The Ant Stack

Daniel Ari Friedman

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ORCID: 0000-0001-6232-9096 Email: daniel@activeinference.institute

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1 Abstract

We present the Ant Stack: a compact, modular framework that emulates an ant from physics to cognition. It comprises three interoperable layers—`AntBody` (morphology, actuation, sensors), `AntBrain` (functional neural circuits templated from conserved insect architectures), and `AntMind` (active inference and stigmergy for individual and collective cognition). The stack uses explicit I/O contracts, sparse/low-power compute, and species-parameterized configurations aligned with current myrmecology.

The proposed methods couple physics-based locomotion and olfactory–visual sensing with a lightweight neural pipeline (local plasticity) and a minimal generative model for active-inference policy selection that composes across agents via pheromone-mediated stigmergy. We specify evaluation suites for navigation, trail following, task allocation, and robustness under noise/adversaries. The framework is reproducible, extensible, and transferable to swarm robotics and other complex systems, with open evaluation assets and baseline species configurations.

Contributions: (1) an explicit, executable Input/Output contract between proposed Body, Brain, and Mind layers; (2) a compact neural control pipeline with local plasticity; (3) a minimal active-inference ant nestmate agent that composes via stigmergy; (4) a standardized evaluation suite with species presets and seeds for direct replication; (5) a species-parameterized, manifest-driven, and version-pinned artifact set for reproducible translational entomologicalresearch.

For myrmecology, the stack links empirical findings (pheromone dynamics, polarized-light navigation, species-level diversity) to executable models for hypothesis testing and cross-species comparison. Beyond biology, it provides a tractable substrate for energy-efficient synthetic intelligence, cognitive security, and alignment research where distributed, naturally aligned agents yield resilient group behavior.

1.1 Keywords

Myrmecology; ant colony; stigmergy; pheromone trails; active inference; Antennal Lobes (AL); Mushroom Bodies (MB); Central Complex (CX); ring attractor; sparse spiking; energy-efficient AI; swarm robotics; cognitive security; alignment; polarized-light navigation.

2 The Ant Stack

The Ant Stack is a compact, modular framework for simulating an ant agent—body, brain, and mind—to study how robust intelligence emerges from sensorimotor grounding and collective interaction. It emphasizes biologically plausible interfaces, sparse/low-power computation, and clear I/O contracts. The aim is pragmatic: a small, interoperable stack that is easy to test, extend, and transfer to real systems.

The framework is composed of three primary layers: `AntBody`, `AntBrain`, and `AntMind`. This structure allows for a separation of concerns, where physical simulation, neural architecture, and cognitive modeling can be developed and studied independently while remaining interoperable. The goal is to build upon foundational research in other insects, such as *Drosophila* and *Apis*, to accelerate the development of a sophisticated ant model with wide-ranging applications.

2.1 Roadmap & Contributions

- Implement `AntBody` I/O contract; `AntBrain` AL$\rightarrow$MB$\rightarrow$CX with sparse learning; `AntMind` minimal generative model and stigmergy field; evaluation benchmarks and baseline species presets
- Ship species parameter presets and experiment manifests (YAML/JSON) for one-click reruns

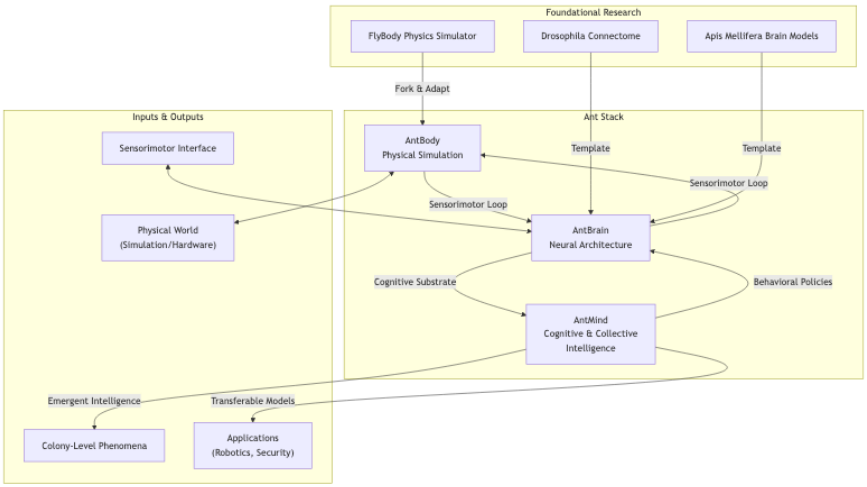

Figure 1: Computational architecture diagram (4829)

- Contributions welcome via pull requests. Keep edits small; include seeds, units, and benchmarks. Propose task variants aligned with the evaluation suite.

2.2 Ant Stack Summary

Compact agents with realistic bodies, efficient brains, and principled minds provide a tractable route to study intelligence-as-compression and alignment in multi-agent settings. The Ant Stack offers a minimal, testable path from physics to collective behavior with explicit interfaces and benchmarks.

3 Background and State of the Art

This Introduction situates the Ant Stack within computational neuroscience, robotics, and entomology, and highlights gaps motivating a compact, interoperable framework. The emphasis is on functional fidelity, explicit interfaces, and small-footprint operation that transfers from simulation to hardware and across species.

