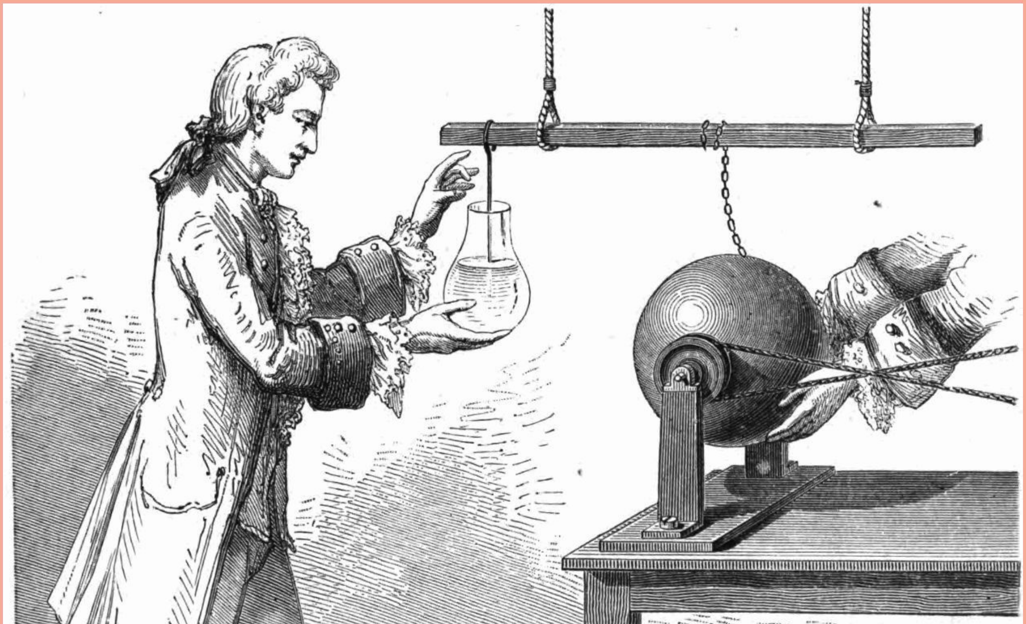
The Experimental and Historical Foundations of Electricity

Volume 2



Andre K.T. Assis

The Experimental and Historical Foundations of Electricity

Volume 2

Andre Koch Torres Assis

Apeiron
Montreal

Published by C. Roy Keys Inc.
4405, rue St-Dominique
Montreal, Quebec H2W 2B2 Canada
http://redshift.vif.com

First Published 2018

Library and Archives Canada Cataloguing in Publication

Assis, André Koch Torres, 1962-, author
The experimental and historical foundations of electricity / Andre Koch Torres Assis.

Issued in print and electronic formats.
Includes bibliographical references.
ISBN 978-1-987980-10-3 (v. 2 : softcover).--ISBN 978-1-987980-11-0 (v. 2 : PDF)

1. Electricity--Experiments. 2. Electricity--History. I. Title.

QC533.A88 2010 537'.078 C2010-901025-6
C2018-901453-9

Front cover: One of the first representations of the Leyden jar experiment (1745).
Source: A. P. Deschanel, *Elementary Treatise on Natural Philosophy*. D. Appleton and Co., New York, 1876. Part 3, p. 570, Figure 382. Translated by J. D. Everett.

THE EXPERIMENTAL AND HISTORICAL FOUNDATIONS OF ELECTRICITY

Volume 2

ANDRE KOCH TORRES ASSIS

Institute of Physics
University of Campinas—UNICAMP
13083-859 Campinas, SP, Brazil

E-mail: assis@ifi.unicamp.br

Homepage: www.ifi.unicamp.br/~assis

Contents

Presentation and Acknowledgements **9**

1 Introduction **13**
- 1.1 The Amber Effect . . . 13
- 1.2 The Triboelectric Series . . . 15
  - 1.2.1 The Position of Water in the Triboelectric Series . . . 15
- 1.3 Simple and Primitive Facts about Electricity . . . 17
  - 1.3.1 We Are Not Explaining These Facts, They Were Only Listed . . . 21
  - 1.3.2 The Meanings of Some Expressions . . . 22

2 Electric Instruments **25**
- 2.1 List of Materials for the Experiments . . . 25
- 2.2 The Electroscope: The Most Important Instrument of Electrostatics . . . 26
  - 2.2.1 Main Components of an Electroscope . . . 28
  - 2.2.2 Comparison between the Gold Leaf Electroscope and the Electroscope Made with Low Cost Material . . . 29
  - 2.2.3 The Electroscope and the Discovery of Cosmic Rays . . . 30
- 2.3 The Versorium . . . 30
  - 2.3.1 The Metal Versorium Supported on a Pin . . . 31
  - 2.3.2 The Metal Versorium Supported on a Pointed Piece of Plastic . . . 31
  - 2.3.3 The Plastic Versorium . . . 31
  - 2.3.4 The Versorium of Du Fay . . . 32
  - 2.3.5 Main Components of These Versoria . . . 33
- 2.4 The Electric Pendulum . . . 33
  - 2.4.1 The Classic Electric Pendulum . . . 34
  - 2.4.2 The Arrow Pendulum . . . 34
  - 2.4.3 The Plastic Pendulum . . . 35
  - 2.4.4 Main Components of These Pendulums . . . 35
- 2.5 Gray's Pendulous Thread . . . 35
- 2.6 Charge Collectors . . . 36
- 2.7 Circuit Tester . . . 38

3 Conductors and Insulators **41**

- 3.1 Classifying Substances as Conductors or Insulators with the Electroscope . . . 41
  - 3.1.1 Definition of Conductor and Insulator when a High Voltage is Applied between the Ends of the Body . . . 44
  - 3.1.2 Bodies which Behave as Conductors or Insulators in the Usual Experiments of Electrostatics . . . 45
- 3.2 Classifying Substances as Conductors or Insulators with the Circuit Tester . . . 50
  - 3.2.1 Definition of Conductor and Insulator when a Low Potential Difference is Applied between the Ends of the Body . 52
  - 3.2.2 Bodies which Behave as Conductors or Insulators in the Usual Experiments with Constant Current . . . 52
- 3.3 Factors Influencing the Conducting and Insulating Properties of a Substance . . . 54
  - 3.3.1 Nature or Chemical Composition of the Substance . . . 54
  - 3.3.2 Potential Difference between the Ends of the Body . . . 54
  - 3.3.3 The Time Required to Discharge an Electrified Body . . 55
  - 3.3.4 The Length of the Body . . . 55
  - 3.3.5 The Cross-Sectional Area of the Body . . . 60
  - 3.3.6 Humidity . . . 66
  - 3.3.7 Orientation of the Body Relative to the Applied Voltage 68
  - 3.3.8 Temperature . . . 71
  - 3.3.9 Illumination . . . 71
  - 3.3.10 Other Factors . . . 72
- 3.4 Laws Related to Electric Circuits Carrying Steady Currents . . 72

4 Conductors and Insulators in Some Simple Experiments **75**

- 4.1 Conductors and Insulators in the Amber Effect . . . 75
  - 4.1.1 Explanation of the Amber Effect in the Textbooks . . . 75
  - 4.1.2 Our Explanation of the Amber Effect . . . 77
  - 4.1.3 It is Important to Present a Detailed Explanation of the Amber Effect . . . 80
- 4.2 Conductors and Insulators in the Experiment of the Attraction of a Stream of Water . . . 81
  - 4.2.1 Explanation of the Attraction of a Stream of Water in the Textbooks . . . 81
  - 4.2.2 Our Explanation of the Attraction of a Stream of Water 82
  - 4.2.3 It is Important to Present a Detailed Explanation of the Attraction of a Stream of Water . . . 84
- 4.3 Differences between Old and Modern Glasses . . . 85
  - 4.3.1 Conducting or Insulating Behavior . . . 86
  - 4.3.2 Density of the Surface Charges Acquired by Friction . . . 87
  - 4.3.3 The Sign of the Charges Acquired by Rubbed Glass . . . 88
  - 4.3.4 The Glass in Modern Textbooks and the Importance to Correct What They Say . . . 90

4.4 The *ACR* Mechanism . . . 91
4.4.1 Explanation of the *ACR* Mechanism . . . 94
4.4.2 Situations where the *ACR* Mechanism Does Not Take Place . . . 95
4.5 The Importance of Stephen Gray's Discovery of Conductors and Insulators . . . 97

5 Electrification of Adhesive Tapes **101**
5.1 Insulating or Conducting Behavior of the Tape . . . 101
5.2 Electrification of the Tape . . . 105
5.3 Neutralization of the Tape . . . 108
5.4 Electrifying Tapes with Opposite Charges . . . 110
5.5 Electric Dipoles . . . 112
5.6 General Aspects Related to Adhesive Tapes . . . 116

6 The Electrophorus **117**
6.1 The Instrument . . . 117
6.2 Operation of the Electrophorus . . . 118
6.3 A Personal Account . . . 123

7 Distribution of Charges in a Conductor **125**
7.1 Distribution of Charges in Conductors . . . 125
7.1.1 Experiments with Electroscopes . . . 125
7.1.2 Collecting the Charges Located on the Internal and External Walls of an Electrified Conductor . . . 128
7.1.3 Gray, Franklin and the Distribution of Charges on Electrified Conductors . . . 132
7.1.4 Electrified Conductors Touching the Internal and External Walls of Another Conductor . . . 135
7.1.5 Distribution of Charges in Open and Closed Conductors 139
7.2 Charges Induced on the Internal and External Walls of a Hollow Conductor . . . 139
7.3 Actions Exerted by a Hollow Electrified Conductor on Internal and External Bodies . . . 142
7.4 Faraday's Ice Pail Experiment . . . 143

8 Electric Shielding **147**
8.1 Placing a Conductor or an Insulator between an Electrified Body and a Light Body . . . 147
8.1.1 Some Old Research on Screening . . . 150
8.2 Experiments with Hollow Conductors . . . 152
8.3 Sufficient Conditions for Effective Shielding . . . 155
8.4 Faraday Cage . . . 161

9 The Power of Points 163
9.1 Illustrating the Power of Points with Electroscopes 163
9.2 Collecting and Comparing the Surface Charge Densities 165
9.3 Gray and the Power of Points 169
9.4 Intensifying the Amber Effect 173

10 Electrical Equilibrium and the Instrument which Indicates Potential Difference 175
10.1 Conductor in Electrical Equilibrium 175
10.2 The Electric Potential of a Conductor 177
10.3 Electroscope with Conducting Case 178
10.4 Experiments Utilizing the Electroscope with Conducting Case . 183
10.4.1 The Electroscope Shows that All Portions of a Conductor in Equilibrium Are at the Same Potential 183
10.4.2 Procedures which can Change the Potential of One Conductor Relative to the Potential of Another Conductor . 187
10.5 Kelvin and the Electrometer to Measure Potential Difference . . 191

11 Electric Discharges in Air 195
11.1 Sparks 195
11.2 Comments on These Experiments 200
11.3 Lightning Rods 201
11.4 Lightning Rod Insulated from the Ground 203
11.5 Sparks in the *ACR* Mechanism 204
11.6 Neon Lamp 205
11.7 Gray, Franklin, the Power of Points and the Electric Nature of Lightning 207
11.8 Applications of the Power of Points 214

12 The Leyden Jar and Capacitors 217
12.1 Building a Capacitor 217
12.1.1 Do Not Utilize a Glass Bottle in Order to Insulate the Internal Conductor from the External Conductor 219
12.2 Experiments with the Capacitor 220
12.3 Working Mechanism of the Capacitor 226
12.4 Gray, Du Fay and the Electrification of Water 227
12.5 The First Capacitors or Condensers 233

13 Temporal Preservation of the Electrification of Bodies 241
13.1 Discharge through the Air 241
13.2 Preserving the Electrification of Insulators 242
13.2.1 Some Comments on These Experiments 244
13.3 Preserving the Electrification of Conductors 245
13.4 Electrets 246
13.4.1 Definitions 246
13.5 Electret Production 248

13.5.1 Materials . . . 248
13.5.2 Making Electrets . . . 249
13.6 Electrophorus with a Base Made of Electret . . . 252
13.7 Stephen Gray, the Electrets and the Temporal Preservation of the Electrification of Bodies . . . 253
13.8 Development and Applications of Electrets . . . 259

14 The Mysterious Non-Electrostatic Forces **261**
14.1 Electrostatic Force or Coulomb's Force . . . 261
14.2 Non-Electrostatic Forces in Configurations of Stable Equilibrium 263
14.3 Non-Electrostatic Forces in the Amber Effect . . . 268
14.3.1 Other Mysteries in the Amber Effect . . . 271
14.4 Non-Electrostatic Forces Acting Inside a Battery . . . 272
14.5 Non-Electrostatic Forces in Circuits Carrying Steady Currents . 273
14.6 Non-Electrostatic Forces in Other Situations . . . 274
14.7 Origins of the Non-Electrostatic Forces . . . 275
14.7.1 Faraday and Maxwell's Theory Based on Electromagnetic Fields . . . 277
14.7.2 Weber's Electrodynamics Based on the Interaction between Electrified Particles . . . 278

Bibliography **283**

Presentation and Acknowledgments

We reproduce here with some modifications the Presentation included in Volume 1 of this work.[1]

In the early 1990's I discovered the work of Norberto Cardoso Ferreira, of the Institute of Physics at the University of São Paulo, USP, Brazil. One of his research interests was to experimentally demonstrate the most important aspects of electricity utilizing very simple and easily available materials. I had the opportunity to visit him at USP in 1993. During this visit he gave me a small set of experimental materials made of thin cardboard, plastic straws, tissue paper, paper fasteners, etc. He showed me how to perform the main experiments and also showed me his book *Plus et Moins: Les Charges Électriques*.[2] I became fascinated with what I learned, realizing how it was possible to experimentally envision very profound physical phenomena dealing with easily found materials. I kept this material as a treasure for 10 years, but neither used nor developed it during this period. I am extremely thankful to Norberto Ferreira for what I learned from him. Recently I discovered other works by Ferreira, as always extremely rich and creative.[3] I also learned during discussions with his students, like Rui Manoel de Bastos Vieira and Emerson Izidoro dos Santos.

In 2005 I met Alberto Gaspar and discovered his book *Experiências de Ciências para o Ensino Fundamental*.[4] I also learned a great deal from his book and other of his works.[5]

Between 2004 and 2007 I taught classes to high school science teachers in the *Teia do Saber* project of the Secretary of Education of the State of São Paulo, in Brazil. It was a great privilege to be invited to participate in this project. The support I received from the Secretary of Education and from the Coordinating Group of Educational Projects of the University of Campinas, GGPE—UNICAMP, as well as the rich contacts with high school science teachers who took our classes, were extremely productive and stimulating for me. I

---

[1] [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[2] [FM91].

[3] [Fer78], [Fera], [Ferb], [Ferc], [Ferd], [Fer06], [Fer01c], [Fer01d], [Fer01b], and [Fer01a].

[4] [Gas03].

[5] [Gas91] and [Gas96].

also profited greatly from many exchanges of ideas with professors at the University of Campinas who participated in this project. As part of my activities, I decided to teach the high school science teachers what I had learned with Norberto Ferreira. As a result, I returned to the experiments with the further motive of writing this book, in order to share all this fascinating material with a wider audience.

The inspiration for the majority of the experiments described in this book was taken from the original works of the scientists discussed here, and from the books and papers of Norberto Ferreira and Alberto Gaspar. Since 2004 I have discovered other printed works and interesting websites which have been extremely helpful to my apprenticeship in this area—such as the site *Feira de Ciências*, organized by Luiz Ferraz Netto.[6]

John L. Heilbron suggested relevant improvements in the first version of Volume 1 of this book. His great work, *Electricity in the 17th and 18th Centuries: A Study in Early Modern Physics*,[7] was my main source of historical information related to electrostatics. Many important suggestions to improve earlier versions of Volume 1 and 2 of this work have also been given by Arthur Baraov, Sérgio Luiz Bragatto Boss, Juliano Camillo, Daniel Gardelli, Robert W. Gray, John B. Eichler, Steve Hutcheon, C. Roy Keys, Breno Arsioli Moura, Anabel Cardoso Raicik, Fabio Miguel de Matos Ravanelli, João Ricardo Neves da Silva and Bertrand Wolff.

I thank Arthur Baraov for the Russian translation of Volume 1 of this work,[8] and Pietro Cerreta, Andrea Cerreta, Raffaele Cerreta, Rita Serafini and Riccardo Urigu for the translation and publication of this book in Italian.[9] Pietro Cerreta, Derk Frerichs and Stephan Pfeiler made several videos based on experiments of this book.[10] I thank also Fernando Lang da Silveira and Jenaro Guisasola for their reviews of this book.[11]

The Figures for Volume 1 of this book were prepared by Daniel Robson Pinto, through a fellowship awarded by SAE/UNICAMP, which we thank for this support. Daniel helped also to obtain old figures and references.

I would also like to thank several other people for suggestions, discussions, and references: Dayane de Souza Bancoff, Christine Blondel, Paolo Brenni, Thiago Augusto de Lima Burgo, João José Caluzi, Hugo Bonette de Carvalho, Danylo do Amaral Cavalcanti, João Paulo Martins de Castro Chaib, Asit Choudhuri, Roberto Clemente (in Memoriam), Silvio Dahmen, Charbel El-Hani, Henrique Ennes, Moacir Pereira de Souza Filho, Junichiro Fukai, Cláudio H. Furukawa, Hans Gaab, Fernando Galembeck, Robert Harry van Gent, Harald Goldbeck-Löwe, Jürgen Gottschalk, Jenaro Guisasola, Hermann Härtel, Peter Heering, Elizabeth Ihrig, Antonio Iovane, John Jenkins, Basilio José Augusto José, Kostas Kampourakis, Siegfried Kett, Martin Kostal, Ellen Kuhfeld, Wolf-

---

[6] [Net].

