ENTROPIC SUCTION THEORY v2

Working Paper WP-MaxwellGeometry

Maxwell's Equations Paired with Substrate Vortex Geometry: What Each Equation Is Actually Describing

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Abstract

Maxwell's four equations are the most successful mathematical description of electromagnetic phenomena in the history of physics. They correctly predict radio wave propagation, optical behavior, and X-ray interactions from one unified framework. This paper proposes that the four equations are not equally physically active across all electromagnetic phenomena — and that understanding which equation is doing what physical work for which substrate geometry class reveals both the power and the hidden limits of Maxwell's framework. EST v2 identifies three substrate geometry classes within what standard physics calls electromagnetic radiation: Class I (substrate wave disturbances, radio/microwave), Class II (discrete traveling toroidal vortex rings, infrared through UV), and Class III (complex topology structures, hard X-ray through gamma). Each of Maxwell's equations is mapped to its physical meaning in EST v2 substrate terms, and then to its active role in each class. The paper shows that Maxwell's source equations are fully physically active only in Class II; that his propagation equations (the wave pair) are universal across all three classes; and that Class III requires topology beyond Maxwell's framework — which is exactly why QED and QCD were needed. Finally, this paper highlights an extraordinary historical fact: Maxwell himself derived his equations using a model of molecular vortices in an elastic medium — a physical picture almost identical to the EST v2 substrate. He then discarded the mechanical model and kept only the mathematics. EST v2 restores the physical mechanism Maxwell originally envisioned.

Status: WORKING PAPER. Physical picture established. Every equation pairing grounded in cited sources. Speculative claims clearly labeled.

1. Maxwell's Original Physical Model

1.1 The Vortex Medium Maxwell Discarded

James Clerk Maxwell derived his electromagnetic equations not from abstract mathematics but from a concrete physical model. In his 1861 paper On Physical Lines of Force, he constructed a mechanical model of the electromagnetic field as a sea of molecular vortices in an elastic medium [Maxwell, 1861]. The magnetic field was the rotational velocity of these vortices. The electric field was the stress transmitted between them through idle wheel particles. Electromagnetic waves were transverse disturbances propagating through this vortex medium.

As the Wikipedia History of Maxwell's equations documents: 'In these papers, he used mechanical models, such as rotating vortex tubes, to model the electromagnetic field. He also modeled the vacuum as a kind of insulating elastic medium to account for the stress of the magnetic lines of force given by Faraday.' [Wikipedia, History of Maxwell's Equations]. The four modern equations emerged directly from this vortex medium model.

In his 1865 paper A Dynamical Theory of the Electromagnetic Field, Maxwell abstracted away the mechanical model and presented only the field equations [Maxwell, 1865; Longair, 2015]. This was mathematically cleaner but physically impoverished. The vortex medium that generated the equations was stripped out. What remained were equations that worked without any physical picture of what they were describing.

Oliver Heaviside then condensed Maxwell's original twenty equations into the four vector equations taught today [Heaviside, 1884; Wikipedia, History of Maxwell's Equations]. A physical model of molecular vortices in an elastic medium became four abstract differential equations. The mechanism was lost. The mathematics survived.

EST v2 restores the mechanism. The substrate is the vortex medium Maxwell originally modeled. The difference is that EST v2 identifies three distinct geometry classes within what Maxwell treated as one uniform phenomenon — and shows that this distinction is why different regions of the electromagnetic spectrum require completely different physical descriptions and detection mechanisms.

1.2 What Maxwell's Equations Actually Are

The four modern Maxwell equations in differential form are:

M1 — Gauss's Law (Electric): div(E) = rho / epsilon_0

Physical statement: the divergence of the electric field at any point equals the charge density at that point divided by the permittivity of free space. Electric field lines originate on positive charges and terminate on negative charges. Where there is no charge, field lines neither begin nor end [Gauss, 1835; Jackson, 1999].

M2 — Gauss's Law (Magnetic): div(B) = 0

Physical statement: the divergence of the magnetic field is always zero. Magnetic field lines always close on themselves. There are no magnetic monopoles — no sources or sinks of magnetic field [Jackson, 1999].

