "pre-filtering" strategy drastically reduces the vector search space.

SQL

```
SELECT
  e.content,
  e.timestamp,
  v.distance
FROM episodic_memory e
JOIN vec_episodic v ON e.id = v.rowid
WHERE
  -- 1. Coarse Filter: Keyword match (optional, narrows scope)
  e.id IN (SELECT rowid FROM episodic_fts WHERE content MATCH 'project OR deadline')
  AND
  -- 2. Semantic Search via sqlite-vec
  v.embedding MATCH :query_embedding
  AND k = 20 -- Retrieve top 20 candidates
ORDER BY v.distance
LIMIT 10;
```

*Insight:* This query leverages SQLite's query planner. If the FTS filter is restrictive, sqlite-vec only computes distances for the rows returned by the FTS engine, reducing the CPU load from  $O(N)$  to  $O(K)$ , where  $K$  is the FTS result count.

## 2.4 Embedding Storage in BLOB Columns

While sqlite-vec is the primary recommendation, storing embeddings as binary BLOBs in a standard column is a viable fallback or archival strategy.

- **Mechanism:** Python's `struct.pack('384f', *vector)` converts a list of floats into a compact C-struct byte string.
- **Size:** 384 dimensions \* 4 bytes (float32) = 1536 bytes per row.
- **Capacity:** 100,000 rows require ~150MB of disk space.
- **Limitation:** To search these, one must load the BLOBs into Python (NumPy) to calculate cosine similarity. This incurs a serialization penalty and RAM overhead. Thus, BLOB storage should be reserved for **backup/archival** purposes, while `sqlite-vec` virtual tables handle the active index.

## 2.5 Full-Text Search (FTS5) Performance on <100K Records

SQLite's FTS5 extension is extremely performant for datasets of this magnitude. Benchmarks indicate that FTS5 can handle millions of rows with sub-millisecond query times.<sup>8</sup> For ATLAS (<100k records), the overhead is negligible.

- **Configuration:** The use of `content='episodic_memory'` (external content table) in the FTS definition is critical. This prevents data duplication; the FTS index only stores the token map, while the actual text remains in the main table. This reduces the database file size by approximately 40-50% compared to a standard FTS table.<sup>7</sup>

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## 3. Lightweight Embedding Alternatives & Benchmarks

### 3.1 The Champion Model: all-MiniLM-L6-v2

The constraint of 4GB VRAM and limited system RAM disqualifies large state-of-the-art embedding models like `e5-large` or `bge-large` (which can exceed 1GB+ VRAM). The optimal choice for ATLAS is **sentence-transformers/all-MiniLM-L6-v2**.

- **Dimensions:** 384. This low dimensionality is the single biggest factor in reducing storage and RAM usage.
- **Architecture:** 6-layer DistilBERT.
- **Performance:** It consistently punches above its weight class on MTEB (Massive Text Embedding Benchmark) leaderboards, offering a "good enough" semantic representation for personal agent tasks (retrieval, clustering).<sup>16</sup>

### 3.2 ONNX Runtime vs. PyTorch: The Critical Pivot

Running the model in standard PyTorch is inefficient for the ATLAS environment. PyTorch carries a heavy initialization overhead, loading CUDA kernels and massive libraries that bloat the process memory (RSS) by 1GB+ just on import.<sup>18</sup> **ONNX Runtime (ORT)** is the mandatory execution engine for ATLAS.

**Benchmarking Memory Footprint & Latency (RTX 3050 Ti / Modern CPU):**

Configuration	System RAM	VRAM Usage	CPU Latency (Batch=1)	Disk Footprint
PyTorch (FP32)	~450 MB	~350 MB	~15-20 ms	~90 MB
ONNX (FP32)	~180 MB	~100 MB	~8-12 ms	~90 MB
ONNX (INT8)	~50 MB	~30 MB	~2-5 ms	~22 MB

Data synthesized from.<sup>5</sup>

**Recommendation:** ATLAS must use the **INT8 Quantized ONNX model**. While quantization introduces a minor loss in precision (typically <1-2% drop in retrieval accuracy), the 4x reduction in memory footprint and the 2-3x speedup in CPU inference are non-negotiable benefits for the hardware constraints.<sup>13</sup>

### 3.3 Comparative Analysis: SBERT vs. SimCSE

- **SBERT (all-MiniLM):** Trained on large sentence-pair datasets (1B+ pairs). Excellent at "asymmetric search" (short query finding long passage) which is the primary use case for RAG.<sup>16</sup>
- **SimCSE (Simple Contrastive Learning of Sentence Embeddings):** Uses dropout noise as data augmentation. While conceptually elegant, SimCSE models often require larger base models (like BERT-base or RoBERTa-base) to outperform SBERT. A SimCSE-BERT-base model is 420MB+ (FP32), nearly 5x the size of MiniLM, without a proportional gain in accuracy for this specific domain.<sup>23</sup>
- **Conclusion:** SimCSE is rejected in favor of the highly distilled all-MiniLM-L6-v2.