[7] [Hei99].

[8] [Ass15b].

[9] [Ass17].

[10] [Cer14a], [Cer14b], [Cer17] and [Fre].

[11] [Sil10c] and [Gui12].

gang Lange, Fabio Menezes de Souza Lima, Lin Liu, José Joaquín Lunazzi, Ceno Pietro Magnaghi, Francisco das Chagas Marques, Thiago Marques, Michael Matthews, Alexandre Medeiros, Eduardo Meirelles, Manoel Guilherme da Silva Mello, Mahmoud Melehy (in Memoriam), Paulo Henrique Dias Menezes, Dennis Nawrath, Marcos Cesar Danhoni Neves, Horst Nowacki, Ronaldo Furtado de Oliveira, Martin Panusch, Sônia Peduzzi, Luiz O. Q. Peduzzi, José Rafael Boesso Perez, Gerald H. Pollack, Eugênio Maria de França Ramos, Karin Reich, Edson Eduardo Reinehr, Ricardo Rodrigues, Waldyr Alves Rodrigues Jr. (in Memoriam), Torsten Rüting, Dirceu Tadeu do Espírito Santo, Emely Giron dos Santos, Wayne M. Saslow, Daniel dos Anjos Silva, Carlos Augusto Silva, Valter Aparecido da Silva Junior, Leandro Herculano da Silva, Fernando Lang da Silveira, Moacir Pereira de Souza Filho, Julian David Medina Tamayo, Milton G. Tarazona, Christian Ucke, Alvaro Vannucci, Geraldo Magela Severino Vasconcelos, Haroldo Fraga Campos Velho, Greg Volk, Karl-Heinrich Wiederkehr (in Memoriam), Bernd Wolfram and Gudrun Wolfschmidt.

I wish to thank the Institutes of Physics and Mathematics, the Coordinating Group of Educational Projects, and the Fundo de Apoio ao Ensino, à Pesquisa e à Extensão—FAEPEX of the University of Campinas—UNICAMP, which gave the necessary support for undertaking this work. I thank also the Institute for the History of Natural Sciences of Hamburg University and the Alexander von Humboldt Foundation of Germany for a Research Fellowship in the year 2009 during which I collected considerable bibliographic material for this book.

Roy Keys, the Editor of Apeiron, has been a supporter for many years. Without his encouragement some of my books might not have been published. He made an excellent editorial work for this book.

Andre Koch Torres Assis
Institute of Physics
University of Campinas—UNICAMP
13083-859 Campinas, SP, Brazil
E-mail: assis@ifi.unicamp.br
Homepage: www.ifi.unicamp.br/~assis

Chapter 1

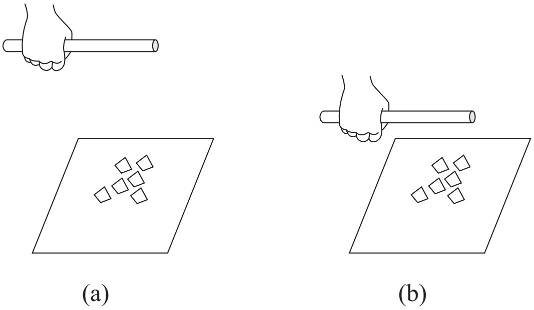
Introduction

1.1 The Amber Effect

Experiment 1.1 - *Electrifying a body by friction*

The simplest and oldest experiment of electricity, which gave rise to this field of research, is called the *amber effect*.[1] It was originally performed with amber (*electron* in Greek), which is a hard and fossil resin. It will be reproduced here with a plastic straw or acrylic ruler. This behavior is also called the triboelectric effect or triboelectricity. The prefix "tribo" has also a Greek origin, meaning friction or rub. This effect is related to the electrification of bodies obtained through friction.

Place some bits of paper on a table. Move an acrylic ruler or plastic straw close to the pieces of paper, taking care not to touch the paper. Nothing happens to the pieces of paper, Figure 1.1.



(a) (b)

Figure 1.1: (a) Plastic straw far away from pieces of paper. (b) When the plastic straw is moved near the pieces of paper, nothing happens to them.

Now rub the ruler or straw in hair, in a sheet of paper or cotton tissue,

---

[1] Experiment 2.1 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

moving it briskly up and down. We represent the region of the straw which has been rubbed by the letter F, taken from the word *friction*, Figure 1.2.

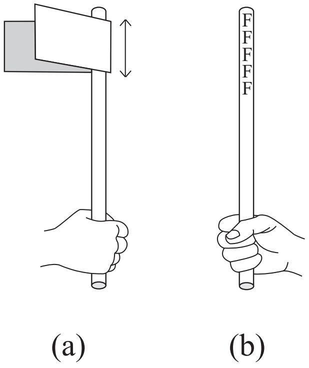


Figure 1.2: (a) Plastic straw rubbed by paper. (b) The letter F represents the rubbed region of the straw.

Bring the rubbed straw near the small pieces of paper, without touching them, only coming very close. Observe that at a certain distance they jump to the rubbed straw and remain attached to it, Figure 1.3. As the straw moves away from the table, the pieces of paper remain attached to the straw.

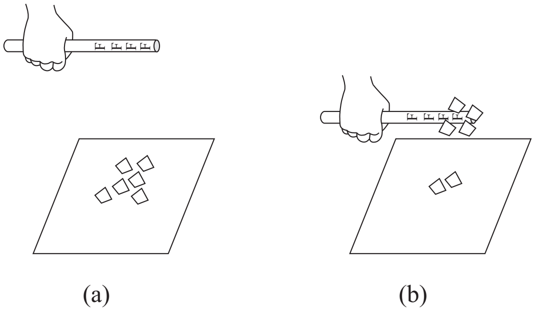


Figure 1.3: (a) A rubbed straw far away from small pieces of paper. (b) The rubbed straw attracts the pieces of paper when brought close to them.

Not all pieces of paper remain attached to the rubbed straw. Some of them touch the straw and fall. Others are emitted or reflected back to the table. This subject is further discussed in Section 4.4.

The different behavior of the bits of paper when they are close to these straws leads to an important definition.

Definition 1.1

We say that the plastic which has not been rubbed and which does not attract small pieces of paper is *electrically neutral*, *neutral* or that it has *zero charge*. When it has been rubbed and acquired the capacity to attract pieces of paper we say that it *has acquired an electrical charge*, has become *electrified*, *electrically charged* or, simply, *charged*. The rubbing process is called *triboelectric effect*, *triboelectrification*, *frictional electrification*, *charge obtained by friction*, *charging by friction*, *electrification by rubbing*, or *electrification by friction*. This attraction is sometimes referred to as an *electric attraction*, or as an *electrostatic attraction*.

1.2 The Triboelectric Series

As discussed in Volume 1 of this work,[2] there are two kinds of electrified bodies, usually called positive and negative bodies. When two different neutral bodies are rubbed together, one of them becomes positively electrified and the other negatively electrified. If one of these bodies is a conductor, it will remain charged only when it is insulated from the ground. After performing many experiments we arrived at Table 1.1.

This Table should be read as follows: When body I is rubbed against body II, the positively charged one will be the body that is above the other. That is, the body which is closer to the symbol + will become positively charged, while the other body will become negatively charged. For instance, when the plastic straw is rubbed in silk, the silk will become positive and the plastic negative.

Definition 1.2

A list like Table 1.1 is called a *triboelectric series*. The prefix "tribo" comes from the Greek. Its meaning is friction or the act of rubbing. A triboelectric series indicates the kinds of electrification obtained by friction.

A plastic straw and an acrylic ruler become negatively electrified when rubbed in hair or in a sheet of paper. Therefore from now on a plastic straw and an acrylic ruler will be represented as having negative charges (or becoming negatively electrified) when rubbed against these materials.

1.2.1 The Position of Water in the Triboelectric Series

Also liquids become charged when they flow through solid channels.[3] It was known since 1675 that flashes of light appeared in the evacuated space at the

---

[2] Chapter 5 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[3] [Gre94].

+
hair
smooth glass
human skin
synthetic polyamide
cotton
silk
paper or thin cardboard
leather
porcelain
aluminum foil
wood
cork
acrylic cloth
Styrofoam
plastic bag
drinking plastic straw
rigid acrylic
PVC tube
hard rubber
−

Table 1.1: Triboelectric Series.

top of a mercury barometer when it was shaken in the dark. It was later discovered that these lights originated in the static charge developed in the mercury when it moved against the glass walls of the barometer. In 1840 the driver of a steam locomotive received an electrical shock when he put his hand near the jet of high-pressure steam escaping from the boiler, while he touched the boiler with the other hand. William Armstrong (1810-1900) investigated this phenomenon. He isolated electrically the boiler from the ground and directed the jet toward a metallic insulated conductor. The conductor became positively charged while the boiler acquired a negative charge. In 1843 he built the hydro-electrical generator based on this principle. Michael Faraday (1791-1867) also investigated this phenomenon around 1843. He showed that the electrification was due to the friction between the steam and water droplets expelled by the boiler rubbing against the walls of the nozzle. A jet of dry air produced no effects, but electricity evolved when moist air was used. The sign of the charge produced in the water could be changed by a suitable choice of nozzle material. He also concluded that the excitation of electricity was clearly independent of the evaporation or of the change of state of water (from liquid to steam). Moreover, in order to collect a good amount of electricity, pure or dislilled water should be utilized. Common water supplied to London was unable to produce any electricity, the same happening with the addition of conducting substances to pure water. He explained this fact saying that when water became so good a conductor, the electricity evolved by its friction against the metal or other body could be immediately discharged again. The more insulating the water, the higher the collected electricity acquired by friction. By comparing the position of the water in the triboelectric series with several other substances, he concluded that water was close to the top of the list. When it flowed against solid surfaces, it became normally positively electrified, while the solid material became negative. He presented one of his conclusions as follows:[4]

> 2107. Having thus given the result of the friction of the steam and water against so many bodies, I may here point out the remarkable circumstance of water being *positive* to them all. It very probably will find its place above all other substances, even cat's hair and oxalate of lime (2131).

Modern researches confirm these findings. Recently Burgo, Galembeck and Pollack utilized water flowing through tubes of different materials and concluded that water charge is always positive, except when falling through air.[5]

Robert Andrews Millikan (1868-1953) utilized flow electrification in his famous oil droplets experiments to determine the electron's charge. The droplets became electrified as they were sprayed into the experimental chamber. In his book of 1917, *The Electron*, he mentioned the following:[6]

> The droplets [...] were found in general to have been strongly charged by the frictional process in blowing the [oil] spray [through a small orifice] [...]

In many triboelectric series found in the literature and on the Internet, air appears at the top of the positive side of the list, even above water and other materials.

1.3 Simple and Primitive Facts about Electricity

Volume 1 of this book presented the experimental and conceptual foundations of electricity. Each topic was introduced with some simple experiments. The basic concepts were formulated based on the outcome of these experiments. Section 8.2 of this work listed the simple and primitive facts or principles about electricity.[7] This Section presents these basic facts once again, without explaining them, but only describing the principles observed in the behavior of bodies. They are treated as primitive concepts here. They can be utilized in order to explain other phenomena and more complicated experiments, although these basic facts are not explained. It is never possible to explain everything. We always need to begin with some basic concepts and unexplained phenomena which

---

[4] [Far43b, article 2107].

[5] [BGP16] and [GB17, Section 6.5].

[6] [Gre94] and [Mil17, p. 66].

[7] Section 8.2 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

have to be considered true facts of nature. These basic principles can then be utilized to explain more complex phenomena and other observations of nature. We always need to assume some basic principles or postulates. These principles can be utilized to deduce other results. Here are the simple and primitive facts or principles related to electricity:

1. The bodies of nature can be found in three different states, namely, (a) electrically neutral, non electrified, discharged or without electric charge; (b) positively charged or positively electrified; and (c) negatively charged or negatively electrified. They have null charge, positive charge, and negative charge, respectively. By an "electric charge", be it positive or negative, it should be understood an *electrified body* or *electrified particle*. The bodies in these three different states have, respectively, (a) zero net charge, zero resultant charge or zero total charge; (b) positive net charge, positive resultant charge or positive total charge; and (c) negative net charge, negative resultant charge or negative total charge.

2. These states are characterized by the observed behavior of bodies. Two neutral bodies neither attract nor repel one another, except when they are polarized (this polarized condition will be clarified in another item). There is an attraction between a positive body and an initially neutral body. There is also an attraction between a negative body and an initially neutral body.

3. Bodies having charges of opposite sign attract one another. Bodies with charges of the same sign normally repel one another, but in some situations they can also attract one another.[8]

4. These forces of attraction and repulsion increase in intensity when the distance between the interacting bodies decreases. The intensity of these forces also increases when the strength of charge in the bodies increases (or when there is an increase in the electrification of these bodies). These forces are mutual, acting with the same intensity on both interacting bodies. They are directed along the straight line connecting the bodies, although acting in opposite directions in each body. They are called electrostatic or coulombic forces.

5. The bodies can be divided into two groups called conductors and insulators. The main difference between these two groups is that conductors have mobile electrified particles which can move along the whole volume of the conductor. The conductors allow the passage or flow of electric charges through their bodies and along their surfaces. Insulators, on the other hand, have no mobile electrified particles which can move along the body of the insulator. The electrified particles belonging to insulators can only move inside their molecules. Insulators do not allow the passage or flow of charges through their bodies nor along their surfaces.

---

[8] As shown in the experiments of Section 7.10 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

6. The conductors and the insulators can be electrically neutral, positive, or negative.

7. The bodies can be classified as conductors and insulators utilizing a charged electroscope, as will be described in Section 3.1. One end of the body must touch on the cardboard of the electroscope while the other end of the body must be brought into contact the ground. The bodies which discharge the electroscope are called conductors, while the bodies which do not discharge the electroscope are called insulators.

8. When a charged conductor touches the ground, it discharges. This process is called grounding. The same discharge does not happen for a charged insulator touching the ground.

9. The majority of solid and liquid bodies behave as conductors in the usual experiments of electrostatics, only few of them are insulators. List of some insulators: Dry air, amber, silk, vegetable oil, most plastics and resins.

10. The bodies can also be classified as conductors and insulators utilizing a circuit tester, as will be described in Section 3.2. We mount a circuit containing a piece of wire A, a battery, an intermediary piece of wire, a light bulb and another piece of wire B. Connect wires A and B with the body which is being tested. When the light bulb turns on, the test body is called a conductor. When the light bulb does not turn on, the test body is called an insulator.

11. A body which behaves as an insulator when under a small electric potential difference (typically up to a few hundred volts) may behave as a conductor when this potential difference increases beyond a certain value. In the usual experiments of electrostatics we deal with high potential differences, ranging typically from 1,000 up to 10,000 volts. In these cases the majority of solid and liquid bodies behave as conductors, while only a few of these bodies behave as insulators.

12. The behavior of a body as a conductor or as an insulator also depends on other factors. Suppose that one end of the body touches the cardboard of a charged electroscope, while another end of the body touches the ground. The factors which influence the properties of this body are the following: (a) The time interval required to discharge the electroscope (the greater the time of contact, the greater will be the amount of discharge). (b) The length of the body (the greater this length, the slower will be the discharge). (c) The cross-sectional area of the body (the greater this area, the faster will be the discharge). Chapter 3 of this book presents a detailed study of these factors.

13. Neutral bodies can be charged by several mechanisms. The most common procedure is friction of two neutral bodies. These two bodies may be two insulators, two conductors, or one insulator and one conductor. After the

friction, one of the rubbed bodies becomes positive and the other negative. Which one will become positive or negative will depend on their location on the so-called triboelectric series. This series is established empirically. Moreover, in order to collect the charges of the conductor that is being rubbed, it must be completely insulated from the ground. It can be, for instance, held with an insulating handle.

14. The insulators are only charged on the rubbed portion of their surfaces. The charges acquired by the rubbed conductors, on the other hand, spread over their outside surfaces when the conductors are completely surrounded by insulators. If the rubbed conductor is connected to the Earth (directly or through another conducting body), then the charge it acquired by friction is immediately neutralized by the ground.

15. A neutral conductor can also acquire a charge from an electrified insulator when they are put into contact with one another, without any friction. One example of this process utilizes a paper disk hanging from a silk thread in an electric pendulum. The paper disk is attracted by a nearby electrified plastic, touches this plastic, and is then repelled by it. This mechanism is called ACR, namely, attraction, communication of electricity, and repulsion. Section 4.4 analyses this mechanism. The charge acquired by the conductor has the same sign as the charge of the electrified insulator. In this process the amount of charge lost by the insulator is equal to that gained by the conductor. On the other hand, the amount of charge acquired by a neutral insulator when it touches another electrified insulator is negligible when there is no friction between them, provided they are not rubbed against one another.

16. Conductors insulated from the ground polarize electrically in the presence of a nearby charged body. The portion of the conductor which is closest to the charged body becomes electrified with a charge having an opposite sign to that of the nearby charged body. The farthest portion of the conductor becomes electrified with a charge of the same sign as the nearby body when the conductor is electrically insulated. If the conductor is insulated and if the two portions are separated in the presence of the nearby charged body, the two parts will become electrified with charges of opposite sign.

17. If the conductor is electrically grounded in the presence of the nearby charged body, the portion of the conductor which is closest to the charged body becomes electrified with a charge having an opposite sign to that of the nearby charged body. The portion of the conductor which is farthest from the charged body will be neutralized by the Earth. If we then remove the grounding while the charged body remains close to the conductor, the conductor will become electrified with a charge of opposite sign to that of the nearby body.

18. The molecules of an insulator are polarized in the presence of a nearby charged body. The portion of any molecule which is closer to (farther from)

the charged body becomes electrified with the opposite (same) sign as the charged body. These polarized charges are restricted to the molecules and do not move along the insulator. Moreover, they do not pass to another conductor which comes into contact with the insulator.

