

An Extensive Report on the Principles, History, and Application of Electromagnetism

Chapter 1: Briefing Document on the Fundamentals of Electromagnetism

1.1. Executive Summary

Electromagnetism is one of the four fundamental forces of nature, a unifying principle that governs phenomena as elemental as the structure of atoms and as complex as modern global communications. From the invisible fields that hold matter together to the technologies that power our world, its principles are deeply woven into the fabric of physical reality. Understanding this force is not merely an academic exercise; it is a strategic imperative for comprehending and advancing the scientific and technological landscape.

This briefing document distills the core tenets of electromagnetism into four critical takeaways:

- Electricity and magnetism, once viewed as separate phenomena, are two aspects of a single, unified electromagnetic force mediated by electromagnetic fields.
- A set of fundamental laws, including the Lorentz Force Law, Gauss's Law, and Ampère's Law, precisely governs the interactions between electric charges, currents, and the fields they generate.
- The work of James Clerk Maxwell culminated in a complete classical theory, encapsulated in his equations, which not only unified the forces but also predicted the existence of electromagnetic waves, identifying light as one such wave.
- Classical electromagnetism is intrinsically linked with Einstein's theory of special relativity, which reveals that electric and magnetic fields are observer-dependent manifestations of the same underlying phenomenon.

This summary provides a high-level strategic overview; the subsequent sections will delve into a more detailed analysis of these foundational concepts and their profound implications.

1.2. The Foundational Concepts of Electromagnetic Forces and Fields

At the heart of electromagnetism is the concept of electric charge, a fundamental property of matter. Charges generate electric fields that permeate the space around them, and an understanding of these static fields is the essential first step before exploring their more complex, dynamic interactions. The principles of electrostatics and magnetostatics, while distinct in their manifestations, are inextricably intertwined.

Principles of Electrostatics

This is the study of stationary electric charges. The primary principle, formalized in **Coulomb's Law**, is that charges exert forces on one another: opposite charges (positive and negative) attract, while like charges repel. This force is inversely proportional to the square of the distance between the charges. The phenomena of static electricity, such as an amber rod attracting straw after being rubbed with fur, are direct manifestations of these electrostatic forces.

Principles of Magnetostatics

This is the study of the forces between magnets. Magnetic poles, unlike electric charges, always exist in north-south pairs. It is impossible to isolate a single "monopole." Similar to electrostatics, opposite poles attract one another, while like poles repel. A common example is the alignment of



a compass needle with the Earth's magnetic field, a macroscopic effect governed by these fundamental magnetic interactions.

While these static fields describe charges and magnets at rest, the unification of these phenomena emerges when charges are set in motion, creating the dynamic interplay known as electrodynamics.

1.3. The Guiding Laws of Electrodynamics

The behavior of moving charges and the dynamic, time-varying fields they produce are not random; they are governed by a set of precise and powerful mathematical laws. These principles form the bedrock of classical electrodynamics, providing the framework for calculating the forces and fields that arise from currents and changing field strengths.

1. The Lorentz Force Law

- **Description:** This law defines the total force ($\vec{F}$) exerted on a charged particle (q) moving with velocity ($\vec{v}$) through a combination of an electric field ($\vec{E}$) and a magnetic field ($\vec{B}$). In SI units, the formula is $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$.
- **Significance:** It distinguishes between the electric force, which acts parallel to the electric field, and the magnetic force. The magnetic component is always perpendicular to both the particle's velocity and the direction of the magnetic field. A key consequence is that magnetic forces can change the direction of a charged particle's motion—often causing it to move in a circular or helical path—but they do no work on the charge. The work done dW is given by $dW = \vec{F} \cdot d\vec{s} = \vec{F} \cdot \vec{v} dt$. Since the magnetic force $q(\vec{v} \times \vec{B})$ is always perpendicular to the velocity $\vec{v}$, their dot product is zero, and therefore no work is performed.

