

# **JANUS**

## **Neuromorphic Architecture**

*Brain-Inspired Algorithmic Trading System  
Mapping Neuroscience to Market Intelligence*

**Classification: Architecture Specification**

**Version: 1.0**

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**Neuromorphic Design Principles:**

- **Cognitive Mapping:** Each brain region maps to a trading subsystem
- **Hierarchical Processing:** From sensory input to strategic planning
- **Parallel Computation:** Multiple regions process simultaneously
- **Homeostatic Regulation:** Self-balancing risk and reward
- **Fear-Conditioned Safety:** Emotional override for threat response

## Abstract

JANUS implements a **neuromorphic architecture** that maps cognitive neuroscience principles to algorithmic trading. Each brain region's computational role is replicated in the system architecture, creating a biologically-inspired trading intelligence that combines:

- **Cortex:** Strategic planning and long-term memory (Manager Agent)
- **Hippocampus:** Episodic memory and experience replay (Worker Agent)
- **Basal Ganglia:** Action selection via Actor-Critic RL
- **Thalamus:** Attention gating and multimodal fusion
- **Prefrontal Cortex:** Logic, planning, and regulatory compliance
- **Amygdala:** Fear detection and emergency circuit breakers
- **Hypothalamus:** Homeostatic risk regulation
- **Cerebellum:** Motor control and optimal execution
- **Visual Cortex:** Pattern recognition via GAF and ViViT
- **Integration:** Brainstem coordination and lifecycle management

This architecture enables emergent intelligence through parallel processing, hierarchical control, and homeostatic self-regulation—principles proven effective in biological systems over millions of years of evolution.

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# 1 Neuromorphic Design Philosophy

## 1.1 Why Brain-Inspired Architecture?

Traditional trading systems follow rigid, hierarchical designs. JANUS instead adopts principles from cognitive neuroscience:

1. **Parallel Processing:** Multiple brain regions process different aspects of market data simultaneously
2. **Hierarchical Abstraction:** Low-level pattern recognition feeds mid-level tactics which inform high-level strategy
3. **Homeostatic Regulation:** Self-balancing mechanisms maintain system health (like biological homeostasis)
4. **Emotional Override:** Fear systems can immediately halt trading when threats are detected
5. **Memory Consolidation:** Wake-sleep cycles transfer episodic experiences to long-term schemas
6. **Adaptive Learning:** Continuous learning at multiple timescales (fast hippocampal, slow cortical)

## 1.2 Neuroscience-to-Trading Mapping

Brain Region	Neuroscience Function	Trading Function
<b>Cortex</b>	Executive function, strategic planning, declarative memory	Manager agent, portfolio strategy, market knowledge
<b>Hippocampus</b>	Episodic memory, spatial navigation, memory replay	Worker agent, trade history, experience replay
<b>Basal Ganglia</b>	Action selection, habit formation, reward learning	Actor-Critic RL, action gating, Q-learning
<b>Thalamus</b>	Sensory relay, attention gating, arousal	Data fusion, attention mechanisms, signal filtering
<b>Prefrontal</b>	Logic, planning, impulse control, ethics	LTN constraints, compliance, goal decomposition
<b>Amygdala</b>	Fear conditioning, threat detection, emotional memory	Risk detection, circuit breakers, kill switch
<b>Hypothalamus</b>	Homeostasis, motivation, energy balance	Risk appetite, position sizing, cash management
<b>Cerebellum</b>	Motor coordination, procedural learning, error correction	Order execution, slippage prediction, PID control
<b>Visual Cortex</b>	Visual processing, feature extraction, object recognition	GAF encoding, ViViT, pattern recognition
<b>Brainstem</b>	Basic life functions, arousal/sleep cycles	System orchestration, wake/sleep coordination

Table 1: Neuroscience to Trading Mapping

## 2 Brain Region Architectures

### 2.1 Cortex: Strategic Planning & Long-term Memory

#### 2.1.1 Neuroscience Background

The cerebral cortex handles executive function, strategic planning, and declarative (fact-based) memory. It operates on slow timescales, consolidating knowledge over days to years.