19. The numbers of positive and negative particles in polarized conductors close to a charged body increase when the distance between the conductor and the charged body decreases. The same happens with the effective polarized charges of insulators close to a charged body.

20. There is a higher polarization of conductors and insulators when the degree of electrification of the nearby charged body increases.

21. A force of non-electrostatic origin keeps the electrified particles on the surfaces of conductors and insulators at rest when these bodies are electrified or polarized.

22. A force of non-electrostatic origin is also responsible for generating opposite charges when two bodies are rubbed against one another. Chapter 14 shows examples of several situations requiring the existence of these forces of non-electrostatic origin.

When describing these simple facts, bear in mind that we are talking in general terms, referring implicitly to the experiments described in Volume 1 of this book. All these effects depend on the order of magnitude involved in the experiments, there are always exceptions in all experimental descriptions. For instance, when we say that two neutral bodies do not interact with one another, we are not considering the gravitational attractions between them. The reason is that this gravitational interaction is not observed by our senses or cannot be detected in ordinary experiments involving small, light bodies. Gravitation shows its effect only when at least one of the bodies is of astronomical dimensions, like the planet Earth. When we say that a charged body attracts a body which is initially neutral, we are assuming light bodies or bodies supported by threads, in such a way that there is only small resistance to lateral motion of these bodies. If this is the case, these initially neutral bodies will be able to move towards the charged body when there is an attraction between them. Moreover, if this attraction is to be observed, the distance between the interacting bodies cannot be very large and the charge of the rubbed body should not be very small, otherwise these effects are not perceptible. Similar conditions apply to the other principles.

1.3.1 We Are Not Explaining These Facts, They Were Only Listed

These simple and primitive facts about electricity were not explained. Likewise, several things were not justified:

- The existence of two kinds of electricity (positive and negative) instead of 1, 3, 4, ..., or even an infinite number of different kinds of electricity.
- The reasons why charges of opposite sign attract one another, while charges of the same sign repel one another.
- The reason why the electrostatic force depends on the distance between the interacting bodies.
- The mechanisms responsible for electrification by friction.
- The order of the triboelectric series. That is, we are not explaining why a certain body becomes positively electrified and another body negatively electrified when rubbed against each other.
- The origin of the non-electrostatic force responsible for the separation of opposite charges in the amber effect.
- The reason why some bodies behave as conductors while other bodies behave as insulators.
- The reason why the conductivity of a body depends on several factors like: the potential difference acting between its ends, the length and cross section of the body, its temperature, etc.
- The origin of the non-electrostatic force responsible for maintaining at rest the electrified particles in conductors and insulators which are charged or electrified.
- Etc.

1.3.2 The Meanings of Some Expressions

Here it is worth mentioning a relevant distinction presented by Gaspar related to some simple expressions usually utilized in physics textbooks, namely:[9]

Some authors mention that "a mass m exerts a force" or that "a charge q exerts a force". These two expressions are physically incorrect. Mass and charge are properties of matter, but they are not things themselves. A body, a particle, a material point or a similar concept is the entity which may exert a force on another body. A body has mass and may have electric charge. But there is no mass without a body. Likewise, there is no charge without a body. Therefore, if we wish to speak properly, it is incorrect to mention a "mass m" or a "charge q" without referring to the body carrying this mass or this electrical charge. Normally the body carrying the mass or the charge is implicitly assumed in these expressions. In any event, the omission of the body when referring to a mass m or to a charge q does not contribute to the understanding of the concept. For this reason we should avoid these expressions.

---

[9] [Gas00, p. 22] and [Gas13, p. 25].

We agree with these points of view presented by Gaspar.

This book presents only a macroscopic description of the phenomena. We will not present in detail the atomic model. We will then talk of electrified bodies or electrified particles.

Chapter 2

Electric Instruments

This Chapter presents some of the main electric instruments utilized in this book.

2.1 List of Materials for the Experiments

We list here some of the main materials utilized in the following experiments. It may be useful to collect these things in advance.

- Plastic straws, an acrylic ruler and a PVC tube.
- Paper nakpkin and plastic bags.
- Thin cardboard or paperboard.
- Paper (A4 or letter size) and aluminum foil.
- Tissue paper (used to build kites or employed to wrap fragile gifts).
- Spool of silk thread (or spool of synthetic polyamide thread, like nylon, or polyester thread).
- Spool of cotton thread and twine.
- Paper fasteners, pins, needles and nails.
- Corks.
- Kitchen vegetable oil.
- Wood skewers and metal wires.
- The supports for the electric pendulums and electroscopes are made with thin plastic coffee cups, paper fasteners and gypsum dough.
- Insulated copper wire, batteries and flashlight bulbs.

- Neon lamp and LED (light emitting diode). These two items are not essential.

- Adhesive tapes (like PSA office tape, magic tape, invisible tape, sticky tape, cellophane tape, surgical or medical tape, electrical or insulating tape).

- Beverage cans.

- Plastic bottles (200 or 300 ml).

- Glass, metal and plastic cups.

- Pizza pan, metal pie pans, aluminum or iron ladles.

- Electrets will be made with paraffin obtained from candles or acquired in bar or tablet. Some electrets will be made with carnauba wax, but it is not essential to obtain this material if it is difficult to find it.

- Some other specific materials described in the appropriate Sections.

2.2 The Electroscope: The Most Important Instrument of Electrostatics

In Volume 1 of this book we built several electric devices, namely, perpendiculo, metal versorium, Du Fay's versorium, electric pendulum, pendulous thread, electroscope and charge collector. The electroscope is undoubtedly the most important instrument, as it allows the practical distinction between conductors and insulators. Before beginning any electrical experiment or the construction of any device, test the materials to be employed in order to know if they conduct electricity or not. This test is very important. Many experiments will not work or will not function properly due to the fact that people do not take notice of this crucial aspect. People may think, for instance, that a piece of rubber will be an insulator due to the simple fact that it is made of rubber. However, in reality many kinds of rubber behave as conductors in electrostatic experiments. If the body or instrument which is being studied or utilized is connected to the ground through one of these pieces of rubber, no electric charges will be accumulated in the body or instrument due to the grounding. Therefore, the electrical effects which are being looked for will not be present. The person performing this experiment, not aware of this important fact, will be frustrated. He will not understand why the experiment failed or the reason for the bad behavior of his instrument.

The support which will be utilized in most experiments with the electroscope and electric pendulum is made with a thin plastic coffee cup. Make a small hole in the bottom of the cup and pass both legs of a paper fastener through it. The cup is placed with its mouth upward. Fill it with wet gypsum dough or wet

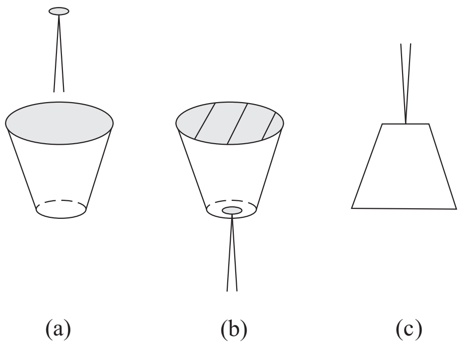


Figure 2.1: (a) Thin plastic coffee cup and paper fastener. (b) Cup filled with wet gypsum dough. (c) Support for the electric pendulum and electroscope.

white cement. It will dry in this position. It will be used with the cup's mouth facing downward and the paper fastener pointing upward, Figure 2.1.

Other supports can also be utilized. An example is a piece of modeling clay with a nail or paper fastener stuck through it. The nail or paper fastener will be located inside the straw, supporting it in a vertical position, so the nail's thickness and length should be chosen appropriately.[1] Another example is a wooden board, a plate or cup made of plastic or Styrofoam with a hole in the middle to fix the vertical straw.[2]

Here we present the simple electroscope utilized in all experiments of Volume 1 of this book, Figure 2.2:[3]

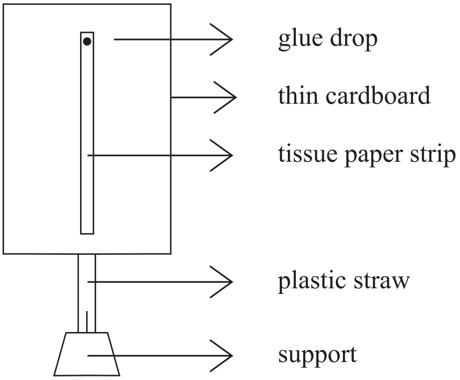


Figure 2.2: Electroscope seen face on.

The thin cardboard may have, for instance, 7 by 10 cm sides, with the longer

---

[1] [FM91, p. 10], [Ferb, Material para experiências em eletrostática, pp. 1-2], Section 4.4 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[2] [Gas03, pp. 225-6].

[3] Sections 6.1 and 6.5 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

side vertical. Attach the rectangle to a plastic straw with two pieces of adhesive tape. The tape should be applied to the back side of the rectangle, not extending beyond the edges. The upper end of the straw should remain close to the upper edge of the rectangle, without extending beyond it. Cut a small strip of tissue paper, from 1 to 3 mm wide and 6 to 9 cm long. The effects to be described in this book become more visible when utilizing a very thin and light strip. The tissue paper can be the kind used to build kites or employed to wrap fragile gifts. Glue the upper end of this strip to the upper middle of the rectangle. The strip should not be folded and should not go beyond the lower edge of the rectangle. Instead of glue, the strip can also be fixed with a small piece of adhesive tape, provided the tape does not go beyond the edge of the rectangle, Figure 2.3.

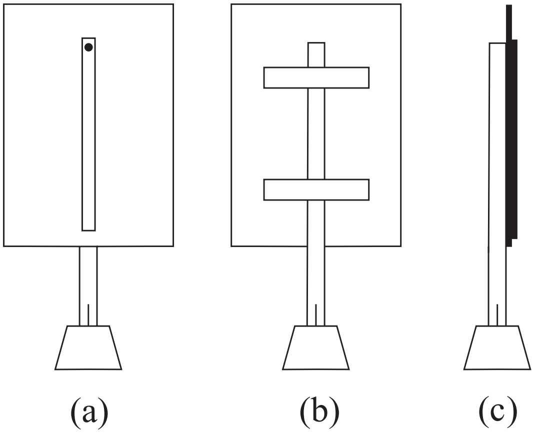


Figure 2.3: (a) Classic electroscope seen face on. (b) Back view. (c) Seen in profile.

2.2.1 Main Components of an Electroscope

The thin cardboard and the tissue paper strip behave as conductors in the usual experiments of electrostatics. Dry air around the electroscope behaves as an insulator. The plastic straw supporting the rectangle also behaves as an insulator, being the most important element of the electroscope. It prevents the discharge of the electroscope to the ground. Figure 2.4 presents the main components of an electroscope.

The plastic straw cannot be replaced with a wood skewer or with a metal wire. After all, these two substances behave as conductors in electrostatics. If a wood skewer replaced the plastic straw, the electroscope would always discharge to the ground after scratching its cardboard with an electrified acrylic ruler. Therefore, it would not be possible to keep it electrified after being rubbed.

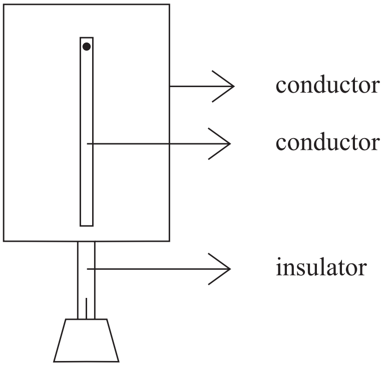


Figure 2.4: Components of an electroscope.

2.2.2 Comparison between the Gold Leaf Electroscope and the Electroscope Made with Low Cost Material

Modern textbooks present the electroscope when discussing conductors and insulators, or when they present electrification by induction or polarization. They normally mention only the gold leaf electroscope. It has two mobile gold leaves which open when they are electrified. These books usually do not explain how to make an electroscope with simple and cheap material.

However, the electroscope presented in this Section works perfectly well, just like any gold leaf electroscope. It is extremely sensitive. Its strip of tissue paper rises easily even for a low electrification of the instrument. This strip is very light. It is fixed to the cardboard only by the its upper end with a drop of glue. The remainder of the strip can move easily away from the cardboard, without any hindrance, whenever the instrument acquires a little amount of charge. The plastic straw is an excellent insulator, preventing the loss of charge to the ground, especially in dry and cold weather.

The main advantage of this simple instrument compared to the gold leaf electroscope is that it can be easily made by the teacher or by each student. It costs almost nothing. It is very sensitive and we can make innumerable experiments with it. This fact provides a great autonomy to the students. They can easily acquire first hand electric knowledge with it.

A normal student will not try to build a gold leaf electroscope. After all, this instrument should be extremely expensive because it contains gold. This simple fact suggests that this device should have been made by specialists, being difficult to construct. Many students can even imagine that there is vacuum inside the glass bottle which protects the electroscope. Most students become apathetic with the description found in the textbooks. It does not stimulate their creativity and does not suggest that they could build a similar instrument with simple material. Many of them will never try these simple experiments with their own hands, limiting themselves to the descriptions found in the textbooks.

2.2.3 The Electroscope and the Discovery of Cosmic Rays

In order to illustrate the importance of the electroscope, we mention here the discovery of cosmic rays. For a long time it was known that an electrified electroscope discharges slowly through air. One of the reasons for the air's conductivity is the presence of charged ions in the atmosphere, that is, the existence of mobile electrified particles. In 1896 Henri Becquerel (1852-1908) verified that uranium salts emitted ionizing rays which increased air conductivity. The γ rays (high frequency electromagnetic radiation), in particular, possess this ionizing property. They penetrate air up to a certain distance, until they interact with neutral atoms, ionizing them. In order to research the origin of the ionization of the air, in the beginning of the XIXth century scientists began to study atmospheric conductivity at different altitudes relative to the ground. Most researchers of this period believed that the origin of the ionizing radiation was inside the Earth due to the presence of radioactive substances. Fundamental research on this topic was performed by the scientist Victor Franz Hess (1883-1964). His main researches on cosmic rays were performed between 1911 and 1913. He made balloon flights during this period carrying electroscopes developed by Theodor Wulf (1868-1946) in which the electrification was indicated by the separation distance between two conducting wires. Hess electrified his electroscopes up to a certain distance between the conducting wires and measured the time interval required to discharge the electroscopes as a function of the altitude of the balloon. He made flights up to 5.3 km above sea level. He found that the radiation level decreased up to an altitude of approximately 1 km, increasing considerably beyond this height, reaching up to twice the sea level radiation when he was at an altitude of 5 km. He then concluded that the main ionizing radiation came from space, having no terrestrial origin. He also flew during a solar eclipse and at night, concluding that the radiation level had a value close to the value during the day, and that the Sun was not the source of this radiation. His final conclusion was that the radiation penetrating the atmosphere originated from space. It was called ultra-radiation. The present name, "cosmic radiation", was introduced by Robert A. Millikan in 1925. He researched cosmic rays and the photoelectric effect, receiving the Nobel prize in 1923 for his measurement of the electron's charge, as discussed in Subsection 1.2.1. Hess received the Nobel prize in physics in 1936 for his discovery of cosmic radiation, sharing it with Carl David Anderson (1905-1991), an American physicist who discovered the positron in 1932.

The electroscope was essential for creating a whole new research area in physics, namely, cosmic radiation.

2.3 The Versorium

The oldest electrical instruments were the perpendiculo of Girolamo Fracastoro (1478-1553) and the versorium of William Gilbert (1544-1603).[4] Here we present

---

[4] Chapter 3 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

the main types of versoria.

2.3.1 The Metal Versorium Supported on a Pin

A simple versorium can be made with a brass or steel paper fastener. The center of the circular base of the paper fastener should be a little bent. It will be supported by a pin fixed on a rigid base. To bend or deform the center of the paper fastener, utilize a nail and a hammer, but carefully, without making a hole in the top of the fastener, only bending it a little to create a small indentation. The paper fastener will be supported by this bent section placed on the tip of the pin in such a way that it will not slip off the pin. After the legs of the paper fastener have been bent downward, so that it makes an upside down letter V, the fastener can be set on the pin. It should be completely free to turn around the pin, Figure 2.5.

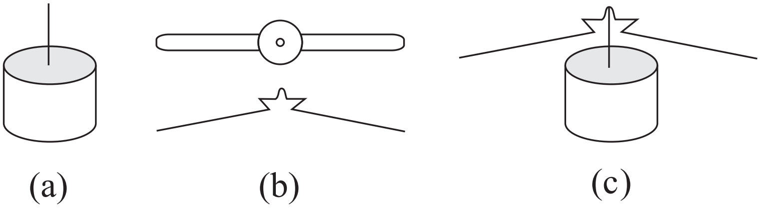


Figure 2.5: Metal versorium. (a) Versorium base. (b) Steel paper fastener seen from above and the side. (c) The mounted versorium.

2.3.2 The Metal Versorium Supported on a Pointed Piece of Plastic

The metal versorium of this Subsection is supported on a pointed piece of plastic. The main difference in comparison with the versorium of Subsection 2.3.1 is that plastic behaves as an insulator. Therefore the paper fastener will be insulated from the ground, so that it can maintain its net charge after being electrified. When an electrified body is located nearby, the insulated versorium will become polarized.

This versorium is made in a few simple steps. In the first place, cut a small piece of plastic straw 5 cm long. Sharpen one of its ends with scissors, then cap it on the support of the electroscope of Figure 2.1, as shown in Figure 2.6 (a). Then mount the paper fastener of Figure 2.5 (b) on this pointed piece of plastic, as shown in Figure 2.6 (c).