M3 — Faraday's Law: curl(E) = -dB/dt

Physical statement: a time-varying magnetic field produces a circulating electric field. This is electromagnetic induction — the physical basis of generators, transformers, and electromagnetic wave propagation [Faraday, 1831; Jackson, 1999].

M4 — Ampere-Maxwell Law: curl(B) = mu_0 * J + mu_0 * epsilon_0 * dE/dt

Physical statement: a circulating magnetic field is produced by either an electric current (J term) or a time-varying electric field (displacement current term, Maxwell's addition). The displacement current term closes the wave equation and enables electromagnetic wave propagation at speed c [Maxwell, 1865; Jackson, 1999].

1.3 The Three EST v2 Substrate Geometry Classes

WP-PhotonGeometry (June 3, 2026) establishes that what standard physics calls electromagnetic radiation spans at least three physically distinct substrate geometry classes:

Class I — Substrate Wave Disturbances: radio waves, microwaves. Extended substrate oscillations below the discrete vortex nucleation threshold. No compact topology, no winding number, no discrete vortex core. Propagate as phonon-like substrate waves. Detected by macroscopic resonant conductors.

Class II — Discrete Traveling Toroidal Rings: infrared through ultraviolet. Compact traveling toroidal vortex rings with well-defined topology, winding number, and spin-1. Shed from proton boundaries during electron field transitions. Detected by electronic transitions in molecular pi systems. This is the 'photon' in the precise EST v2 sense.

Class III — Complex Topology Structures: hard X-ray through gamma ray. Compact vortex structures at or below nuclear scales. Simple ring topology becomes unstable at these energies; candidate geometries are helical or knotted vortex structures. Detected only by inner electron shell or nuclear geometry coupling.

2. Each Maxwell Equation in EST v2 Substrate Terms

2.1 M1 — Gauss's Law (Electric): The Substrate Pressure Source Equation

Mathematical form: div(E) = rho / epsilon_0

Standard physical meaning: electric field lines originate on charges. Positive charge is a source of diverging field lines; negative charge is a sink of converging field lines.

EST v2 substrate meaning: charge is rotating substrate vortex geometry. A proton vortex spinning at the c ceiling creates a radial substrate pressure deficit around it — the substrate flows inward toward the lower-pressure core. This inward flow is what we measure as the electric field of a positive charge. The divergence of the electric field equals the charge density because the strength of the inward substrate flow divergence equals the number of vortex sources per unit volume.

Epsilon_0 in EST v2 is the substrate's compliance — its resistance to being deflected from equilibrium by a rotating vortex. It is not a fundamental constant of nature; it is a property of the substrate at its current energy density and state. This is consistent with the EST v2 principle that constants are measurements of how the substrate currently behaves, not eternal fixed quantities (V34, Section 10.11).

Critical observation: M1 requires a discrete source — a localised rotating vortex creating a radial pressure deficit. It has full physical meaning only where discrete vortex structures with winding number exist. This is Class II (toroidal rings with defined topology) and Class III (compact nuclear-scale structures). For Class I substrate wave disturbances — which have no discrete vortex core and no localised source — M1 is physically empty. There is no divergence source. The wave propagates without any charge-like structure. M1 neither constrains nor describes Class I propagation.

2.2 M2 — Gauss's Law (Magnetic): The Closed Field Line Equation

Mathematical form: div(B) = 0

Standard physical meaning: no magnetic monopoles. Magnetic field lines always close on themselves — they have no sources or sinks.

EST v2 substrate meaning: the rotational component of substrate vortex flow always closes on itself. A spinning vortex creates circulation that loops back — the substrate that rotates around the vortex axis must return, forming closed loops. There is no substrate monopole that generates outward-only rotational flow without return. This is a geometric consequence of the substrate being a continuous incompressible-like medium: circular flow in a medium always closes [Helmholtz, 1858; Saffman, 1992].

Helmholtz's vortex theorems (1858) establish that vortex lines in an ideal fluid cannot end inside the fluid — they must either close on themselves or terminate at a boundary [Helmholtz, 1858]. M2 is the electromagnetic expression of Helmholtz's first vortex theorem applied to the substrate medium.

Active status across classes: M2 is universal. All three substrate geometry classes have closed rotational field topology. Class I wave disturbances have closed oscillatory field loops. Class II toroidal rings have the most explicit closed-loop topology — the toroidal flow is self-evidently closed. Class III complex structures have closed topology by the same Helmholtz theorem. M2 applies everywhere without distinction.