### 3.4 Implementation Code Pattern (ONNX Runtime)

To completely remove the PyTorch dependency, ATLAS should utilize the tokenizers library (Rust-based, zero-copy) coupled with onnxruntime. This combination allows embedding generation with a memory footprint under 100MB.

Python

```
import onnxruntime as ort
from tokenizers import Tokenizer
```

```
import numpy as np
```

```
class LightweightEmbedder:
```

```
    def __init__(self, model_path="model_int8.onnx", tokenizer_path="tokenizer.json"):
```

```
        # Load the fast Rust tokenizer
```

```
        self.tokenizer = Tokenizer.from_file(tokenizer_path)
```

```
        # Initialize ONNX Runtime with GPU priority, falling back to CPU
```

```
        # This setup respects the 4GB VRAM limit by using a tiny model
```

```
        self.session = ort.InferenceSession(
```

```
            model_path,
```

```
            providers=
```

```
        )
```

```
    def embed(self, text):
```

```
        # 1. Tokenize
```

```
        encoded = self.tokenizer.encode(text)
```

```
        # 2. Prepare Inputs (ONNX expects distinct arrays)
```

```
        input_ids = np.array([encoded.ids], dtype=np.int64)
```

```
        attention_mask = np.array([encoded.attention_mask], dtype=np.int64)
```

```
        token_type_ids = np.array([encoded.type_ids], dtype=np.int64)
```

```
        inputs = {
```

```
            'input_ids': input_ids,
```

```
            'attention_mask': attention_mask,
```

```
            'token_type_ids': token_type_ids
```

```
        }
```

```
        # 3. Inference
```

```
        outputs = self.session.run(None, inputs)
```

```
        # 4. Mean Pooling (Manual implementation for ONNX)
```

```
        # The model outputs raw token embeddings; we must average them
```

```
        # accounting for the attention mask to ignore padding.
```

```
        last_hidden_state = outputs # Shape: (1, seq_len, 384)
```

```
        # Expand mask to match embedding dimensions
```

```
        # Mask shape: (1, seq_len) -> (1, seq_len, 384)
```

```
        mask_expanded = np.expand_dims(attention_mask, axis=-1)
```

```
        mask_expanded = np.broadcast_to(mask_expanded, last_hidden_state.shape)
```

```
        # Sum embeddings * mask
```

```
sum_embeddings = np.sum(last_hidden_state * mask_expanded, axis=1)
sum_mask = np.clip(mask_expanded.sum(axis=1), a_min=1e-9, a_max=None)
```

```
embedding = sum_embeddings / sum_mask
```

```
# 5. Normalization (L2) - Crucial for Cosine Similarity
```

```
norm = np.linalg.norm(embedding)
```

```
return (embedding / norm).flatten().tolist()
```

*Insight:* This implementation avoids the entire sentence-transformers and torch stack, effectively functioning as a micro-inference engine suitable for the edge.<sup>18</sup>

### 3.5 Approximate Nearest Neighbor without Libraries

If sqlite-vec were unavailable, a pure Python implementation of Cosine Similarity using NumPy is feasible for  $N < 50,000$  vectors.

- **Formula:**  $\text{Cosine}(A, B) = \frac{A \cdot B}{\|A\| \|B\|}$ . If vectors are pre-normalized (as in the code above), this simplifies to the dot product:  $A \cdot B$ .
- **Vectorized Operation:** `scores = np.dot(query_vector, all_vectors_matrix.T)`.
- **Performance:** NumPy links against BLAS/LAPACK (often Intel MKL or OpenBLAS), which utilizes SIMD instructions (AVX2). A dot product of (1, 384) against (50000, 384) takes milliseconds.
- **Memory Warning:** Loading 100,000 vectors into a NumPy float32 array requires ~150MB RAM. This fits the ATLAS budget, but scaling to 1 million vectors would require 1.5GB+, entering the danger zone. Thus, sqlite-vec remains the primary recommendation to keep vectors on disk/paged memory.<sup>25</sup>

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## 4. Memory Consolidation Without Infrastructure

### 4.1 The "Sleep" Cycle Algorithm

Biological brains do not consolidate memory instantly; they transfer episodic traces (hippocampus) to semantic knowledge (neocortex) during sleep. ATLAS requires a synthetic analogue: an **Asynchronous Consolidation Loop**. Since we cannot run heavy clustering algorithms continuously, we use a trigger-based approach.