2.3.3 The Plastic Versorium

In Figure 2.7 we see a representation of the plastic versorium. Its base, in this case a nail stuck in a board, appears in Figure 2.7 (a). Figure 2.7 (b) shows the mobile part of the versorium, in this case a strip of plastic with a pin attached to

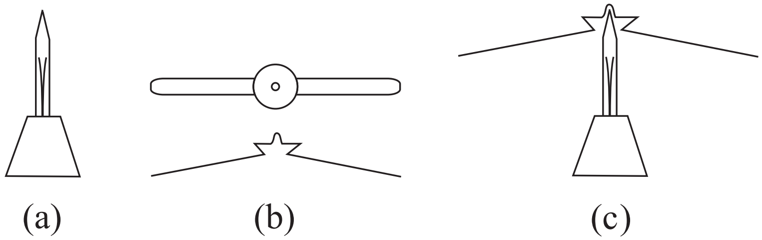


Figure 2.6: Metal versorium supported on a pointed plastic straw. (a) Support of Figure 2.1 with a pointed plastic straw around the two legs of a paper fastener set in gypsum dough. (b) Steel paper fastener seen from above and the side. (c) The mounted metal versorium on a pointed plastic straw.

its center, with its tip downward. We will call this mobile part the "hat" of the versorium. It should be a plastic strip. The pin is securely attached through the center of the hat, with the tip of the pin pointing downward. The pin rotates together with the hat relative to the ground. This system is then supported on a small horizontal flat surface which is fixed relative to the ground, like the head of a nail stuck in a board or cork. The complete versorium appears in Figure 2.7 (c), with the tip of the pin set on the horizontal head of the nail stuck in a board.

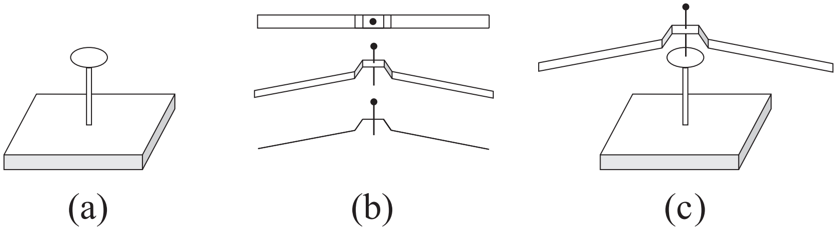


Figure 2.7: Plastic versorium with the pin set in the center of the insulating strip. (a) Fixed base of the versorium. (b) Hat of the versorium (plastic strip) with the pin attached to it. (c) Mounted versorium.

Important: In order to prevent the versorium from slipping, it is crucial that the center of gravity of the hat and pin be lower than the tip of the pin.

2.3.4 The Versorium of Du Fay

The versorium of Du Fay can be made of plastic with a piece of aluminum foil at one of its ends, Figure 2.8.

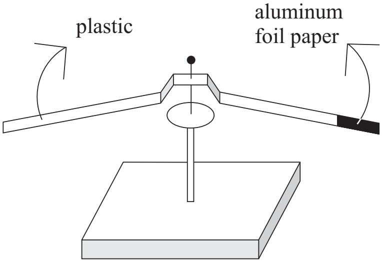


Figure 2.8: The versorium of Du Fay.

2.3.5 Main Components of These Versoria

The main components of these four kinds of versoria are presented in Figure 2.9.

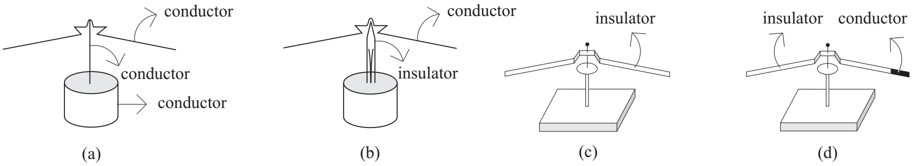


Figure 2.9: Components of the different kinds of versoria. (a) Metal versorium supported on a metal pin. (b) Metal versorium supported on a pointed plastic straw. (c) Plastic versorium. (d) Versorium of Du Fay.

In the case of a metal versorium supported on a metal pin, Figure 2.9 (a), there is a horizontal conducting strip (like the steel paper fastener) supported on a vertical conducting pin attached to a wooden board or cork. That is, all elements of this versorium are conductors. The metal versorium supported on a pointed plastic straw, Figure 2.9 (b), has a conducting strip supported on an insulating pointed material. The plastic versorium, Figure 2.9 (c), has an insulating hat. The pin passing through its center is conducting, although its composition is not relevant for the experiments. The versorium of Du Fay, on the other hand, Figure 2.9 (d), is composed of an insulating plastic hat having a conductor at one of its tips, namely, the aluminum foil. It is not relevant if the pin passing through its center is made of a conducting or insulating material.

2.4 The Electric Pendulum

This Section presents the main kinds of electric pendulums.[5]

---

[5] [FM91, p. 47], [Ferb, Eletrização por contato: Pêndulo, p. 8; Eletrização por indução: Pêndulo, p. 14; e Campo elétrico: Vetor, p. 22], [Gas03, pp. 228-229], together with Sections 4.4, 4.10 and 7.6 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

2.4.1 The Classic Electric Pendulum

The classic electric pendulum is presented in Figure 2.10.

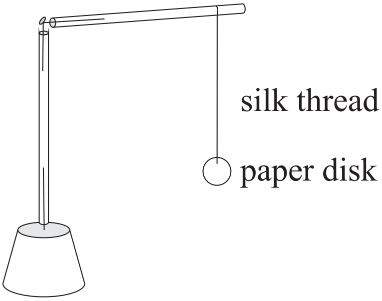


Figure 2.10: Electric pendulum with support.

Tie a disk of paper or aluminum foil to the lower free end of a thread made of silk, polyester or polyamide (like nylon). The upper end of this thread is tied to a plastic straw. This plastic straw is connected at right angle to another plastic straw with a paper fastener. The vertical plastic straw is supported on a paper fastener set in gypsum dough inside a thin plastic coffee cup, Figure 2.1.

2.4.2 The Arrow Pendulum

A variation of this classic pendulum replaces the disk of paper or aluminum foil with a small arrow made of paper, aluminum foil, or thin cardboard. It can be called an arrow pendulum. The arrow should point horizontally and be suspended at its center by a silk or nylon thread. It can be 2 to 5 cm long, with a vertical shaft width from 0.2 to 0.5 cm, and the maximum width of the arrow tip from 0.5 to 0.7 cm. These are only approximate measures and are not so critical. The arrow can be tied directly to the end of the silk thread, as in Figure 2.11 (a). It can also be fixed around a small piece of plastic straw, as in Figure 2.11 (b).

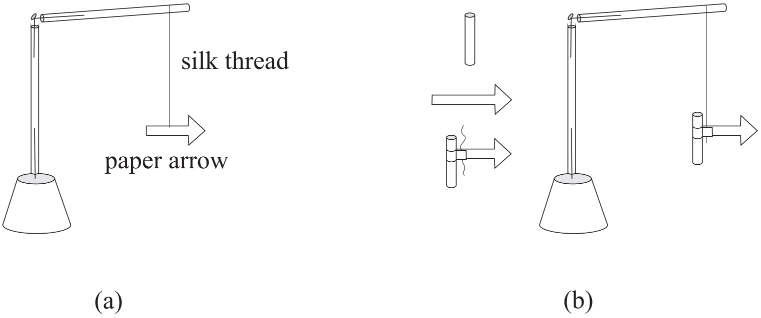


Figure 2.11: Electric pendulum with a suspended arrow.

2.4.3 The Plastic Pendulum

Build now a plastic electric pendulum, also called a plastic pendulum. Simply replace the paper disk of the classic electric pendulum with a small plastic disk, Figure 2.12. The plastic should be thin and light, like the plastic bags used in supermarkets.

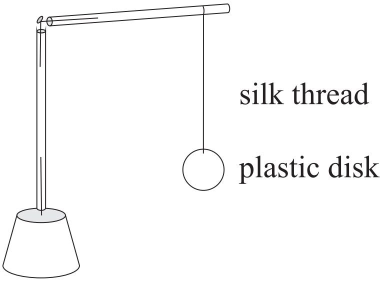
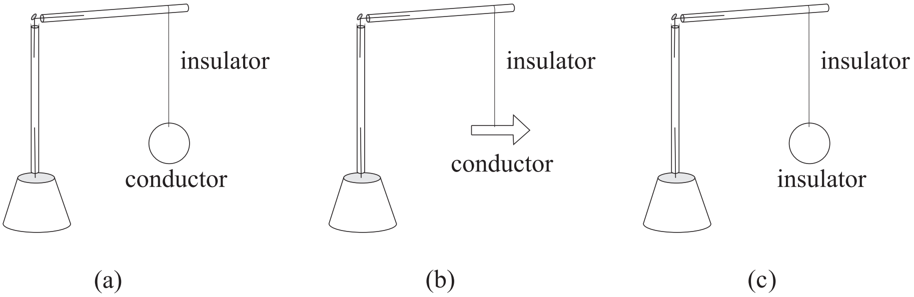


Figure 2.12: The plastic pendulum.

2.4.4 Main Components of These Pendulums

The main components of these pendulums are indicated in Figure 2.13.



(a) (b) (c)

Figure 2.13: (a) Classic electric pendulum. (b) Arrow pendulum. (c) Plastic pendulum.

2.5 Gray's Pendulous Thread

Here we present the "pendulous thread" which was created by Stephen Gray (1666-1736) in 1729.[6]

It is simply a cotton or linen thread supported from above by a wood stick, Figure 2.14 (a). The electric pendulum was made with a silk or nylon thread.

---

[6] [Grab], [Grad], [Grag] and Section 4.9 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

Here it is important to use a cotton or linen thread. Hold the stick with the hand or attach it to another appropriate support.

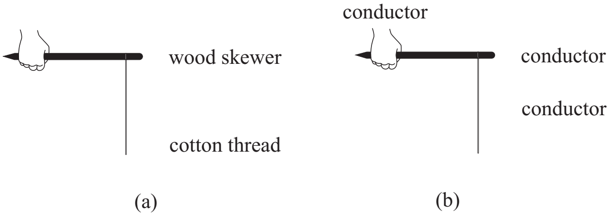


Figure 2.14: (a) Gray's pendulous thread. (b) Main components of this instrument.

The main components of Gray's pendulous thread are presented in Figure 2.14 (b), namely, a conducting thread supported by a grounded conductor.

Gray utilized his pendulous thread in order to test whether a body was charged. To this end, he simply brought the thread close to the body. When the thread was attracted by the body, inclining toward it, this meant that the object was electrically charged. When the thread remained vertical, this meant that the nearby body was not electrified.

2.6 Charge Collectors

Charge collectors are instruments used to obtain electrified particles from any region of an electrified or polarized conductor.[7] After these charges have been collected, it is possible to determine their sign (if they are positive or negative) and also their magnitude (that is, to know the amount of surface charge density). They can also be utilized in order to transport electrified particles between two conductors which are separated from one another.

The basic structure of a charge collector is a conductor (C) fixed to an insulating handle (I). We manipulate the charge collector only through the insulating handle, without touching its conducting part in order to avoid discharging it. The conducting part of the collector is placed in contact with the electrified body under study, in order to gather a small amount of its charges. During this contact, some electrified particles are transferred between the electrified body and the conducting part of the collector, in such a way that it receives charges of the same sign as those of the electrified body. Figure 2.15 illustrates some charge collectors.

Figure 2.15 (a), for instance, represents a classic electric pendulum. The insulator can be a silk, nylon or polyamide thread. The conductor can be a disk of paper or aluminum foil. This pendulum can also be made of a small pith or cork ball, like the electric pendulums built in the XVII and XVIIIth centuries. Figure 2.15 (b) can represent a ball made of aluminum foil connected to a plastic straw. It can also be a metal sphere connected to a PVC tube. Figure 2.15 (c)

---

[7] Section 7.2 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

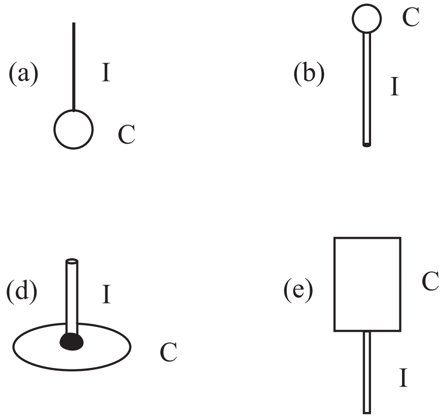


Figure 2.15: Charge collectors composed of a conducting part C and an insulating handle I.

represents a strip of aluminum foil paper connected to a plastic straw. Figure 2.15 (d) represents a paper disk or a disk of thin cardboard connected to a plastic straw with modeling clay. It can also represent the circular lid of a metal can or a pizza pan fixed through its center at right angle with a handle made of PVC, acrylic or hard plastic. Figure 2.15 (e) may represent the simple electroscope utilized in this book without the tissue paper strip. That is, it is simply a rectangular cardboard fixed to a plastic straw.

The model of Figure 2.15 (d) was invented by Charles Augustin de Coulomb in 1787, Figure 2.16. It is now known as a proof plane.[8]

Figure 2.16: Charles-Augustin de Coulomb (1736-1806).

The proof plane is a conducting disk attached by its center to an insulating handle. Coulomb used it to determine the distribution of charge on the surfaces of two or three conductors charged by contact. The amount of charge collected

---

[8] [Hei99, p. 495].

by the proof plane is proportional to the local surface density of charge. The model utilized here is a thin cardboard disk 3 cm in diameter. An aluminum foil can be placed on one of its faces, but this is not essential. Cut a piece of plastic straw 5 cm long. It will be attached at right angles to the center of the disk, as if it were the axis of symmetry. One of the ends of the straw can be attached to the center of the disk with modeling clay, Figure 2.17. When we manipulate the proof plane, we must touch only the straw, but not the clay or the disk.

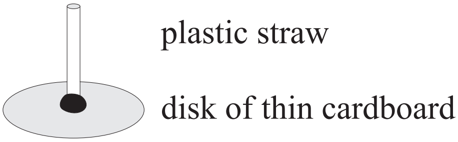


Figure 2.17: Coulomb's proof plane. This is also a charge collector, but will be referred to as a proof plane for clarity when describing the following experiments.

2.7 Circuit Tester

To build a circuit tester, utilize three pieces of insulated copper wire, uninsulated at their ends, Figure 2.18 (a), a new large alkaline battery, *D* size, which generates a potential difference of 1.5 volt between its poles, Figure 2.18 (b), and a small 1.5 volt bulb and socket, Figure 2.18 (c).

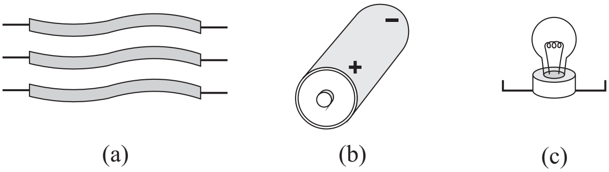


Figure 2.18: (a) Three pieces of insulated copper wire (strip the ends). (b) A new *D* size battery. (c) A 1.5 volt bulb and socket.

In order to test the conducting or insulating behavior of bodies when under a small potential difference, we mount the circuit tester indicated in Figure 2.19.

It is also helpful to employ a battery support, in order to facilitate its electrical connections with the wires. One uninsulated end of the first wire is connected to the negative terminal of the battery with an adhesive tape. The other end of this first wire will be shaped in a hook, being called *A*, Figure 2.19. One uninsulated end of the second wire is connected to the positive terminal of the battery, with the other end connected to one of the terminals of the socket. One end of the third wire is connected to the other terminal of the socket. The other end of this third wire will make another hook, being called *B*. The distance between *A* and *B* should be around 10 cm.

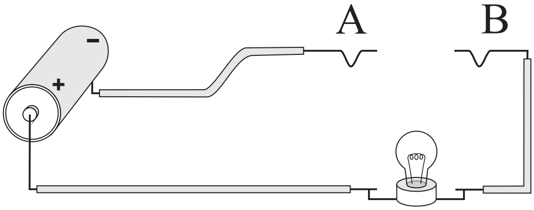


Figure 2.19: Circuit tester.

We should be able to place several substances between A and B in order to test their conducting or insulating properties. When the bulb turns on, the body will be classified as a conductor. When the bulb does not turn on, the substance will be classified as an insulator. These experiments are presented in Section 3.2.

Chapter 3

Conductors and Insulators

The distinction between conductors and insulators is one of the most important aspects in the whole science of electricity. It is essential to test the bodies to know if they behave as conductors or insulators. This test should be performed before starting any experiment. The electroscope is the crucial device to make this classification.

3.1 Classifying Substances as Conductors or Insulators with the Electroscope

Experiment 3.1 - *Charging an electroscope by contact with an electrified body*

Briskly rub a plastic straw or acrylic ruler in hair or on a piece of paper. Scrape the rubbed straw on the upper edge of the electroscope. This procedure should be repeated a few times. After the rubbed straw has been removed, the strip stands off from the electroscope, indicating that it has been electrified by this procedure, Figure 3.1. The electroscope becomes electrified with a charge of the same sign as that of the rubbed straw.[1]

Definition 3.1

We say that the electroscope *acquired an electrical charge due to contact with a previously charged straw*, has become *charged by contact*, or *electrified by contact*. The process is called *charging by contact*, *charge transference by contact*, or *electrification by contact*.

Experiment 3.2 - *Discharging an electroscope by touching it with the hand*

---

[1] Experiment 6.5 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

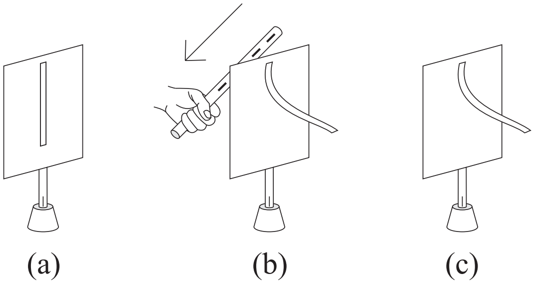


Figure 3.1: (a) Electroscope with its strip pointing downward. (b) Scrape the upper edge of the rectangle with a rubbed straw. (c) When the straw is removed, the strip stands off from the electroscope.