3.1 Key Developments

- **Neural simulators (e.g., Nengo, Spaun):** Feasibility of insect-like behaviors and decision-making; proof of concept for functional brain emulation
- **Neurokernel:** GPU-accelerated, modular simulation of the fly brain; a blueprint for ant-specific simulation
- **Ant-inspired robotics/navigation:** Swarms and navigation (visual odometry, polarized light) validate robust ant-like strategies
- **Field data pipelines:** Increasing availability of arena/field datasets enables data-driven parameterization and validation
- **Tracking/pose tools:** Open-source video tracking and pose estimation (e.g., DeepLabCut, idtracker.ai) enable parameter extraction and validation

3.2 What Has Not Been Achieved

Despite progress, no high-fidelity ant brain emulation exists that closes the loop with a realistic body at interactive rates.

- **No complete ant connectome:** Requires templates from other insects and functional abstraction

- **No synapse-level emulation:** No model meets biological functional fidelity
- **No real-time embedded simulation:** No robot runs a full, real-time ant brain
- **Limited cross-species transfer:** Few studies quantify how models transfer across ant taxa and environments

3.3 Technical Challenges

- **Sensorimotor integration:** Pheromones, polarized light, chemical gradients, and motor coupling
- **Connectomics:** Incomplete wiring data
- **Hardware miniaturization:** Embedded control at ant scale remains unsolved
- **Data scarcity:** Sparse, noisy, or heterogeneous ecological data complicate validation and benchmarking
- **Standardization:** Lack of common I/O contracts impedes replication and comparison
- **Systems integration:** Bridging simulation and hardware via standardized message schemas (e.g., ROS 2) and unit registries

3.4 Recent Conceptual Advances in AI

- **Agentic AI and world models:** `AntMind`'s generative model serves as a compact world model for goal-directed behavior
- **Compression over memorization:** Intelligence as compression; ant colonies achieve complexity with ~250k neurons/agent
- **From tokens to cognition:** Embodiment, grounding, and predictive processing over disembodied token prediction
- **Cognitive security:** Security at the cognitive layer (deception-resilient agents) as a design objective
- **Energy-aware design:** Sparse activity and local learning align with on-edge constraints

3.5 Assumptions and Limits

- No complete ant connectome; template from Drosophila/Apis with functional abstractions
- Real-time, embedded control out of scope for v0; simulation-first with explicit I/O
- Energy/compute constraints modeled as design targets, not hardware-fitted
- Biological realism is subordinated to functional parsimony where trade-offs are explicit and documented

3.5.1 Section Summary

- Prior work validates components but not a full, embodied real-time ant brain
- Data gaps and hardware constraints justify functional abstraction and simulation-first scope
- Explicit assumptions/limits enable reproducibility and focused progress

4 AntBody

`AntBody` is a physics-based model of ant morphology, biomechanics, and sensors. It adapts the `FlyBody` MuJoCo simulator to ant-specific leg kinematics, exoskeletal properties, and antennae/mandible actuation (portable to PyBullet). It emits the raw sensorimotor stream to `AntBrain` and executes motor commands. The objective is not photorealism but functional fidelity: reproduce contact dynamics, gradient sensing, and actuation latencies that pose the same control problems real ants solve.

4.1 Morphology and Biomechanics

- **Segmented body:** Head, thorax, gaster with articulated joints.
- **Six articulated legs:** Multiple degrees of freedom (DOF) per leg for tripod gait and uneven terrain.

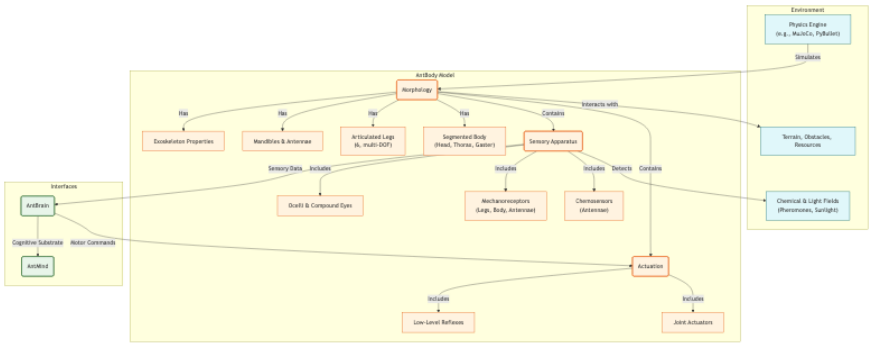

Figure 2: Computational architecture diagram (6ce7)

- **Mandibles and antennae:** Grasping/manipulation; near-field chemosensation.
- **Exoskeleton properties:** Rigidity and mass distribution for realistic contact.
- **Thermoregulation & hydration:** Optional environmental coupling for temperature and humidity tolerance experiments.

4.2 Actuation and Motor Control

- **Joint actuators:** Muscle-like force generation per joint.
- **Low-level control:** Reflexive stabilization (e.g., stance) beneath `AntBrain` commands; optionally PID/impedance at joints for robust terrain contact.

4.3 Sensory Apparatus

- **Chemosensors:** Antennal channels detect pheromone gradients and absolute concentration.
- **Mechanoreceptors:** Leg/body/antennal contact, forces, joint angles/velocities.
- **Ocelli/compound eyes:** Ambient luminance, polarized-light compass, low-res motion/landmarks.
- **Auditory/vibration (optional):** Substrate-borne vibration sensing for alarm/communication experiments.

Goal: a functionally accurate ant nestmate body posing the same control problems a real ant brain evolved to solve.