2.3 M3 — Faraday's Law: The Substrate Wave Propagation Equation (Part 1)

Mathematical form: curl(E) = -dB/dt

Standard physical meaning: a time-varying magnetic field produces a circulating electric field. This is the induction mechanism — the physical basis of all electromagnetic wave propagation.

EST v2 substrate meaning: a time-varying rotational substrate flow (B) produces a time-varying pressure gradient flow (E). This is the wave mechanics of the substrate itself. When a region of substrate is set into oscillatory rotation, it produces oscillatory pressure gradients in adjacent regions, which in turn produce oscillatory rotations — the disturbance propagates outward. This is how all substrate disturbances of any geometry class travel through the medium.

The minus sign (Lenz's law) in EST v2 is the substrate's self-restoring behavior: the pressure gradient induced by the rotating region acts to oppose the rotation that caused it, just as any elastic medium resists distortion. The substrate is not merely passive — it pushes back. This restoring behavior is what produces wave propagation rather than diffusion.

Active status across classes: M3 is the universal propagation equation. It describes substrate wave propagation regardless of the topology or geometry of the disturbance. Class I wave disturbances, Class II toroidal rings, and Class III complex structures all propagate by this mechanism. M3 does not distinguish between them. It is the equation that correctly describes all electromagnetic phenomena propagating at c — because all substrate disturbances of any geometry travel via this mechanism.

2.4 M4 — Ampere-Maxwell Law: The Substrate Wave Propagation Equation (Part 2)

Mathematical form: curl(B) = mu_0 * J + mu_0 * epsilon_0 * dE/dt

Standard physical meaning: circulating magnetic field is produced by electric current (J term) or by time-varying electric field (displacement current term). Maxwell's addition of the displacement current term in 1861 was the crucial step that closed the wave equation [Maxwell, 1861; Longair, 2015].

EST v2 substrate meaning: the J term describes the rotational substrate flow produced by moving vortex structures — currents are moving charged vortices dragging the substrate into circulation as they pass. The displacement current term (epsilon_0 * dE/dt) describes the substrate's inertial response: a time-varying pressure gradient flow in the substrate produces time-varying rotational flow in return. This is the feedback half of the wave cycle — M3 gives pressure gradient from rotation; M4 gives rotation from pressure gradient. Together they close the propagating wave.

Mu_0 in EST v2 is the substrate's inertia against being set into rotational flow — the rotational analog of epsilon_0's compliance against radial flow. Together mu_0 and epsilon_0 give the wave speed: c = 1/sqrt(mu_0 * epsilon_0). In EST v2 this is not a coincidence — the substrate's compliance and inertia jointly determine how fast disturbances propagate through it. The speed of light is a property of the substrate, not a fundamental constant independent of it.

The displacement current was Maxwell's greatest insight. He recognised that a time-varying electric field in free space — even with no physical current — must produce a magnetic field, or else the wave equation would not close. In substrate terms: he recognised that the substrate itself, being a physical medium, must respond dynamically to time-varying pressure gradients, even where no vortex structures are present. He was right. He just did not have a name for the medium.

Active status across classes: M4, like M3, is universal. The J term is more physically active where discrete vortex structures exist (Classes II and III) because those classes have well-defined charge currents. In Class I, J is effectively zero for free-space propagation — the wave carries no discrete charge structure. Only the displacement current term drives Class I propagation. This is quantitatively accurate: radio wave propagation in free space is entirely described by the displacement current feedback, with no charge current involved.

3. Maxwell's Equations Paired with Substrate Geometry Classes

The following table summarises the physical status of each Maxwell equation across the three EST v2 substrate geometry classes. 'Full' means the equation describes a real physical mechanism active in that class. 'Propagation only' means the equation drives wave propagation but not the source structure. 'Empty' means no physical mechanism in that class corresponds to the equation.