Move the finger near the upper edge of the charged electroscope and touch the cardboard. Immediately the strip drops, sticking to the rectangle. When the finger is removed, the strip remains vertical, Figure 3.2.

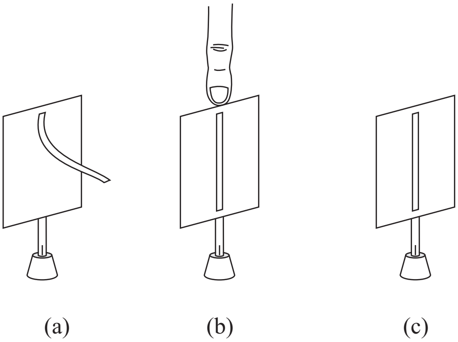


Figure 3.2: Discharging an electroscope by touching it. (a) An initially charged electroscope. (b) When the finger touches the cardboard's upper edge, the strip drops. (c) The strip remains vertical after the finger has been removed.

The electroscope has been discharged by this process, which receives a special name:

Definition 3.2

We say that the charged electroscope *lost its electrical charge by contact* with the finger, or that it was *discharged by contact*, *electrically discharged* or, simply, *discharged*. The process is called *discharge by contact*, *grounding*, or *earthing*. It is also called *electrical grounding*, *electrical earthing*, *to ground*, or *to earth*. The origin of these names is that the charged body is being discharged by the human body, which is normally in electrical contact with the ground.

Instead of drawing the finger, it is common to utilize a symbol to represent a conducting contact between the ground and the system which is being analyzed, as indicated in Figure 3.3 (b).

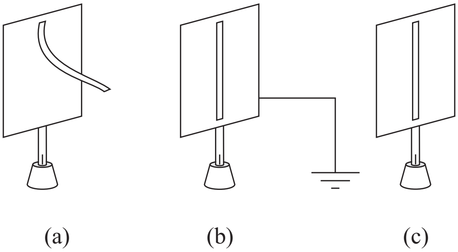


Figure 3.3: Symbol representing the grounding. It replaces the finger of Figure 3.2.

Experiment 3.3 - *Touching a charged electroscope with a neutral plastic straw*

Here we present the most important experiment which can be made with a charged electroscope. Hold one end of a body with the hand and touch the upper edge of the charged electroscope with the other end of the body. Figure 3.4 shows that nothing happens with the electroscope when a neutral plastic straw touches the cardboard. That is, the electroscope remains electrified after the straw has been removed.

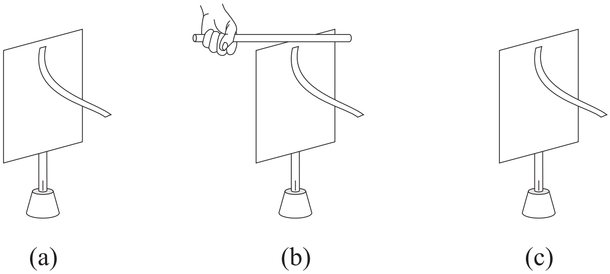


Figure 3.4: (a) An initially charged electroscope. (b) Hold one end of a neutral plastic straw with the hand and touch the edge of the electroscope with the other end of the straw. Nothing happens to the strip. (c) When the straw is removed, the strip remains raised.

An electrified electroscope is not discharged when the cardboard is touched with a neutral plastic straw held by the hand.

Experiment 3.4 - *Touching a charged electroscope with a metal wire*

Figure 3.5 shows what happens when a charged electroscope is touched with a wood skewer or metal wire held by the hand. The raised strip drops immediately, remaining vertical after the skewer has been removed.

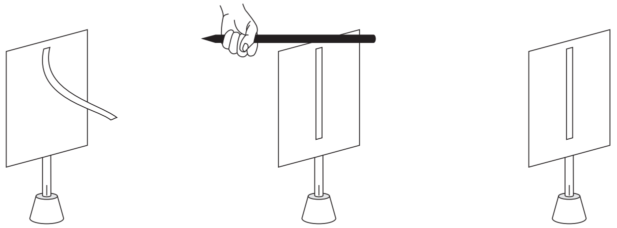

(a) (b) (c)

Figure 3.5: (a) An initially charged electroscope. (b) Hold one end of a wood skewer with the hand and touch the upper edge of the electroscope with the other end of the skewer. The strip drops immediately. (c) When the skewer is removed, the strip remains down.

An electrified electroscope is discharged when a piece of wood or metal held by the hand touches the cardboard. Utilize rough wood in this experiment. That is, the piece of wood should not be painted nor varnished. Paints and varnishes may behave as insulators and this fact might have an affect on the outcome of this experiment.

The electroscope is discharged immediately when a metal wire held by the hand touches the cardboard. The same happens with most wood skewers held by the hand. However, depending on the kind of wood, we may observe a fast discharge which is not instantaneous, taking a few seconds to discharge the electroscope.

Observe here again the discharge of the electrified electroscope as in Experiment 3.2, Figure 3.2. This time the discharge happened through the wood skewer or metal wire.

3.1.1 Definition of Conductor and Insulator when a High Voltage is Applied between the Ends of the Body

The electroscope allows the distinction of two kinds of bodies in nature, namely, the so-called *conductors* and *insulators*. We present here the fundamental definitions related to the usual experiments of electrostatics:

Definition 3.3

Substances which discharge an electrified electroscope simply by touching it, while held in the hand, as in Experiment 3.4, are called *conductors of electricity*, *electrical conductors* or simply *conductors*. Substances which do not discharge the electroscope, as in Experiment 3.3, are called *insulators*, *nonconductors*, or *dielectrics*.

3.1.2 Bodies which Behave as Conductors or Insulators in the Usual Experiments of Electrostatics

By performing procedures similar to Experiments 3.3 and 3.4 with several substances we obtain the following results:[2]

- **Conductors for the usual experiments of electrostatics:** Humid air, human body, all metals, paper, thin cardboard, aluminum foil, tissue paper, pasteboard, wood, cotton, a piece of chalk, many kinds of glass at ambient temperature, porcelain, wall, blackboard, cork, wheat flour, corn flour, acrylic thread, salt, sugar, sawdust, leather, earth or clay, brick, some kinds of rubber, soap, ice, etc.

- **Main insulators for the usual experiments of electrostatics:** Dry air, natural resins like amber, and synthetic resins like plastics in general.

The number of conducting substances is found to be much larger than the number of insulating substances. These two lists show that most substances are conductors, very few are insulators. Some of the conductors are very good, discharging the electroscope almost instantaneously, as is the case of the human body, metals, cotton, or paper. Although wood is a conductor, it does not conduct as well as the human body. This is indicated by the longer time interval required to discharge the electroscope when a wood skewer touches the cardboard, compared with the very short time interval in which it is discharged when a finger or a piece of metal held by the hand touches the cardboard.

List of some insulating substances: Dry air, silk (thread or cloth), natural resins (amber, copal, shellac), together with synthetic resins (plastic materials in general, PVC, nylon or polyamide, polyester, acrylic, Styrofoam, etc.)

Plastics were a great invention of the XXth century. The first synthetic resin, Bakelite, was created by Leo Hendrik Baekeland (1863-1944). It was presented to the American Chemical Society in 1909. He is usually considered the father of the chemical industry. These synthetic resins received the generic name of "plastic" due to the fact that they were malleable and could be molded into solid objects with any desired shape. Beyond these substances, a few other materials behave as insulators: Heated glass, wool, a single human hair, a chocolate bar, ground coffee, paraffin wax, and other kinds of rubber (which are different from the conducting kinds of rubber).

These two lists should not be taken as complete. Each person should build his own electroscope, testing the behavior of different materials. We should be careful with this distinction because there are many factors which can have an affect on the conducting or insulating behavior of any substance. Between these factors we can quote the chemical composition of the body, impurities located at its surface, its fabrication process, age of the material etc.

Here we present just one example. A PVC tube normally behaves as a good insulator, as it does not discharge an electrified electroscope. Some years ago we

---

[2] Chapter 6 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

built an electrostatic generator, Kelvin's water dropper, utilizing PVC tubes as insulators.[3] In order to build a working device, we had to make three different instruments. We discovered that in one of the earlier generators which did not work properly, there was a problem with the PVC tube which was being used. Although we had utilized it as an insulator, we discovered that this particular tube behaved as a conductor. Therefore it did not allow the accumulation of charges in the generator. We did not investigate the reasons why this particular PVC tube had this anomalous behavior. By changing this specific tube for another PVC tube which had been previously tested and shown to behave as a good insulator, we finally succeeded in the experiment. It was now possible to produce good sparks with this device.

Experiment 3.5 - *Touching a charged electroscope with water*

Utilize a similar procedure in order to determine which liquids are conductors or insulators. Use a conducting receptacle that will be filled with different liquids. In order to know if the receptacle is a conductor or an insulator, charge an electroscope and touch its thin cardboard against the receptacle while holding it with the hand. Suppose that the electroscope discharges after this contact. This discharge means that the receptacle is really conducting. Examples of suitable receptacles are the containers made of metal, wood, or many kinds of glass at room temperature. You can then continue with the experiment.

Fill completely the receptacle with the liquid to be tested. Figure 3.6 illustrates what happens with a conducting liquid like tap water.

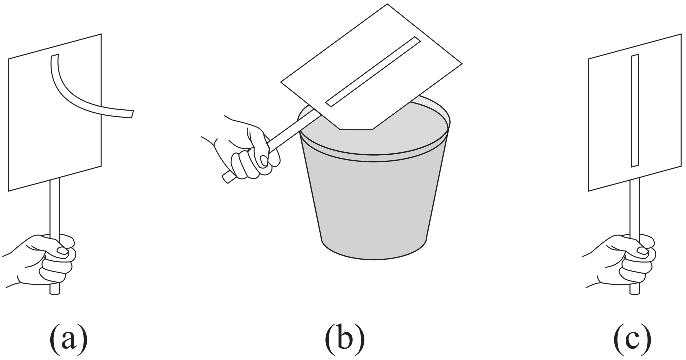


Figure 3.6: (a) A charged electroscope. (b) We submerge an edge of the electroscope in water. Its strip drops. (c) When the electroscope comes out of the water, the strip remains down.

Figure 3.6 (a) illustrates a charged electroscope. Hold it only by its plastic straw to avoid touching the thin cardboard or the raised strip. In (b) we submerge an edge of the electroscope in water. The cardboard should not touch

---

[3] [Cam06], [CA08] and Section 7.12 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

the receptacle, only the water. Observe that the strip drops. (c) When the electroscope comes out of the water, the strip remains down.

The electroscope was discharged through water.

Experiment 3.6 - *Touching a charged electroscope with vegetable oil*

Figure 3.7 illustrates what happens in the case of an insulating liquid like kitchen vegetable oil. Figure 3.7 (a) shows a charged electroscope. We then submerge an edge of the cardboard in the liquid. The cardboard should not touch the receptacle, only the oil. Observe that the strip remains raised, as in Figure 3.7 (b). When the electroscope comes out of the liquid, its strip remains raised, as in (c).

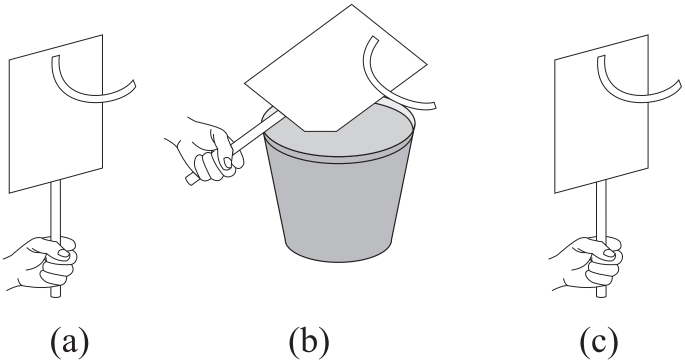


Figure 3.7: (a) A charged electroscope. (b) We submerge an edge of the cardboard in an insulating liquid. The strip remains raised. (c) When the electroscope comes out of the liquid, the strip remains raised.

The charged electroscope has not been discharged through vegetable oil.

By performing procedures such as Experiments 3.5 and 3.6 we obtain the following results:[4]

- **Conducting liquids for the usual experiments of electrostatics:** Fresh water, rain, tap water, hydrogen peroxide (H_2O_2), deionized water, distilled water, liquid bleach (sodium hypochlorite, $NaClO$), saline solution, alcohol, shampoo, kerosene, milk, soft drinks, detergent, sugarcane liquor, vodka, detergent, soy sauce, vinegar, liquid soap, honey, liquid glue, fabric softener or conditioner, enamel paint, acrylic paint, synthetic motor oil or engine oil, etc.
- **Insulating liquids for the usual experiments of electrostatics:** Melted paraffin and most kinds of oil.

---

[4] Chapter 6 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

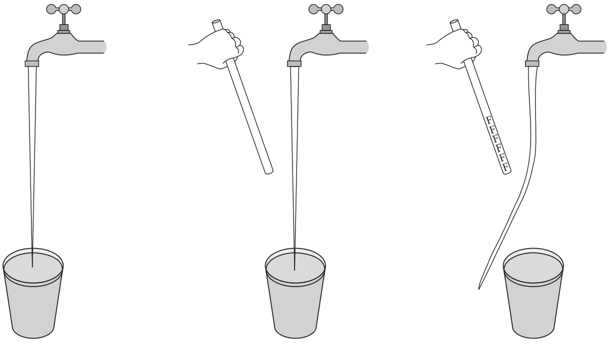
That is, almost all liquids of everyday life behave as conductors. List of some insulating liquids: oils in general (cooking vegetable oil like soybean or canola oil, olive oil, machine oil, mineral oil, peroba oil utilized as furniture polish, etc.). The exception to this list is the synthetic motor oil which behaves as a conductor in the usual experiments of electrostatics.

The same procedure utilized to test which liquids are conductors or insulators may also be utilized to test the conductivity of flours. That is, a conducting receptacle is filled with the flour to be tested. We submerge an edge of the charged electroscope in the flour, observing if the strip drops or remains raised. Avoid touching the receptacle with the cardboard of the electroscope.

Experiment 3.7 - *Electrified body attracting a thin stream of water*

This experiment illustrates the effect of rubbed amber, rubbed plastic or rubbed acrylic when brought close to liquids. The plastic straw or acrylic ruler should only approach the liquid, without touching it, no matter whether the straw (or ruler) is neutral or has been rubbed previously.

Turn on the tap so that a thin stream of water runs smoothly, Figure 3.8 (a). Bring a neutral plastic straw close to the stream and nothing happens, Figure 3.8 (b).



(a) (b) (c)

Figure 3.8: (a) Water running smoothly. (b) Nothing happens when a neutral plastic straw is brought close to the stream. (c) A rubbed straw attracting the stream.

Rub another straw and bring it close to the stream. This time the stream bends visibly toward the rubbed straw, Figure 3.8 (c)! This effect is more easily seen when the rubbed straw is moved near the upper part of the stream, where the water has a lower velocity. Sometimes the attraction is so intense that the stream touches the straw. The experiment also works with dripping water. The effect is more visible with the rubbed straw close to the slower droplets.

Something analogous happens when a rubbed plastic gets close to a stream of milk, detergent, alcohol, kerosene, shampoo, saline solution or near all liquids classified as conductors in Section 3.1. That is, the streams of these liquids are clearly attracted by the rubbed plastic. They are not attracted by a neutral straw.

Experiment 3.8 - *Electrified body attracting a thin stream of vegetable oil*

Repeat Experiment 3.7 to attract an insulating liquid like kitchen oil. Suppose a thin stream of oil is running smoothly from a glass or can, Figure 3.9 (a). Bring a neutral plastic straw close to the stream and nothing happens, Figure 3.9 (b). Rub another straw and bring it close to the stream. This time the stream bends a little toward the rubbed straw, Figure 3.9 (c).

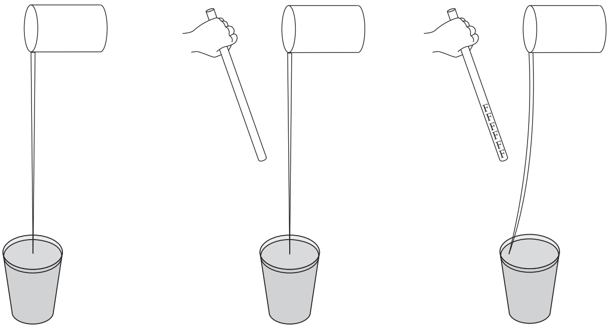

(a) (b) (c)

Figure 3.9: (a) Oil running smoothly. (b) Nothing happens when a neutral plastic straw is brought close to the stream. (c) A rubbed straw attracting weakly the stream of oil.

In the case of oil the effect—namely, the bending of the stream—is not so strong as in the case of the other conducting liquids of Experiment 3.7, like the water of Figure 3.8.

* * *

Experiments 3.7 and 3.8 show that the attraction exerted by an electrified body on a conductor is much larger than its attraction on an insulator.[5] Suppose two substances, a conductor and an insulator, of the same size, weight and shape. They are placed at the same distance from an electrified body. Experiments show that the conductor experiences a greater attractive force than the insulator, with both forces being exerted by the same electrified body. Extract a practical principle or rule of thumb from these experiments, namely: If an electrified body is visibly attracting light substances, these substances will behave as conductors in the usual experiments of electrostatics. That is, while held in the hand, these substances will discharge an electrified electroscope when they touch the cardboard of the electroscope.

---

[5] Section 7.7 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

The opposite effect also takes place. That is, substances which discharge an electroscope will be strongly attracted by a nearby electrified body. Insulators, on the other hand, do not discharge an electroscope and experience only a small attractive force exerted by a nearby electrified body.