#### 2.1.2 Trading Implementation

**Directory:** `src/janus/neuromorphic/cortex/`

**Components:**

- **Manager:** Feudal RL manager agent for high-level strategy
- **Memory:** Long-term knowledge consolidation and schema storage
- **Planning:** Scenario analysis, Monte Carlo, portfolio optimization

### Key Responsibilities:

1. Set strategic goals (e.g., "maximize Sharpe ratio while maintaining drawdown <15%")
2. Generate subgoals for Worker agent (e.g., "accumulate position in AAPL over 2 hours")
3. Consolidate episodic memories into abstract schemas (e.g., "morning volatility regime")
4. Store declarative knowledge (e.g., "FOMC announcements increase volatility")

### Mathematical Formulation:

Manager policy selects subgoals  $g$  for Worker:

$$g_t = \pi_{\text{Manager}}(s_t^{\text{high}}) \quad (1)$$

where  $s_t^{\text{high}}$  is high-level state (portfolio metrics, regime, time-to-horizon).

Value function:

$$V_{\text{Manager}}(s) = \mathbb{E} \left[ \sum_{t=0}^T \gamma^t r_t^{\text{high}} \mid s_0 = s \right] \quad (2)$$

## 2.2 Hippocampus: Episodic Memory & Experience Replay

### 2.2.1 Neuroscience Background

The hippocampus rapidly encodes episodic memories and replays them during sleep at 10-20× speed. Pattern separation prevents interference. Sharp Wave Ripples (SWR) prioritize important experiences.

### 2.2.2 Trading Implementation

**Directory:** `src/janus/neuromorphic/hippocampus/`

#### Components:

- **Worker:** Feudal RL worker agent for tactical execution
- **Replay:** Prioritized Experience Replay (PER) buffer

- **Episodes:** Trade sequences and market events
- **SWR:** Sharp Wave Ripple simulator for compressed replay

### Key Responsibilities:

1. Execute subgoals from Manager (e.g., "buy 100 shares incrementally")
2. Store trade experiences in episodic buffer
3. Prioritize replay based on TD-error + logic violations
4. Compress replay 10-20× during sleep (Backward service)

### Mathematical Formulation:

Worker policy conditioned on subgoal  $g$ :

$$a_t = \pi_{\text{Worker}}(s_t^{\text{low}}, g_t) \quad (3)$$

Intrinsic reward for subgoal completion:

$$r_t^{\text{intrinsic}} = -||s_t - g_t||^2 \quad (4)$$

Prioritized replay sampling:

$$P(i) = \frac{p_i^\alpha}{\sum_j p_j^\alpha}, \quad p_i = |\delta_i| + \lambda_{\text{logic}} v_i + \lambda_{\text{reward}} |r_i| \quad (5)$$

## 2.3 Basal Ganglia: Action Selection & Reinforcement Learning

### 2.3.1 Neuroscience Background

The basal ganglia implement action selection via dual pathways: direct (Go) promotes actions, indirect (No-Go) inhibits them. This is the biological substrate for reinforcement learning.

### 2.3.2 Trading Implementation

**Directory:** `src/janus/neuromorphic/basal_ganglia/`

#### Components:

- **Actor:** Policy network for action distribution
- **Critic:** Value network for advantage estimation
- **Praxeological:** Go/No-Go signal computation

- **Selection:** Competitive action selection mechanisms

**Key Responsibilities:**

1. Generate action proposals (BUY, SELL, HOLD, sizes)
2. Compute action values (Q-values)
3. Gate actions through dual pathways (safety)
4. Maintain habit cache for frequent patterns