2. Ampère's Law

- **Description:** Ampère's Law states that the line integral of a magnetic field around any closed loop is proportional to the total electric current (I_{encl}) passing through the area enclosed by that loop. The formula in SI units is $\oint_C \vec{B} \cdot d\vec{s} = \mu_0 I_{\text{encl}}$, where μ_0 is the magnetic permeability of free space.
- **Significance:** This law plays a role for magnetic fields similar to that played by Gauss's Law for electric fields. Both laws are powerful tools that simplify the calculation of fields by exploiting symmetry to make an otherwise complex integral trivial. For a long, straight wire carrying a current I , Ampère's Law can be used to derive the magnetic field strength $B(r) = \mu_0 I / 2\pi r$, showing that the field circulates around the wire (with its direction determined by the right-hand rule) and its strength diminishes in proportion to $1/r$.

3. Gauss's Law and its Magnetic Counterpart

- **Description:** Gauss's Law for electricity states that the net electric flux (Φ_E) through any closed surface is directly proportional to the net electric charge (q_{enc}) enclosed within that surface: $\Phi_E = \oint_S \vec{E} \cdot d\vec{A} = q_{\text{enc}}/\epsilon_0$, where ϵ_0 is the electric permittivity of free space. In contrast, the magnetic equivalent is always zero: $\oint_S \vec{B} \cdot d\vec{A} = 0$.



- **Significance:** This mathematical statement, $\nabla \cdot \mathbf{B} = 0$, has a profound physical meaning: there are no magnetic monopoles. While positive and negative electric charges can exist in isolation, a north or south magnetic pole cannot. If you were to cut a bar magnet in half, you would not get a separate north and south pole; you would get two smaller magnets, each with its own north and south pole. This law confirms that the net magnetic flux through any closed surface must be zero because there is no isolated "magnetic charge" to enclose.

These individual laws provided the essential components that James Clerk Maxwell would later synthesize into a single, unified theory of electromagnetism.

1.4. The Unification by Maxwell and the Nature of Light

For much of scientific history, electricity and magnetism were investigated as two distinct, albeit related, natural forces. The monumental achievement of the Scottish physicist James Clerk Maxwell was to synthesize decades of experimental findings and theoretical insights into a single, comprehensive mathematical framework. In his 1873 publication, *A Treatise on Electricity and Magnetism*, Maxwell demonstrated that the interactions between positive and negative charges were all mediated by a single, unified electromagnetic force.

The most profound prediction to emerge from Maxwell's set of four equations was the existence of self-propagating electromagnetic waves that travel through space at a constant speed—the speed of light. His calculations showed that this speed was determined solely by the electrical permittivity and magnetic permeability of free space.

Based on this, Maxwell drew a revolutionary conclusion: light itself is an electromagnetic wave. This insight unified not only electricity and magnetism but also the field of optics. He correctly theorized that visible light was just one small part of a much broader electromagnetic spectrum. Subsequent discoveries confirmed that other forms of radiation, all traveling at the speed of light, are also electromagnetic waves, differing from light only in their frequency and wavelength. This spectrum includes:

- Gamma-rays
- X-rays
- Ultraviolet radiation
- Visible light
- Infrared radiation
- Microwaves
- Radio waves

Maxwell's unification stands as one of the key accomplishments of 19th-century physics, providing a complete classical theory whose modern implications continue to shape our world.

1.5. Modern Perspectives: Relativity and Applications

While Maxwell's equations represent the culmination of classical electrodynamics, their implications rippled through physics, directly inspiring the development of modern theories in the 20th century. The framework was so complete that its internal consistencies, particularly



regarding the constant speed of light, revealed cracks in classical mechanics, paving the way for Albert Einstein's theory of special relativity in 1905.

The relationship between electromagnetism and special relativity is fundamental. The theory reveals that electric and magnetic fields are not absolute but are instead different manifestations of the same phenomenon, whose appearance depends on the observer's inertial frame of reference.