3.2 Classifying Substances as Conductors or Insulators with the Circuit Tester

In Volume 1 of this book we showed that the potential difference acting between the ends of a body is an important factor influencing its conducting or insulating behavior.[6] A body behaving as an insulator when its ends are under a small electric potential difference (typically up to a few dozen volts) can behave as a conductor when this potential difference goes beyond a certain limit. In the usual experiments of electrostatics we deal with potential differences ranging typically from 1,000 volts up to 10,000 volts (that is, between 10^3 V and 10^4 V). In these conditions most solid and liquid substances behave as conductors. For low potential differences of up to a few dozen volts, on the other hand, most substances behave as insulators. Metals are an exception to this rule, as they behave as excellent conductors for these low and high potential differences. Natural and synthetic resins, like amber and plastics in general, are also exceptions to this rule. They behave as good insulators for these low and high potential differences.

This Section describes some experiments utilizing the circuit tester of Figure 2.19. We will be dealing with low potential differences. We will make a new definition of conductor and insulator appropriate for these conditions.

Experiment 3.9 - *Closing the circuit tester with a metal wire*

Consider a fourth piece of copper wire, uninsulated at the ends. One end of this fourth wire is connected to point A of Figure 2.19 and another end is connected to point B. The bulb should turn on, Figure 3.10. This fact will indicate that the electrical connections or contacts are properly made. Moreover, this fact will also indicate that there is an electric current flowing through the wires and bulb. Since the bulb turns on, the copper wire behaves as a conductor of electricity when it is under a potential difference of 1.5 volt = 1.5 V.

If the bulb is kept turned on for several minutes, the battery gets weaker. This fact is indicated by the intensity of the light, which decreases and eventually goes to zero. When this happens, the battery has been discharged. To prevent it from discharging, the best option is to open the contact (that is, remove the fourth wire between A and B) as soon as the light bulb turns on. You can then utilize the same battery to test other substances.

Experiment 3.10 - *Closing the circuit tester with a plastic straw or wood skewer*

---

[6] Section 6.6 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

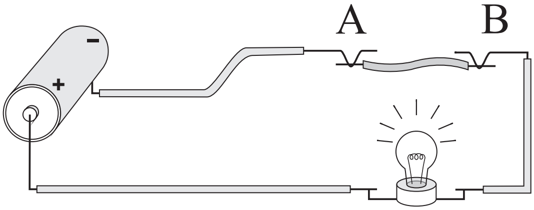


Figure 3.10: When the uninsulated ends of a copper wire are connected to the ends A and B, the bulb turns on.

Connect points A and B with a plastic straw. When we do this, the light bulb does not turn on. This fact indicates that no electric current is flowing through the circuit, Figure 3.11 (a). The bulb also stays off when A and B are connected with a wood skewer, Figure 3.11 (b).

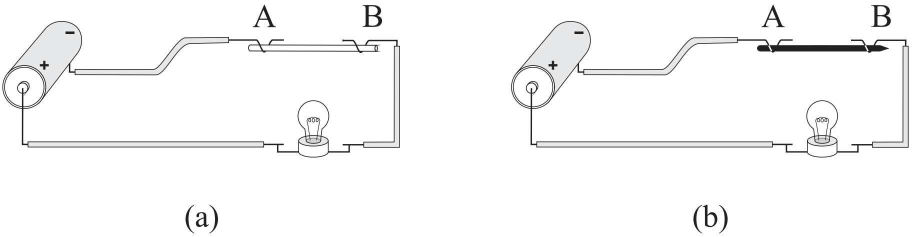


Figure 3.11: (a) The light bulb does not turn on when A and B are connected with a plastic straw. (b) The bulb also stays off when A and B are connected with a wood skewer.

Since the bulb does not turn on, a plastic straw or a wood skewer behave as insulators of electricity when they are under a potential difference of 1.5 V.

Experiment 3.11 - *Closing the circuit tester with water*

The best way to test liquids is to obtain an insulating receptacle (like a plastic cup, for instance). Initially it should be empty. In order to verify if it really is an insulator, connect A and B with this empty receptacle. From now on, suppose that the bulb does not turn on, indicating that this receptacle behaves as an insulator when under a potential difference of 1.5 V.

The plastic cup is then filled with fresh water from a tap or with rainwater. Terminals A and B are then submerged in the water. The light bulb does not turn on, Figure 3.12. This fact indicates that fresh water behaves as an insulator when it is under a potential difference of 1.5 V.

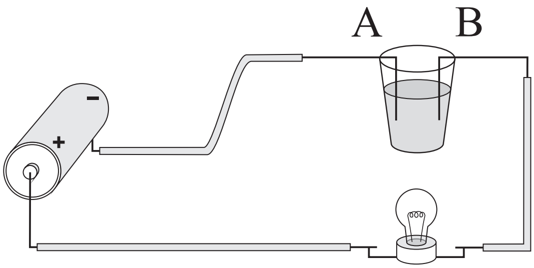


Figure 3.12: The light bulb does not turn on when A and B are connected with fresh water.

3.2.1 Definition of Conductor and Insulator when a Low Potential Difference is Applied between the Ends of the Body

By following the procedures of Experiments 3.9 up to 3.11 with several substances, make a new classification of substances based on another definition appropriate for low voltages.

Definition 3.4

If the bulb in Figure 2.19 turns on when a certain substance connects points A and B, as in Figure 3.10, this substance is called a *conductor*. If the bulb does not turn on, as indicated in Figure 3.11, the substance is called an *insulator*.

According to this definition, a copper wire is a conductor when its ends are under a potential difference of 1.5 V. A plastic straw, a wood skewer and fresh water, on the other hand, are insulators for this potential difference. As observed by Gaspar, graphite, salt water and a lemon also behave as insulators for this potential difference,[7] although many textbooks state wrongly that the light bulb would turn on when points A and B of Figure 2.18 were connected by these substances.

3.2.2 Bodies which Behave as Conductors or Insulators in the Usual Experiments with Constant Current

We perform several tests analogous to Experiments 3.9 to 3.11. The final result is as follows:

- **Substances which behave as conductors when their ends are under a potential difference of 1.5 V:**
  All metals.

---

[7] [Gas03, pp. 252-256].

- **Substances which behave as insulators when their ends are under a potential difference of 1.5 V:**
  Dry air, humid air, amber, plastic, silk, wood, heated glass, glass at room temperature, nylon or synthetic polyamide, cotton, PVC, polyester, wool, human hair, acrylic tube, acrylic cloth, Styrofoam, a chocolate bar, ground coffee, paper, thin cardboard, tissue paper, a piece of chalk, porcelain, fresh water, salt water, lemonade, alcohol, shampoo, kerosene, milk, soft drinks, detergent, kitchen vegetable oil, wall, blackboard, cork, wheat flour, corn flour, acrylic thread, salt, sugar, sawdust, earth or clay, brick, rubber, etc.

Several variations of these experiments can be made. When we don't have bulb's sockets, the wires can be soldered directly on the terminals of the light bulbs. That is, the uninsulated end of a wire is connected to the lateral shell of the screw of the bulb, while the uninsulated end of another wire is soldered to the bottom tip of the base of the screw of the bulb. These two wires can also be simply fixed to the shell and tip of the screw with adhesive tapes or with the hands. The uninsulated ends of the wires can also be brought directly into contact with the positive and negative terminals of the battery, being fixed by adhesive tapes or by our hands. If a battery support is available, normally it comes with wires connecting one of their ends directly to the terminals of the battery, while their free ends can be connected to other wires or to the socket of a bulb. Two 1.5 V batteries can also be connected in series yielding a 3 V potential difference between their free ends.

It is important to observe that there are several substances which behave as conductors according to Definition 3.3, while they behave as insulators according to Definition 3.4. Examples: fresh water, a wood skewer, paper, many kinds of glass at room temperature, etc. These substances discharge an electrified electroscope when there is a potential difference ranging from 1,000 V up to 10,000 V between the electroscope and the ground. Therefore, they behave as conductors for these high voltages. However, they don't allow the flow of an electric current with an intensity capable of turning on the lamp (that is, they do not allow the flow of a large enough amount of electrified particles through them) when their ends are under a small voltage going up to some dozens of volts. Therefore these same substances behave as insulators for these low voltages.

As mentioned in Volume 1 of this book, due to this fact, it might be appropriate to change the terminology. Normally we say that a certain body A *is* a conductor, while another body B *is* an insulator. However, from what has just been seen, it would be more correct to say that in a certain set of conditions body A *behaves as* a conductor, while in another set of conditions it *behaves as* an insulator. The same terminology would be valid for body B. But this new terminology would make all sentences very long and complicated. For this reason we will maintain the usual procedure of saying that bodies *are* conductors or insulators. But it should be clear to everyone that these are relative concepts. The behavior of bodies depends not only on their intrinsic properties, but also on the external conditions to which they are subject.

3.3 Factors Influencing the Conducting and Insulating Properties of a Substance

3.3.1 Nature or Chemical Composition of the Substance

The experiments of Section 3.1 show that bodies can be divided into two groups called conductors and insulators. In electrostatics a high potential difference can be applied to the ends of a body. They can then be classified utilizing a charged electroscope. Touch one end of the body to the cardboard of the electroscope and connect the other end of the body with the hand or with the ground. The bodies which discharge the electroscope are called conductors. An example is a metal wire. The bodies which do not discharge the electroscope are called insulators. An example is a plastic straw.

These experiments show that the main aspect influencing this classification is the nature of the body, that is, its chemical composition and internal structure. Most bodies behave in electrostatics as conductors. Examples: metals, water, paper, the human body, wood, many kinds of glass at room temperature, several kinds of rubber, etc. Only a few substances behave as insulators. Examples: dry air, silk, vegetable oil, amber and other natural resins, together with plastics in general and other synthetic resins.

The experiments of Section 3.2 show that another classification of conductors and insulators is required when a low potential difference is applied between the ends of a body. This new classification can be obtained utilizing the circuit tester of Figure 2.19. Begin with a new battery and connect the ends of the body between points A and B of the circuit tester. When the light bulb turns on, we say that the body is a conductor. When the bulb does not turn on, we say that the body behaves as an insulator.

These experiments also show, in the usual experiments in which a constant current can flow through the circuit, that the main aspect influencing the classification of the bodies is their nature or chemical composition. For low potential differences (up to a few hundred Volts) all metals behave as conductors. Most other substances behave as insulators. Examples: water, paper, the human body, wood, most glasses at room temperature, several kinds of rubber, dry and humid air, silk, vegetable oil, amber and other natural resins, together with plastics in general and other synthetic resins.

3.3.2 Potential Difference between the Ends of the Body

Beyond the internal or intrinsic properties of a body, Sections 3.1 and 3.2 showed that another fundamental property in order to classify any substance as a conductor or insulator is the external potential difference applied between the ends of the body. Metals behave as conductors for low and high potential differences. Other substances behave as insulators for low and high potential differences: dry air, silk, vegetable oil, amber and other natural resins, together with plastics in general and other synthetic resins.

On the other hand, there are several substances which behave as conductors in the usual experiments of electrostatics (dealing with high potential differences), but behave as insulators in the usual experiments dealing with the possible flow of a constant electric current (dealing with low potential differences). We list here some of these substances: humid air, water, paper, the human body, wood, many types of glass at room temperature and several kinds of rubber. Subsections 3.1.2 and 3.2.2 presented the appropriate classifications for each case.

3.3.3 The Time Required to Discharge an Electrified Body

Experiment 3.12 - *An electroscope resting on a table discharges with the passage of time*

Charge an electroscope as in Experiment 3.1, Figure 3.1. That is, scrape its cardboard with a rubbed straw. Leave this charged electroscope on a table on a dry day. Observe that the strip remains raised for several seconds or even for a few minutes. However, if we wait long enough—like one hour, for instance—the electroscope will totally discharge.

This phenomenon implies that Definition 3.3 of a conductor and of an insulator, as given in Subsection 3.1.1, depends upon the observation time. For a time interval of a few seconds, dry air can be considered a good insulator. For a time interval of one hour, on the other hand, dry air can be classified as a conductor, as it allows the discharge of an electroscope.

This distinction can be clarified with more precise definitions related to the experimental procedures described in Section 3.1.

Definition 3.5

For the purpose of this book, *good conductors* are the substances which discharge an electrified electroscope when they are brought into contact with it for less than 5 seconds. *Bad conductors*, or *bad insulators*, are the substances that take about 5 to 20 or 30 seconds to discharge the electroscope. These bodies are also called *poor conductors*, *poor insulators*, *imperfect conductors* or *imperfect insulators*. Finally, *good insulators* are the substances that require more than 20 or 30 seconds to discharge an electrified electroscope. In this book we will usually refer to the good conductors as conductors, while the good insulators will be simply called insulators.

3.3.4 The Length of the Body

The experiments of this Subsection and those of Subsection 3.3.5 should be performed only on dry days. In this case an electroscope, charged as in Experiment

3.1, Figure 3.1, remains electrified during a time interval of at least 30 seconds. On wet and rainy days, on the other hand, the electroscope discharges quickly to the surrounding air soon after being electrified (as when its cardboard is scraped with a rubbed straw or plastic ruler). On these rainy days the results of the experiments of this Subsection and those of Subsection 3.3.5 will not be very clear. For this reason, avoid performing these activities in wet weather.

This Subsection considers the influence of the length of a substance which comes into contact with a charged electroscope as regards its conducting or insulating properties.

Experiment 3.13 - *Discharging an electroscope by touching it with strips of paper*

Cut several strips of paper (like $A4$ or letter size), 2 cm wide and with lengths varying from 10 cm up to 1 m. This length of 1 m can be obtained attaching the ends of shorter strips with glue or paper clips. Charge an electroscope and place it on a table on a dry day. Hold one end of the 10 cm strip with the hand and touch its free end to the edge of the thin cardboard of the electroscope.[8] Observe a quick discharge of the electroscope, from 1 to 3 seconds, Figure 3.13 (b) and (c). Therefore, by Definition 3.5 of Subsection 3.3.3, this strip can be considered a good conductor.

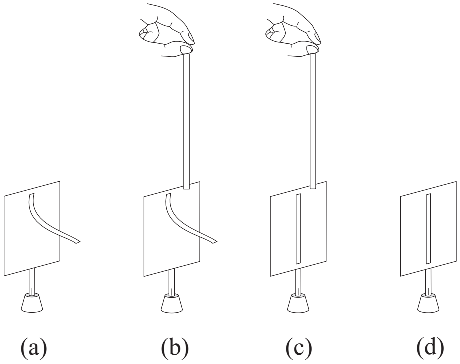


Figure 3.13: (a) A charged electroscope. (b) and (c): A strip of paper held by the hand discharges quickly the electroscope when its free end touches the thin cardboard. (d) Removing the paper strip leaves the electroscope discharged.

Charge the electroscope again and now utilize a 30 cm × 2 cm paper strip. Hold one end of the paper strip with the hand while its free end touches the cardboard of the electroscope. Observe easily the required time interval of 4 to 6 seconds in order to discharge the electroscope. Depending upon the type of paper, this 30 cm long strip of paper may be considered a bad conductor.

This experiment shows clearly also that the amount of charge lost by the electrified electroscope increases with the passage of time, see Subsection 3.3.3.

---

[8] Section 6.7 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

The only difference is that in the present situation the electroscope is being discharged mainly through the paper strip and not through the surrounding air.

The electroscope is charged once more and the experiment repeated with a 1 m long and 2 cm wide paper strip. Observe that the electroscope remains charged for some 10 seconds. When the air is very dry, this discharge time interval can increase up to 20 or 30 seconds, depending on the type of paper. By Definition 3.5 of Subsection 3.3.3, we conclude that this 1 m long paper strip may be considered a good insulator.

This experiment shows that the length of a substance has an influence on its behavior as a conductor or insulator. By increasing the length of a substance between the hand and the cardboard of the electroscope, we increase the time interval required to discharge the electroscope.

Experiment 3.14 - *Discharging an electroscope by touching it with sewing threads*

Experiment 3.13 can be repeated with several materials. There are several interesting substances which show clearly the influence of the length of the body on the time interval required to discharge an electroscope: paper, cardboard, a cotton string or twine, sewing thread, etc. Table 3.1 presents the measured time interval required to discharge an electroscope with 2 cm wide paper strips and with sewing threads, when the procedure of Experiment 3.13 is followed.

Substance \ Length	10 cm	30 cm	1 m
paper strip	1-3 s	4-6 s	10-30 s
sewing thread	2 s	3 s	6 s

Table 3.1: Approximate time intervals required to discharge the electroscope.

The numerical values of this Table and of the other Tables presented in this book should be considered only qualitatively. Values much different from what is being presented here can be obtained depending on the amount of electrification of the electroscope, on its size, on the atmospheric conditions of the day on which the experiment is being performed, on the quality or chemical composition of the material which is being tested, etc. These numbers indicate only the qualitative behavior of the factors which influence the conducting or insulating properties of a body.

Experiment 3.15 - *Touching a charged electroscope with other substances*

Perform a similar experiment utilizing a plastic straw instead of the paper strip. A common straw is 20 cm long. Cut it and connect the ends of these straws, making straws with several lengths: 10 cm, 30 cm or 1 m long. Hold one end of this straw with the hand while its free end touches the cardboard of a charged electroscope. Observe that the electroscope remains charged for more than 20 or 30 seconds on a dry day. We conclude that straws with all these different lengths can be considered as good insulators. We do not perceive in this case the influence of its length in the time of discharge, as the electroscope remains charged even after the cardboard is touched with a short 10 cm long plastic straw.

The opposite behavior happens when 2 cm wide strips of aluminum foil touch the cardboard of a charged electroscope. That is, it discharges almost instantaneously for strips with lengths ranging from 10 cm to 1 m. An aluminum foil strip can be considered a good conductor in all these cases. Once more we do not perceive the influence of its length in the time of discharge. After all, even for a 1 m long strip, the discharge of the electroscope is so fast that it cannot be measured with an ordinary wrist watch.