**Mathematical Formulation:**

Actor policy:

$$\pi_\theta(a|s) = \text{softmax}(\mathbf{W}_\pi \mathbf{h}(s) + \mathbf{b}_\pi) \quad (6)$$

Critic value estimate:

$$V_\omega(s) = \mathbf{W}_V \mathbf{h}(s) + b_V \quad (7)$$

Advantage:

$$A(s, a) = Q(s, a) - V(s) \quad (8)$$

Go signal (direct pathway):

$$\text{Go}(a) = \max (\mathbf{W}_{\text{direct}} \mathbf{h}(s))_a \quad (9)$$

No-Go signal (indirect pathway):

$$\text{NoGo}(a) = \text{sigmoid}(\mathbf{W}_{\text{indirect}} [\mathbf{h}(s); \text{risk}; \text{VPIN}]) \quad (10)$$

Final action gate:

$$a_{\text{final}} = \begin{cases} a_{\text{proposed}} & \text{if } \text{NoGo}(a) < \tau_{\text{veto}} \\ \text{HOLD} & \text{otherwise} \end{cases} \quad (11)$$

## 2.4 Thalamus: Attention & Multimodal Fusion

### 2.4.1 Neuroscience Background

The thalamus acts as a sensory relay station, gating information flow to cortex based on attention and relevance. It integrates multimodal sensory inputs.

### 2.4.2 Trading Implementation

**Directory:** `src/janus/neuromorphic/thalamus/`

**Components:**

- **Attention:** Cross-attention mechanisms
- **Gating:** Sensory gating and relevance filtering
- **Routing:** Dynamic information routing
- **Fusion:** Price, volume, orderbook, sentiment fusion

### **Key Responsibilities:**

1. Gate incoming market data (filter noise)
2. Fuse multiple data modalities (price, volume, text)
3. Route relevant information to appropriate regions
4. Implement attention mechanisms for saliency

### **Mathematical Formulation:**

Gated cross-attention:

$$\text{Attention}(\mathbf{Q}, \mathbf{K}, \mathbf{V}) = \text{softmax}\left(\frac{\mathbf{Q}\mathbf{K}^\top}{\sqrt{d_k}}\right) \mathbf{V} \quad (12)$$

Gating scalar:

$$\lambda_{\text{gate}} = \text{sigmoid}(\mathbf{W}_g[\mathbf{h}_m; \mathbf{h}_n] + b_g) \quad (13)$$

Fused representation:

$$\mathbf{h}_{\text{fused}} = \mathbf{h}_m + \lambda_{\text{gate}} \cdot \text{Attention}(\mathbf{h}_m, \mathbf{h}_n, \mathbf{h}_n) \quad (14)$$

## 2.5 Prefrontal Cortex: Logic, Planning & Compliance

### 2.5.1 Neuroscience Background

The prefrontal cortex implements logical reasoning, impulse control, and ethical decision-making. It's the "executive" that enforces rules and long-term goals.

### 2.5.2 Trading Implementation

**Directory:** `src/janus/neuromorphic/prefrontal/`

**Components:**

- **LTN:** Logic Tensor Networks for rule encoding
- **Conscience:** Compliance constraints (wash sale, risk limits)
- **Planning:** Goal decomposition and plan synthesis

- **Goals:** Goal hierarchy management

**Key Responsibilities:**

1. Encode trading rules as differentiable logic
2. Enforce regulatory compliance (wash sale, position limits)
3. Block actions violating constraints
4. Decompose high-level goals into actionable plans

**Mathematical Formulation:**

LTN predicate grounding:

$$\mathcal{G}(P)(\mathbf{x}) = \text{sigmoid}(\mathbf{W}_P \mathbf{x} + b_P) \in [0, 1] \quad (15)$$

Łukasiewicz conjunction:

$$\mathcal{G}(A \wedge B) = \max(0, \mathcal{G}(A) + \mathcal{G}(B) - 1) \quad (16)$$