4.4 Interfaces (I/O Contract)

- **Observation o_t (100 Hz; SI units unless noted):**
  - Chemosensors: K channels/antenna, normalized [0,1]; gradient and absolute concentration
  - Mechanoreceptors: per-leg contact (bool), ground reaction forces (N), joint angles (rad), joint velocities (rad/s)
  - Vision: ocelli luminance (normalized), optional optic flow (px/s), polarized-light compass (deg)
  - IMU (optional): linear acceleration (m/s^2), angular velocity (rad/s)
- **Action a_t (100 Hz):**
  - Joint targets: position (rad) or torque (N·m) per DOF (configurable)
  - Mandible aperture (rad), antennae joint targets (rad)
- **Timing:** Physics step $\Delta t = 1$ ms; control loop acts every 10 steps (100 Hz)
- **Latency budget:** End-to-end sensor$\rightarrow$actuator latency target ≤ 20 ms (configurable)
- **Synchronization:** Monotonic timebase; max drift between body and brain clocks ≤ 2 ms; timestamp every observation

Strict units and update rates enable drop-in replacement of bodies and simplify benchmarking across engines.

4.5 Configuration

- Dynamics: position or torque control
- Terrain: flat, rough, slope
- Sensor noise: Gaussian σ per channel
- Pheromone field: on/off, diffusion D, decay λ
- Energy model (optional): per-actuator energy and baseline metabolism for efficiency metrics
- Contact/friction: Coulomb friction coefficients (μ_s, μ_k) and restitution per material
- Sensor/actuator calibration: per-channel offset/gain with auto-calibration routines and logs
- Batch mode: offline rollout/export of o_t, a_t, and internal state for dataset generation

Recommended defaults: 3–4 DOF/leg, $\Delta t = 1$ ms, 100 Hz control, Gaussian sensor noise $\sigma \in [0.01, 0.05]$.

4.5.1 Section Summary

- Concrete physics/sensing substrate with explicit I/O rates and units
- Built-in stabilization simplifies higher-level policies and improves robustness
- Parameterized terrain, control, noise, and stigmergy for reproducible experiments

4.6 Further Technical Notes and References

- **Dynamics and Engines**
  - Typical stable physics step: $\Delta t \approx 1$ ms (1 kHz) with a 100 Hz control loop, as used in MuJoCo and similar engines.
  - Engines: MuJoCo (site; Todorov et al., IROS 2012: IEEE Explore), PyBullet (site).
- **Leg Kinematics and Gaits**
  - Practical hexapod configurations use 3–4 DOF per leg (e.g., hip yaw/pitch, knee, optional ankle) to reproduce tripod gaits and turning.
  - Tripod gait overview and insect walking control: Cruse (1990) review (Springer) and summary (Wikipedia).
- **Sensors**
  - Polarization compass via ocelli/sky light: Wehner (2003) annual review on desert ant navigation (Annual Reviews).
  - Optic flow and landmark guidance in insects: Seelig & Jayaraman (2015) for orientation integration (Nature).
- **Pheromone Field (Environment Model)**
  - Diffusion–decay dynamics follow Fick's law with evaporation; see Fick's laws (Wikipedia) and ant colony trail models (Wikipedia).
  - Contact modeling: Coulomb friction and restitution parameterization; terrain moisture can modulate slip

5 AntBrain

`AntBrain` is a functional abstraction of an ant's neural architecture. It models key circuits and principles sufficient for adaptive behavior, initially at the circuit level and eventually at the cellular (neuron and glia) and synaptic level.

The architecture is templated from mapped insect brains (e.g., *Drosophila* hemibrain; *Apis* models) to remain biologically plausible and computationally tractable. Future ant-specific neuroanatomy can be mapped onto this template. Where available, species-level differences (e.g., glomerular counts, CX architecture) parameterize modules.

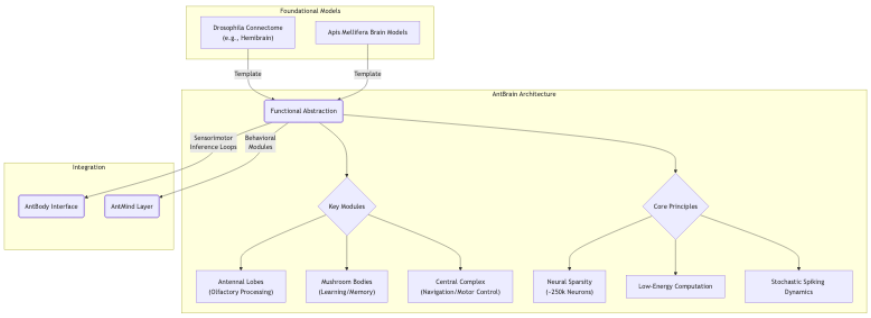

Figure 3: Computational architecture diagram (5c37)

5.1 Scope and Assumptions

- Functional, not synapse-accurate; modules align to conserved circuits (AL, MB, CX)
- Sparse, low-power operation at 100 Hz closed loop; ~1e5–2.5e5 neurons (configurable)
- Local learning (e.g., STDP) with simple modulatory signals; no global backprop
- Noise is a feature: stochasticity aids exploration and regularization; parameters expose variance at module boundaries

5.2 Template Resource: Virtual Fly Brain (VFB)

Virtual Fly Brain (About) is an interactive resource for exploring the neuroanatomy, neuron connectivity, and gene expression of Drosophila melanogaster. It integrates curated literature and image datasets onto a common brain template, enabling cross-search, similarity queries, and 3D comparison of neurons and regions.