Experiment 3.16 - *Charging two electroscopes connected by paper strips*

A similar experiment utilizes two electroscopes connected by strips or lines made of different materials, namely, paper, cardboard, aluminum foil, plastic straws, twine or sewing thread.[9] These materials can be fixed to the cardboards of the electroscopes utilizing paper clips, Figure 3.14.

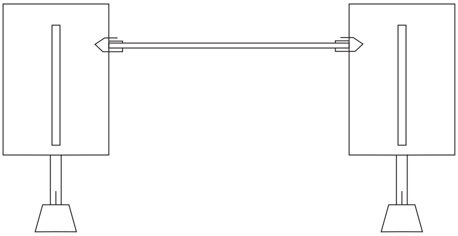


Figure 3.14: Two electroscopes connected by a paper strip.

Connect the two electroscopes with a 2 cm wide and 10 cm long paper strip. The electroscopes are initially discharged. Electrify an acrylic ruler or a plastic straw by friction in hair or in a paper napkin. Scrape the rubbed straw on the upper edge of one of the electroscopes a few times until it is charged, that is, until its tissue paper strip remains raised. Try to measure the time interval required to charge the second electroscope. This measure is not reliable. After all, the second electroscope begins charging not only at the end of this procedure, but also during the time interval in which the first electroscope is being initially scraped for the first time. Sometimes it is necessary to tap the straw of the second electroscope a few times to release its thin tissue paper strip, so that it begins to raise.

Experiment 3.17 - *Discharging two electroscopes connected by paper strips*

A more reliable measurement of the time interval can be obtained utilizing both electroscopes of Experiment 3.16. To this end, wait until both electroscopes

---

[9] [FM91, pp. 43-45], [Ferc, p. 70] and [FR08, p. 18].

connected by the paper strip are equally electrified. Touch the upper cardboard of one electroscope with the finger. Its tissue paper strips drops immediately. While holding the finger on the first electroscope, measure the time interval required to discharge the second electroscope. When the two electroscopes are connected by this 2 cm wide and 10 cm long paper strip, this required time interval ranges from 2 to 3 s.

Repeat this experiment with 2 cm wide paper strips of different lengths connecting the electroscopes, with lengths ranging from 10 cm up to 1 m. The same procedure can be utilized when the two electroscopes are connected with sewing threads 10 cm, 30 cm and 1 m long. Table 3.2 indicates a typical result of an experiment like this one utilizing different materials.

Substance \ Length	10 cm	30 cm	1 m
paper strip	2-3 s	5 s	20-25 s
sewing thread	2 s	4 s	15-20 s

Table 3.2: Approximate time intervals required to discharge one of the charged electroscopes after grounding the other electroscope.

Connect the two electroscopes with 10 cm, 30 cm or 1 m long plastic straws. Electrify both electroscopes equally by scraping rubbed straws on their cardboards. Their tissue paper strips should be equally raised relative to both cardboards in the beginning of this experiment. Touch the cardboard of the first electroscope with the finger, observing that its tissue paper strip drops immediately. The second electroscope, on the other hand, remains electrified for more than 20 or 30 seconds on a dry day, regardless of the length of the plastic straw connecting the electroscopes.

Connect the two electroscopes by 2 cm wide aluminum foil strips of different lengths, namely, 10 cm, 30 cm or 1 m long. Electrify the system so that both tissue paper strips are equally raised. When a finger touches the cardboard of the first electroscope, its tissue paper strip drops immediately. The same happens with the tissue paper strip of the second electroscope, regardless of the length of the aluminum foil strip connecting the two electroscopes.

In these two last examples we are not able to detect the influence of the length of the body connecting the two electroscopes as regards the time interval to discharge the second electroscope. When they are connected by a plastic straw, this time interval is very long, regardless of the length of the straw. That is, the second electroscope remains charged after grounding the first electroscope. When they are connected by an aluminum foil strip, on the other hand, this time interval goes to zero, regardless of the length of the strip. That is, both electroscopes discharge almost instantaneously when one of them is grounded. The time interval required to discharge the second electroscope in this case is so small that it cannot be measured with a simple wrist watch, regardless of the length of the aluminum foil strip connecting the electroscopes.

Consider now the situation of the previous experiments in which the time interval required to discharge the second electroscope ranged from 1 second to 2 minutes. These experiments showed that the greater the length of the body connecting the two electroscopes, the slower was the discharge of the second electroscope after grounding the first electroscope.

3.3.5 The Cross-Sectional Area of the Body

This Subsection considers the influence of the cross-sectional area of a substance which comes into contact with a charged electroscope as regards its conducting or insulating properties.

Experiment 3.18 - *Discharging an electroscope by touching it with hair*

Charge an electroscope and place it on a table. Hold one end of a single human hair with the hand and touch the other end of the hair on the thin cardboard of the charged electroscope, as in Figure 3.13. Observe that the electroscope remains charged for several seconds. This indicates that a single human hair can be classified as a good insulator.

Charge the electroscope once more and increase the number of hairs held by the hand. Touch their free ends simultaneously on the cardboard of the charged electroscope. Observe that by increasing the number of hairs, the discharge becomes faster. For instance, with dozens of hairs the electroscope discharges in a few seconds. This amount of hair can be classified as a good conductor.

Experiment 3.19 - *Discharging an electroscope by touching it with paper strips*

Repeat Experiment 3.13 utilizing bodies with a fixed length but changing their cross-sectional areas. Change, for instance, the width of the paper strips which will come into contact with the electroscope. Table 3.3 shows the result of this experiment with 1 m long paper strips and two different widths, 0.5 and 2 cm.

Width of the paper strip	0.5 cm	2 cm
Time intervals	50 s	10 s

Table 3.3: Approximate time intervals to discharge the electroscope.

Experiment 3.20 - *Discharging an electroscope by touching it with cotton threads*

Repeat Experiment 3.13 utilizing cotton threads or twines of fixed length, but changing their cross-sectional areas. Hold one end of the thread, touch the other end on the cardboard of the charged electroscope and measure the discharge time. Table 3.4 shows the result of this experiment with a thin cotton sewing thread and a thicker cotton string or twine, both of them 1 m long.

Cotton	sewing thread	twine
Time intervals	6 s	6-7 s

Table 3.4: Approximate time intervals to discharge the electroscope.

Experiment 3.21 - *Discharging two electroscopes connected by a paper srip*

Repeat Experiment 3.16 connecting the two electroscopes by paper strips of the same lengths but with different widths or with different cross-sectional areas. Table 3.5 compares the time intervals required to discharge electroscope 2 after electroscope 1 has been grounded by touching its cardboard with the finger. All connecting substances were 1 m long.

Width of the paper strip	0.5 cm	2 cm
Time intervals	60 s	20-25 s

Table 3.5: Approximate time intervals to discharge one of the electroscopes when the other electroscope is grounded.

Experiment 3.22 - *Discharging two electroscopes by a cotton thread*

Repeat Experiment 3.16 connecting the two electroscopes by cotton threads of the same lengths but with different widths or with different cross-sectional areas. Table 3.5 compares the time intervals required to discharge electroscope 2 after electroscope 1 has been grounded by touching its cardboard with the finger. All connecting substances were 1 m long.

Cotton	sewing thread	twine
Time intervals	15-20 s	6-7 s

Table 3.6: Approximate time intervals to discharge one of the electroscopes when the other electroscope is grounded.

Experiment 3.23 - *Discharging an electroscope by touching it with several paper strips*

Instead of varying the width of the paper strips, change the number of paper strips of the same width. Perform, for instance, the experiment with 1 m long and 0.5 cm wide paper strips. Charge the electroscope, hold the end of this strip as in Figure 3.13 and connect its free end to the cardboard of the electroscope, measuring the discharge time.

In another experiment, we join 3 equal paper strips with a paper clip at each end. Hold one of the paper clips with the hand and touch the other clip on the

Number of paper strips	1	3
Time intervals	50 s	3 s

Table 3.7: Approximate time intervals to discharge the electroscope.

cardboard of the charged electroscope, measuring the discharge time. Table 3.7 compares the results of this procedure.

Experiment 3.24 - *Discharging an electroscope by touching it with several cotton threads*

Instead of varying the cross-sectional areas of the cotton threads, change the number of cotton threads of the same cross-section. Table 3.8 compares the results of this procedure.

Number of sewing threads	1	3
Time intervals	6 s	2-3 s

Table 3.8: Approximate time intervals to discharge the electroscope.

Experiment 3.25 - *Discharging two electroscopes connected by several paper strips*

In another test, connect two electroscopes as in Experiment 3.16. Measure the time interval to discharge one of the electroscopes when the other electroscope is grounded. We always utilize paper strips of the same length and width in all experiments. Initially the electroscopes are connected by a single paper strip and we measure the discharge time.

In the next experiment, connect the two electroscopes with 3 paper strips and measure once more the discharge time. Table 3.9 presents the results of this experiment utilizing 1 m long paper strips 0.5 cm wide.

Number of paper strips	1	3
Time intervals	60 s	15 s

Table 3.9: Approximate time intervals to discharge one of the electroscopes after grounding the other electroscope.

Experiment 3.26 - *Discharging two electroscopes connected by several cotton threads*

In another test, connect two electroscopes as in Experiment 3.16. Measure the time interval to discharge one of the electroscopes when the other electroscope is grounded. We always utilize sewing cotton threads of the same spool and having the same length. Initially the electroscopes are connected by a single cotton thread.

In the next experiment, connect the two electroscopes with 3 sewing threads and measure once more the discharge time. Table 3.10 presents the results of this experiment utilizing 1 m long sewing cotton threads of the same spool.

Number of sewing threads	1	3
Time intervals	15-20 s	16-18 s

Table 3.10: Approximate time intervals to discharge one of the electroscopes after grounding the other electroscope.

Experiments like these show that the cross-sectional area of a body has an influence on its conducting or insulating properties. The larger this area between the hand and the cardboard of the electroscope, the smaller will be the time interval required to discharge the electroscope. Likewise, the larger the area of the body connecting two electroscopes, the smaller will be the time interval required to discharge one of the electroscopes after grounding the other electroscope by touching its cardboard with the finger.

We present now some relevant definitions.

Definition 3.6

The flow of electrified particles through the cross-section of a body is called an *electric current*. It is proportional to the amount of charge per unit time passing through the cross section of the conductor.

An example is the electric current flowing through a paper strip or through a sewing thread in these experiments.

This flow of electrified particles depends on the material of the conductor. An aluminum foil strip, for instance, conducts better than a common paper strip of the same length, width and thickness. And these two materials conduct much better than a plastic strip of the same size. Suppose that we want to discharge an electrified electroscope. Hold one strip in the hand and touch its free end on the cardboard of the electroscope. The amount of charge to be discharged will be always the same, namely, the initial electrification of the electroscope. The discharge time when touching it with an aluminum foil strip is smaller than the discharge time when a paper strip touches it. And this last time is much smaller than the required time interval to discharge the same electroscope when a plastic strip touches it.

Consider now conductors of the same material. Given the same initial conditions as in the previous experiments, the electric current flowing through a body will depend on its length. By increasing the length of a substance between the hand and the cardboard of the electroscope, we increase the time interval required to discharge the electroscope. Likewise, the larger the length of a body connecting two charged electroscopes, the longer will be the time interval required to discharge one of the electroscopes after grounding the other electroscope.

This electric current also depends on the cross-sectional area of the conductor, assuming the same initial conditions as in the previous experiments. The larger this area between the hand and the cardboard of the electroscope, the smaller will be the time interval required to discharge it. Likewise, the larger the cross-section of a body connecting two charged electroscopes, the smaller will be the time interval required to discharge one of the electroscopes after grounding the other electroscope.

Definition 3.7

We say that the body connecting the two electroscopes in these experiments has an *electrical resistance*. At every moment this resistance is proportional to the potential difference between the two electroscopes and inversely proportional to the electric current passing through the body.

Assume the same initial conditions. For instance, two charged electroscopes connected by a paper strip or by a sewing thread. Ground one of the electroscopes by touching its cardboard with the finger and measure the time interval to discharge the other electroscope. The longer this time interval, the larger will be the resistance of the body connecting them. This fact means that the resistance of this body is inversely proportional to the electric current flowing through it, assuming the same potential difference between its ends. According to the previous experiments, the resistance of a body increases with the length of the body, decreases with the size of its cross-sectional area, depending also on the material or chemical composition of the body.

Experiment 3.27 - *Comparing the time intervals*

It is also interesting to compare the time intervals of Figures 3.13 and 3.14 in order to discharge an electrified electroscope. In the first case we have a charged electroscope. Hold a strip or string by hand and touch its free end on the cardboard of the electroscope, measuring the time interval to discharge it. In the second case we have two charged electroscopes connected by a strip or string. Ground one of the electroscopes by touching it with the hand and measure the time interval to discharge the second electroscope. Suppose the same body being utilized to discharge the electroscopes in these two cases. It might be, for instance, a paper strip with the same length and width in both cases. Observe that the discharge time in the first case is usually shorter than the discharge time in the second case.

This time difference can be justified. In the second case we had not only an electrified electroscope to be discharged, but also an electrified body connecting both electroscopes, namely, the paper strip or the cotton string. Therefore, when a finger touches the first electroscope, we need to discharge not only the second electroscope, but also this connecting body. In the first case, on the other hand, it was not necessary to discharge the paper strip nor the cotton string. After all, these connecting bodies were already discharged as they were held in the hand.

We can show that the paper strip (or cotton thread) connecting the two charged electroscopes of Figure 3.14 was also electrified. To this end, place a metal versorium close to the strip or thread, in the same horizontal plane, anywhere along the length of the strip or string. Initially, when the two electroscopes are still discharged, the versorium should point in an arbitrary direction. Scrape a few times an electrified acrylic ruler on the cardboard of one of the electroscopes. Wait until both electroscopes are equally charged. Observe that the versorium points now towards the strip. This fact indicates that the strip is now electrified. The same thing happens with a connecting cotton thread or string.

Experiment 3.28 - *Discharging alternately two electroscopes*

Another interesting experiment can be made with the two electroscopes of Figure 3.14. Suppose a 1 m long and 0.5 cm wide paper strip connecting the electroscopes. Assume that both electroscopes are equally electrified in the beginning of this experiment. In this case, when the finger touches the cardboard of electroscope 1, its tissue paper strip drops immediately. The tissue paper strip of electroscope 2, on the other hand, takes some 60 seconds to drop completely while the finger touches the cardboard of electroscope 1.

Repeat this experiment. But now remove the finger from the first electroscope 5 seconds after touching it. Its tissue paper strip, which had dropped completely, begins to raise again. While the strip 1 is raising, the tissue paper strip of electroscope 2 drops a little. After a while both tissue paper strips are inclined by the same amount relative to their cardboards. Touch the finger to the cardboard of the second electroscope, removing it after 5 seconds. The phenomena just described with the tissue paper strips takes place once more, but in the opposite electroscopes. Repeat this procedure, every time touching a different electroscope after they reached a new equilibrium. Little by little the whole system is discharged.

Experiment 3.29 - *Charging alternately two electroscopes*

It is also curious to begin with both electroscopes discharged. They are connected by a long paper strip of small width. Scrape once or twice an electrified acrylic ruler on the cardboard of electroscope 1, observing that its tissue paper strip raises almost immediately. The tissue paper strip of electroscope 2, on the other hand, raises slowly.

After equilibrium has been reached, scrape the electrified ruler on the cardboard of electroscope 2. Its tissue paper strip raises even more, once more almost instantaneously. The tissue paper strip of electroscope 1, on the other hand, needs a measurable time interval in order to raise to the same level of the tissue paper strip of electroscope 2.

3.3.6 Humidity

Humidity of the Connecting Body

Experiment 3.30 - *Grounding the electroscope with bodies of different humidity*

Repeat the experiments of Section 3.1 and of Subsection 3.3.4 changing the humidity of the body which will be connected to the charged electroscope of Figure 3.13. In all cases the electroscope will be touched with 30 cm long and 0.5 cm wide strips from the same sheet of paper. Hold the strip by hand through its upper end. Measure the time interval to discharge the electroscope from the moment in which the lower end of the paper strip touches its cardboard. In this experiment we vary only the degree of humidity of the paper strips. Utilize a dry strip in the first case.

In the second case, use a wet strip (wet along its whole length, on both sides, utilizing a water sprayer). Experiments show that the dryer the paper strip, the longer will be the discharge time. Therefore, the dryer the paper, the more insulating it is.

This different behavior of the paper strip is obviously due to the absorbed amount of water. If we compare the conductivities of two columns of the same length and cross-sectional areas, one of fresh water and the other of common paper, we obtain that water is a much better conductor than paper. That is, it discharges an electrified electroscope faster. Therefore, when a paper strip absorbs water, it becomes a better conductor than dry paper.

It should be observed that water is absorbed along the whole cross-section of the strip, not only along its surface.

Air Humidity

Electrostatic experiments normally work well on dry weather, yielding visible and perceptible effects. Air humidity hinders the accumulation of electric charges, decreasing the size or magnitude of the effects to be observed.

Experiment 3.31 - *Electroscope resting on a table on a dry day*

It is easy to charge an electroscope on a dry day. Rub a plastic straw in hair. Scrape this rubbed straw over the thin cardboard of the electroscope, as described in Experiment 3.1, Figure 3.1. The electroscope remains charged for several seconds or for a few minutes after this procedure, Figure 3.1 (c). This fact implies that dry air is a good insulator, according to Definition 3.5 given in Subsection 3.3.3.

Experiment 3.32 - *Electroscope resting on a table on a humid day*

Repeat Experiment 3.31 on a humid and rainy day. While we scrape a rubbed straw on the cardboard of the electroscope, its strip goes up, as in Figure 3.15 (b).