Wash sale constraint:

$$\forall t, k \in [1, 30] : \neg(\text{SaleAtLoss}(t) \wedge \text{Buy}(t+k)) \quad (17)$$

Satisfiability:

$$\text{SatAgg}(\mathcal{K}) = \left( \frac{1}{m} \sum_{i=1}^m \mathcal{G}(\phi_i)^p \right)^{1/p} \quad (18)$$

## 2.6 Amygdala: Fear, Threat Detection & Circuit Breakers

### 2.6.1 Neuroscience Background

The amygdala detects threats and triggers immediate fear responses, overriding rational planning when danger is present. Fear-conditioned memories persist long-term.

### 2.6.2 Trading Implementation

**Directory:** `src/janus/neuromorphic/amygdala/`

**Components:**

- **Fear:** Fear-conditioned inhibition network (FNI-RL)
- **VPIN:** Volume-synchronized toxicity detection
- **Circuit Breakers:** Kill switch, position freeze, cancel all

- **Threat Detection:** Anomaly, flash crash, black swan detection

### **Key Responsibilities:**

1. Detect market panic and flash crashes
2. Trigger emergency circuit breakers
3. Override all other systems in extreme conditions
4. Learn fear-conditioned responses to past disasters

### **Mathematical Formulation:**

VPIN (Volume-Synchronized Probability of Informed Trading):

$$\text{VPIN}_t = \frac{\sum_{i=1}^n |V_{\text{buy},i} - V_{\text{sell},i}|}{\sum_{i=1}^n V_i} \quad (19)$$

Fear activation:

$$f_{\text{fear}}(s) = \text{sigmoid}(\mathbf{W}_f[\text{VPIN}; \sigma_{\text{vol}}; \Delta p_{\text{max}}] + b_f) \quad (20)$$

Circuit breaker trigger:

$$\text{KillSwitch} = \begin{cases} \text{ACTIVATE} & \text{if } f_{\text{fear}} > \tau_{\text{fear}} \text{ OR VPIN} > \tau_{\text{VPIN}} \\ \text{STANDBY} & \text{otherwise} \end{cases} \quad (21)$$

## 2.7 Hypothalamus: Homeostasis & Risk Appetite

### 2.7.1 Neuroscience Background

The hypothalamus maintains homeostasis—internal balance of temperature, hunger, thirst, etc. It regulates motivation and energy expenditure.

### 2.7.2 Trading Implementation

**Directory:** `src/janus/neuromorphic/hypothalamus/`

#### **Components:**

- **Homeostasis:** Balance tracking and deviation correction
- **Position Sizing:** Kelly criterion, volatility scaling
- **Risk Appetite:** Dynamic risk tolerance adaptation
- **Energy:** Capital allocation and cash reserves

### Key Responsibilities:

1. Maintain target portfolio balance (setpoints)
2. Adjust position sizes based on volatility and drawdown
3. Regulate risk appetite (fear vs. greed)
4. Ensure cash reserves and leverage limits

### Mathematical Formulation:

Kelly criterion (fractional):

$$f^* = \frac{p(b+1) - 1}{b}, \quad \text{position size} = \frac{f^*}{2} \cdot \text{capital} \quad (22)$$

Volatility scaling:

$$\text{size}_{\text{adjusted}} = \text{size}_{\text{base}} \cdot \frac{\sigma_{\text{target}}}{\sigma_{\text{current}}} \quad (23)$$

Drawdown scaling:

$$\text{size}_{\text{DD}} = \text{size}_{\text{base}} \cdot \max \left( 0.1, 1 - \frac{\text{DD}_{\text{current}}}{\text{DD}_{\text{max}}} \right) \quad (24)$$

Homeostatic correction:

$$\Delta \text{allocation} = K_p \cdot (\text{target} - \text{current}) + K_d \cdot \frac{d(\text{target} - \text{current})}{dt} \quad (25)$$

## 2.8 Cerebellum: Motor Control & Execution

### 2.8.1 Neuroscience Background

The cerebellum coordinates fine motor control, learns procedural skills, and predicts sensory consequences of actions (forward models).

