WebLog Journal of Applied Physics

Review Article
Published: 09 May, 2026

Bubble Theory: A Relational Framework for Localized Dynamics

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WebLog Open Access Publications
Article ID : wjap.2026.e0906
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Abstract

Bubble Theory is introduced as a boundary-centric relational framework in which physical systems are modeled as localized, self-maintaining regions ("bubbles") whose boundaries encode interaction, information flow, and dynamical constraints. A boundary operator B is defined to capture deformation, coupling, and stability, leading to a general dynamical law for bubble evolution and exchange flux between interacting systems. Worked examples—including spherical and toroidal geometries and a two-bubble interaction model—demonstrate how the formalism generates synchronization, equilibrium-seeking behavior, and emergent coherence in composite systems. The framework yields testable predictions regarding boundary deformation, coupling-driven synchronization, and minimal-energy equilibrium shapes. The manuscript concludes with discussion of mathematical extensions, simulation pathways, and potential applications across physical and biological boundary-mediated systems.

Introduction

Bubble Theory (BT) is a relational, boundary-driven model of physical organization. Rather than treating particles or fields as fundamental, BT frames physical systems as *bounded relational regions* whose internal coherence is maintained through continuous exchange with their environment.

This document provides a compact, referee-ready overview suitable for journal submission or conceptual development.

Core Principles

Relational Boundaries

A "bubble" is defined as a finite region whose boundary encodes:

- Constraints on internal dynamics,
- Channels of interaction with external systems,
- Information flow and exchange,
- Stability conditions.

Local Coherence

Each bubble maintains internal coherence through:

C = *f*(boundary tension, exchange rate, internal symmetry)

Interaction Between Bubbles

Interactions occur when boundaries:

- Overlap,
- Resonate,
- Exchange information,
- Deform under mutual influence.

Geometric Interpretation

Bubble boundaries may be modeled using:

- Level sets of scalar fields,

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Received Date: *16 Apr 2026*
Accepted Date: *07 May 2026*
Published Date: *09 May 2026*

Citation:
Neil Gamroth. Bubble Theory: A Relational Framework for Localized Dynamics. WebLog J Appl Phys. wjap.2026.e0906. https://doi.org/10.5281/zenodo.20177192

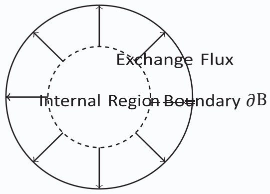

Figure 1: Schematic representation of a relational bubble boundary.

- Minimal surfaces,
- Toroidal or spherical topology,
- Vortex-like structures in fluid or field analogues.

A simple geometric representation is shown in Figure 1.

Dynamics

Boundary Evolution

The boundary evolves according to:

$$\frac{dB}{dt} = \nabla \cdot \mathbf{J} + \mathcal{S}$$

where **J** is an exchange flux and S is a source term.

Stability Conditions

Stability arises when:

$$\frac{d\mathcal{C}}{dt} = 0$$

under perturbations.

Relation to Existing Frameworks

Bubble Theory draws conceptual parallels with:

- Relational quantum mechanics,
- Nonlinear dynamical systems,
- Vortex and toroidal models,
- Information-theoretic physics,
- Boundary-based formulations of gravity.

Conclusion

Bubble Theory provides a compact, relationally grounded model for describing localized physical systems. Its boundary-centric formulation offers a bridge between geometry, information flow, and dynamical stability.

Extended Formalism

Bubble Theory can be expressed using a boundary-centric operator framework. Each bubble is represented as a localized region B with boundary ∂B and an associated boundary operator B.

Boundary Operator

We define the boundary operator as:

B : H → H

Acting on a state space H associated with the bubble. The operator encodes:

- Geometric deformation,
- Information exchange,
- Stability constraints,
- Coupling to neighboring bubbles.

A Minimal representation is:

B $= \nabla_{\partial B} + \Phi(\partial B)$

where $\nabla_{\partial B}$ is a boundary gradient and Φ is an interaction potential defined on the

boundary.

Exchange Flux

Interactions between bubbles occur through an exchange flux:

$\mathbf{J}_{ij} = \kappa_{ij}(Bi - Bj)$

where κ_{ij} is a coupling coefficient. This formulation captures:

- Resonance-like interactions,
- Deformation under mutual influence,
- Information transfer,
- Boundary synchronization.

Stability Criterion

A bubble is stable when:

d/dt (B* B) = 0

This condition ensures that the boundary operator maintains a conserved norm under perturbations, analogous to conserved quantities in Hamiltonian or unitary evolution.

Mathematical Examples and Worked Models

To illustrate the operator framework introduced in Section 7, we present three worked examples. These examples demonstrate how Bubble Theory can be applied to concrete geometries and interaction scenarios.