We use VFB to align region nomenclature, ground functional abstractions of AL/MB/CX in mapped fly circuits, and inform parameters where ant-specific data are sparse. Where ant data exist, we override defaults via species presets.

5.3 Design Principles

5.3.1 1. Functional Emulation

Simulate functional roles of key structures rather than replicate every neuron. Favor minimal sufficient mechanisms with measurable interfaces.

5.3.2 2. Neural Sparsity and Efficiency

- **Neuron count:** ~250k target; biologically plausible and tractable
- **Optimization:** Low-energy computation and sparse representations
- **Dynamics:** Stochastic spiking and local learning (Hebbian, STDP)
- **Neuromodulation:** Reward/aversive signals (dopamine, octopamine, other biogenic amines) gate plasticity and policy bias with per-task schedules exported for reproducibility

5.3.3 3. Integration

- **Sensorimotor loops:** Tight closed loop with `AntBody`
- **Behavioral modules:** Substrate for higher-level programs orchestrated by `AntMind`
- **Multi-modal fusion:** AL/MB olfaction with visual/vestibular cues into CX heading and action channels with explicit timing constraints to maintain closed-loop stability at 100 Hz

5.4 Implementation Notes

- Engine: spiking (Brian2 / Nengo / SpikingJelly) or hybrid rate-based
- I/O: map `AntBody` observations to AL→MB→CX; policy head drives CX motor channel
- Interfaces are stable and testable: each module exposes a minimal API with typed tensors and unit metadata.
- **Cross-module timing:** AL/MB update at 100 Hz; CX policy head 50–100 Hz depending on task
- Learning:
  - MB: sparse coding (Kenyon cells); local plasticity with reward/punishment gating
  - CX: ring-attractor heading; soft WTA for action selection
- Targets: neurons ~1e5–2.5e5; sparse activity; 100 Hz closed-loop
- **Memory:** short-term eligibility traces; long-term synaptic consolidation checkpoints for reproducibility; model cards documenting learning rules and seeds
- Neuromodulation API: dopamine/octopamine gating channels exposed via a minimal interface for reproducible learning schedules
- Footprint reporting: track neuron counts, parameter sizes, and update rates per module

5.4.1 Technical Pointers and References

- **Antennal Lobe (AL):** Glomerular combinatorial codes and projection neuron mapping from ORNs; review in Wilson (2013) (Annual Reviews).
- **Mushroom Bodies (MB):** Sparse coding via Kenyon cells and associative plasticity; Caron et al. (2013) (Science).
- **Central Complex (CX):** Ring attractor for heading; Seelig & Jayaraman (2015) (Nature).
- **Efficient Spiking Simulation:** Brian2 (docs), Nengo (site), SpikingJelly (GitHub).
- **Virtual Fly Brain (VFB):** Structural templates and nomenclature (about).

These resources ground the AL→MB→CX pipeline and support sparse, energy-efficient implementations suitable for 100 Hz closed-loop control.

5.5 Key Neural Circuits and Their Functions

While a full connectome is absent, we can model the primary functions of key, conserved insect brain regions.

- **Antennal Lobes (AL):** This is the first-order olfactory processing center. It receives input from chemosensors on the antennae and organizes odor information into a combinatorial code. Different odors evoke unique patterns of glomerular activation, forming a "scent signature" that is passed to higher brain centers.
- **Mushroom Bodies (MB):** The MB is a critical center for associative learning and memory, homologous to the hippocampus in vertebrates. It receives processed olfactory information from the AL and integrates it with other sensory modalities and internal state information. Its sparse coding scheme, enforced by a large number of Kenyon cells, is ideal for forming and storing specific memories, such as linking an odor to a food reward or a threat.
- **Central Complex (CX):** This is a highly-structured region crucial for spatial navigation, goal-directed behavior, and action selection. It integrates sensory cues (especially visual information like polarized light for sky-compass navigation) to maintain a representation of the ant's heading and orientation relative to its environment. It plays a key role in translating high-level goals (e.g., "return to the nest") into specific directional motor commands.

5.5.1 Selected References

- See `Resources.md` for core literature on insect brain organization and active inference, and for datasets/tools (e.g., VFB) used to template modules.

5.5.2 Section Summary

- Compact, biologically grounded AL→MB→CX control stack with sparse coding and local plasticity
- Tight interfaces with `AntBody` (sensorimotor) and `AntMind` (policy/context)
- Efficiency and configurability prioritized over full connectomic fidelity

6 AntMind

`AntMind` is the cognitive layer bridging `AntBrain` with symbolic abstraction and collective intelligence. It specifies how individual agents decide and how those decisions compose into colony-level intelligence. The focus is on minimal, testable machinery that scales from one agent to many without changing local rules.

