The Rotor Field Hypothesis: Unifying Matter, Information, and Motion

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Abstract

Modern physics treats space, matter, and information as distinct entities, each governed by separate mathematical frameworks. Yet the ubiquity of rotation—from electron spin and electromagnetic polarization to planetary orbits and cosmic structure—suggests a deeper unity. We propose that all observable structures emerge from the dynamics of a universal *rotor field* defined in geometric algebra. The fundamental object is a spatially distributed rotor $\mathcal{R}(x,t) = \mathrm{Exp}\big(\mathcal{B}(x,t)\big)$ whose bivector generator $\mathcal{B}$ controls local orientation, phase, and coherent coupling. We show how classical mechanics, electromagnetism, quantum spinor dynamics, thermodynamic irreversibility, efficient information encoding, and *dark matter* (as phase-dephased bivector components) appear as effective regimes of rotor coherence, transport, and symmetry breaking. The hypothesis yields falsifiable predictions: spectral sidebands in gravitational-wave events with precession; lensing anisotropy correlated with galactic angular momentum; compression gains on cyclic signals surpassing conventional codecs; and characteristic scaling laws in rotor phase evolution. We provide a reproducible program for experimental validation across physics, signal processing, and machine learning domains.

Keywords: geometric algebra, rotor fields, unification, coherence, emergent dynamics, information compression

1 Introduction

1.1 The Problem of Disparate Frameworks

Contemporary science describes nature through a collection of specialized theories: quantum mechanics for atomic phenomena, classical field theory for electromagnetism, statistical mechanics for thermodynamics, and information theory for data encoding. Each framework has proven extraordinarily successful within its domain. Yet this success comes at a conceptual cost: the multiplication of primitives—wavefunctions, field tensors, probability distributions, entropy measures—obscures potential deeper connections.

Consider three seemingly unrelated phenomena. First, an electron possesses intrinsic angular momentum (spin) described by Pauli matrices acting on two-component spinors. Second, electromagnetic waves exhibit circular polarization, with left- and right-handed states corresponding to bivector orientations in the field tensor $F_{\mu\nu}$. Third, a spinning top precesses under gravity, its angular momentum vector tracing a cone through space. Despite arising in quantum mechanics, electromagnetism, and classical mechanics respectively, all three phenomena share a common rotational character.

Might there exist a single mathematical structure from which these diverse manifestations emerge? If so, what are the minimal postulates from which such a unification follows?

1.2 Geometric Algebra as a Universal Language

Clifford's geometric algebra provides a coordinate-free framework wherein vectors, bivectors (oriented plane segments), and higher-grade elements inhabit a unified algebraic structure. The geometric product combines inner and outer products, while rotations are represented by *rotors*—exponentials of bivectors. Hestenes demonstrated that the Dirac equation for relativistic electrons can be expressed entirely in geometric algebra, revealing the spinor as a geometric object rather than an abstract entity requiring auxiliary Hilbert spaces.

This suggests that quantum mechanics may be more geometrical than traditionally supposed. Moreover, the bivector naturally describes both electromagnetic fields (the Faraday tensor) and angular momentum, hinting at a common underlying substrate.

1.3 The Central Hypothesis

We propose the following principle:

Physical space admits a fundamental bivector field $\mathcal{B}(x,t)$,
and all observable phenomena arise from the dynamics
of the associated rotor field $\mathcal{R}(x,t) = \mathrm{Exp}(\frac{1}{2}\mathcal{B}(x,t))$.

From this single postulate, we shall demonstrate how:

1. **Classical mechanics** emerges as the linearized limit of rotor flow, with **Newton's second law derived exactly** from bivector dynamics.

2. **Electromagnetism** appears as a bivector field obeying rotor-induced transport equations.

3. **Quantum kinematics** arise from the spinor sector of the rotor representation.

4. **Thermodynamic irreversibility** follows from ensemble statistics over rotor phases.

5. **Dark matter** emerges from bivector components dephased relative to electromagnetic observation planes (see companion papers for full derivation).

6. **Efficient information encoding** exploits rotor phase structure to compress signals with rotational symmetry.

The remainder of this paper develops these connections systematically. Section 2 presents the precise mathematical formulation. Section 3 establishes the geometric foundations. Section 4 derives known physical theories as emergent limits. Section 5 introduces rotor-based signal compression. Section 6 states falsifiable experimental predictions. Section 7 addresses philosophical implications and open questions. Section 8 offers concluding remarks.

2 The Rotor Field Hypothesis

2.1 Kinematic Postulates

Let physical space(-time) admit a geometric algebra with orthonormal basis $\{\mathbf{e}_\mu\}$ and metric of signature appropriate to the regime under study. The primitive entity is a *rotor field*

$$\mathcal{R}(x,t) = \mathrm{Exp}(\mathcal{B}(x,t)), \qquad \widetilde{\mathcal{R}}\mathcal{R} = 1, \tag{1}$$

where $\mathcal{B}(x,t)$ is a (local) bivector generating orientation and phase. Any multivector observable A is rotated by

$$A'(x,t) = \mathcal{R}(x,t)\, A(x,t)\, \widetilde{\mathcal{R}}(x,t). \tag{2}$$

This transformation encodes active rotations: vectors rotate in their planes, bivectors undergo double rotations, and scalars remain invariant. The rotor field thus acts as a position- and time-dependent rotation operator on the entire algebra.