- An excellent example illustrates this principle: consider a charge moving parallel to a current-carrying wire.
 - In the "**lab frame**," where the wire is stationary, an observer sees a magnetic field generated by the current. This magnetic field exerts a Lorentz force on the moving charge, causing it to be attracted to the wire.
 - However, in the "**charge frame**," the charge is stationary. Since it is not moving, it cannot experience a magnetic force. For the physics to be consistent across both frames of reference, the charge must still feel an attractive force. In this frame, the principles of special relativity show that the moving charges within the wire create an imbalance, resulting in a net **electric field** that pulls the stationary charge toward the wire.

What one observer measures as a pure magnetic field, another observer in relative motion will measure as a combination of both electric and magnetic fields.

The practical applications of this unified theory are ubiquitous, forming the technological backbone of modern civilization.

- **Household Appliances:** Electric motors, which operate on the principle of the Lorentz force, are found in countless kitchen appliances like mixers and grinders. Alarming systems, such as doorbells, use electromagnets to create sound.
- **Communication:** Mobile phones function by transmitting and receiving signals via radio waves, a form of electromagnetic radiation.
- **Power Infrastructure:** Transformers are essential devices in the power grid. They use the principle of electromagnetic induction to "step up" voltage for efficient long-distance transmission and "step down" voltage for safe use in homes and businesses.
- **Aerospace Engineering:** Electromagnets are critical in aerospace applications, from controlling flight surfaces on aircraft to providing the precise forces needed for missile guidance systems.
- **Medical Technology:** Magnetic Resonance Imaging (MRI) is a non-invasive diagnostic tool based on the principles of Nuclear Magnetic Resonance (NMR), which relies on powerful magnetic fields to generate detailed images of soft tissues within the body.

From the deepest theoretical questions about the nature of space and time to the most practical devices we use daily, the impact of electromagnetism is truly pervasive.



Chapter 2: Study Guide for Electromagnetism

As a research assistant and tutor, I have designed this study guide to accompany the preceding briefing document. Its purpose is to help you reinforce your understanding of the core concepts of electromagnetism. This chapter includes a comprehension quiz to test your recall of key principles, a set of critical thinking questions to encourage deeper synthesis of the material, and a glossary of essential terms and figures for quick reference.

2.1. Comprehension Quiz: Short-Answer Questions

1. Describe the Lorentz force and its two main components.
2. Explain the key difference between Gauss's Law for electricity and the equivalent law for magnetism. What does this imply about magnetic poles?
3. What fundamental discovery did Hans Christian Ørsted make in 1820, and why was it significant?
4. According to Faraday's Law of Induction, what condition is necessary to induce an electric current in a wire loop using a magnet?
5. How does a transformer utilize electromagnetic induction to change voltage levels?
6. In the context of electromagnetism, what is the "right-hand rule" used to determine?
7. What did James Clerk Maxwell predict about the nature of light?
8. Why is symmetry considered essential for the practical application of Ampère's Law to calculate magnetic fields?
9. Explain why magnetic forces do no work on moving charges.
10. Based on the case study in Lombardy, Italy, what is a primary concern regarding mobile communication antennas, and what is one method used to mitigate it?

2.2. Answer Key

1. The Lorentz force is the total force on a charged particle due to electric and magnetic fields. Its two components are the electric force $q\vec{E}$, which acts in the direction of the electric field, and the magnetic force $q(\vec{v} \times \vec{B})$, which acts perpendicularly to both the particle's velocity and the magnetic field.
2. Gauss's Law for electricity states that the electric flux through a closed surface is proportional to the enclosed charge. The magnetic equivalent, $\vec{\nabla} \cdot \vec{B} = 0$, states that the net magnetic flux is always zero. This implies that magnetic poles always exist in pairs (north and south) and that isolated magnetic monopoles do not exist.
3. In 1820, Hans Christian Ørsted discovered that an electric current flowing through a wire deflected a nearby compass needle. This was significant because it was the first experimental proof of a direct connection between electricity and magnetism, paving the way for the field of electrodynamics.
4. To induce an electric current in a wire loop, the magnetic field passing through the loop must be *changing*. This can be achieved by moving the magnet toward or away from the



loop, or by moving the loop relative to the magnet. A stationary magnet and a stationary loop will not produce a current.