### 2.8.2 Trading Implementation

**Directory:** `src/janus/neuromorphic/cerebellum/`

#### Components:

- **Execution:** Order routing, TWAP/VWAP algorithms
- **Impact:** Almgren-Chriss optimal execution
- **Forward Models:** Latency compensation, fill prediction
- **Error Correction:** PID control, adaptive feedback

**Key Responsibilities:**

1. Route orders to exchanges with minimal slippage
2. Predict and minimize market impact
3. Compensate for execution latency (Smith predictor)
4. Learn from execution errors and adapt

**Mathematical Formulation:**

Almgren-Chriss optimal trajectory:

$$x_t = X \cdot \frac{\sinh(\kappa(T-t))}{\sinh(\kappa T)}, \quad \kappa = \sqrt{\frac{\eta\sigma}{\tau}} \quad (26)$$

Market impact:

$$\text{Impact} = \eta \cdot \sigma \cdot \sqrt{\frac{v}{V_{\text{avg}}}} \quad (27)$$

Smith predictor (latency compensation):

$$u(t) = K_c \left[ e(t) + \frac{1}{\tau_I} \int e(\tau) d\tau + \tau_D \frac{de(t)}{dt} \right] + \hat{p}(t + \Delta t) \quad (28)$$

Execution error:

$$\epsilon_{\text{exec}} = |p_{\text{actual}} - p_{\text{predicted}}| \quad (29)$$

## 2.9 Visual Cortex: Pattern Recognition & Vision

### 2.9.1 Neuroscience Background

The visual cortex processes images hierarchically: V1 detects edges, V2 detects shapes, V4 detects objects. It implements hierarchical feature extraction.

### 2.9.2 Trading Implementation

**Directory:** `src/janus/neuromorphic/visual_cortex/`

#### Components:

- **Eyes:** Data ingestion, preprocessing, streaming
- **GAF:** Gramian Angular Fields (GASF, GADF, DiffGAF)
- **ViViT:** Video Vision Transformer for spatiotemporal patterns
- **Visualization:** UMAP, GradCAM, saliency maps

**Key Responsibilities:**

1. Ingest and preprocess raw market data
2. Transform time series to visual manifolds (GAF)
3. Extract spatiotemporal patterns (ViViT)
4. Visualize learned representations (UMAP)

### **Mathematical Formulation:**

GAF normalization:

$$\tilde{x}_i = \tanh \left( \frac{x_i - \min(X)}{\max(X) - \min(X) + \epsilon} \cdot \alpha + \beta \right) \quad (30)$$

GASF:

$$\text{GASF}_{i,j} = \cos(\phi_i + \phi_j), \quad \phi_i = \arccos(\tilde{x}_i) \quad (31)$$

GADF:

$$\text{GADF}_{i,j} = \sin(\phi_i - \phi_j) \quad (32)$$

ViViT patch embedding:

$$\mathbf{z}_{f,i,j}^{(0)} = \mathbf{E} \cdot \text{flatten}(\mathcal{V}_{f,i:i+P,j:j+P}) + \mathbf{p}_{f,i,j} \quad (33)$$

## 2.10 Integration: Brainstem & Global Coordination

### 2.10.1 Neuroscience Background

The brainstem controls basic life functions, arousal/sleep cycles, and global state coordination. It's the "operating system" of the brain.