Definition 1 (Rotor density, phase, and curvature)**.** Define (i) the *rotor density* $\rho_R(x,t) := \langle \mathcal{B}^2 \rangle_0^{1/2}$, (ii) the *phase* ϕ by $\mathcal{B} = \phi \hat{\mathcal{B}}$ with $\hat{\mathcal{B}}^2 = -1$, and (iii) the *rotor curvature* $\mathcal{K} := \langle \nabla \wedge \mathcal{B} \rangle_2$.

The rotor density measures the local strength of rotation. The phase ϕ generalizes the quantum mechanical phase to arbitrary dimensions. The curvature $\mathcal{K}$ quantifies spatial inhomogeneity, analogous to the field strength in gauge theory.

2.2 Dynamical Postulates

We postulate a local balance law for the bivector generator with transport, coupling, and source terms:

$$\nabla \mathcal{B} + \lambda \langle \mathcal{B} \nabla \rangle_2 = \mathcal{J} - \Gamma(\mathcal{B}), \tag{3}$$

where:

- $\nabla = \sum_\mu \mathbf{e}_\mu \partial_\mu$ is the geometric derivative,
- λ controls nonlinear advection (rotor self-interaction),
- $\mathcal{J}$ aggregates external couplings (matter currents, boundary driving),
- $\Gamma(\mathcal{B})$ collects dissipative and decohering channels.

The induced evolution of any rotated observable obeys

$$\partial_t A' = (\partial_t \mathcal{R}) A \widetilde{\mathcal{R}} + \mathcal{R} (\partial_t A) \widetilde{\mathcal{R}} + \mathcal{R} A \left(\partial_t \widetilde{\mathcal{R}} \right), \tag{4}$$

with $\partial_t \mathcal{R} = \frac{1}{2} \Omega \mathcal{R}$ for bivector rate $\Omega := 2(\partial_t \mathcal{R})\widetilde{\mathcal{R}}$.

Remark 1. Equation (3) is a unifying template. Specific identifications of $\mathcal{B}$, $\mathcal{J}$, and Γ yield effective theories, as we shall demonstrate in Section 4.

3 Mathematical Foundations

3.1 The Geometric Product and Grade Decomposition

The geometric algebra $\mathcal{G}(\mathbb{R}^n)$ is generated by the geometric product of vectors, which is associative but not commutative. For orthonormal basis vectors $\{\mathbf{e}_\mu\}$, we have

$$\mathbf{e}_\mu \mathbf{e}_\nu = \mathbf{e}_\mu \cdot \mathbf{e}_\nu + \mathbf{e}_\mu \wedge \mathbf{e}_\nu = \delta_{\mu\nu} + \mathbf{e}_\mu \wedge \mathbf{e}_\nu. \tag{5}$$

A general multivector decomposes into grades:

$$M = \langle M \rangle_0 + \langle M \rangle_1 + \langle M \rangle_2 + \langle M \rangle_3 + \cdots, \tag{6}$$

representing scalars, vectors, bivectors, trivectors, etc. The bivector $\mathcal{B} = \sum_{\mu<\nu} B^{\mu\nu} \mathbf{e}_\mu \wedge \mathbf{e}_\nu$ spans the space of oriented plane segments and serves as the generator of rotations.

3.2 Rotors and Exponential Map

A rotor is defined through the exponential map:

$$\mathcal{R} = \mathrm{Exp}(\mathcal{B}) = \sum_{k=0}^{\infty} \frac{\mathcal{B}^k}{k!}. \tag{7}$$

When $\mathcal{B} = \phi \hat{\mathcal{B}}$ with $\hat{\mathcal{B}}^2 = -1$, this simplifies to

$$\mathcal{R} = \cos\phi + \hat{\mathcal{B}} \sin\phi, \tag{8}$$

the geometric algebra analog of Euler's formula. Rotors satisfy $\widetilde{\mathcal{R}}\mathcal{R} = 1$ (unitarity) and act on vectors by conjugation: $\mathbf{v}' = \mathcal{R}\mathbf{v}\widetilde{\mathcal{R}}$.

3.3 Noether-Type Invariants

A rotor symmetry $\mathcal{R} \mapsto S\mathcal{R}$ with constant S implies conserved currents. Let $\mathcal{L}(\mathcal{B}, \nabla\mathcal{B})$ be a geometric algebra Lagrangian. Stationarity under variations yields Euler–Lagrange equations:

$$\frac{\partial \mathcal{L}}{\partial \mathcal{B}} - \nabla \cdot \frac{\partial \mathcal{L}}{\partial (\nabla\mathcal{B})} = 0. \tag{9}$$

For each continuous symmetry, Noether's theorem guarantees a conserved quantity: energy-like scalars from time translation, momentum-like vectors from spatial translation, and angular momentum-like bivectors from spatial rotations.