#### The Episodic-to-Semantic Pipeline:

1. **Buffer Accumulation:** Incoming interactions are logged in `episodic_memory` with a `status processed = 0`.
2. **Idle Trigger:** A background thread monitors CPU usage. When the system is idle (or every  $N=20$  turns), the consolidation job activates.<sup>26</sup>
3. **Heuristic Extraction (The Pre-Filter):** Before paying for LLM tokens, use a lightweight

NLP heuristic (like RAKE - Rapid Automatic Keyword Extraction) to identify "information-dense" episodes. If an episode contains only phatic communication ("Hello", "Okay"), it is marked processed and ignored.

4. **LLM "Dreaming"**: Send the dense episodes to the Cloud Claude API with a consolidation prompt:
  - *System Prompt*: "You are a memory archivist. Extract distinct, atomic facts about the user from this conversation. Return a JSON list of {concept, relationship, object} triples."
5. **Graph Upsert**:
  - Check semantic\_memory for existing concepts.
  - If New: Insert node + embedding.
  - If Existing: Update the node's recall\_count and last\_recalled.
  - If Contradiction: Trigger the "Semantic Drift" protocol (see 4.3).
6. **Pruning**: "Fade" the raw episodic logs by moving them to a .jsonl.gz archive file, keeping the SQLite index lean.

## 4.2 Spaced Repetition for Retention (Adapting SM-2)

To prevent the semantic database from becoming a "junkyard" of trivial facts, ATLAS implements a variation of the **SuperMemo-2 (SM-2)** algorithm—traditionally used for human flashcards, but here adapted for *machine forgetting*.

The Agent-Forgetting Curve:

We assign a stability score to every semantic fact.

- **Formula**:  $I(n) = I(n-1) \times EF$ 
  - $I(n)$ : The interval (in days) until the next "relevance check".
  - $EF$  (Easiness Factor): Starts at 2.5.
- **Mechanism**:
  - When a fact is retrieved by RAG and used in a response, the user (or a critic model) implicitly validates it. If the response is good, the fact's  $EF$  increases (memory strengthened).
  - If the fact is retrieved but deemed irrelevant (low relevance score by the LLM),  $EF$  decreases.
  - **Garbage Collection**: A nightly job checks facts where  $CurrentDate > LastRecalled + I(n)$ . These facts are candidates for "pruning"—moving to cold storage JSON files.<sup>28</sup>

This mimics the biological "Use It or Lose It" principle, ensuring the active search index contains only high-value, frequently accessed knowledge.

## 4.3 Detecting Semantic Drift

Semantic patterns change (e.g., "User is learning Python"  $\rightarrow$  "User is learning Rust").

- **Conflict Detection**: When the consolidation LLM extracts a new fact, it must perform a

vector search against semantic\_memory.

- **Threshold Logic:** If a highly similar fact exists (Similarity > 0.85) but the specific details differ (e.g., "Python" vs "Rust"), this flags a potential **Semantic Drift**.
- **Resolution:**
  1. The system marks the old memory as state: archival.
  2. The new memory is inserted with state: active.
  3. A semantic\_edges link is created: (Old\_Node)-->(New\_Node).  
This preserves the history (the user used to learn Python) while ensuring the RAG pipeline retrieves the current truth.<sup>3</sup>

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## 5. File-Based Knowledge Graphs (The "Graph-Lite" Architecture)

### 5.1 YAML/JSON as Graph Storage

Running a dedicated graph database like Neo4j is impossible on a laptop with 4-6GB usable RAM; the Java Virtual Machine (JVM) alone would consume 512MB-1GB just to idle. ATLAS must utilize a **Relational-to-Graph** mapping within SQLite or a file-based approach.

#### Storage Strategy:

- **Nodes:** Stored in the semantic\_memory SQLite table.
- **Edges:** Stored in the semantic\_edges SQLite table (Foreign Keys to Nodes).
- **Properties:** Complex node properties (metadata) are stored as JSON strings within the SQLite columns.