Equation	Physical Mechanism in EST v2	Class I (Substrate Waves)	Class II (Toroidal Rings)	Class III (Complex Topology)
M1 — Gauss Electric: div(E) = rho/epsilon_0	Radial substrate pressure deficit around discrete rotating vortex sources. Epsilon_0 = substrate compliance.	EMPTY. No discrete vortex core. No charge-like source. No divergence source. M1 does not apply to Class I free propagation.	FULL. Toroidal ring is a discrete vortex with winding number and pressure field. M1 describes the radial field of each photon ring.	FULL. Compact nuclear-scale structures have discrete vortex cores with strong pressure deficits. M1 fully active.
M2 — Gauss Magnetic: div(B) = 0	Closed rotational substrate flow — Helmholtz vortex theorem: vortex lines	UNIVERSAL. Wave disturbances have closed	UNIVERSAL. Toroidal ring topology is explicitly	UNIVERSAL. Helical and knotted vortex topologies are

	cannot end inside a continuous medium.	oscillatory field loops. M2 holds trivially.	closed. M2 is the topological statement of the torus.	closed by construction. M2 holds for all compact topology.
M3 — Faraday: curl(E) = -dB/dt	Time-varying rotational substrate flow produces oscillatory pressure gradient. Self-restoring substrate response drives wave propagation.	UNIVERSAL — propagation. The substrate wave propagates entirely by this mechanism. M3 fully drives Class I.	UNIVERSAL — propagation. Toroidal ring propagation driven by M3. Also describes ring emission from electron field transitions.	UNIVERSAL — propagation. Complex topology structures propagate by the same substrate wave mechanism.
M4 — Ampere-Maxwell: curl(B) = mu_0*J + mu_0*epsilon_0*dE/dt	Moving vortex structures drag substrate into circulation (J term). Time-varying pressure gradient produces rotational response (displacement current). Mu_0 = substrate rotational inertia.	DISPLACEMENT CURRENT ONLY. J = 0 for free-space Class I propagation. Only the displacement current term is physically active. M4 correctly describes Class I with J dropped.	FULL. Both J term (moving charge rings) and displacement current active. M4 fully describes Class II field structure and propagation.	FULL at nuclear scale. J term dominant for compact high-energy structures. Displacement current secondary.

4. Where Maxwell's Framework Ends and Why

4.1 The Topology Maxwell Cannot See

Maxwell's equations are topology-blind. They describe field magnitudes and directions at every point in space but carry no information about the topological winding number of the structures generating those fields. A toroidal vortex ring (Class II) and a knotted vortex structure (Class III) can generate identical far-field patterns — Maxwell's equations cannot distinguish them from their fields alone. Only the interaction behavior at close range reveals the topological difference.

This is not a failure of Maxwell's mathematics. It is a fundamental limitation of differential equations that describe field values at points. Topology is a global property — it describes how the field is connected to itself over extended regions — and point-by-point differential equations cannot capture it directly.

This is why quantum electrodynamics (QED) was needed for Class II at the single-photon level, and why quantum chromodynamics (QCD) was needed for Class III at the nuclear level. QED introduces photon number states — discrete topological objects — that Maxwell's continuous field description cannot represent. QCD introduces color charge — a topological property of quark confinement — that has no analog in Maxwell's framework. Both were necessary extensions precisely because the underlying structures are topologically richer than Maxwell's equations can see.

EST v2 identifies the physical reason: QED corrects for the discrete toroidal ring topology of Class II that Maxwell's continuous field description approximates but cannot capture exactly. QCD corrects for the compact nuclear-scale topology of Class III that Maxwell's framework was never built to handle. The extensions are geometrically motivated, not arbitrary.

4.2 The Class I Simplification

For Class I substrate wave disturbances, two of Maxwell's four equations — M1 and the J term of M4 — are physically empty. The system reduces to the wave equation driven by M3 and the displacement current term of M4 alone. This is not an approximation. It is exact for free-space radio wave propagation because Class I disturbances genuinely have no discrete charge source structure.

Classical antenna theory and microwave engineering treat electromagnetic waves in free space using exactly this simplified picture [Pozar, 2011]. The displacement current drives propagation; charge sources appear only at the antenna boundaries where the wave is generated or received. Between source and receiver, M1 and the J term are absent. The two-equation propagation picture is not an engineering shortcut — it is the complete physical description for Class I.

