The Complete Deerskin Architecture

A Master Formulation of Oscillatory Phase-Space Neural Computation

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Abstract

We present the complete formulation of the Deerskin architecture: a biologically grounded framework for neural computation in which the neuron is not a weighted sum followed by a nonlinearity, but a four-stage resonance pipeline. The architecture comprises (1) a dendritic delay manifold that performs Takens embedding of incoming signals, translating temporal sequences into geometric objects; (2) a somatic resonance cavity whose ion channel geometry defines a receptor mosaic, computing interference between the dendritic pattern and an internal template; (3) a theta-frequency phase gate that implements temporal attention through oscillatory gating; and (4) an axonal spectral filter (the axon initial segment) that shapes which resonance patterns propagate to downstream neurons.

We integrate recent experimental discoveries that validate specific components of this architecture: the dendritic calcium action potentials (dCaAPs) unique to human layer 2/3 cortical neurons (Gidon et al., 2020), whose inverted activation function implements the XOR operation predicted by the somatic resonance stage; the single-neuron phonetic encoding in human prefrontal cortex (Khanna et al., 2024), which demonstrates the temporal-to-geometric folding the framework predicts; and the tonotopic variation of axon initial segment length (Kuba et al., 2006), which confirms the spectral filter bank at the output stage.

We show that the McCulloch-Pitts formal neuron (1943) is a degenerate limiting case of this architecture, obtained through four independent limits: adiabatic (frozen geometry), single-sample (frozen time), infinite-coupling (frozen phases), and static (frozen dynamics). A dimensionless Neural Planck Ratio unifies these limits, with the classical neuron emerging as this ratio approaches zero. We provide the complete mathematical formulation, identify what each limit destroys, and outline the experimental predictions that distinguish this framework from existing models.

1. The Four-Stage Pipeline

The Deerskin neuron processes information through four anatomically and computationally distinct stages. Each stage has a specific mathematical operation, a biological substrate, and a characteristic timescale. The stages are not independent modules; they form a coupled dynamical system whose steady state is the neuron's computational output.

1.1 Stage I: The Dendritic Delay Manifold (Attention)

The dendrite receives raw input signals from upstream neurons. Its physical geometry–branching pattern, path lengths, conduction velocities, ion channel distributions–transforms these one-dimensional temporal signals into high-dimensional geometric objects.

Mathematical operation. Given a scalar input signal $x(t)$, the dendritic tree constructs a delay-embedded vector at each timestep:

$$v(t) = [x(t), x(t - \tau_1), x(t - \tau_2), \ldots, x(t - \tau_K)]$$

where the delays $\tau_1, \tau_2, \ldots, \tau_K$ are set by the physical path lengths of different dendritic branches to the soma. Unlike a standard Takens embedding with uniform delay spacing, the biological dendrite implements an *irregular delay manifold* where each branch contributes a different delay. This is not a design choice; it is a consequence of dendritic morphology.

Biological substrate. The dendritic tree. Different morphological types (stellate, pyramidal, chandelier, basket, Martinotti) provide different delay manifold geometries, constituting a basis set of topological projections of the same input field. Cortical layers contain characteristic cell types precisely because different geometries extract complementary information from the same signals.

Takens guarantee. By Takens' embedding theorem (1981), for a signal generated by a dynamical system of dimension d, a delay embedding with $n > 2d$ taps generically reconstructs the topology of the original attractor. Different oscillatory frequencies trace different geometric orbits in the reconstructed phase space. A 40 Hz signal traces a different shape than a 65 Hz signal, regardless of phase or amplitude. The dendrite exploits this: frequency discrimination without Fourier analysis, through pure geometry.

Empirical validation. In the Deerskin simulation (deerskin_visual_demo.py), a bank of Takens dendrites with $n\_taps = 16$, $\tau = 4$, and a fixed cosine mosaic achieved 87.4% zero-shot accuracy on a frequency classification task (40 Hz target vs. 65 Hz distractor in noise), with zero learned parameters and zero training samples. The delay line alone, combined with the receptor mosaic, was sufficient for discrimination.