### 5.2 Cypher-like Queries in SQLite (Recursive CTEs)

The power of Graph databases lies in traversing relationships (e.g., "Find all friends of friends"). SQLite supports this natively via **Recursive Common Table Expressions (CTEs)**. This allows ATLAS to perform multi-hop graph traversal directly in the C-based SQL engine, which is orders of magnitude more memory-efficient than loading a graph into a Python NetworkX object.<sup>31</sup>

Example: 2-Hop Traversal Query

To find all concepts connected to "Project Alpha" within 2 degrees of separation:

```
SQL
```

```
WITH RECURSIVE traversal(id, depth, path) AS (
```

```

-- Base Case: Start at the node for 'Project Alpha'
SELECT id, 0, id |

| "
FROM semantic_memory WHERE concept = 'Project Alpha'

UNION ALL

-- Recursive Step: Join edges to find neighbors
SELECT e.target_id, t.depth + 1, t.path |

| '->' |
| e.target_id
FROM semantic_edges e
JOIN traversal t ON e.source_id = t.id
WHERE t.depth < 2 -- Limit depth to 2 hops to prevent infinite loops
)
SELECT n.concept, t.depth
FROM traversal t
JOIN semantic_memory n ON t.id = n.id;

```

*Insight:* This query executes entirely within SQLite. No data is moved to Python RAM until the final result set is ready. This is the definition of "Lazy Loading" at the database level.<sup>33</sup>

## 5.3 Lazy Loading with Python

If complex graph algorithms (like PageRank or Betweenness Centrality) are required, they cannot be run on the whole graph in SQLite.

- **Strategy:** Use networkx but construct the graph **ephemerally**.
- **Implementation:**
  1. Identify the "Active Subgraph" based on the current context (e.g., nodes relevant to the user's current query).
  2. Query SQLite to fetch *only* those nodes and their immediate edges.
  3. Build a nx.Graph object in Python with just those 50-100 nodes.
  4. Run the algorithm.
  5. Destroy the object.

This prevents the memory bloat associated with keeping a monolithic graph in RAM.<sup>34</sup>

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## 6. Memory Injection & In-Context Learning

## 6.1 The Context Window Budget

While Cloud Claude models offer 200k+ context windows, utilizing the full window is anti-pattern for ATLAS due to latency and cost.

Optimal Budget: 8k - 16k tokens per turn.

**Token Allocation Strategy:**

1. **System Persona:** 500 tokens (Fixed instructions).
2. **Core Memory:** 500 tokens (The "Bio" - strict constraints).
3. **Active Plan/Goal:** 500 tokens (What is the agent currently trying to achieve?).
4. **RAG Retrieval:** 4000 tokens (Dynamic slots for Episodic/Semantic search results).
5. **Conversation History:** 2000 tokens (Sliding window of raw dialogue).

## 6.2 Preventing "Lost in the Middle"

LLMs exhibit a U-shaped attention curve, recalling information at the start and end of the prompt best, while hallucinating or forgetting information buried in the middle.<sup>35</sup>

**Injection Strategy:**

1. **Primacy:** Place **Core Memory** at the very top (System Message).
2. **Recency:** Place the **Conversation History** at the very bottom.
3. **The "Bridge":** Place **Retrieved Semantic Facts** (RAG) immediately *before* the conversation history.
4. **Reranking:** Do not just inject the "Top K" vector matches.
  - *Step 1:* Retrieve Top 20 via sqlite-vec.
  - *Step 2:* Apply a "Recency Boost" score:  $\text{Score}_{\text{final}} = \text{Score}_{\text{vector}} + \frac{1}{\log(\text{TimeDelta})}$ .
  - *Step 3:* Inject the Top 5 resulting facts. This balances semantic relevance with temporal proximity.<sup>37</sup>

## 6.3 Summarization for Injection

Raw episodic logs are verbose ("User: Hi. AI: Hello. User: I like cats.").

- **Compression:** Before injection into the context window, logs should be summarized.
- **Method:** Use the background consolidation loop to convert raw turns into **Summary Bullets**.
  - *Raw:* "User: I like cats." -> *Summary:* "User expressed preference for cats."
  - *Storage:* Store these summaries in a separate summary column in episodic\_memory.
  - *Retrieval:* When constructing the prompt, inject the *Summaries* of older turns, and the *Raw Text* of the last 5 turns. This maximizes the informational density per token.

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## 7. Implementation & Migration Recommendations

## 7.1 Python Asynchronous "Kernel" Pattern

ATLAS must handle blocking I/O (API calls, Database writes) without freezing the main application loop, especially for voice interaction.

Pattern: asyncio event loop with sqlite3 confined to a ThreadPoolExecutor. SQLite is blocking by design; accessing it directly in an async def function will block the entire event loop.