4.3 The Class II Sweet Spot

All four of Maxwell's equations are simultaneously physically active and physically meaningful for Class II. The toroidal ring has a discrete source (M1 active), closed topology (M2 active), propagates by Faraday induction (M3 active), and carries both field energy and charge coupling (M4 fully active). This is the energy range — infrared through UV — for which Maxwell's equations were primarily calibrated by experiment in the nineteenth century. Optical experiments, electrical experiments, and induction experiments are all Class II phenomena.

This is why Maxwell's equations work so extraordinarily well for everyday electromagnetism and optics. They were developed from and calibrated against Class II phenomena. Their full physical content — all four equations simultaneously active — is realized precisely in the energy range where all the nineteenth century experiments were conducted.

4.4 The Class III Breakdown

For Class III complex topology structures, Maxwell's equations become progressively less complete as energy increases into the gamma ray range. M1 and M2 remain structurally valid but describe a substrate pressure field whose source topology is geometrically richer than a simple spherically symmetric charge. The curl equations M3 and M4 describe propagation correctly but cannot predict the interaction cross-sections with nuclear geometry because those interactions depend on the detailed topology of the Class III structure.

The experimental evidence for this breakdown is precisely the need for QED at high energies and QCD at nuclear energies. Both theories were developed because Maxwell's equations gave wrong predictions for Class III interactions — pair production, nuclear photoelectric effect, quark-gluon plasma. Each failure point corresponds to a topological feature of Class III structures that Maxwell's topology-blind equations cannot represent.

5. EST v2 as the Completion of Maxwell's Original Program

Maxwell began with rotating vortices in an elastic medium. He derived four equations that correctly described electromagnetic phenomena across the range experimentally accessible to him. He then discarded the physical model and kept the mathematics — partly for elegance, partly because the vortex model had known limitations (the idle wheel mechanism was artificial), and partly because no one in 1865 had the tools to make the vortex picture physically precise.

What was missing in 1865 and is present now:

(1) Superfluid vortex physics — the experimental and theoretical tools to describe quantised vortices in a real medium with topological stability, winding number conservation, and defined interaction behavior [Onsager, 1949; Donnelly, 1991].

(2) Topological classification of vortex structures — the mathematical framework to distinguish torus topology from sphere topology from knotted topology and predict which pairs can annihilate and which cannot [Kleckner & Irvine, 2013].

(3) Scale-spanning experimental data — radio telescope observations, optical experiments, X-ray crystallography, and gamma ray astronomy all in one framework,

revealing that the same equations describe phenomena that require three physically distinct substrate mechanisms.

EST v2 restores Maxwell's original physical intuition — rotating vortex structures in an elastic substrate medium — and adds what Maxwell could not have had: the topological classification of vortex geometry that explains why different electromagnetic phenomena require different physical descriptions. Maxwell's four equations are not wrong. They are the correct description of substrate wave mechanics and vortex field structure. What they lack is topology. EST v2 provides it.

Maxwell wrote in 1865: 'The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws.' [Maxwell, 1865, as cited in Wikipedia Electromagnetic Wave Equation]. He was right. The substance is the substrate. The disturbance is the vortex structure. The laws are the substrate's mechanical response to vortex geometry. EST v2 names the substance he identified and classifies the disturbances he could not yet differentiate.

6. Summary: What Each Equation Is Really Describing

Maxwell Equation	EST v2 Physical Identity	Universal or Class-Specific
M1 — Gauss Electric: div(E) = rho/epsilon_0	Radial substrate pressure deficit around a discrete rotating vortex core. Epsilon_0 = substrate compliance against radial deflection.	Class-specific: full only where discrete vortex sources exist (Class II, III). Empty for Class I.
M2 — Gauss Magnetic: div(B) = 0	Helmholtz vortex theorem: rotational substrate flow always closes on itself. No substrate monopoles because no vortex line can end inside a continuous medium.	Universal: Helmholtz's theorem holds for all vortex structures in any continuous medium regardless of topology.
M3 — Faraday: curl(E) = -dB/dt	Time-varying rotational substrate flow produces time-varying pressure gradient. The substrate's self-restoring elastic response drives wave propagation. Half of the wave cycle.	Universal: all substrate disturbances propagate by this mechanism regardless of geometry class.

M4 — Ampere-Maxwell: curl(B) = mu_0*J + mu_0*epsilon_0*dE/dt	J term: moving vortex structures drag substrate into circulation. Displacement current: substrate inertial response to time-varying pressure gradient. Second half of wave cycle. Mu_0 = substrate rotational inertia.	Universal for displacement current. J term class-specific: full for Classes II/III, absent for Class I free propagation.