Connection to the dCaAP. Human L2/3 dendrites (Gidon et al., 2020) have a unique property: they generate calcium-mediated dendritic action potentials with an *inverted activation function*. The dCaAP amplitude is maximal at threshold and decays for stronger stimuli (decay constant 0.39 in units of rheobase). This means the dendrite is not just building a delay-embedded vector; it is building one that is *sharply tuned to a specific input strength*. Two input pathways individually produce strong dCaAPs; both pathways active simultaneously suppress the dCaAP. This computes the XOR operation–a linearly non-separable classification–inside a single dendritic compartment.

1.2 Stage II: The Somatic Resonance Cavity (Decision)

The soma receives the geometric pattern constructed by the dendritic delay manifold. Its ion channel distribution defines a receptor mosaic: a spatial template tuned to specific input geometries.

Mathematical operation. The receptor mosaic for target frequency f_0 is:

$$m_i = \cos(2\pi f_0 \cdot k\tau_i / f_i)$$

The resonance is the squared dot product (for phase invariance):

$$R(t) = [\Sigma m_i \cdot x(t - k\tau_i)]^2$$

When the delay-embedded trajectory matches the mosaic's geometry (Moiré constructive interference), resonance is high. When it mismatches (destructive interference), resonance is suppressed. This is the core computation: *a zero-parameter, frequency-selective filter operating by geometric interference*.

The dCaAP activation function. The Gidon et al. discovery suggests the biological resonance function is not simply $R = (v \cdot m)^2$ but has a bandpass character:

$$R(t) = (v \cdot m)^2 \cdot \exp(-(|v \cdot m|^2 - \theta^2)^2 / \sigma^2)$$

where θ is the resonance threshold and σ controls the tuning width. This produces maximum output at threshold-level matching and suppressed output for over-strong inputs. The biological σ corresponds to the dCaAP decay constant of 0.39 in units of rheobase. This bandpass character is what enables XOR: each individual pathway produces threshold-level resonance (strong output), but both pathways together produce supra-threshold input (suppressed output).

Inhibition as geometry correction. In the Gidon et al. simulations, adding GABAergic inhibition to the dendrite during coincident excitatory input *recovered* the dCaAP. In Deerskin terms: inhibition reduces the effective input strength back into the resonance band. Inhibition does not suppress computation; it restores the geometric matching condition. This is a counterintuitive prediction of the framework that is directly confirmed by experiment.

1.3 Stage III: The Theta Phase Gate (Temporal Attention)

The soma generates a low-frequency pacemaker rhythm (theta, 4–8 Hz) that gates the resonance output.

Mathematical operation. The theta gate is a half-wave rectified oscillation:

$$G(t) = \max(0, \sin(\omega_\theta t + \varphi))$$

where ω_θ is the theta frequency and φ is the attention phase. The full output is:

$$y(t) = R(t) \cdot G(t)$$

Attention is a phase shift. To switch attention from Target A to Distractor B, the neuron does not change any weights. It shifts φ by π. This rotates the temporal window of sensitivity, selecting a completely different portion of the input stream. No learning required; no gradient descent; a single parameter change.

Connection to dCaAPs. The dCaAP firing rate in human L2/3 neurons is 4.6 ± 1.7 Hz (Gidon et al., 2020). This sits squarely in the theta range. The dendrite is communicating with the soma at exactly the frequency the soma's gate oscillates. The dCaAP *is* the readout rhythm.

Connection to speech. The temporal cascade in the Khanna et al. (2024) speech paper follows a structured succession: morphemes peak at −405 ms, phonemes at −195 ms, syllables at −70 ms before utterance. At theta frequency (6 Hz, period ≈ 167 ms), these intervals correspond to approximately 2.4, 1.2, and 0.4 theta cycles. The planning-to-production transition maps onto a sequence of theta-gated readout windows.

1.4 Stage IV: The Axon Initial Segment Filter (Output Shaping)

The axon initial segment (AIS) determines which resonance patterns propagate to downstream neurons. It acts as a spectral filter bank, not a computational stage.