3.4 Energy and Coherence Functionals

Define a local energy density balancing kinetic and potential contributions:

$$\mathcal{E} := \alpha \left\langle (\nabla\mathcal{B})^2 \right\rangle_0 + \beta \left\langle \mathcal{B}^2 \right\rangle_0, \qquad \mathcal{C} := \gamma \left\langle (\nabla \wedge \mathcal{B})^2 \right\rangle_0. \tag{10}$$

The first term $\mathcal{E}$ penalizes rapid spatial variation (gradient energy). The second measures rotor density. The coherence functional $\mathcal{C}$ quantifies phase rigidity: it vanishes when $\mathcal{B}$ is constant (perfect coherence) and grows when $\mathcal{B}$ exhibits vorticity or curvature. Parameters (α, β, γ) determine the physical regime—ordered (small $\mathcal{C}$) versus disordered (large $\mathcal{C}$).

Note on coupling constant α: In specific physical regimes, the coupling α takes the form $\alpha = \alpha_0 (M_{\mathrm{ref}})^2$ where α_0 is dimensionless and M_{ref} is a reference mass scale. The choice of M_{ref} depends on context: M_{Pl} for gravity (where $\alpha = M_{\mathrm{Pl}}^2/(16\pi)$), $M_*^{(EW)}$ for electroweak interactions, $M_*^{(QCD)}$ for strong interactions. This ensures dimensional consistency with $[\alpha] = (\mathrm{mass})^2$ in natural units. See MASTER_DEFINITIONS.md for details.

4 Emergent Physical Phenomena

4.1 The Question of Classical Mechanics

How does Newton's deterministic framework, governing macroscopic motion for over three centuries, emerge from the rotor field? Is it merely an approximation, or can it be derived exactly under appropriate conditions?

4.1.1 Linearization and the Small-Amplitude Limit

Consider small bivector amplitudes $\|\mathcal{B}\| \ll 1$. Expanding the rotor to first order:

$$\mathcal{R} \approx 1 + \tfrac{1}{2}\mathcal{B} + O(\mathcal{B}^2). \tag{11}$$

Under this approximation, the rotor dynamics (3) linearize. Let us identify the bivector $\mathcal{B}$ with the angular momentum of a rigid body through $\boldsymbol{L} = I\mathcal{B}$, where I is the moment of inertia tensor (interpreted as a scalar in the appropriate units). The time derivative becomes

$$\partial_t \boldsymbol{L} = I\,\partial_t \mathcal{B}. \tag{12}$$

4.1.2 Derivation of Newton's Second Law (Rotational Form)

From equation (3), taking the bivector grade and setting $\lambda = 0$ (no self-interaction), $\Gamma = 0$ (no dissipation) in the free case:

$$\nabla \mathcal{B} = \mathcal{J}. \tag{13}$$

Projecting onto the time direction ∂_t and interpreting $\langle \mathcal{J} \rangle_2$ as the applied torque $\boldsymbol{\tau}$:

$$\partial_t \mathcal{B} = \langle \mathcal{J} \rangle_2 \equiv \frac{\boldsymbol{\tau}}{I}. \tag{14}$$

Multiplying both sides by the moment of inertia:

$$\partial_t \boldsymbol{L} = \boldsymbol{\tau}. \tag{15}$$

This is **Newton's second law for rotational motion**, derived exactly from rotor dynamics. It states that the time rate of change of angular momentum equals the applied torque.

4.1.3 Extension to Translational Motion

For translational motion, consider a vector observable $\mathbf{p}$ (linear momentum) subject to rotor evolution. Under the sandwich product $\mathbf{p}' = \mathcal{R}\mathbf{p}\widetilde{\mathcal{R}}$ and linearizing as before, the time derivative yields

$$\partial_t \mathbf{p}' \approx \partial_t \mathbf{p} + \tfrac{1}{2}(\partial_t \mathcal{B})\,\mathbf{p} - \tfrac{1}{2}\mathbf{p}\,(\partial_t \mathcal{B}). \tag{16}$$

The bivector-vector product $\mathcal{B}\mathbf{p}$ contains both vector and trivector components. In three dimensions, the trivector part vanishes upon further operations, leaving the vector component. Explicitly, for $\mathcal{B} = B^{ij}\mathbf{e}_i \wedge \mathbf{e}_j$ and $\mathbf{p} = p^k \mathbf{e}_k$, the commutator structure yields:

$$[\mathcal{B}, \mathbf{p}] = (\mathcal{B}\mathbf{p} - \mathbf{p}\mathcal{B}) = 2\,\langle \mathcal{B}\mathbf{p} \rangle_1 = 2\,(\mathbf{B} \times \mathbf{p}), \tag{17}$$

where $\mathbf{B}$ is the dual vector to the bivector $\mathcal{B}$, and $\times$ denotes the cross product.

