

Electrostatic Field-Guided State Encoding in Microtubules: A Constraint-Bounded Transport Hypothesis

Author

Thomas S. Mitchell Sr.

Independent Researcher, Phoenix, Arizona

April 2026

Abstract

We propose a testable classical mechanism by which microtubules may encode persistent state information through electrostatic field-guided conformational dynamics.

Microtubules are polar dielectric polymers composed of tubulin dimers with intrinsic dipole moments. External electric fields—arising from membrane potentials and intracellular ion flux—can bias these dipoles, influencing local conformational states.

We introduce a constraint-bounded transport model in which field-biased conformational changes are irreversibly recorded through GTP hydrolysis during polymerization. This provides a potential mechanism for converting transient electrostatic signals into durable structural patterns without invoking quantum coherence. The framework is formulated using $\Delta\Phi = \rho \times v$ as a modeling construct for field-guided state propagation.

We outline experimentally testable predictions, including voltage-dependent GTP hydrolysis patterning, hysteresis in cytoskeletal response to oscillating fields, and persistence of transport bias following field removal. The model is presented as a hypothesis to be evaluated experimentally rather than a confirmed biological mechanism.

Keywords

microtubule

cytoskeleton

electrostatic memory

bioelectrochemistry

cellular information storage

constraint-bounded systems

nonlinear dynamics

tubulin

GTP hydrolysis

1. Introduction

1.1 Intermediate Timescale Memory in Cells

Biological systems encode information across multiple timescales. Fast signaling occurs at the membrane level through ion channels and synaptic transmission, while long-term storage is associated with genetic and epigenetic mechanisms. The intermediate regime—minutes to hours—remains less clearly understood.

Microtubules, as dynamic structural elements of the cytoskeleton, are potential candidates for this intermediate regime due to their continuous polymerization, polarity, and sensitivity to intracellular conditions.

1.2 Classical Electrostatics as a Mechanism

Prior models have explored quantum coherence in microtubules. However, decoherence timescales in biological environments are extremely short, limiting the plausibility of sustained quantum effects.

This work instead examines classical electrostatic interactions. Tubulin dimers possess dipole moments and exist within spatially structured electric fields generated by membrane potentials and ion flux. These fields can bias conformational states through dipole-field interactions.

1.3 Modeling Framework

We adopt:

$$\Delta\Phi = \rho \times v$$

as a modeling construct representing field-guided transport of conformational state information, where:

ρ represents local dipole alignment (state proxy)

v represents effective propagation of state adjustments under field influence

This formulation is not derived from first principles for microtubules but serves as a compact representation of field-mediated state dynamics.

2. Microtubule System Overview

2.1 Structure

Microtubules are cylindrical polymers (~25 nm diameter) composed of $\alpha\beta$ -tubulin dimers arranged into protofilaments. Each dimer exhibits an intrinsic dipole moment, a GTP binding site, and structural polarity along the filament axis.

2.2 Electrostatic Environment

Microtubules are embedded in a heterogeneous electric environment influenced by membrane potentials, ion channel activity, and intracellular ionic gradients.

The relevant requirement for this model is that field fluctuations persist over timescales comparable to or longer than local polymerization events (seconds to minutes), allowing field-biased conformational states to be incorporated into the growing structure.

2.3 Field–Dipole Interaction

A dipole in an electric field experiences:

$$U = -\mu \cdot E$$

This interaction biases conformational states of tubulin dimers.

3. Field-Guided State Encoding Model

3.1 State Representation

Let $\rho_i(t)$ represent a normalized proxy for dipole alignment.

State evolution:

$$\rho_i(t+1) = \rho_i(t) + \alpha \cdot \Delta\Phi_i - \gamma(\rho_i - \rho_{eq}) + \xi_i(t)$$

3.2 Irreversible Structural Recording

GTP hydrolysis following polymerization provides a persistent structural mark:

$$H_i = H(\rho_i \text{ at time of polymerization})$$

This converts transient states into durable structural patterns.

3.3 Hypothesized Mechanism

Fields bias dipole alignment

Polymerization captures the biased state

Hydrolysis fixes the configuration

Stored structure influences future dynamics

4. Constraint-Bounded Dynamics

Microtubule behavior includes:

polymerization (source)

depolymerization (sink)

structural constraints

Such systems are expected to exhibit non-linear response to coupling strength and may show intermediate regimes of stable transport behavior.

This aligns qualitatively with constraint-bounded transport behavior observed in prior simulation work (Mitchell, 2026a).

5. Experimental Predictions

5.1 Field-Dependent Structural Patterning

Test: Voltage-clamp neurons with fluorescent GTP analog (BODIPY-GTP).

Measurement: Spatial GTP hydrolysis distribution.

Prediction: Polymerization under depolarization produces distinct hydrolysis patterns scaling with time-integrated potential.

5.2 Hysteresis Under Oscillating Fields

Test: Apply oscillating fields (1–100 mV/mm, 0.1–10 Hz).

Measurement: Phase lag ϕ between field and conformation.

Prediction: $\phi > 0$, increasing with frequency.

5.3 Persistence After Field Removal

Test: Apply sustained field, then remove.

Measurement: Transport bias decay.

Prediction: Persistent bias with gradual decay.

5.4 Coupling-Dependent Transport Behavior

Test: Vary membrane potential via extracellular K^+ .

Measurement: Transport efficiency vs field strength.

Prediction: Non-linear dependence with intermediate regime of enhanced transport.

6. Discussion

This framework proposes a classical mechanism for cytoskeletal state encoding. It does not assert that microtubules function as memory systems in vivo but identifies a plausible pathway.

Limitations include simplified modeling and lack of direct experimental validation.

7. Comparison to Existing Models

Approach

Mechanism

Timescale

Testability

Orch OR

Quantum coherence

$\sim 10^{-13}$ s

Limited

Fröhlich models

Vibrational coherence

$\sim 10^{-9}$ s

Limited

Cytoskeletal signaling

Biochemical

ms–s

Established

This work

Electrostatic structural encoding

s–hours

Directly testable

8. Conclusion

We propose that microtubules may encode persistent state information through electrostatic field-guided conformational dynamics coupled with irreversible structural recording via GTP hydrolysis.

This hypothesis is classical, testable, and grounded in known physics.

Acknowledgments

Conceptual development supported by iterative modeling and analysis.

Critical evaluation assisted by AI-based collaborative tools.