5. A transformer uses an alternating current in a primary coil to create a changing magnetic field in a magnetic core. This changing field then induces an alternating voltage and current in a secondary coil wrapped around the same core. The ratio of turns between the primary and secondary coils determines whether the voltage is stepped up or down.
6. The right-hand rule is used to determine the direction of the magnetic field around a current-carrying wire. If you point your right thumb in the direction of the current, your fingers curl in the direction of the circular magnetic field lines.
7. Based on his unified equations of electromagnetism, Maxwell predicted the existence of self-propagating electromagnetic waves that travel at the speed of light. This led him to the profound conclusion that light itself is a form of electromagnetic radiation.
8. Ampère's Law is most useful for calculating magnetic fields when the system has a high degree of symmetry (e.g., a long straight wire or a solenoid). This symmetry allows one to assume that the magnetic field is constant along the chosen integration path, making the calculation of the integral simple. Without symmetry, solving the integral is often too difficult.
9. Magnetic forces do no work because the force is always perpendicular to the velocity of the charged particle. Since work is defined as $dW = \vec{F} \cdot d\vec{s} = \vec{F} \cdot \vec{v} dt$, and the magnetic force vector is always perpendicular to the velocity vector, their dot product is zero. Therefore, the work done by the magnetic force is always zero.
10. A primary concern is the penetration of non-ionizing electromagnetic waves from antennas into buildings where people spend significant time, as E.U. law limits this to 6 V/m. One mitigation method is to adjust the "electrical tilt" of the antennas, angling them upwards by a few degrees to prevent the main lobe of the signal from directly impacting nearby buildings.

2.3. Essay and Critical Thinking Questions

1. Analyze the historical progression from viewing electricity and magnetism as separate phenomena to their unification as electromagnetism. Citing at least three key scientists and their experiments, explain how this conceptual shift occurred.
2. Compare and contrast the roles and mathematical forms of Ampère's Law and Gauss's Law. Discuss why these laws are powerful yet limited tools, and explain the importance of symmetry in their application using examples for each (e.g., a long wire for Ampère's Law, a spherical shell for Gauss's Law).
3. "What looks like a pure magnetic field in one frame of reference looks (at least in part) like an electric field in another frame of reference." Evaluate this statement, explaining its connection to Einstein's theory of special relativity and the fundamental unity of the electromagnetic field.
4. Discuss the societal impact of Michael Faraday's discovery of electromagnetic induction. Citing specific applications mentioned in the texts, such as electric generators and transformers, explain how this single principle underpins modern electrical technology.



5. Using the examples of solenoids and toroidal coils, analyze how the geometry of a current-carrying conductor determines the shape and properties of the magnetic field it produces. Explain how Ampère's law is applied to derive the uniform field inside a long solenoid.

2.4. Glossary of Key Terms and Figures

- **Ampère's Law:** A fundamental law of magnetostatics stating that the line integral of a magnetic field around a closed loop is proportional to the electric current flowing through that loop.
- **Coulomb's Law:** A law describing the electrostatic force of attraction or repulsion between two charged particles, which is inversely proportional to the square of the distance between them.
- **Electromagnetic Induction:** The phenomenon, discovered by Michael Faraday, where a changing magnetic field in proximity to a conductor induces an electromotive force (voltage) and thus a current in that conductor.
- **Faraday, Michael (1791-1867):** An English scientist credited with the discovery of electromagnetic induction, paramagnetism, and diamagnetism. His work formed the basis for electric motors, generators, and transformers.
- **Gauss's Law:** A fundamental law of electrostatics stating that the net electric flux out of a closed surface is proportional to the electric charge enclosed within that surface.
- **Hertz, Heinrich (1857-1894):** A German physicist who experimentally proved the existence of the electromagnetic waves predicted by James Clerk Maxwell. The unit of frequency is named in his honor.
- **Inductance:** The property of an electrical circuit whereby a change in current induces an electromotive force. The SI unit of inductance is the henry (H), named after Joseph Henry.
- **Lorentz Force:** The total force exerted on a moving charged particle by electric and magnetic fields.
- **Maxwell, James Clerk (1831-1879):** A Scottish physicist whose set of equations (Maxwell's equations) unified electricity, magnetism, and light as different manifestations of the same phenomenon: the electromagnetic field.
- **Ørsted, Hans Christian (1777-1851):** A Danish physicist who discovered that an electric current produces a magnetic field, establishing the first direct link between electricity and magnetism.
- **Solenoid:** A coil of wire wound into a cylindrical shape. When carrying a current, it produces a nearly uniform magnetic field in its interior.
- **Superconductivity:** A phenomenon observed in certain materials at very low temperatures, characterized by the complete loss of electrical resistance. First observed by Heike Kamerlingh Onnes.
- **Tesla (T):** The SI unit of magnetic flux density (magnetic field strength). Named after Nikola Tesla. One Tesla equals 10,000 Gauss (G).