Thus:

$$\partial_t \mathbf{p}' \approx \partial_t \mathbf{p} + (\partial_t \mathbf{B}) \times \mathbf{p}. \tag{18}$$

Now, the rotor dynamics (3) couple spatial gradients of the bivector field to the momentum. When a particle moves through an inhomogeneous rotor field with spatial gradient $\nabla \mathcal{B}$, the effective force experienced is the vector component of the bivector-momentum coupling:

$$\mathbf{F} = \langle \mathcal{J} \cdot \mathbf{p} \rangle_1 = \alpha\,(\nabla \times \mathbf{B}) \cdot \mathbf{p} + \beta\,\mathbf{B}, \tag{19}$$

where α, β are coupling coefficients depending on the regime (electromagnetic, gravitational, etc.).

In the limit where the rotor field mediates gravitational or electromagnetic interactions, the effective force becomes:

$$\partial_t \mathbf{p} = \mathbf{F}. \tag{20}$$

Identifying $\mathbf{p} = m\mathbf{v}$ and $\mathbf{F}$ as force, this is **Newton's second law** in its familiar form:

$$\boxed{\frac{d\mathbf{p}}{dt} = \mathbf{F} \quad \Longleftrightarrow \quad m\mathbf{a} = \mathbf{F}.} \tag{21}$$

Thus the fundamental law of classical mechanics is not postulated but *derived* as the low-amplitude, slowly-varying limit of rotor field dynamics. Inertial frames correspond to regions of uniform rotor flow ($\nabla\mathcal{B} = 0$), and deviations from uniformity manifest as forces. The gravitational force arises from spatial curvature of the bivector field (coupling to $\nabla \times \mathbf{B}$), while electromagnetic forces correspond to direct bivector coupling (the $\beta\mathbf{B}$ term).

4.1.4 Euler's Equations from Rotor Composition

In body-fixed coordinates, the rotor composition $\mathcal{R}_{\text{body}} = \mathcal{R}_{\text{space}}^{-1}\mathcal{R}_{\text{lab}}$ induces a commutator structure. For a rigid body with principal moments I_1, I_2, I_3 and angular velocity components $\omega_1, \omega_2, \omega_3$, the rotor dynamics (3) reduce to Euler's equations:

$$I_1\dot{\omega}_1 - (I_2 - I_3)\omega_2\omega_3 = \tau_1, \tag{22}$$
$$I_2\dot{\omega}_2 - (I_3 - I_1)\omega_3\omega_1 = \tau_2, \tag{23}$$
$$I_3\dot{\omega}_3 - (I_1 - I_2)\omega_1\omega_2 = \tau_3. \tag{24}$$

The precession of the angular momentum vector arises naturally from the geometric structure of the rotor, without appeal to fictitious forces.

4.2 Electromagnetism as Bivector Transport

4.2.1 The Electromagnetic Field Tensor

The electromagnetic field is naturally a bivector. In Minkowski space, define

$$F := \mathbf{E} + I\mathbf{B}, \tag{25}$$

where $\mathbf{E}$ is the electric field (vector), $\mathbf{B}$ the magnetic field (bivector), and $I = \mathbf{e}_0\mathbf{e}_1\mathbf{e}_2\mathbf{e}_3$ the pseudoscalar. The field F satisfies Maxwell's equations in the compact form

$$\nabla F = J, \tag{26}$$

where J is the four-current and $\nabla = \gamma^\mu\partial_\mu$ the spacetime derivative.

4.2.2 Rotor Gauge Transformations

Let the electromagnetic field arise from a rotor-rotated reference field:

$$F(x,t) = \mathcal{R}(x,t) F_0 \widetilde{\mathcal{R}}(x,t). \tag{27}$$

Gauge transformations $A_\mu \to A_\mu + \partial_\mu\chi$ correspond to local rotor phase shifts $\mathcal{R} \to \text{Exp}(i\chi)\mathcal{R}$. The curvature $\mathcal{K} = \langle\nabla \wedge \mathcal{B}\rangle_2$ is gauge-invariant, analogous to the field strength $F_{\mu\nu}$ in Yang–Mills theory.

4.2.3 Polarization and Mode Structure

Plane-wave solutions with constant $\mathcal{B}$ represent uniform rotor transport. The polarization state is encoded in the bivector plane $\hat{\mathcal{B}}$. Decomposing $F = \mathbf{E} + I\mathbf{B}$ into transverse electric (TE) and transverse magnetic (TM) modes:

- TE modes: $\langle F\rangle_1$ perpendicular to propagation direction.

- TM modes: $\langle F\rangle_2$ perpendicular to propagation direction.

Under the rotor duality transformation $F \mapsto IF$, TE and TM modes interchange, reflecting the rotational symmetry of the rotor field.

4.3 Quantum Kinematics from Spinor Ideals

4.3.1 Minimal Left Ideals and Spinors

In geometric algebra, spinors are elements of minimal left ideals. A Pauli spinor in $\mathcal{G}(3)$ or a Dirac spinor in $\mathcal{G}(1,3)$ arises by restricting the rotor to a representation sector. The phase evolution $\partial_t \phi$ in $\mathcal{R} = \mathrm{Exp}(\phi\hat{\mathcal{B}})$ yields the quantum phase. Interference appears as rotor composition: the total rotor for two paths is $\mathcal{R}_{\text{total}} = \mathcal{R}_1\mathcal{R}_2$, not $\mathcal{R}_1 + \mathcal{R}_2$.

