

## Electrodynamics of Moving Media and the Force on a Current Loop

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**Abstract.** The development of the Chu formulation of the electrodynamics of moving media is reviewed. The force on a current loop and/or magnetic dipole is developed for three different models and all three are shown to be identical, as already shown in previous publications. The electromagnetic momentum associated with the three different models is derived and the equality of the force expressions is confirmed on the basis of the momentum conservation theorem of electrodynamics. The paper is based on a lecture delivered at Technion at the occasion of Professor Franz Obendorff's 80th birthday.

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This paper reviews the history of the development of the so-called "Chu formulation of electrodynamics". The basic tenets of the formulation are briefly stated and the objections raised by Tellegen against the Chu formulation are described. Then the arguments are described that overcome these objections, using a careful study of the force on a current loop. Finally, an overview is given of the well-known momentum conservation theorem with some indications as to how the force on a current loop can be interpreted in terms of this momentum conservation theorem. The details of the mathematical steps are contained in appendices.

In the 50's, the Electrical Engineering Department at MIT was engaged in the reformulation of the undergraduate curriculum. Professor Chu was deeply involved in defining the intellectual underpinnings of the undergraduate education. He had participated in the MIT Radiation Laboratory development of radar and was made aware of the fact that physicists, with a solid background in physical principles, outdid engineers in the development of new devices and systems. Professor Chu believed that every student of electrical engineering ought to have more than a passing familiarity with the theory of electrodynamics both as an example of a well developed theory, as well as background for the understanding of electrical devices. Because the in-

teraction between fields and matter is the basis of operation of such devices, the undergraduate ought to learn about Maxwell's equations in the presence of polarization and magnetization.

Chu went further. Because electromechanical energy conversion involves motion, he believed that students ought to be introduced to the equations of electromagnetism in the presence of moving and deforming matter. Or at the very least, the instructors ought to understand the issues arising from the motion of polarizable and magnetizable matter. When he consulted the literature, and when he tried to distill the ideas, so that an undergraduate could understand them, he found that the issues were confused and confusing. An example is the well known controversy between the proponents of the Abraham stress-energy tensor and those of the one proposed by Minkowski.

The treatment of polarization by Panošky and Phillips [1] offered a rather simple physical model, which is relativistically correct, of the current density  $\mathbf{J}_p$  produced by a polarizable medium of polarization density  $\mathbf{P}$  and with the velocity  $\mathbf{v}$ , a function of position and time.

$$\mathbf{J}_p = \frac{\partial \mathbf{P}}{\partial t} + \mathbf{P} \times (\nabla \times \mathbf{v}). \quad (1)$$

# Electrodynamics Of Moving Media

**Paul Penfield, Hermann A. Haus**



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## **Table of Contents Electrodynamics Of Moving Media**

1. Understanding the eBook Electrodynamics Of Moving Media
  - The Rise of Digital Reading Electrodynamics Of Moving Media
  - Advantages of eBooks Over Traditional Books
2. Identifying Electrodynamics Of Moving Media
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Electrodynamics Of Moving Media
  - User-Friendly Interface
4. Exploring eBook Recommendations from Electrodynamics Of Moving Media
  - Personalized Recommendations

- Electrodynamics Of Moving Media User Reviews and Ratings
- Electrodynamics Of Moving Media and Bestseller Lists
- 5. Accessing Electrodynamics Of Moving Media Free and Paid eBooks
  - Electrodynamics Of Moving Media Public Domain eBooks
  - Electrodynamics Of Moving Media eBook Subscription Services
  - Electrodynamics Of Moving Media Budget-Friendly Options
- 6. Navigating Electrodynamics Of Moving Media eBook Formats
  - ePub, PDF, MOBI, and More
  - Electrodynamics Of Moving Media Compatibility with Devices
  - Electrodynamics Of Moving Media Enhanced eBook Features
- 7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Electrodynamics Of Moving Media
  - Highlighting and Note-Taking Electrodynamics Of Moving Media
  - Interactive Elements Electrodynamics Of Moving Media
- 8. Staying Engaged with Electrodynamics Of Moving Media
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Electrodynamics Of Moving Media
- 9. Balancing eBooks and Physical Books Electrodynamics Of Moving Media
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Electrodynamics Of Moving Media
- 10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
- 11. Cultivating a Reading Routine Electrodynamics Of Moving Media
  - Setting Reading Goals Electrodynamics Of Moving Media
  - Carving Out Dedicated Reading Time
- 12. Sourcing Reliable Information of Electrodynamics Of Moving Media
  - Fact-Checking eBook Content of Electrodynamics Of Moving Media

- Distinguishing Credible Sources
- 13. Promoting Lifelong Learning
  - Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
- 14. Embracing eBook Trends
  - Integration of Multimedia Elements
  - Interactive and Gamified eBooks

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