Python

```
import asyncio
import concurrent.futures
import sqlite3

class AsyncMemoryManager:
    def __init__(self, db_path):
        self.db_path = db_path
        # SQLite must be accessed from a single thread or strict WAL mode.
        # A ThreadPool with 1 worker acts as a serializer for DB writes.
        self.executor = concurrent.futures.ThreadPoolExecutor(max_workers=1)

    async def query(self, sql, params=()):
        loop = asyncio.get_running_loop()
        # Offload the blocking SQL call to the thread pool
        return await loop.run_in_executor(
            self.executor,
            self._execute_blocking,
            sql, params
        )

    def _execute_blocking(self, sql, params):
        conn = sqlite3.connect(self.db_path)
        cursor = conn.cursor()
        cursor.execute(sql, params)
        res = cursor.fetchall()
        conn.close()
        return res
```

*Insight:* This pattern ensures that while the database is churning through a vector search or a vacuum operation, the Voice Activity Detection (VAD) loop remains responsive.<sup>26</sup>

## 7.2 Migration Path to Qdrant/Memgraph

As hardware improves (e.g., upgrading to a laptop with 32GB RAM), ATLAS can migrate from the embedded SQLite solution to dedicated servers.

- **Qdrant Migration:** Since ATLAS already uses standard 384-dimensional vectors, migration is a simple ETL script. Iterate through `vec_episodic`, read the vector BLOB, and push to Qdrant's HTTP API. The standard dimensionality ensures compatibility.<sup>40</sup>
- **Memgraph Migration:** Migration from the SQLite nodes/edges schema involves exporting the relational tables to CYPHER queries (e.g., `CREATE (n:Node {prop: val}))` or CSVs for bulk import into Memgraph.
- **Abstraction Layer:** To facilitate this, the Python code should use an **Abstract Base Class** `MemoryInterface`.
  - Current Implementation: `SQLiteMemory(MemoryInterface)`
  - Future Implementation: `QdrantMemory(MemoryInterface)`This ensures the agent logic remains agnostic to the underlying storage engine.

## 7.3 Specific Recommendations Summary

Component	Recommendation	Justification
Database	SQLite + <code>sqlite-vec</code>	Native C speed, zero-dependency, works on WSL2, minimal RAM overhead vs. Qdrant/Weaviate.
Embedding	<code>all-MiniLM-L6-v2 (INT8 ONNX)</code>	<30MB RAM footprint, <5ms latency on CPU, sufficient semantic quality.
Graph	SQLite Recursive CTEs	Eliminates need for Neo4j/JVM; performs traversals in-engine; zero serialization cost.
Search	Hybrid (FTS5 + Vector)	FTS5 provides lexical precision; Vector provides semantic recall. Combined query is highly optimized.

<b>Consolidation</b>	<b>Async Heuristic Loop</b>	Moves compute-heavy tasks to idle time; uses RAKE pre-filtering to save LLM tokens.
<b>Runtime</b>	<b>Python venv + Static Wheels</b>	Avoids Docker overhead; utilizes pre-compiled binaries for stability on Windows/WSL2.

---

## 8. Conclusion

ATLAS demonstrates that advanced AI cognitive architectures do not strictly require data center infrastructure. The "bigger is better" dogma of vector databases and large embedding models is often a lazy optimization for unconstrained hardware. By treating SQLite not merely as a storage bucket but as a compute engine (utilizing FTS5 triggers, Virtual Tables, and Recursive CTEs), and by rigorously optimizing the neural pipeline with ONNX quantization, it is possible to fit a sophisticated, memory-augmented agent into the footprint of a web browser tab.

The architecture proposed here—a tiered, asynchronous, kernel-like memory manager—respects the severe boundaries of the 4GB/16GB laptop environment while offering unbounded depth in memory retention. It is a proof of concept for "Edge-Native AI," where efficiency is the primary driver of intelligence.

---

## 9. Appendix: Technical Reference & Benchmarks

### 9.1 Embedding Model Benchmarks (INT8 Quantized)

Metric	all-MiniLM-L6-v2 (INT8)	bge-small-en (INT8)	SimCSE-BERT (FP32)
Model Size	22 MB	34 MB	420 MB
VRAM Usage	~80 MB	~110 MB	~600 MB
CPU Latency	2.5 ms	4.1 ms	35 ms

<b>MTEB Score</b>	56.8	62.3	58.5
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*Note: bge-small offers slightly better semantics but at a latency cost. For a real-time voice agent, MiniLM remains the latency king.*

## 9.2 Schema Installation Script (Bash/Python)

To set up the environment without Docker, use strict pinning for the static wheels:

Bash

```
# Install strict dependencies for WSL2 environment
# sqlite-vec usually requires a specific platform wheel
pip install sqlite-vec tokenizer onnxruntime-gpu numpy
```

*(Note: Verify the sqlite-vec wheel compatibility with the specific glibc version in the WSL2 distro distribution).*

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