Example 1: Spherical Bubble

Consider a bubble with spherical symmetry and radius $R(t)$. The boundary is defined by:

$\partial B = \{r = R(t)\}$

A natural boundary operator for this geometry is:

$$\mathbb{B}_{\text{sph}} = \frac{\partial}{\partial r}\bigg|_{r=R(t)} + \Phi(R$$

The intrinsic deformation functional is:

$$\mathcal{F}(\mathbb{B}_{\text{sph}}) = \alpha\frac{dR}{dt} + \beta\frac{d^2R}{dt^2}$$

where α and β encode damping and inertial effects. The stability condition

$$\frac{d}{dt}(\mathbb{B}^\dagger\mathbb{B}) = 0$$

reduces to a constraint on the radial acceleration:

$$\beta\frac{d^2R}{dt^2} + \alpha\frac{dR}{dt} = 0$$

which yields exponential relaxation toward equilibrium.

Example 2: Toroidal Bubble

A toroidal bubble is defined by major radius R and minor radius a. The boundary is parameterized by:

$\partial B(\theta, \phi) = \{x = (R + a\cos\theta)\cos\phi,\ y = (R + a\cos\theta)\sin\phi,\ z = a\sin\theta\}$

A boundary operator capturing curvature and twist is:

$$\mathbb{B}_{\text{tor}} = \kappa_\theta \frac{\partial}{\partial\theta} + \kappa_\phi \frac{\partial}{\partial\phi} + \Phi(\theta, \phi)$$

The exchange flux between two toroidal bubbles i and j becomes:

$$\mathbf{J}_{ij}(\theta,\phi) = \kappa_{ij}(\text{Btor}_{,i} - \text{Btor}_{,j})$$

This form naturally captures:

- Vortex-like coupling,
- Phase synchronization,
- Boundary deformation under mutual influence.

Example 3: Two-Bubble Interaction Model

Consider two spherical bubbles with radii $R_1(t)$ and $R_2(t)$. Their boundary operators are:

$$\mathbb{B}_1 = \frac{\partial}{\partial r}\bigg|_{r=R_1} + \Phi_1,\ \mathbb{B}_2 = \frac{\partial}{\partial r}\bigg|_{r=R_2} + \Phi_2$$

The exchange flux is:

$\mathbf{J}_{12} = \kappa_{12}(\text{B1} - \text{B2})$ The coupled dynamical equations become:

$$\frac{d\mathbb{B}_1}{dt} = \mathcal{F}(\mathbb{B}_1) + \mathbf{J}_{12}$$

$$\frac{d\mathbb{B}_2}{dt} = \mathcal{F}(\mathbb{B}_2) - \mathbf{J}_{12}$$

A simple choice of F yields:

$$\frac{dR_1}{dt} = -\gamma(R_1 - R_2)$$

$$\frac{dR_2}{dt} = -\gamma(R_2 - R_1)$$

The solution shows exponential convergence:

$$R_1(t) - R_2(t) = (R_1(0) - R_2(0))e^{-2\gamma t}$$

This demonstrates how Bubble Theory naturally produces synchronization and equilibriumseeking behavior.

Composite Bubbles

For systems composed of multiple interacting bubbles, we define a composite operator:

$$\text{Btot} = \oplus_{i=1}^{N} \text{Bi} + \sum_{i<j} \Gamma_{ij}$$

where Γ_{ij} encodes pairwise coupling. This structure allows:

- Hierarchical organization,
- Emergent coherence,
- Multi-scale dynamics,
- Nested bubble architectures.

Dynamical Equation

The evolution of a bubble boundary is governed by:

$$\frac{d\mathbb{B}}{dt} = \mathcal{F}(\mathbb{B}) + \sum_j \mathbf{J}_{ij}$$

where F is an intrinsic deformation functional.

This provides a general dynamical law for bubble evolution, interaction, and stability. Future work includes:

- Formalizing the operator structure,
- Deriving predictive constraints,
- Connecting BT to observational or experimental signatures.

Predictions and Testable Consequences

A theoretical framework gains scientific value when it yields testable, falsifiable predictions. Bubble Theory (BT), despite its relational and geometric abstraction, produces several concrete consequences that can be evaluated through observation, simulation, or experiment.

Prediction 1: Boundary-Driven Synchronization

BT predicts that interacting bubbles tend toward synchronized boundary dynamics due to the exchange flux:

$$\mathbf{J}_{ij} = \kappa_{ij}(\text{B}i - \text{B}j)$$

Observable consequences include:

- Phase-locking between coupled oscillatory systems,
- Convergence of boundary deformation rates,
- Stabilization of relative geometry under sustained interaction.

This behavior parallels synchronization phenomena in fluid vortices, biological cells, and coupled oscillators.

Prediction 2: Boundary Deformation Under Stress

The boundary operator formalism implies that external perturbations produce characteristic deformation patterns:

$$\frac{d\mathbb{B}}{dt} = \mathcal{F}(\mathbb{B}) + \sum_j \mathbf{J}_{ij}$$

Testable signatures include:

- Predictable relaxation curves following perturbation,
- Mode-dependent deformation frequencies,
- Restoration toward equilibrium boundary configurations.