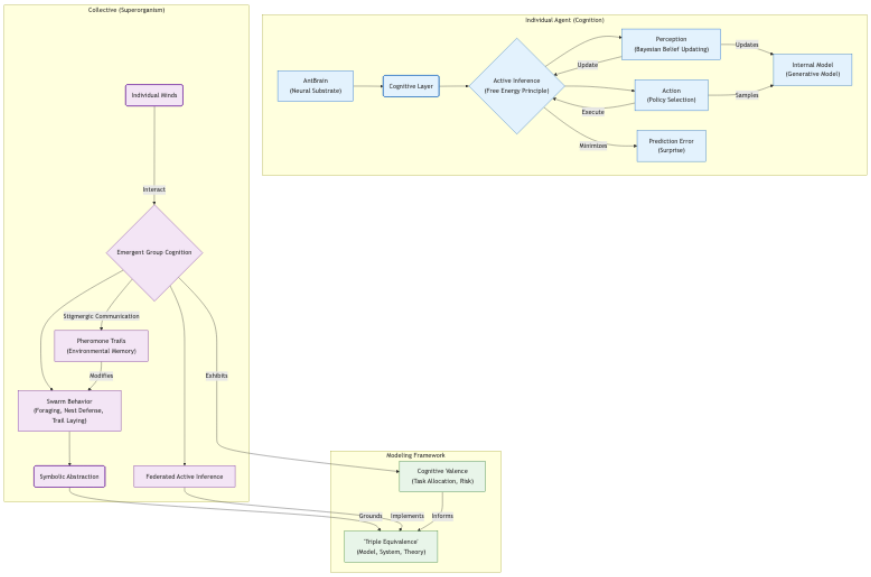

Figure 4: Computational architecture diagram (3c9d)

6.1 Scope and Assumptions

- Active Inference links perception and action via a compact generative model
- Symbolic abstraction emerges from grounded sensorimotor predictions
- Colony cognition uses stigmergy and sparse sharing; no centralized controller
- Policies are small: short horizons (≤ 2 s), low channel counts, and local updates favor transparency and transfer

6.2 Key Concepts

6.2.1 Individual Cognition: Active Inference

- **Predictive processing:** Perception updates a generative model to reduce prediction error
- **Free Energy Principle:** Actions minimize expected free energy over time
- **Symbolic grounding:** Symbols emerge from sensorimotor predictions (supports the "triple equivalence")
- **Risk sensitivity:** Preferences encode risk/ambiguity attitudes; policy selection trades off exploration vs exploitation

6.2.2 Collective Intelligence: Emergence via Stigmergy

- **Stigmergy:** Environmental traces (pheromones) coordinate behavior; the trail is the memory
- **Distributed cognition:** Memory, decision-making, and learning are shared across agents and environment
- **Low-footprint:** ~250k neurons/agent with simple rules yield rich emergent intelligence
- **Resilience:** Redundant environmental memory (pheromones) and local priors improve recovery from deception

6.2.3 From Sub-symbolic to Symbolic Cognition

The stack offers a pathway from sub-symbolic processing to symbolic reasoning via grounded predictions. Symbols are treated as compressed, re-usable predictions tied to tasks and sensory contexts.

6.3 Minimal Generative Model (Single Agent)

- Latent state s_t: pose, heading, internal drive (hunger), local pheromone expectation
- Observation o_t: from `AntBody` I/O
- Action a_t: joint targets
- Preferences: priors over outcomes (food proximity$\uparrow$, energy cost$\downarrow$, collision$\downarrow$)
- Constraints: energy budget and temperature/humidity limits (optional) shape expected free energy
- Update: variational free energy minimization (amortized); policy selection over 0.5–2.0 s
- Rates: control 100 Hz; policy update 10 Hz
- Diagnostics: report expected free energy terms (risk, ambiguity), action entropy, and policy dwell time
- Diagnostics: report EFE decomposition (epistemic/pragmatic value), action entropy, policy dwell time, and constraint violations

6.4 Pheromone Field (Stigmergy)

- Grid $c_t(x)$: $c_{t+1} = (1-\lambda)\, c_t + D\,\nabla^2 c_t + \sum$ deposits
- Parameters: λ decay, D diffusion; deposits increase on reward return
- Agents follow ∇c; following probability rises with |∇c|
- Interfaces: deposit/read operations are unit-aware; decay and diffusion are version-pinned for replication
- Stability: saturation/clipping on c_t and deposit rates to prevent runaway trails; optional anisotropic diffusion under wind

6.4.1 Technical Pointers and References

- **Active Inference (Foundations):** Various primers and tutorials (Nature Neuroscience, Frontiers in Human Neuroscience, Active Inference Institute resources).
- **Active Inference in Ants:** ActiveInferAnts simulation and paper (Frontiers 2021) (Frontiers in Behavioral Neuroscience, ActiveInferAnts).
- **Population-Based/Swarm AIF:** Recent applications to swarm intelligence and search (arXiv).
- **Stigmergy and Ant Trails:** Canonical formulations in ant optimization and diffusion-decay fields (Ant colony optimization, Fick's laws of diffusion).

6.5 Colony-Level Arbitration

- Federated active inference: local beliefs shared sparsely via stigmergy; no central controller
- Task allocation: soft constraints via internal drives and pheromone-mediated opportunities
- Safety: monitor for deceptive gradients; trigger re-exploration and attenuate deposit under conflict
- Belief sharing: lossy compression of shared statistics (e.g., recent reward rates, local gradient summaries)

6.5.1 Section Summary

- Cognitive bridge from neural substrate to behavior and collective intelligence
- Minimal, testable generative model with explicit stigmergy dynamics
- Small-footprint policies that compose across agents

7 Applications

The Ant Stack is a transferable framework for real-world problems. Emulating ant-colony efficiency, robustness, and distributed control enables solutions in robotics, security, and complex systems.

Design intent: a single, compact agent architecture that ports from high-fidelity simulation to embedded platforms and multi-agent swarms with minimal change.

7.1 Cross-cutting Evaluation Metrics

- **Efficiency**: energy per reward; compute per action
- **Robustness**: success under sensor/actuator noise and partial failures
- **Scalability**: performance vs number of agents; communication overhead
- **Alignment**: deviation from intended norms under perturbations/adversaries
- **Reproducibility**: standardized configs, seeds, and dataset/version pinning

7.2 Swarm Robotics

Ant-inspired control deployable to physical platforms.