### 2.10.2 Trading Implementation

**Directory:** `src/janus/neuromorphic/integration/`

**Components:**

- **Workflow:** State machine orchestration
- **State:** Global state management, message bus
- **API:** REST, gRPC, WebSocket interfaces
- **Engine:** Wake-sleep cycle coordination

**Key Responsibilities:**

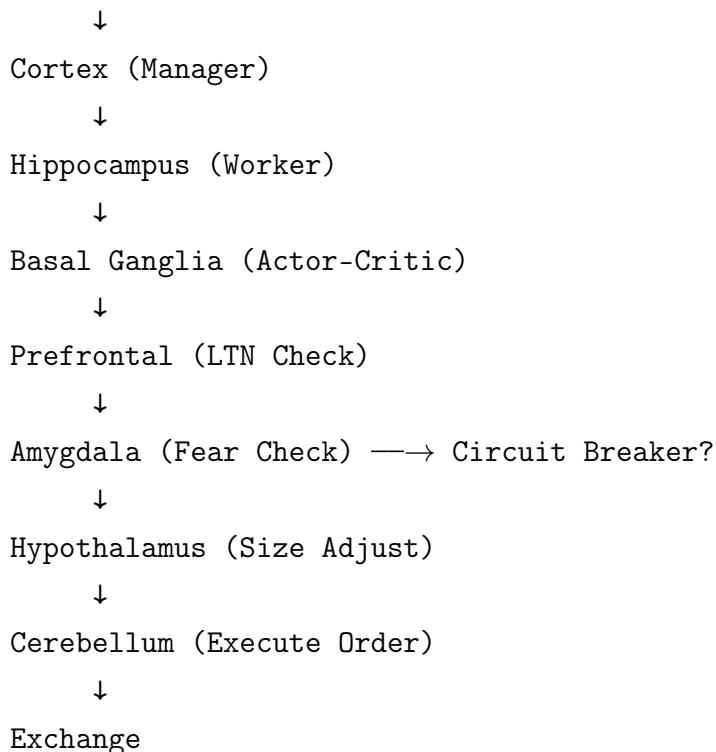
1. Coordinate wake (Forward) and sleep (Backward) cycles

2. Manage global system state
3. Route messages between brain regions
4. Expose external APIs

## 3 Information Flow Diagrams

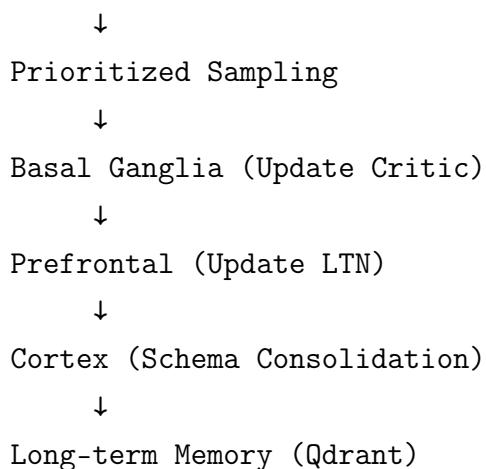
### 3.1 Wake State (Forward Service)

Market Data → Visual Cortex (GAF/ViViT) → Thalamus (Fusion)



### 3.2 Sleep State (Backward Service)

Hippocampus (Episodic Buffer) → SWR Replay (10-20x speed)



## 4 Implementation Guide

### 4.1 Directory Structure

```

src/janus/neuromorphic/
    └── lib.rs                         # Main library entry point
    └── common/                          # Shared types and utilities
    └── cortex/                          # Strategic planning & LTM
        ├── manager/                     # Feudal RL manager
        ├── memory/                      # Consolidation, schemas
        └── planning/                     # Scenario analysis
    └── hippocampus/                   # Episodic memory & replay
        ├── worker/                       # Feudal RL worker
        ├── replay/                       # PER buffer
        ├── episodes/                     # Trade sequences
        └── swr/                           # Sharp wave ripples
    └── basal_ganglia/                 # Action selection & RL
        ├── actor/                        # Policy network
        ├── critic/                       # Value network
        ├── praxeological/               # Go/No-Go signals
        └── selection/                    # Action selection
    └── thalamus/                       # Attention & fusion
        ├── attention/                  # Cross-attention
        ├── gating/                      # Sensory gates
        ├── routing/                     # Information routing
        └── fusion/                       # Multimodal fusion
    └── prefrontal/                    # Logic & compliance
        ├── ltn/                          # Logic Tensor Networks
        ├── conscience/                  # Compliance rules
        ├── planning/                     # Goal decomposition
        └── goals/                        # Goal management
    └── amygdala/                      # Fear & circuit breakers
        ├── fear/                         # FNI-RL network
        ├── vpin/                          # Toxicity detection
        ├── circuit_breakers/             # Kill switch
        └── threat_detection/            # Anomaly detection
    └── hypothalamus/                  # Homeostasis & risk
        ├── homeostasis/                  # Balance tracking
        └── position_sizing/              # Kelly, vol scaling