- **Toroidal Coil (Toroid):** A coil of wire wound around a doughnut-shaped core (a torus). It is designed to create a magnetic field that is confined almost entirely within the coil.
- **Transformer:** A device that transfers electrical energy from one alternating-current circuit to another, either stepping the voltage up or down, based on the principle of electromagnetic induction.

Mastering this foundational knowledge is an invaluable asset for anyone pursuing studies or a career in the physical sciences and engineering.

Chapter 3: Frequently Asked Questions (FAQs)

This section presents a curated list of the most common and important questions regarding electromagnetism. The answers provided are designed to be clear, concise, and grounded in the scientific principles discussed in the preceding chapters, offering quick clarification on fundamental concepts, historical context, and practical applications.

1. **What is the fundamental relationship between electricity and magnetism?** Electricity and magnetism are two aspects of a single fundamental force known as electromagnetism. An electric current (moving charges) creates a magnetic field, and conversely, a changing magnetic field induces an electric current in a conductor. Their interconnectedness was mathematically unified by James Clerk Maxwell.
2. **Why can't you have a separate magnetic north or south pole?** According to the fundamental laws of magnetism, magnetic poles always exist in pairs. The law $\nabla \cdot \vec{B} = 0$ (Gauss's law for magnetism) mathematically implies that there are no "magnetic charges" or monopoles. If you cut a bar magnet in half, you get two new magnets, each with its own north and south pole.
3. **What was so revolutionary about Maxwell's Equations?** Maxwell's equations were revolutionary because they provided a single, complete mathematical framework for all classical electric and magnetic phenomena. Most importantly, they predicted the existence of electromagnetic waves that travel at the speed of light, leading Maxwell to correctly theorize that light itself is an electromagnetic wave.
4. **How does an electric motor work?** An electric motor operates on the principle of the Lorentz force. When an electric current flows through a wire loop placed in a magnetic field, the interaction between the current's magnetic field and the external field exerts a torque on the loop, causing it to rotate. This rotation can be sustained to perform mechanical work.
5. **What is the difference between cgs and SI units for magnetism?** The primary difference lies in the formulation of the magnetic force law and the units used. In cgs units, the magnetic force equation includes the speed of light ($\vec{F} = q \vec{v} / c \times \vec{B}$), and the unit of magnetic field is the Gauss (G). In SI units, the equation is $\vec{F} = q \vec{v} \times \vec{B}$, and the unit is the Tesla (T), where 1 Tesla is equal to 10,000 Gauss.
6. **Are the electromagnetic fields from mobile phone antennas dangerous?** Mobile communication antennas emit non-ionizing electromagnetic waves. While the health effects of long-term exposure to this type of radiation are difficult to measure empirically,



regulatory bodies like the E.U. have established safety limits to mitigate potential risks. For instance, the permissible limit inside buildings where people spend significant time is 6 V/m.