- **Disaster response:** Navigate debris, locate survivors, perform cleanup in hazardous settings
- **Logistics and construction:** Stigmergic coordination for warehousing and build tasks
- **Environmental monitoring:** Distributed mapping/sampling with trail-guided coverage
- **Fieldable constraints:** low compute/energy budget, lossy comms, intermittent GPS/vision

7.2.1 Evaluation (swarm robotics)

- Time-to-food, path efficiency, energy per reward, success under sensor noise
- Robustness to actuator loss and terrain changes; recovery time
- Communication budget (bandwidth/duty cycle); MTTF/MTTR under staged failures

7.3 Networks and Optimization

- **Routing/load balancing:** ACO grounded in realistic diffusion/decay for routing, caching, congestion
- **Distributed scheduling:** Colony-inspired task allocation under constraints; throughput, fairness, resilience
- **Resilient overlays:** Decoy trails and evaporation parameters for adaptive rerouting under attack
- **Cache placement:** Use pheromone analogs for content popularity and decay-based invalidation

7.4 Cognitive Security

Secure systems at the cognitive layer: resilience to deception, spoofing, and manipulation.

- **Secure swarms:** Decentralized, emergent control resists compromise
- **Defending complex systems:** Colony-style distributed detection/response for critical infrastructure
- **Cognitive honeypots:** Deploy deceptive pheromone fields to study adversary behavior and improve defenses
- **Incident triage:** Prioritize actions via expected free energy; quantify trade-offs under uncertainty

7.4.1 Evaluation (cognitive security)

- Adversary success probability vs defense; detection AUC on deceptive signals; recovery time
- False-positive/negative balance; cost-of-delay under competing alerts

7.5 Biosurveillance & Biodefense

- **Cognitive anomaly detection:** Learn baselines from sensors; flag deviations
- **Disease spread modeling:** Reuse pheromone diffusion/decay for pathogen propagation
- **Sentinel networks:** Agent subsets specialized for detection/triage to reduce false alarms
- **Adaptive sampling:** Allocate sensing effort via stigmergy when anomalies persist

7.5.1 Evaluation (biosurveillance)

- Anomaly PR-AUC on simulated outbreaks; detection latency vs false alarms
- Spatial coverage vs resource budget; escalation pathways

7.6 Foundational AI Research

- **Emergent intelligence:** Study complex goal-directed behavior from simple local rules
- **Calibration standard:** Benchmark for energy-efficient AI designs
- **Embodiment ablations:** Vary body/brain/mind couplings to test contributions to generalization
- **Neural efficiency:** Map performance–energy trade-offs; quantify sparse spiking benefits

7.6.1 Evaluation (foundational AI)

- Navigation success on mazes/rough terrain; memory capacity via odor–reward associations
- Policy entropy, sample efficiency, and transfer across terrains/species presets

7.7 AI Alignment and Safety

- **Natural alignment:** Local incentives align with collective welfare
- **Emergent goals:** Test designs that avoid undesirable emergent behaviors without central control
- **Norm compliance:** Measure deviation under resource stress and adversarial signals
- **Value handshakes:** Encode minimal priors that align individual incentives with group welfare

7.7.1 Evaluation (alignment)

- Colony social welfare under scarcity; deviation from norms under adversarial pheromones
- Collateral risk vs objective attainment; robustness to deceptive gradients

7.7.2 Section Summary

- One compact stack supports robotics, security, networks, biosurveillance, foundational AI, and alignment tasks
- Shared metrics enable apples-to-apples comparisons and principled ablations

7.7.3 Terminology Note

- We follow community guidance on language and update in consultation with myrmecologists
- Domain experts are invited to propose task variants and metrics; small PRs welcome

8 Discussion

8.1 Significance for Myrmecology

- **Empiricism → executable theory**: Trail dynamics, polarized-light navigation, and associative olfaction become testable modules (pheromone field, ring-attractor CX, AL→MB learning), enabling hypothesis tests and cross-species comparisons
- **Individuals → superorganisms**: Stigmergic composition supports division of labor, trail reinforcement, and resilience with field-measurable levers (diffusion, decay, deposit)
- **Experiment ↔ field loop**: Parameters map to measurable field quantities, enabling calibration and out-of-sample prediction
- **Data leverage**: Bibliometrics and curated datasets guide species/trait prioritization and parameter ranges

8.2 Relation to Recent Findings

- **Urgency-tuned trails**: Context-dependent deposition/following to study exploration–exploitation shifts
- **Environmental stability**: Species-parameterized noise, energy costs, terrain for robustness under heat/drought/fragmentation
- **Ant–plant mutualisms**: Resource–reward dynamics to test protection-for-nectar feedbacks and colony outcomes
- **Collective risk management**: Study alarm signaling, quorum thresholds, and evacuation under threat
- **Navigation cues**: Integrate polarized light and landmarks into CX to test cue-combination strategies

8.3 Limitations

- No ant connectome is currently available; template from fly/bee with functional abstractions
- Real-time embedded operation is future work; scope is simulation-first reproducibility
- Field validation requires collaboration and standardized data collection protocols
- Chemical ecology is complex; microclimate and substrate effects can shift pheromone dynamics and sensing

8.4 Future Directions

- **Species libraries**: Parameter presets for representative taxa/ecoregions
- **Learning mechanisms**: Local plasticity beyond STDP (neuromodulated Hebbian) under energy budgets
- **Collective tasks**: Nest construction, brood care, adversarial decoys to test colony cognition
- **Validation**: Benchmarks vs field/arena datasets (trail formation, polarized-light homing, task allocation)
- **Open protocols**: Share standardized tasks and seeds to enable cross-lab replication
- **Tooling**: Programmatic APIs for species presets, parameter sweeps, and experiment manifests
- **Systems bridges**: Minimal ROS 2 bindings and message schemas; unit-registry enforcement end-to-end
- **Security**: Counter-deception benchmarks and ablations (e.g., spoofed gradients, adversarial deposits)

9 Foundational Research and Resources

Key projects, literature, and meta-analyses that ground the Ant Stack in integrative systems entomology, cognitive science, and computational modeling.