```

```

    └── risk_appetite/      # Dynamic tolerance
        └── energy/         # Capital allocation
    cerebellum/
        ├── execution/     # Motor control & execution
        ├── impact/          # Almgren-Chriss
        ├── forward_models/ # Latency compensation
        └── error_correction/ # PID control
    visual_cortex/
        ├── eyes/           # Data ingestion
        ├── gaf/             # GAF transformation
        ├── vivit/           # ViViT model
        └── visualization/   # UMAP, GradCAM
    integration/
        ├── workflow/        # System coordination
        ├── state/            # State machines
        ├── api/              # Global state
        └── engine/           # External APIs

```

## 4.2 Implementation Checklist

### 1. Phase 1: Core Infrastructure (Weeks 1-2)

- Set up neuromorphic module structure
- Implement common types and error handling
- Create inter-region message bus
- Set up integration/engine orchestrator

### 2. Phase 2: Visual Processing (Weeks 3-4)

- Implement Visual Cortex data ingestion
- Implement GAF transformation (GASF, GADF)
- Integrate ViViT model (ONNX or tch-rs)
- Add UMAP visualization

### 3. Phase 3: Decision Making (Weeks 5-7)

- Implement Basal Ganglia Actor-Critic
- Implement Prefrontal LTN constraints
- Implement Thalamus fusion mechanisms

- Connect visual → decision pipeline

#### 4. Phase 4: Memory Systems (Weeks 8-10)

- Implement Hippocampus episodic buffer
- Implement Prioritized Experience Replay
- Implement Cortex schema consolidation
- Implement SWR compressed replay

#### 5. Phase 5: Safety & Control (Weeks 11-12)

- Implement Amygdala fear network
- Implement circuit breakers and kill switch
- Implement Hypothalamus homeostasis
- Implement Cerebellum execution control

#### 6. Phase 6: Integration & Testing (Weeks 13-14)

- Connect all brain regions
- Implement wake-sleep cycle coordination
- End-to-end integration tests
- Performance optimization

## 5 Architectural Invariants

### 5.1 Safety-Critical Invariants

1. **Amygdala Override:** Fear system ALWAYS overrides all other regions
2. **Prefrontal Veto:** LTN constraints MUST block non-compliant actions
3. **No Panic:** No `panic!()`, `unwrap()`, or `expect()` in production code
4. **Fail-Safe:** Circuit breakers must be fail-safe (default to HALT)
5. **Homeostasis:** Cash reserves must never fall below 20%

## 5.2 Performance Invariants

1. **Forward Latency:** Visual Cortex → Decision <100ms
2. **Backward Throughput:** Process >10k experiences per sleep cycle
3. **Memory Efficiency:** Hippocampal buffer <10k transitions (FIFO eviction)
4. **Parallel Processing:** Brain regions process concurrently

## 5.3 Learning Invariants

1. **Dual Timescale:** Fast hippocampal learning, slow cortical consolidation
2. **Recall Gating:** Cortical updates gated by recall strength AND logic validity
3. **Priority Replay:** Replay prioritized by TD-error + logic violations + reward
4. **Schema Formation:** Clusters detected via UMAP + DBSCAN

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