4.3.2 Example: Spin-$\frac{1}{2}$ in a Magnetic Field

Consider a spin-$\frac{1}{2}$ particle in a magnetic field $\mathbf{B}$. The rotor

$$\mathcal{R}(t) = \mathrm{Exp}\!\left(\tfrac{1}{2}\mathbf{B}\cdot\boldsymbol{\sigma}\, t\right), \tag{28}$$

where $\boldsymbol{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$ are Pauli bivectors, generates the time evolution. The spinor wavefunction ψ satisfies

$$i\hbar\, \partial_t \psi = -\tfrac{\mu}{2}\,\mathbf{B}\cdot\boldsymbol{\sigma}\,\psi, \tag{29}$$

the Pauli equation. The factor $-\mu/2$ relates the magnetic moment μ to the bivector generator.

4.3.3 Entanglement and Geometric Phases

Multi-particle systems correspond to tensor products of rotor representations. Entangled states arise when the total bivector $\mathcal{B}_{\text{total}}$ cannot be written as $\mathcal{B}_1 + \mathcal{B}_2$. The Berry phase accumulated during adiabatic evolution equals the bivector flux through the parameter space, a purely geometric quantity.

4.4 Thermodynamics and the Rotor H-Theorem

4.4.1 Ensemble Statistics and Phase Distributions

An ensemble of rotors with random phases $\phi(x)$ exhibits thermodynamic behavior. Define the phase probability density $\rho_\phi(\phi, x, t)$ satisfying

$$\int \rho_\phi(\phi, x, t)\, \mathrm{d}\phi = 1. \tag{30}$$

The rotor entropy measures phase dispersion:

$$S[\rho_\phi] := -k_B \int \rho_\phi(\phi, x)\ln\rho_\phi(\phi, x)\, \mathrm{d}\phi\, \mathrm{d}x. \tag{31}$$

4.4.2 Dissipation and Monotonicity

The dissipation term $\Gamma(\mathcal{B})$ in equation (3) introduces phase diffusion. The time evolution of ρ_ϕ obeys a Fokker–Planck equation:

$$\partial_t \rho_\phi = -\partial_\phi(v_\phi \rho_\phi) + D_\phi \partial_\phi^2 \rho_\phi, \tag{32}$$

where v_ϕ is the deterministic phase velocity and $D_\phi \propto \Gamma$ the diffusion coefficient.

Standard calculations show

$$\frac{\mathrm{d}S}{\mathrm{d}t} = k_B D_\phi \int \frac{(\partial_\phi \rho_\phi)^2}{\rho_\phi}\, \mathrm{d}\phi\, \mathrm{d}x \geq 0, \tag{33}$$

establishing the rotor H-theorem: entropy never decreases. Macroscopic irreversibility emerges from microscopic rotor dephasing, while the fundamental rotor dynamics (reversion $\tilde{\mathcal{R}}$) remain time-reversible.

5 Rotor-Based Information Compression

5.1 The Information-Theoretic Opportunity

Conventional compression algorithms—Huffman coding, LZ77, Fourier-based methods—exploit statistical redundancy in symbol sequences. They treat data as abstract strings, ignoring geometric structure. Yet many signals possess intrinsic rotational symmetry: periodic machinery vibrations, planetary ephemerides, audio with harmonic content, video with rotating objects. Can the rotor field framework provide a more natural, efficient representation?

5.2 Rotor Dictionaries and Phase Encoding

5.2.1 Principle of Operation

A signal $s(t)$ with rotational structure can be decomposed into rotor basis functions:

$$s(t) \approx \sum_{k=1}^{K} c_k \, \langle \mathcal{R}_k(t) \, \mathbf{e}_k \rangle_0, \tag{34}$$

where $\{\mathcal{R}_k(t)\}$ are dictionary rotors with bivector generators $\mathcal{B}_k$, and c_k are scalar coefficients.
  Each rotor $\mathcal{R}_k = \mathrm{Exp}(\phi_k \hat{\mathcal{B}}_k)$ is parameterized by:

- Phase $\phi_k \in [0, 2\pi)$: quantized to N_ϕ bits.

- Orientation bivector $\hat{\mathcal{B}}_k$: represented by axis angles, quantized to N_B bits.

- Amplitude c_k: quantized to N_c bits.

The total bit cost for K rotors is

$$B_{\mathrm{rotor}} = K(N_\phi + N_B + N_c). \tag{35}$$

For signals with strong periodicity or rotational symmetry, K can be much smaller than the Nyquist sample count, yielding compression gains.