Use a consistent, hyperlink-first citation style. When referencing elsewhere, prefer concise inline links to these entries. Prefer stable DOIs; provide short context on relevance.

9.1 Core Inspirations: Foundational Projects

Direct conceptual inputs to the Ant Stack's design, especially data integration and agent-based modeling.

9.1.1 FORMINDEX: FORMIS Integrated Database Exploration

- **Description**: Analysis of the FORMIS database using bibliometrics and AI for summarization/network analysis
- **Relevance**: Guides species/topic prioritization and parameter sweeps via bibliometrics; supports reproducible, literature-grounded assumptions
- **Reference**: FORMINDEX

9.1.2 MetaInformAnt: Data Fusion Platform

- **Description**: Framework for fusing diverse bioinformatic data to analyze ant biodiversity
- **Relevance**: Blueprint for modular ingestion and schema mapping across ecological/neuro datasets used in the Ant Stack
- **Reference**: MetaInformAnt

9.1.3 ActiveInferAnts: Active Inference Simulation Framework

- **Description**: Applies Active Inference to ant colony behavior (foraging, trail-following) via MDPs
- **Relevance**: Primary theoretical inspiration for `AntMind`; maps AIF from MDPs to continuous control, informing priors and short-horizon policies
- **References**: ActiveInferAnts, Frontiers in Behavioral Neuroscience, PMC Article

9.1.4 Virtual Fly Brain (VFB)

- **Description**: Interactive atlas and platform integrating neuroanatomy, connectivity, and gene expression of Drosophila on a standardized template with 3D viewing and cross-search
- **Relevance**: Provides anatomical templates, region nomenclature, and programmatic access to inform AL/MB/CX abstractions and species parameterization; enables cross-species alignment where ant data are incomplete
- **References**: VFB About, Court, R., Costa, M., Pilgrim, C., Millburn, G., Holmes, A., McLachlan, A., Larkin, A., Matentzoglu, N., Kir, H., Parkinson, H., Brown, N. H., O'Kane, C. J., Armstrong, J. D., Jefferis, G. S. X. E., & Osumi-Sutherland, D. (2023). Virtual Fly Brain—An interactive atlas of the Drosophila nervous system. Frontiers in Physiology, 14. DOI: 10.3389/fphys.2023.1076533

9.1.5 Blue Brain Project

- **Description**: Digital reconstruction and simulation of mammalian cortical microcircuits with detailed neuron morphologies and synaptic connectivity
- **Relevance**: Methods for structured connectivity, simulation tooling, and energy considerations inform sparse, modular implementations in `AntBrain`
- **Reference**: Blue Brain Project (overview)

9.1.6 Eyewire

- **Description**: Citizen science connectomics project mapping retinal circuits through large-scale image segmentation and validation
- **Relevance**: Demonstrates scalable human-in-the-loop segmentation and quality control useful for building/validating anatomical templates and datasets; suggests patterns for community-curated ant neurodata
- **Reference**: Eyewire (overview)

9.2 Key Literature & Meta-Analyses

Key findings informing the Ant Stack's biological and ecological assumptions.

9.2.1 Global Biodiversity and Distribution

- **Species richness**: >15,000 species; tropical peak; climate as primary driver (Science Advances, PMC, PNAS, Harvard DASH, PEC, ScienceDirect, Nature Communications)
- **Abundance/biomass**: ~20 quadrillion individuals; exceeds wild birds and mammals combined (PNAS)

9.2.2 Ecological Impact and Community Dynamics

- **Invasive species**: Non-native ants reduce local abundance (~43%) and species richness (~54%) (PubMed, PMC)
- **Ecosystem services**: Pest control, decomposition, nutrient cycling; strong effects in shaded agriculture (Royal Society, PMC, Functional Ecology)
- **Interaction networks**: Links between 47 ant genera and >1,100 bird species (Royal Society, PubMed)

9.2.3 Functional and Elevational Patterns

- **Elevational gradients**: Hump-shaped, low-plateau, monotonic declines; climate models explain variance (PubMed, PLOS ONE)
- **Functional diversity**: Group-specific responses to succession and urbanization (PubMed, ScienceDirect, PMC)

9.2.4 Methodological Advances

- **Biogeographic regionalization**: Distributional and phylogenetic framework for ants (Nature Communications)
- **Active Inference applications**: Swarm intelligence and population-based search (arXiv, Alphanome Blog)
- **Open datasets/tools**: Pheromone trail datasets, arena navigation benchmarks, and VFB programmatic APIs for parameter extraction; deposit/evaporation parameter ranges for reproducible stigmergy
- **Human Brain Project**: Large-scale data integration and simulation platforms informing standards and tooling for neuro data pipelines (overview)