7. New Open Problems

Problem	Statement	Priority
OP37	Derive epsilon_0 (electric permittivity of free space) from EST v2 substrate properties — specifically from the substrate compliance against radial deflection by a proton vortex. If epsilon_0 is a substrate property, it should be derivable from rho_Lambda, G, c, and the proton vortex geometry. Compare to NIST CODATA value.	HIGH — connects to OP12
OP38	Derive mu_0 (magnetic permeability of free space) from EST v2 substrate rotational inertia. If c = 1/sqrt(mu_0*epsilon_0) and c is a substrate property (the maximum propagation velocity), and epsilon_0 is derivable (OP37), then mu_0 follows. Verify the relationship c^2 = 1/(mu_0*epsilon_0) from first principles.	HIGH — follows from OP37
OP39	Identify the precise boundary between Class I (substrate wave disturbance) and Class II (discrete toroidal ring) in the microwave-to-infrared transition region. This is the substrate's Landau critical	MEDIUM — connects to OP35

	velocity in photon energy units. Derive it from the substrate field equations and compare to the experimentally observed transition in photon behavior (single-photon detection threshold, wave vs. particle statistics).	

8. Honest Assessment

Solid and grounded:

- The identification of M2 (Gauss magnetic) with Helmholtz's vortex theorem is exact. Helmholtz proved in 1858 that vortex lines cannot end inside a continuous ideal fluid. M2 is this theorem applied to the electromagnetic field. The mapping is not an analogy — it is an identity if the field is a property of a vortex medium [Helmholtz, 1858].

- The identification of M3 and M4 as the two halves of the substrate wave equation is exact. Together they reproduce the electromagnetic wave equation with speed c = 1/sqrt(mu_0*epsilon_0). The physical interpretation as substrate compliance and inertia is consistent and dimensionally correct.

- The historical fact that Maxwell derived his equations from a molecular vortex model is documented and cited [Maxwell, 1861; Longair, 2015; Wikipedia History of Maxwell's Equations]. EST v2 is restoring Maxwell's original physical picture, not departing from it.

- The class-specific activity of M1 is grounded in the physical distinction between Class I (no discrete source) and Classes II/III (discrete vortex sources). The classical antenna theory confirmation — free-space radio propagation uses only the displacement current, no charge source — is standard engineering physics [Pozar, 2011].

Physically motivated but not yet derived:

- Epsilon_0 as substrate compliance and mu_0 as substrate inertia are physically motivated identifications but are not yet derived from the substrate field equations (OP37, OP38). The dimensional relationships are correct. The derivation requires OP12.

- The Class III topology picture (helical or knotted vortex geometry) is proposed in WP-PhotonGeometry but not yet derived. The claim that QED and QCD correct for the topological features Maxwell's equations miss is physically grounded but not formally demonstrated.

Speculative:

- The claim that the constants c, epsilon_0, mu_0 are substrate properties derivable from rho_Lambda and vortex geometry. This is consistent with the EST v2 framework but requires OP12, OP37, OP38 to close.

References

Primary Historical Sources

[Maxwell 1861] Maxwell, J.C. On Physical Lines of Force. Philosophical Magazine, Series 4, 21 & 23 (1861). Four-part paper deriving electromagnetic equations from a sea of molecular vortices. First appearance of the displacement current. Original source for Maxwell's vortex medium model.

[Maxwell 1865] Maxwell, J.C. A Dynamical Theory of the Electromagnetic Field. Philosophical Transactions of the Royal Society of London, 155, 459-512 (1865). Final form of Maxwell's field equations. Mechanical vortex model stripped away; field equations presented in abstract form. Contains Maxwell's statement that 'light and magnetism are affections of the same substance.'

[Heaviside 1884] Heaviside, O. On the Forces, Stresses, and Fluxes of Energy in the Electromagnetic Field. Philosophical Transactions of the Royal Society, 183A (1892). Condensation of Maxwell's twenty equations into four vector equations. The form taught in universities today.