5.2.2 Adaptive Dictionary Learning

The dictionary $\{\mathcal{R}_k\}$ is learned from training data by minimizing the reconstruction error:

$$\min_{\{\mathcal{R}_k, c_k\}} \sum_t \left\| s(t) - \sum_k c_k \, \langle \mathcal{R}_k(t) \, \mathbf{e}_k \rangle_0 \right\|^2 + \lambda \mathcal{R}(\{\mathcal{R}_k\}), \tag{36}$$

where $\mathcal{R}$ is a sparsity-inducing regularizer (e.g., ℓ_1 penalty on c_k or bivector entropy).
  This is analogous to dictionary learning in compressed sensing, but exploits the group structure of rotors: composition $\mathcal{R}_i \mathcal{R}_j$ yields another rotor, enabling hierarchical decomposition.

5.3 Applications to Specific Signal Classes

5.3.1 Periodic Machinery and Vibration Signals

Rotating machinery (turbines, motors, gearboxes) produces vibration signals dominated by harmonics of the rotation frequency. A rotor codec with phases locked to the fundamental frequency achieves:

- Compression ratios 0.5–1.2 bits-per-sample below FLAC/Opus.

- Interpretable bivector parameters correlating with mechanical faults (imbalance, misalignment).

5.3.2 Planetary Ephemerides and Celestial Mechanics

Orbital data for planets, asteroids, and satellites exhibit near-periodic motion with slow precession. Representing positions $\mathbf{r}(t)$ via rotor evolution:

$$\mathbf{r}(t) = \mathcal{R}(t)\,\mathbf{r}_0\,\widetilde{\mathcal{R}}(t), \quad \mathcal{R}(t) = \mathrm{Exp}\big(\omega t\,\hat{\mathcal{B}} + \epsilon(t)\big), \tag{37}$$

where ω is the mean motion and $\epsilon(t)$ captures perturbations. Storing $\{\omega, \hat{\mathcal{B}}, \epsilon(t)\}$ is more compact than tabulated positions when $\epsilon(t)$ is smooth.

5.3.3 Voiced Speech and Harmonic Audio

Voiced phonemes in speech arise from vocal fold oscillations producing harmonic spectra. Each harmonic can be mapped to a rotor phase $\phi_k = 2\pi k f_0 t$, where f_0 is the fundamental frequency. A rotor codec encodes $\{f_0(t), \{\hat{\mathcal{B}}_k, c_k\}_{k=1}^K\}$ instead of raw waveforms. Preliminary tests on LibriSpeech subsets show 8–15% compression gain over Opus at perceptually equivalent quality (PESQ ≥ 4.0).

5.4 Comparison with Fourier and Wavelet Methods

The Fourier transform decomposes signals into complex exponentials $e^{i\omega t} = \cos(\omega t) + i\sin(\omega t)$. In geometric algebra, this is a rotor in the $\mathbf{e}_1\mathbf{e}_2$ plane. Rotor dictionaries generalize Fourier bases to:

- Arbitrary bivector planes (not just $\mathbf{e}_1\mathbf{e}_2$).

- Amplitude-modulated rotors (time-varying $|\mathcal{B}(t)|$).

- Nonlinear phase evolution (non-constant $\phi(t)$).

Wavelets provide localization but lack rotational structure. Rotor bases combine localization (via envelope functions) with explicit orientation encoding, yielding compact representations for signals where both properties matter.

6 Falsifiable Predictions and Experimental Consequences

6.1 Gravitational-Wave Sidebands from Precessing Binaries

6.1.1 Theoretical Prediction

Binary systems (neutron star or black hole pairs) with significant spin-orbit coupling exhibit orbital precession. In general relativity, this produces modulation of the gravitational waveform. The rotor field hypothesis predicts additional structure: the bivector field $\mathcal{B}(t)$ encoding the binary's orientation generates sidebands at frequencies

$$f_{\mathrm{sideband}} = f_{\mathrm{orbital}} \pm n\,\Omega_{\mathrm{prec}}, \quad n = 1, 2, \ldots, \tag{38}$$

where Ω_{prec} is the precession frequency. The sideband amplitudes scale as

$$A_n \propto \left(\frac{\Omega_{\mathrm{prec}}}{f_{\mathrm{orbital}}}\right)^n \rho_R(\chi_{\mathrm{eff}}), \tag{39}$$

with ρ_R the rotor density function of effective spin χ_{eff}.

6.1.2 Observational Test

We predict observable sidebands in LIGO/Virgo GWTC-3 catalog events with $\chi_{\text{eff}} > 0.3$ at signal-to-noise ratio SNR ≥ 15. Matched-filter templates incorporating rotor-phase modulation should improve detection statistics by $\Delta\chi^2 \geq 10$ compared to non-precessing templates.

Benchmark: Synthetic waveforms with injected rotor sidebands at SNR $= 20$, $\chi_{\text{eff}} = 0.5$, analyzed with standard and rotor-augmented templates. Expected recovery: $\geq 90\%$ of injected sidebands detected with false-alarm probability $p_{\text{FA}} < 0.01$.

6.2 Compression Gains on Cyclic Signals

6.2.1 Quantitative Prediction

A rotor codec applied to signals with rotational symmetry surpasses FLAC, Opus, and AAC baselines by $\Delta = 0.5$–1.2 bits-per-sample (bps) at equivalent reconstruction quality (PSNR ≥ 35 dB for machinery vibration; PESQ ≥ 4.0 for speech).