9.3 Synthesis: An Integrative Systems Approach

- **Methodological innovation**: Fuse `FORMINDEX` (data-centric) with `ActiveInferAnts` (agent-based). Plausible agents (`AntBody`, `AntBrain`) within `AntMind` bridge individual behavior and ecosystem-level phenomena. A small set of unit-aware interfaces keeps modules swappable and testable.
- **Transferable framework**: Generalizable principles for swarm robotics and cognitive security
- **Open science**: Open, reproducible, transparent methodology for embodied and collective intelligence

9.3.1 Section Summary

- Curated projects and literature that inform each layer and applications
- Stable anchors for assumptions, parameters, and evaluation choices across the stack

9.4 Notes and Pointers

- **Recent discoveries**: Explore urgency-tuned deposition, environmental impacts on stability, and ant–plant mutualisms

- **Terminology resources**: Track inclusive terminology; update phrasing while preserving scientific clarity; contributions welcome
- **Tooling for datasets**: Pose/tracking frameworks useful for parameter extraction and validation: DeepLabCut, idtracker.ai
- **Units and messaging**: Unit handling via Pint and robotics messaging via ROS 2 can standardize interfaces

10 Appendices

10.1 A. Reproducibility Checklist

- Fixed random seeds (report all)
- Explicit I/O rates and units (see `AntBody`)
- Engine versions: physics, spiking/NN libraries, OS
- Environment configs: terrain, pheromone D, λ, deposit rules
- Agent configs: neuron counts, learning rules, energy budgets
- Evaluation protocols and metrics; trials; confidence intervals
- Data/code availability; exact commit SHA
- Registered experiment manifests (YAML/JSON) to enable one-click reruns
- Model cards: describe objectives, assumptions, limits, and validation datasets
- Unit tests: per-module interface and invariants; scenario tests for end-to-end loops
- Unit registry and versions (e.g., Pint) recorded; message schema versions (e.g., ROS 2) pinned
- Continuous integration manifest for experiment reruns and document/PDF builds

10.2 B. Species Parameterization Quickstart

- `AntBody`: leg DOF, segment masses, antenna channel count K, sensor noise σ, gait presets
- Pheromone: diffusion D, decay λ, baseline deposit, reward/urgency modulation
- `AntBrain`: AL glomeruli count $\leftrightarrow$ K, MB sparsity (Kenyon cell ratio), CX ring size
- `AntMind`: preference priors, policy horizon, update rates; colony size, sharing frequency
- Colony ecology: resource density, nest locations, predator risk profiles (for security experiments)
- Provenance: cite sources for parameter choices and note uncertainties
- Energy/compute envelope; actuator latency distributions; friction coefficients per terrain/material

10.3 C. Evaluation Protocol Templates

- Navigation: maze/slope/rough terrain; success, path ratio, energy per reward
- Trail following: deposit reward-linked trail; formation time, stability, traffic
- Task allocation: mixed stochastic arrivals; utilization, latency, resilience
- Adversarial robustness: deceptive pheromones; deviation from norms, recovery time
- Security drills: spoofed gradients, sensor jamming; detection latency and false-positive rate
- Reporting: include seed ranges, CIs, ablations, and failure cases with traces
- Specify communication-overhead budgets and failure-injection schedules

11 Glossary

- **Active Inference (AIF)**: Agents minimize variational free energy through belief updating and policy selection
- **AL (Antennal Lobes)**: First-order olfactory processing; glomerular odor code
- **Alignment (AI)**: Consistency of behavior with intended objectives under perturbation
- **CX (Central Complex)**: Hub for heading, orientation, and action selection; often a ring attractor
- **Energy budget**: Compute/energy cost per unit behavior; critical for embedded intelligence

- **Eligibility trace**: Short-term memory of recent activity used to gate plasticity updates
- **Generative model**: Predicts sensory inputs; supports policy selection via expected free energy
- **Kenyon cells**: Sparse-coding neurons in Mushroom Bodies; associative learning
- **MB (Mushroom Bodies)**: Learning and memory; multimodal integration
- **Pheromone field**: Diffusion–decay concentration for stigmergic communication
- **Ring attractor**: Network motif for continuous heading representations
- **Sparse spiking**: Low average activity for energy efficiency
- **Stigmergy**: Indirect coordination via environmental modification (e.g., pheromone trails)
- **Tripod gait**: Hexapod locomotion using alternating tripods
- **Expected free energy (EFE)**: Balances risk and ambiguity; minimized to select actions or policies
- **Variational free energy (VFE)**: Upper bound on surprise; minimized to update beliefs and guide inference
- **STDP (Spike-Timing-Dependent Plasticity)**: Local synaptic update rule driven by pre-/post-spike timing
- **WTA (Winner-Take-All)**: Competitive selection mechanism used for action selection or sparsification
- **Quorum sensing**: Thresholded group decision mechanism relevant to task allocation and evacuation
- **I/O contract**: Explicit interface specifying message contents, units, and update rates between modules
- **Unit registry**: Programmatic system for tracking and enforcing physical units across computations
- **Epistemic value**: Information gain component of EFE
- **Pragmatic value**: Goal-directed (extrinsic) utility component of EFE

11.1 Abbreviations

- **AIF**: Active Inference
- **AL**: Antennal Lobes
- **MB**: Mushroom Bodies
- **CX**: Central Complex
- **DOF**: Degrees of Freedom
- **IMU**: Inertial Measurement Unit
- **PR-AUC**: Precision–Recall Area Under Curve