- 7. **What does it mean that electromagnetism is connected to special relativity?** The connection means that electric and magnetic fields are not absolute but depend on the observer's frame of reference. A phenomenon that appears as a pure magnetic field to a stationary observer might be perceived as a combination of an electric and a magnetic field by a moving observer. This insight was a key inspiration for Einstein's theory of special relativity.
- 8. **Who discovered electromagnetic induction, and why is it important?** Michael Faraday discovered electromagnetic induction in 1831. It is critically important because it is the principle behind electric generators (which convert mechanical motion into electricity), transformers (which change voltage levels), and many other modern technologies that form the basis of our electric power grid.
- 9. **What is a solenoid and why is it useful?** A solenoid is a coil of wire shaped like a cylinder. Its utility comes from its ability to produce a strong and nearly uniform magnetic field within its core when an electric current passes through it. This property makes solenoids essential components in devices like electromagnets and inductors.
- 10. **What is the difference between a conductor and an insulator?** In a conductor, such as a metal, electrons are free to move between atoms, allowing an electric current to flow easily. In an insulator, such as glass or silk, electrons are tightly bound to their atoms and cannot move freely, which prevents the flow of electric current.

These foundational principles and modern applications are the product of a long and fascinating intellectual journey, which we will trace in the historical timeline that follows.

Chapter 4: A Timeline of the History of Electromagnetism

This chapter traces the historical development of our understanding of electromagnetism, a journey that spans millennia. It began with ancient observations of the curious properties of amber and lodestone, progressed through the careful, systematic experiments of the 18th and 19th centuries, and culminated in the rigorous mathematical unification by Maxwell and the subsequent quantum revolution of the 20th century. This timeline highlights the key discoveries, theories, and figures that shaped this fundamental branch of physics.

Era / Date	Key Discovery / Event	Key Scientist(s)
~600 B.C.E.	Observed that rubbing amber with fur allowed it to attract light objects (static electricity).	Thales of Miletus
4th Century B.C.	Earliest Chinese literature reference to magnetism, describing a "south-pointer."	(Ancient Chinese Texts)



1600	Published "De Magnete," distinguishing between electricity and magnetism and coining the word "electrica."	William Gilbert
1733	Discovered two types of frictional electricity, which he termed "vitreous" and "resinous."	C. F. du Fay
1745-1746	Independently invented the Leyden jar, a device for storing electric charge.	Ewald von Kleist, Pieter van Musschenbroek
1752	Conducted his famous kite experiment, proving the link between lightning and electricity.	Benjamin Franklin
~1784	Invented the torsion balance and formulated Coulomb's Law, describing the force between electric charges.	Charles-Augustin de Coulomb
1800	Constructed the voltaic pile, the first electric battery capable of producing a continuous electric current.	Alessandro Volta
1820	Observed that an electric current in a wire deflected a nearby compass needle, directly linking electricity and magnetism.	Hans Christian Ørsted
1820-1827	Developed the mathematical theory of electrodynamics, formulating the force law between current-carrying conductors.	André-Marie Ampère
1827	Published his complete law of electrical circuits, defining the relationship between voltage, current, and resistance.	Georg Simon Ohm
1831	Discovered electromagnetic induction, demonstrating that a changing magnetic field creates an electric current.	Michael Faraday
1832	Independently discovered electromagnetic induction and later discovered self-inductance.	Joseph Henry
1864-1873	Published his unified theory of electromagnetism, mathematically describing all electromagnetic phenomena and predicting electromagnetic waves.	James Clerk Maxwell
1887	Experimentally generated and detected electromagnetic (radio) waves, confirming Maxwell's theory.	Heinrich Hertz
1897	Discovered the electron through experiments with cathode rays, identifying it as a fundamental, negatively charged particle.	J. J. Thomson
1905	Published his theory of special relativity, resolving conflicts between classical mechanics and electromagnetism and showing fields are frame-dependent.	Albert Einstein



1920s-1940s	Developed Quantum Electrodynamics (QED), a quantum field theory of electromagnetism.	Paul Dirac, Feynman, Schwinger, Tomonaga
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This historical progression clearly illustrates the scientific method in action, as generations of researchers built upon prior work, moving from simple observation to rigorous theory, prediction, and experimental verification.

Chapter 5: List of Sources

This chapter provides the list of sources used in the compilation of this report, formatted in a scientific style for reference.

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