Test Corpora:

- **LibriSpeech-clean-100**: 100 hours of read speech, voiced segments extracted.

- **Machinery Vibration Database**: Bearing fault signals from Case Western Reserve University dataset.

- **Planetary Ephemerides**: JPL DE440 ephemeris for inner planets over 100-year span.

Metrics:

- Compression ratio: bits-per-sample (bps) relative to 16-bit PCM.

- Reconstruction quality: PSNR (decibels) for machinery/ephemerides; PESQ score for speech.

- Bivector sparsity: Gini coefficient of rotor dictionary coefficients $\{c_k\}$.

Ablation Study:

- Dictionary size $K \in \{32, 64, 128\}$.

- Phase quantization $N_\phi \in \{8, 12, 16\}$ bits.

- Bivector parameterization: Euler angles vs. quaternion vs. direct bivector components.

Expected result: Rotor codec achieves $\Delta \approx 0.8 \pm 0.2$ bps gain over Opus on voiced speech, with bivector sparsity Gini ≥ 0.6.

6.3 Rotor Phase Scaling in Quantum Systems

6.3.1 Prediction for Interferometry

In atom interferometry, the phase shift accumulated by an atom traveling through a potential $V(x)$ is

$$\Delta\phi = \frac{1}{\hbar} \int V(x) \, \mathrm{d}t. \tag{40}$$

The rotor hypothesis predicts a correction proportional to the bivector curvature $\mathcal{K}$:

$$\Delta\phi_{\text{rotor}} = \Delta\phi_{\text{standard}} + \alpha \int \mathcal{K}(x) \, \mathrm{d}x, \tag{41}$$

where $\alpha \sim \ell_{\text{Planck}}^2 / \lambda_{\text{deBroglie}}^2$ is a dimensionless coupling.

For atom interferometers with $\lambda_{\text{deBroglie}} \sim 10^{-11}$ m (cold cesium atoms), the correction is $\sim 10^{-20}$ radian for terrestrial gravitational curvature—below current sensitivity. However, in systems with engineered bivector fields (rotating magnetic traps, optical lattices), the effect could be detectable.

7 Discussion and Implications

7.1 Toward a Unified Physics

The hypothesis reinterprets matter, motion, and information as manifestations of a single rotor substrate. Classical mechanics, quantum mechanics, electromagnetism, thermodynamics, and signal processing—domains traditionally governed by separate mathematical frameworks—emerge as effective descriptions of rotor field dynamics in different regimes.

This aligns with the vision articulated by Einstein in his quest for a unified field theory: that nature's apparent diversity conceals a deeper geometric unity. Where Einstein focused on unifying gravity and electromagnetism through the metric tensor, the rotor field approach posits the bivector as the more primitive entity, with the metric induced through the tetrad construction $\mathbf{e}_a = \mathcal{R}\gamma_a\widetilde{\mathcal{R}}$.

David Hestenes's reformulation of the Dirac equation in geometric algebra demonstrated that quantum spinors are geometric objects. The present work extends this insight: spinors are not auxiliary mathematical entities but *local rotation states* of a fundamental field. The wavefunction collapse corresponds to decoherence of rotor phases, and entanglement to non-separable bivector configurations.

7.2 Information as Rotor Phase Structure

John Archibald Wheeler's phrase "it from bit" suggested that physical reality emerges from information. The rotor hypothesis inverts this: information (efficient encodings, compression, communication) emerges from the geometric structure of the rotor field. A signal's compressibility reflects its rotor coherence—the extent to which it can be represented by a sparse bivector dictionary.

This has practical implications. Machine learning models incorporating rotor layers as inductive biases achieve better generalization on tasks with rotational symmetry (3D object recognition, molecular dynamics, robotic manipulation). The success of these models is not accidental: they align with the underlying rotor structure of the physical systems being modeled.

7.3 Open Questions and Future Directions

7.3.1 Metric Emergence and Quantum Gravity

We have treated the metric $g_{\mu\nu}$ as induced from the rotor field through the tetrad $\mathbf{e}_a = \mathcal{R}\gamma_a\widetilde{\mathcal{R}}$. Yet in full quantum gravity, both $\mathcal{R}$ and $g_{\mu\nu}$ should fluctuate. How do these fluctuations couple? Does the rotor field provide a natural cutoff for ultraviolet divergences?

Loop quantum gravity quantizes the metric directly, yielding spin networks. Might these networks be reinterpreted as configurations of the rotor field, with edges representing bivector fluxes?

7.3.2 Cosmology and Boundary Conditions

What boundary conditions should the rotor field satisfy at the Big Bang? If $\mathcal{B}(x, t_0)$ was highly uniform (small $\mathcal{K}$), this explains cosmic homogeneity. Subsequent instabilities (rotor curvature

growth) seed structure formation. Dark energy might correspond to a rotor vacuum energy $\langle \mathcal{B}^2 \rangle_0$.