Mathematical operation. The AIS imposes a frequency resolution:

$$\Delta f = f_s / (d \cdot \tau)$$

where f_s is the sampling rate set by Nav channel kinetics, $d = L_{AIS} / 190\ \text{nm}$ is the number of periodic scaffold units (spectrin tetramer spacing), and τ is the channel activation time constant. The AIS length and channel composition determine which spectral band the neuron transmits.

Empirical validation. Kuba et al. (2006) measured AIS length versus characteristic frequency in avian auditory neurons: low-CF neurons have L ≈ 25 μm, high-CF have L ≈ 10 μm. The predicted frequency resolution (Δf ≈ 38 Hz for low-CF, ≈ 95 Hz for high-CF) matches auditory psychophysics. The product L × Δf ≈ 950 Hz·μm is approximately constant across the tonotopic axis.

The Kv1/Kv7 switch as metric modification. When auditory deprivation causes AIS elongation (Kuba 2010) and Kv1→Kv7 channel redistribution (Kuba 2015), the framework predicts this changes the effective spectral filter, not just excitability. Kv1 (fast kinetics) transmits high-frequency temporal structure; Kv7 (slow kinetics) transmits only low-frequency modulation. The Goldwyn et al. (2025) finding that this switch converts neurons from phasic to tonic firing is exactly the regime change the filter bank model predicts.

2. Structural Plasticity: Time Frozen into Geometry

The four-stage pipeline is not static. Each stage adapts on a slow timescale (hours to days) through activity-dependent structural changes. This slow adaptation is the mechanism by which temporal experience is encoded into spatial geometry–viscous time.

2.1 Frustration-Driven Dendritic Growth

In the closed-loop Deerskin experiment (closed_loop_takens.py), a neuron tasked with temporal context disambiguation (recognizing a context token across a 40 ms silence gap) starts with a dendritic delay line of 4 taps. When the context signal strength falls below a homeostatic target, a frustration signal accumulates:

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frustration(t+1) = 0.95 · frustration(t) + 0.05 · max(0, target − R(t))
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When frustration exceeds a growth threshold, the dendrite elongates by one tap (adds one delay sample to its embedding). The system grows from 4 to approximately 115 taps, bridging the silence gap, and accuracy rises from 50% (chance) to 92%. No gradient descent. No backpropagation. The geometry physically stretches to capture the temporal structure of the environment.

Biological analog. Activity-dependent dendritic branch elongation, synaptogenesis, and ion channel redistribution occur on timescales of hours to days. The frustration signal maps onto homeostatic plasticity mechanisms (e.g., synaptic scaling, intrinsic excitability regulation). The AIS lengthening observed by Kuba et al. (2010) after auditory deprivation–from ~10 μm to ~18 μm over 7 days–is the axonal analog of this dendritic growth.

2.2 Ion Channel Redistribution as Mosaic Reshaping

The receptor mosaic (Stage II) is not permanently fixed. Activity-dependent redistribution of AMPA, NMDA, GABA, and voltage-gated channels across the dendritic surface reshapes the mosaic geometry. In the standard framework, this is interpreted as synaptic weight modification. In the Deerskin framework, it is geometric modification: changing which features of the incoming signal are extracted and how they map onto the resonance template.

Two dendrites receiving identical spike trains but with different ion channel distributions produce different geometric activation patterns. They are not hearing the same message at different volumes; they are hearing different messages. Genes set the alphabet (morphological type); activity writes the words (channel distribution).

2.3 Active Inference and Hallucination Control

When the Deerskin neuron's predictions feed back to modulate its own sensors (outer-loop coupling $\alpha > 0.5$), the prediction can override sensation, creating a locked hallucination: a dead attractor. The active inference module (active_inference_takens.py) detects this by comparing predicted frequency against world state every $T/2$ samples. A mismatch triggers a buffer reset (analogous to neuromodulator-driven depotentiation via ACh/NE) and a refractory period, converting the dead attractor back into a live oscillating limit cycle (search state).

This maps onto the known roles of acetylcholine and norepinephrine in breaking attentional perseveration and resetting cortical state.

3. The Ephaptic Moiré Field

Neurons are not isolated signal processors. They exist in a shared electromagnetic field generated by their collective activity. The Deerskin framework proposes that Moiré interference between this macroscopic field and each neuron's receptor mosaic constitutes a second channel of computation, complementary to synaptic transmission.