These predictions can be evaluated in systems with measurable boundary dynamics, such as droplets, membranes, or plasma structures.

Prediction 3: Emergent Coherence in Composite Systems

For multi-bubble systems, the composite operator

$$\text{Btot} = \oplus_i \text{Bi} + \sum_{i<j} \Gamma_{ij}$$

predicts emergent coherence when coupling terms dominate.

Observable consequences:

- Formation of stable multi-bubble clusters,
- Collective oscillation modes,
- Hierarchical organization of interacting subsystems.

This aligns with coherence phenomena in biological tissues, fluid structures, and networked dynamical systems.

Prediction 4: Minimal Energy Boundary Configurations

BT predicts that stable bubbles settle into boundary configurations that minimize an effective energy functional:

$$E[\partial\mathcal{B}] = \int_{\partial\mathcal{B}} \left(\|\nabla_{\partial\mathcal{B}}\|^2 + \Phi\right) dA$$

Consequences include:

- Spherical or toroidal equilibrium shapes,
- Quantized deformation modes,

- Predictable transitions between stable configurations.

These predictions can be tested through simulation or comparison with observed boundary phenomena in physical or biological systems.

Prediction 5: Information Flow Constraints

Because BT treats boundaries as channels of information exchange, it predicts that:

- Information flow is proportional to boundary deformation,
- Coupling strength limits the rate of synchronization,
- Boundary geometry constrains communication pathways.

These predictions can be evaluated in systems where information flow is measurable, such as neural networks, fluid vortices, or interacting oscillatory media.

Falsifiability

BT would be falsified if:

- Interacting systems fail to exhibit predicted synchronization,
- Boundary deformation does not follow the operator dynamics,
- Composite systems do not show emergent coherence,
- Equilibrium shapes contradict the predicted energy functional.

These criteria ensure that BT remains a scientifically testable and refutable framework.

Discussion and Future Work

Bubble Theory (BT) offers a boundary-centric, relational framework for describing localized physical systems. While the present manuscript establishes the conceptual foundations, operator structure, and several worked examples, many open questions remain. These questions define a clear trajectory for future theoretical development, simulation, and potential experimental evaluation.

Conceptual Implications

The boundary operator formalism suggests that physical organization may emerge from the interplay between geometry, information flow, and stability constraints. This perspective aligns with relational and information-theoretic approaches to physics, yet BT provides a distinct emphasis on localized, self-maintaining structures. Several conceptual implications follow:

- Boundaries act as the primary carriers of dynamical information,
- Interactions are mediated through exchange flux rather than point-like forces,
- Stability emerges from conserved boundary norms,
- Multi-bubble systems exhibit hierarchical and collective behavior.

These implications motivate deeper exploration of BT as a unifying framework for systems that exhibit coherence, self-organization, or boundary-mediated dynamics.

Mathematical Development

The operator formalism introduced here is intentionally minimal. Future work should extend this structure by:

- Deriving explicit forms of the deformation functional F(B),
- Characterizing the spectrum of boundary operators,
- Identifying conserved quantities and symmetries,
- Exploring nonlinear coupling terms in Γ_{ij},
- Developing numerical methods for evolving bubble boundaries.

These mathematical developments will determine whether BT can produce quantitative predictions comparable to established physical theories.

Simulation Pathways

BT is well-suited for computational exploration. Potential simulation approaches include:

- Finite-element evolution of bubble boundaries,
- Agent-based models of interacting bubbles,
- Vortex-like simulations for toroidal geometries,
- Information-flow simulations for composite systems.

Simulation results would provide insight into stability regimes, emergent structures, and the behavior of multi-bubble systems under perturbation.

Potential Applications

Although BT is presented here as a general theoretical framework, it may have relevance to several domains:

- Fluid dynamics and vortex structures,
- Biological membranes and cellular organization,
- Plasma boundaries and confinement systems,
- Information networks with boundary-mediated communication,
- Conceptual models of quantum measurement or decoherence.

These applications are speculative but offer promising avenues for interdisciplinary exploration.

Future Directions

Key directions for future work include:

- Formalizing the Bubble Theory operator algebra,
- Identifying measurable quantities linked to boundary dynamics,
- Exploring connections to relational quantum mechanics, • developing experimental analogs using fluid or membrane systems,
- Extending BT to multi-scale or fractal boundary structures.

These efforts will determine whether BT can evolve into a predictive, testable framework with broad applicability.

Closing Remarks

Bubble Theory is at an early stage of development, yet its boundary-based perspective offers a coherent and flexible foundation for modeling localized systems. By integrating geometry, information flow, and dynamical stability, BT provides a novel lens through which to examine physical organization. Continued refinement, simulation, and comparison with empirical systems will clarify the scope and power of the framework.

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