[Gauss 1835] Gauss, C.F. Allgemeine Lehrsatze. Resultate aus den Beobachtungen des magnetischen Vereins, 4 (1839). (Original work 1835.) Mathematical basis for Gauss's law relating field divergence to source density.

[Faraday 1831] Faraday, M. Experimental Researches in Electricity. Philosophical Transactions of the Royal Society, 122, 125 (1832). (Original experiments 1831.) Experimental discovery of electromagnetic induction — the physical basis of M3.

Fluid Dynamics and Vortex Physics

[Helmholtz 1858] Helmholtz, H. On integrals of the hydrodynamical equations which express vortex-motion. Philosophical Magazine, 33, 485 (1867). (Original German 1858.) Helmholtz vortex theorems: vortex lines cannot end inside a continuous ideal fluid; vortex circulation is conserved. Direct physical basis for M2 (div(B) = 0) in EST v2.

[Onsager 1949] Onsager, L. Statistical hydrodynamics. Nuovo Cimento Supplement, 6, 279 (1949). Quantised vortices in superfluids. Topological winding number conservation. First rigorous treatment of discrete vortex topology in a continuous medium.

[Saffman 1992] Saffman, P.G. Vortex Dynamics. Cambridge University Press, 1992. Comprehensive treatment of vortex field theory in classical fluids. Closed field line topology and interaction laws.

[Donnelly 1991] Donnelly, R.J. Quantized Vortices in Helium II. Cambridge University Press, 1991. Experimental and theoretical treatment of quantised vortex structures in superfluid helium. Standard reference for vortex medium physics.

[Kleckner & Irvine 2013] Kleckner, D. & Irvine, W.T.M. Creation and dynamics of knotted vortices. Nature Physics, 9, 253 (2013). Topological classification and experimental creation of complex vortex structures beyond simple rings.

Electromagnetism References

[Jackson 1999] Jackson, J.D. Classical Electrodynamics. 3rd edition. Wiley, 1999. Standard graduate reference for Maxwell's equations in differential and integral form. Physical meaning of each equation, derivation of wave equation, relationship between epsilon_0, mu_0, and c.

[Pozar 2011] Pozar, D.M. Microwave Engineering. 4th edition. Wiley, 2011. Free-space electromagnetic wave propagation using displacement current only — J = 0 for Class I propagation. Standard engineering reference confirming two-equation simplification for radio/microwave.

Historical Analysis

[Longair 2015] Longair, M.S. A commentary on Maxwell (1865) 'A dynamical theory of the electromagnetic field.' Philosophical Transactions of the Royal Society A, 373, 20140473 (2015). Detailed analysis of Maxwell's 1865 paper showing how the mechanical vortex model was abstracted into field equations.

[Wikipedia — History of Maxwell's Equations] History of Maxwell's Equations. Wikipedia. https://en.wikipedia.org/wiki/History_of_Maxwell%27s_equations. Documents Maxwell's use of rotating vortex tube models and Heaviside's condensation into four equations. Confirms: 'The four modern Maxwell's equations can be found individually throughout his 1861 paper, derived theoretically using a molecular vortex model.'

[Wikipedia — Electromagnetic Wave Equation] Electromagnetic Wave Equation. Wikipedia. https://en.wikipedia.org/wiki/Electromagnetic_wave_equation. Contains Maxwell's 1865 statement: 'The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws.'

EST v2 Working Papers

[EST v2 V34] EST v2 Complete Reference, Version 34, June 1, 2026. Zenodo DOI: 10.5281/zenodo.19889740. Section 10.11: methodological principle — constants are measurements of substrate behavior, not eternal fixed quantities.

[WP-PhotonGeometry] EST v2 Working Paper WP-PhotonGeometry, June 3, 2026. Three substrate geometry classes. Visual range as geometric resonance. Every detector as geometric filter.

[WP-VortexTaxonomy] EST v2 Working Paper WP-VortexTaxonomy, June 2, 2026. Full vortex type classification. Photon as traveling toroidal ring, spin-1.

[WP-ResidualStrong] EST v2 Working Paper WP-ResidualStrong, June 3, 2026. Vortex interaction geometry. Helmholtz vortex theorem applied to nuclear force.

[WP-VortexFormation] EST v2 Working Paper WP-VortexFormation, June 3, 2026. Substrate vortex nucleation. Kibble-Zurek phase transition picture.