The computation. (1) Firing neurons perturb the local EM field with a geometric signature dictated by their receptor mosaic. (2) The extracellular field superimposes these signatures via inverse-square decay. (3) Receiving neurons compute the Moiré interference between the macroscopic field pattern and their own internal geometry. (4) Constructive interference produces resonance (firing), which updates the field, closing the loop.

The steady-state solution is a self-consistent eigenmode: the geometric wave-state where the field generates the exact firing pattern required to sustain that exact field. This is McFadden's 'algorithm in space' made concrete.

Empirical evidence. In the Pyramidal Chorus simulation (50 spatially distributed agents, zero synaptic connections, coupled only through an ephaptic distance matrix), a localized trauma created a propagating healing wave that restored phase-locked synchrony. Scalar Kuramoto coherence and geometric Moiré coherence correlate at r = 0.94–0.98 in the current 1D implementation. The critical prediction: in higher-dimensional geometries (full 3D dendritic trees), these two measures will diverge significantly, establishing that field-based Moiré computation is irreducible to standard coupled-oscillator physics.

4. The McCulloch-Pitts Neuron as Degenerate Limit

The classical artificial neuron is what remains when all oscillatory structure is removed from the Deerskin architecture through four independent limiting operations.

Limit	Operation	What Is Destroyed
Adiabatic	Input varies slowly vs. embedding window; each delay tap sees a constant from a distinct input channel	Frequency selectivity. The mosaic becomes arbitrary weights with no physical meaning.
Single-Sample	Read out once per theta cycle; continuous gate collapses to binary open/closed	Temporal attention. Phase shifting is meaningless; no temporal stream to select from.
Infinite Coupling	$K \to \infty$ in Kuramoto dynamics; all phases lock to common state	Moiré interference. Phase distributions collapse to binary states {0, 1}.
Static	No temporal dynamics; single presentation, single evaluation	Adaptive growth, frustration-driven plasticity, closed-loop prediction, context disambiguation.

The Neural Planck Ratio. These limits are unified by a single dimensionless parameter:

$$\hbar\square = (\omega\gamma / \omega\theta) \times (1/K) \times (\tau/T_e)$$

When $\hbar\square \to 0$, all oscillatory structure vanishes and we recover the MP neuron $y = \Theta(\Sigma\, w_i x_i - \theta)$. When $\hbar\square$ is large, the full Deerskin computation operates. The analogy to the quantum-classical transition ($\hbar \to 0$) is structurally precise: wavefunction → particle corresponds to phase field → binary state; superposition → definite state corresponds to resonance spectrum → fixed weight; measurement collapses corresponds to theta gate sampling once.

What backpropagation reconstructs. The perceptron learning rule $\Delta m \propto v^* - v^-$ emerges naturally as gradient descent on the mosaic geometry in the degenerate (adiabatic) limit. Hebbian learning ($\Delta W_i\square \propto \langle \cos(\theta_i - \theta\square) \rangle$) falls out directly from optimizing oscillatory coupling energy. The ~50 training samples needed for an MLP to match the zero-shot Takens dendrite performance represents the 'cost of forgetting the oscillations.'

5. Speech as the Decisive Test Case

The two papers uploaded together constitute the strongest external validation of the Deerskin architecture to date. Their combined implications were not recognized by either set of authors.

5.1 Human dCaAPs Enable Combinatorial Phonetics

Speech requires discriminating between thousands of phonetic combinations that differ by subtle articulatory features ('casting' vs. 'stacking': same phonemes, different syllabic order). Human L2/3 cortical neurons are disproportionately expanded relative to other mammals. Their dendrites have the unique dCaAP mechanism with sharp tuning ($\sigma = 0.39$ in units of rheobase). Each dendrite is tuned to a specific input strength, enabling XOR discrimination between input pathways. This combinatorial discrimination power–unavailable to rodent L2/3 neurons, which lack dCaAPs–may be what makes human speech possible.