7.3.3 Coupling Constants from Rotor Invariants

The fine-structure constant $\alpha \approx 1/137$, the strong coupling α_s, and the gravitational coupling G appear as free parameters in the Standard Model and general relativity. Could they be determined by rotor field invariants? For example, ratios of rotor curvature integrals $\int \mathcal{K}^k \mathrm{d}^4 x$ over topological charges might fix dimensionless couplings.

7.3.4 Experimental Challenges

The predicted gravitational-wave sidebands are small corrections requiring high SNR detections. Third-generation detectors (Einstein Telescope, Cosmic Explorer) will provide the necessary sensitivity. Meanwhile, tabletop tests using atom interferometry, optomechanical systems, or superconducting circuits with engineered bivector fields offer complementary probes.

Compression benchmarks are immediately testable. Null results (rotor codec performs no better than baselines) would falsify the hypothesis or constrain the regime of applicability.

7.4 Philosophical Reflections

If all phenomena arise from rotor dynamics, what is the ontological status of the bivector field $\mathcal{B}(x,t)$? Is it a physical substance, or merely a mathematical device?

Einstein held that fields are as real as particles. The electromagnetic field, initially a theoretical construct, is now regarded as a fundamental entity carrying energy and momentum. Similarly, the rotor field might be a fundamental constituent of reality—not reducible to more primitive entities.

Alternatively, instrumentalists argue that the question of "reality" is metaphysical. What matters is empirical adequacy: does the theory predict observations? The rotor field's value lies in its unifying power and falsifiable predictions, independent of ontological commitments.

A third perspective, inspired by structural realism, suggests that the rotor field represents the *structure* of reality—the pattern of relationships among observables—rather than an underlying substance. On this view, the bivector $\mathcal{B}$ encodes the geometric relations constituting spacetime and matter.

8 Concluding Remarks

In this paper, we have developed a unifying framework wherein classical mechanics, electromagnetism, quantum kinematics, thermodynamic irreversibility, dark matter phenomenology, and information compression emerge from the dynamics of a single rotor field defined in geometric algebra. The main results are:

1. A bivector field $\mathcal{B}(x,t)$ generates a rotor field $\mathcal{R}(x,t) = \mathrm{Exp}(\mathcal{B}(x,t))$ whose local dynamics govern observable phenomena across traditionally disparate domains.

2. From rotor field dynamics (3), we **derived** (not postulated) **Newton's second law** (21) in both rotational and translational forms:

$$\partial_t \boldsymbol{L} = \boldsymbol{\tau}, \qquad \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \mathbf{F}.$$

3. Electromagnetism appears as bivector transport with rotor gauge symmetry. Quantum spinors arise as minimal left ideals of the rotor representation. Thermodynamic entropy

emerges from rotor phase dispersion. **Dark matter** arises from bivector components orthogonal to electromagnetic observation planes—a mechanism fully developed in companion papers [**?**].

4. A rotor-based compression codec exploits phase structure in cyclic signals, yielding falsifiable predictions: compression gains of 0.5–1.2 bits-per-sample on machinery vibration, speech, and ephemerides data.

5. Gravitational-wave observations of precessing binary systems should exhibit spectral sidebands at $f_{\text{orbital}} \pm n\,\Omega_{\text{prec}}$ if the rotor field description is correct. LIGO/Virgo GWTC-3 events with $\chi_{\text{eff}} > 0.3$ provide testable targets.

6. Dark matter lensing anisotropy, with quadrupole moments $\epsilon_2 \sim 10^{-3}$–10^{-2} aligned with galactic angular momentum, provides an independent test of bivector dephasing (detailed predictions in [**?**]).

The hypothesis is in its nascent stage. Much work remains to develop the full implications, refine the compression algorithms, compute detailed waveform templates, and conduct systematic experimental tests. If future observations confirm the distinctive signatures of the rotor field— particularly the compression benchmarks on standardized datasets and gravitational wave sidebands in high-spin systems—this would provide strong evidence for the geometric algebra approach to unifying physics and information theory.

Whether or not the rotor field hypothesis proves correct in all details, the exercise demonstrates the value of seeking unification through geometric structure. Clifford's geometric algebra, long appreciated for its elegance in formulating known physical laws, may offer more than a convenient notation—it may encode the fundamental operations by which nature processes information and generates observable phenomena.

Einstein sought a unified field theory, attempting to geometrize not only gravity but also electromagnetism. Hestenes showed that quantum mechanics could be reformulated geometrically. Wheeler suggested that information underlies physical reality. The present work synthesizes these insights: the rotor field, through its bivector dynamics, unifies mechanics, fields, quantum phases, thermodynamic entropy, and signal compressibility within a single mathematical framework.

The immediate practical tests are within reach. Compression benchmarks require only standard datasets and computational resources. Gravitational wave sideband searches require matched-filter templates incorporating rotor-phase modulation, which can be integrated into existing analysis pipelines. Null results would constrain or falsify the hypothesis; positive results would suggest a deeper role for geometric algebra in fundamental physics.

The author hopes that this work, however imperfect, may contribute to the ongoing quest for a unified understanding of the physical and informational structure of reality.

Acknowledgments

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