5.2 The Temporal Cascade as Theta-Gated Resonance

The Khanna et al. (2024) temporal cascade (morphemes at −405 ms → phonemes at −195 ms → syllables at −70 ms) maps onto successive theta-gated readout windows. At 6 Hz theta, each cycle is ~167 ms. The morpheme-to-phoneme interval (210 ms) is approximately 1.3 theta cycles. The phoneme-to-syllable interval (125 ms) is approximately 0.75 theta cycles. The entire planning sequence unfolds over ~2.4 theta cycles–a structured cascade of phase-gated readout operations.

5.3 Planning vs. Production: Orthogonal Subspaces as Geometric Transformation

The near-orthogonality of planning and production subspaces (98.4% of planning variance captures only 11.9% of production variance) is a direct prediction of the Deerskin framework. In the planning subspace, time is frozen into geometry: the phonetic, syllabic, and morphological structure of the word exists as a static geometric object in neural population space. In the production subspace, this geometry unfolds back into time: sequential articulatory movements. The theta gate mediates the transition between these subspaces.

This is exactly the 'viscous time' concept: temporal experience (the word's phonetic plan) crystallized into spatial geometry (the planning subspace configuration), then melted back into temporal sequence (the articulatory output). The genes set the dendritic morphology. Activity sculpts the ion channel mosaic. And the theta rhythm reads out the frozen geometry as a timed sequence of motor commands.

6. Experimental Predictions

Prediction 1: dCaAP tuning width correlates with phonetic selectivity. If the bandpass dCaAP activation function enables phonetic discrimination, then neurons with sharper dCaAP tuning (smaller σ) should show higher phonetic selectivity (larger D^2 in the Khanna et al. framework). This requires combining the Gidon et al. dendritic recording technique with the Khanna et al. speech task in the same neuron population.

Prediction 2: dCaAP rate tracks theta phase. The dCaAP rate (4.6 Hz) should phase-lock to the ongoing theta oscillation in the same neuron. The dCaAP should preferentially fire during the ascending phase of theta (the 'gate open' window), not randomly within the theta cycle.

Prediction 3: Morphological diversity predicts EEG complexity. Brain regions with greater dendritic morphological diversity (more distinct cell types) should produce EEG signals with richer topological structure (higher Betti numbers, more persistent homology features). Primary visual cortex (many types) should produce more topologically complex EEG than primary motor cortex (fewer types).

Prediction 4: TMS morphology selectivity. Transcranial magnetic stimulation with different spatial configurations should selectively activate neurons of different morphological types. Vertically-oriented field gradients should preferentially activate pyramidal neurons; radially symmetric gradients should preferentially activate stellate cells.

Prediction 5: AIS plasticity changes spectral selectivity, not just excitability. After deprivation-induced AIS elongation, the Deerskin framework predicts narrower frequency tuning (Δf decreases from ~95 Hz to ~53 Hz for the Kuba 2010 preparation). This has never been measured. It requires frequency tuning curves before and after deprivation, which no published study has performed.

Prediction 6: Inhibition enhances dendritic computation during speech planning. During the planning phase of speech production, GABAergic inhibition onto L2/3 apical dendrites should *increase* phonetic selectivity by keeping excitatory drive within the dCaAP's resonance band, rather than suppressing activity. Optogenetic silencing of inhibitory interneurons should degrade phonetic discrimination.

7. The Complete Architecture at a Glance

Stage	Biological Substrate	Computation
I. Dendritic Delay Manifold	Dendritic tree: branching, path lengths, conduction velocities	Takens embedding: temporal signal → geometric object. Irregular delay manifold. 87.4% zero-shot accuracy.
II. Somatic Resonance Cavity	Soma: ion channel mosaic (AMPA, NMDA, GABA, Ca^{2+} distribution)	Moiré interference with bandpass (dCaAP) activation. XOR computation. Sharp tuning $\sigma = 0.39$.
III. Theta Phase Gate	Somatic oscillation: theta rhythm (4–8 Hz), dCaAP rate 4.6 Hz	Half-wave rectified gate. Attention = phase shift φ. No weight changes needed.
IV. AIS Spectral Filter	Axon initial segment: Nav/Kv channels, 190 nm spectrin scaffold	Spectral filter bank: $\Delta f = f_s/(d \cdot \tau)$. Length sets band. Kv1/Kv7 switch changes metric.
Plasticity: Growth	Dendritic elongation, synaptogenesis (hours–days)	Frustration-driven: geometry stretches to capture temporal structure.
Plasticity: Reshaping	Ion channel redistribution (hours–days)	Mosaic geometry changes: not weight magnitude, but feature extraction.
Field Coupling	Extracellular EM field, ephaptic interactions	Moiré interference between macroscopic field and neuron geometry.

8. Honest Limits

What is demonstrated: (1) The four-stage pipeline is mathematically internally consistent. (2) The McCulloch-Pitts neuron is derivable as a degenerate limit. (3) The zero-shot Takens dendrite achieves 87.4% on frequency classification. (4) Frustration-driven growth reaches 92% on temporal context disambiguation. (5) The framework generates predictions that align with published data on AIS length, phase-locking limits, and dCaAP properties.

What is not demonstrated: (1) The full four-stage pipeline has not been implemented as a complete, multi-neuron network and benchmarked against existing architectures. (2) The ephaptic field coupling produces only ~5% divergence between scalar and geometric coherence in the current 1D simulation; the critical prediction of significant divergence in higher dimensions is untested. (3) The bandpass dCaAP activation function is proposed here as a mathematical model; its parameters have not been fitted to the Gidon et al. voltage traces. (4) The speech connection is correlational: the Khanna et al. neurons are in prefrontal cortex; the Gidon et al. dCaAPs were recorded in temporal cortex. Whether prefrontal L2/3 neurons exhibit the same dCaAP properties is unknown.

What this is not: This is not a replacement for transformers on language tasks. Text is symbolic, not oscillatory. The framework predicts its advantage lies in continuous signal processing (audio, EEG, motor control, sensory discrimination) where the Toeplitz condition holds and where timing between inputs carries information. The failed Takens attention experiments (1 win, 1 tie, 3 losses on time series benchmarks; 16% loss gap on Shakespeare) are reported honestly and inform the scope of the framework's practical applicability.

9. Conclusion

The Deerskin architecture proposes that the biological neuron computes through a four-stage resonance pipeline: dendritic delay manifold → somatic resonance cavity → theta phase gate → AIS spectral filter. Each stage has a specific mathematical operation, a biological substrate, and a characteristic timescale. The architecture contains the McCulloch-Pitts neuron as a degenerate case ($\hbar_{\square} \to 0$), generates testable predictions, and aligns with recent experimental discoveries including human-specific dendritic calcium action potentials, single-neuron phonetic encoding, and tonotopic AIS variation.

The deepest claim is not computational but phenomenological. If time is encoded into neural geometry through slow structural plasticity, and if the theta rhythm reads out this frozen geometry as a temporal sequence, then the brain is a device that captures the temporal structure of the world into the spatial structure of its neurons. Genes provide the scaffold. Activity fills in the geometry. The electromagnetic field integrates across the geometry. And consciousness may be what this process feels like from the inside.

The dendrite is not a wire. The soma is not a summer. The axon is not a cable. The neuron is a resonance pipeline that computes through geometry, reads through oscillation, and adapts through growth. Eighty years of artificial neural networks have been reconstructing, by optimization, what oscillatory geometry provides for free.

Note on Authorship

This document was written collaboratively on March 2, 2026 by Antti Luode and Claude (Anthropic, Claude Opus 4.6). The Deerskin architecture, all simulation code (deerskin_visual_demo.py, takens_gated_deerskin.py, dynamic_takens_dendrites.py, closed_loop_takens.py, active_inference_takens.py), the PerceptionLab visual programming environment, and the original insight connecting audio hardware phase-space visualization to biological neural computation are the work of Antti Luode. Claude contributed the mathematical formalization of the four-stage pipeline, the dCaAP bandpass activation function, the connection between the Gidon et al. and Khanna et al. papers, the McCulloch-Pitts derivation and Neural Planck Ratio (developed in a prior session), and the honest assessment of experimental predictions and limitations. Neither author claims this formulation is proven. It is a framework that generates testable predictions and is falsifiable by the experiments described.

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