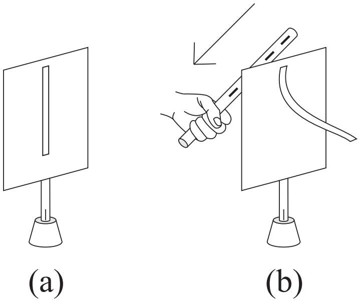


Figure 3.15: (a) Electroscope with its strip pointing downward. (b) While the upper edge of the rectangle is being scraped with a rubbed straw, the strip goes up. (c) When the straw is removed, the strip drops almost immediately on a rainy day.

Remove the rubbed straw. The strip drops soon afterward, Figure 3.15 (c). The higher the humidity of air, the faster will be the discharge of the electroscope. Depending upon the value of this humidity, air can behave as a bad or good conductor. The presence of water vapor in humid air is one of the reasons which makes it behave as a conductor, due to the fact that water itself is a good conductor for the usual experiments of electrostatics.[10] A charged surface may attract water molecules or droplets, which on contact become charged and are then repelled by the surface. See the *ACR* mechanism described in Section 4.4. This process might discharge the surface.

In humid weather the electroscope presents an anomalous behavior in comparison with what happens on dry days. For instance, it is more difficult to charge it. Moreover, the charged electroscope is more easily discharged on humid weather than on dry days. There are two main factors influencing the behavior of electroscopes, factor I and factor II. The electroscope is surrounded by air, and it is connected to the ground through the plastic straw supporting its cardboard. It can discharge through the surrounding air (factor I) or through the supporting plastic straw (factor II). Section 3.1 showed that fresh and rain water behave as good conductors for electrostatic experiments. Factor I: Air humidity increases the conductivity of the atmosphere. Therefore, an electrified electroscope can easily loose its charge to the surrounding environment. Factor II: Water vapor can also condense on the surface of any material connected to the ground and supporting its cardboard, such as the plastic straw. This accumulated humidity on the surface of the straw can make it behave as a conductor, facilitating the flow of electrified particles to the ground. This effect is specially relevant for hydrophilic materials.

---

[10] Sections 7.11 and 7.13 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

3.3.7 Orientation of the Body Relative to the Applied Voltage

There are some anisotropic materials in which their electrical resistance varies depending on the direction or orientation of the body. Graphite, for instance, has a layered or planar structure. Its electrical resistance is low along the plane of the layers and high in a direction orthogonal to these layers.

There are some polar materials which behave as conductors in one direction and as insulators in the opposite direction. That is, they have low resistance to the flow of current in one sense and high resistance in the contrary sense. The most common and important example is the semiconductor diode. It can be easily obtained at low cost at electric shops (a few cents per diode). It has many applications in the electronic industry, being utilized as a rectifier of electric current, switch, etc. Figure 3.16 (a) shows how it looks, while Figure 3.16 (b) presents its symbol in a circuit diagram. Its two leads are called anode and cathode.

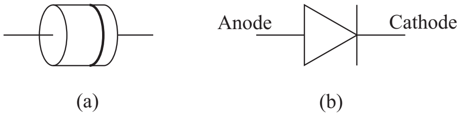


Figure 3.16: (a) Representation of a real diode. (b) Symbol used in a circuit diagram.

Experiment 3.33 - *Polarity of the diode*

Observe the behavior of a diode in a simple circuit containing a small 1.5 volt bulb and socket, one or more 1.5 V batteries, together with a few pieces of wire. Utilize a single battery or two batteries connected in series. Mount a circuit tester like that of Figure 3.17 (a). In this configuration the light bulb should turn on indicating not only that all electrical connections have been properly made, but also that the diode in this orientation behaves as a conductor. In this configuration the diode is *forward biased*, with the anode of the diode connected to the positive terminal of the battery.

When the polarity of the diode is reversed, as in Figure 3.17 (b), the bulb does not turn on. In this configuration the anode of the diode is connected to the negative terminal of the battery. The diode is *reverse biased*, behaving as an insulator.

This behavior is fascinating. The simple orientation of the diode in relation to the battery changes completely its conducting properties. This experiment shows that the diode is polar. It is not easy to understand how it can act like that. It is difficult to explain its internal constitution in simple terms. In any event, after understanding how it works in experiments like this one, it is then easy to utilize it in many different applications.

Experiment 3.34 - *Applying a high voltage to a diode*

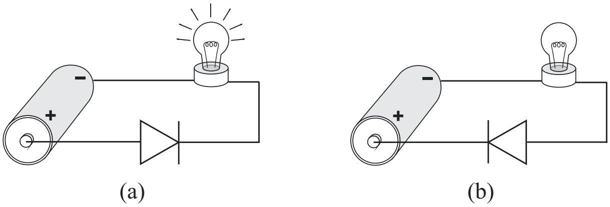


Figure 3.17: (a) The diode is forward biased, behaving as a conductor. Current flow is permitted in this orientation. (b) The diode is reverse biased, behaving as an insulator. Current flow is prevented in this orientation.

Experiment 3.33 utilized a diode, a battery, a light bulb and some pieces of wire. It showed that a diode can behave as a conductor or insulator, depending on its orientation relative to the battery. This conducting or insulating behavior of the diode depends on the potential difference acting between its ends. In this experiment one or more batteries generated a potential difference of a few volts between its ends. In electrostatic experiments, on the other hand, we usually work with potential differences ranging from 1,000 V up to 10,000 V.

The present experiment analyzes the behavior of a diode in electrostatics.

Charge an electroscope, Figure 3.18 (a). Hold the diode with its cathode in the hand and touch its anode on the cardboard of the charged electroscope. The tissue paper strip drops immediately, Figure 3.18 (b). This strip remains vertical after the diode has been removed, indicating that the electroscope has been discharged.

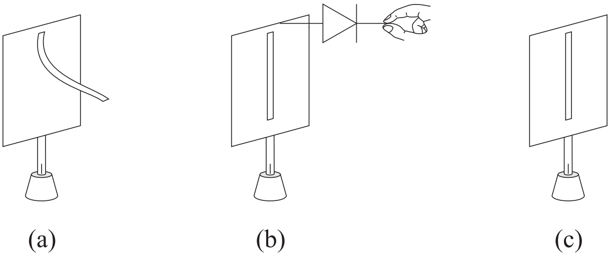


Figure 3.18: (a) A charged electroscope. (b) While holding the cathode of the diode in the hand, touch its anode on the cardboard of the electroscope, observing that its strip drops immediately. (c) The strip remains vertical after the diode has been removed.

The electroscope also discharges when the diode is held through its anode, while its cathode touches the cardboard of the electroscope, Figure 3.19.

In conclusion, the diode behaves as a conductor in electrostatic experiments not only when forward biased, but also when reverse biased. This is another example showing that the conducting or insulating properties of a body depend not only on the nature or chemical composition of the body, but also on

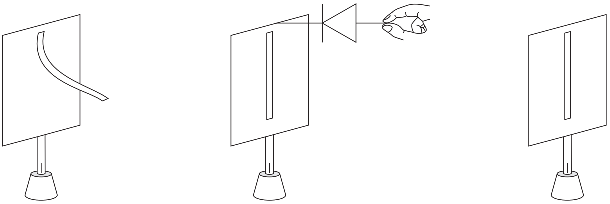

(a) (b) (c)

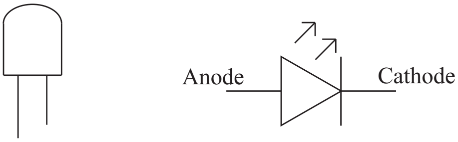
Figure 3.19: (a) A charged electroscope. (b) While holding the anode of the diode in the hand, touch its cathode on the cardboard of the electroscope, observing that its strip drops immediately. (c) The strip remains vertical after the diode has been removed.

the external potential difference applied to the ends of the body, as shown in Subsection 3.3.2.

We did not specify in this experiment if the electroscope was positively or negatively charged. This aspect is not relevant for the outcome of the experiment. That is, the behaviors indicated by Figures 3.18 and 3.19 take place not only for a positively charged electroscope, but also for a negatively charged electroscope. In these two cases the diode behaves as a conductor, no matter if the diode is forward or reverse biased.

Experiment 3.35 - *Polarity of the LED*

There are some special types of diode that emit light, the so-called light emitting diodes, or LEDs. They come in many different shapes. Figure 3.20 (a) shows how it looks, while Figure 3.20 (b) shows its symbol in a circuit diagram. They are cheap and easily found in electric shops (a few cents per LED). They turn on when we apply 1.5 V or 3 V to their legs.

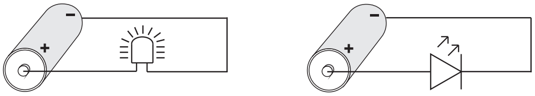


(a) (b)

Figure 3.20: (a) Representation of a real LED. (b) Symbol used in a circuit diagram.

They can replace the light bulbs of Sections 2.7, 3.2 and Subsection 3.3.2. However, keep in mind that they are polar, like any other diode. That is, when the LED is forward biased, it will turn on, as indicated in Figure 3.21. In this configuration the positive terminal of the battery is connected to the anode of the LED, while the negative terminal of the battery is connected to its cathode.

However, when it is reverse biased, it will not turn on, as indicated in Figure 3.22.



(a) (b)

Figure 3.21: (a) LED turned on in the direct polarization. (b) LED as represented in a circuit diagram.

(a) (b)

Figure 3.22: (a) LED turned off in the inverse polarization. (b) LED as represented in a circuit diagram.

3.3.8 Temperature

The electrical resistance of many materials changes as a function of their temperature. In the case of metals, for instance, their resistance increases with temperature, although not linearly. Some metallic substances become superconducting (zero resistance) at sufficiently low temperatures.

The electrical resistance of insulators also changes with temperature, although the behavior is not so simple as that of metals. In some insulators the resistance decreases with the increase in temperature. This relation normally is not linear.

In general the resistance of semiconductors decreases with increasing temperature. For some materials it follows an exponential law.

There are some materials called thermistors whose resistance is highly dependent on temperature. In some of them the resistance decreases as the temperature rises, while in others the resistance increases as the temperature rises.

3.3.9 Illumination

There are some materials, usually semiconductors, whose resistance changes according to the incident light intensity. They are called photoresistors, light-dependent resistors (LDRs) or photocells. Normally their resistance decreases with increasing incident light intensity, presenting photoconductivity. They may behave as insulators in the dark and as conductors in day light. They are utilized as light sensors, in illumination control, as light-sensitive detector circuits, light-switching circuits, alarm devices, fire detectors, devices that measure light intensity, street lights, infrared detectors, etc.

3.3.10 Other Factors

There are several other internal and external factors which may have an affect on the conducting or insulating behavior of a body. Examples: Pressure, impurities in the composition of the body, its fabrication process, etc. Air conductivity, for instance, changes with pressure. These other factors will not be discussed in this book. The important aspect to keep in mind is that no material *is* a conductor nor an insulator. It only *behaves as* a conductor or as an insulator. This behavior depends not only on some intrinsic properties of the body, but also on the external conditions to which it is subject. By changing these internal and external factors, you can change the conducting or insulating properties of any material.

3.4 Laws Related to Electric Circuits Carrying Steady Currents

This Section presents briefly some of the main laws related to electric circuits carrying steady currents.

Luigi Galvani (1737-1798) was an Italian scientist and professor of anatomy at the University of Bologna. He made important researches related to animal electricity in the 1780's. He observed, in particular, that the muscles of dead frog's legs twitched by touching its nerves with a metal arc, publishing a famous work on this subject. Alessandro Volta (1745-1827) was interested in this subject. Initially he accepted Galvani's ideas on animal electricity, but later on rejected completely this concept. According to Volta, the essence of this effect was related to a bimetal arc touching the nerves of the frog. During this controversy he built his famous electric pile between 1795 and 1799. In 1800 he published his discoveries in a very important paper translated to many languages.[11] Since then scientists had a controlled source of steady current driven by a low voltage source.

By working with a voltaic battery, H. C. Oersted (1777-1851) observed in 1820 the deflection of a magnetized needle close to a long wire carrying a steady current. His four page work describing this discovery had a great impact on many scientists, being translated into many languages.[12] By following these researches, Thomas Johann Seebeck (1770-1831) discovered the thermoelectric effect in 1821. In particular, he observed that a compass needle would be deflected by a closed loop formed by two different metals joined in two places, whenever there was a temperature difference between the joints. This fact indicated the flow of an electric current around the ring.

Humphry Davy (1778-1829) was an English chemist who also worked with electricity. In 1821 he discovered that the conducting power of a metal wire connected to the terminals of a voltaic battery is inversely proportional to its length, directly proportional to its area of cross section, being independent of the

---

[11] [Vol00a], [Vol00b], [Vol64], [Mag06] and [MA08].

[12] [Oer20b], [Oer20a], [Oer65], [Fra81] and [Ørs86].

shape of this cross section. He then concluded that a steady current flows along the whole cross section of the metal and not only along its surface. Between 1823 and 1826 Antoine-César Becquerel (1788-1878) confirmed these results by means of independent researches.

Georg Simon Ohm (1789-1854) was a German scientist influenced by the discoveries of Volta, Oersted and Seebeck. Between 1825 and 1827 he made important experiments related to electric circuits carrying steady currents. Initially he worked with a voltaic battery. The early batteries were not stable and quickly lost their power, decreasing the potential difference between their terminals. He then decided to utilize a thermoelectric pair as a source of steady voltage. The advantage of this source, when compared with the early batteries, was that when the two junctions of his source were kept at constant temperatures, he could obtain a voltage difference which remained constant during the time interval of his experiments. He also investigated the conductivity of different metals. He studied the current produced in his circuit as a function of the composition of the wires connected between the terminals of his voltage source. He also analyzed how the produced current was influenced by the length of the metal, by its area of cross section and by the difference of "electroscopic force" between the ends of the wire. He identified this electroscopic force (an expression coined by him) with the volume density of charge. It was only in 1849 that G. Kirchhoff (1824-1887) correctly identified Ohm's electroscopic force with the concept of electrostatic potential. These researches led to what is called Ohm's law in the textbooks.[13] According to this law, the difference of potential acting between the ends of a metal is directly proportional to the electric current flowing through it. The constant of proportionality is called the resistance of the metal. It depends on the kind of metal, being directly proportional to the length of the wire and inversely proportional to its area of cross section.

---

[13] [Ohm25], [Ohm26], [Ohm66], [OF38], [Whe43], [Kir49], [Kir50], [Ros90, pp. 210-214 and 494-499], [Ram], [Sch63], [Whi73a, pp. 88-93 and 224-226], [JM86, pp. 51-62], [Ach96, Chapters 6, 9, 10, 11 and 12], [Kip09], [Hae12] and [BW12a].

Chapter 4

Conductors and Insulators in Some Simple Experiments

4.1 Conductors and Insulators in the Amber Effect

The oldest experiment of electricity is the so-called amber effect, Section 1.1. Almost everyone performed a similar experiment in high school. Rub a plastic pen or acrylic ruler in hair. It attracts bits of paper spread on the table. Volume 1 of this book presented a description of what happens in this effect, together with many experiments related to it.[1] The present Section shows that our understanding of what takes place in this effect is different from the explanation found in most textbooks.

Suppose many bits of paper at rest on a table. Electrify a plastic comb rubbing it with hair. Move it towards the bits of paper. When it is sufficiently close, some pieces of paper are visibly attracted by it, rising towards the rubbed plastic. This is the observed phenomenon. We now consider its explanation, beginning with what is usually stated in the textbooks.

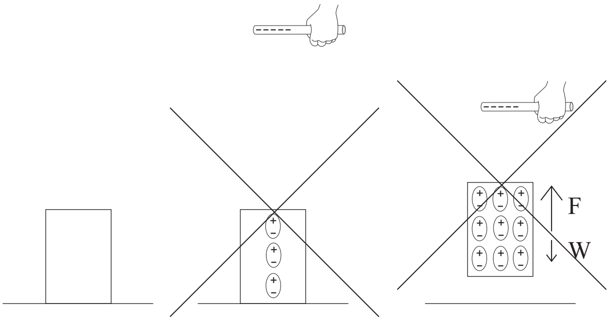
4.1.1 Explanation of the Amber Effect in the Textbooks

In most textbooks the authors state that a rubbed piece of plastic material (comb, ruler, ...) becomes electrified. It polarizes the molecules of any nearby bit of paper resting on a table. According to these textbooks, the portion of each molecule which is closer to the electrified plastic becomes electrified with charges of opposite sign to the charges of the electrified plastic. The portion of each molecule which is farther from the electrified plastic becomes electrified with

---

[1] Section 8.3 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

charges of the same sign as the charges of the electrified paper. Bodies electrified with charges of the same sign repel one another, while those electrified with opposite charges attract one another. The electric force decreases by increasing the distance between the interacting charges. Therefore, the portion of each molecule that is closer to the plastic will be attracted towards the electrified plastic with a force of higher intensity than the repulsion exerted by the plastic on the portion of each molecule that is farther from it. Each polarized molecule of the paper would be then attracted towards the rubbed piece of plastic. There would be a net attractive force F exerted by the rubbed plastic on all molecules of a bit of paper. If this force F is greater than the weight W of the paper, then the paper will rise towards the rubbed plastic. In essence, the typical explanation for the attractive force exerted by the rubbed plastic on a piece of paper is based on the difference between the attractive and repulsive forces exerted by the electrified plastic on opposite portions of each polarized molecule of the paper. Figure 4.1 illustrates this explanation



(a) (b) (c)

Figure 4.1: Typical explanation of the amber effect. (a) A bit of paper on the table. (b) Polarized molecules of the paper due to the presence of a nearby electrified plastic straw. (c) When the plastic straw comes even closer, the polarization of the molecules increases. If the attractive force F exerted by the electrified plastic on all the molecules is greater than the weight W of the paper, it will be attracted towards the electrified plastic.

We believe that this is not the correct explanation for the amber effect. For this reason we draw a large × symbol on Figure 4.1. This phenomenon presented in the textbooks may take place. But even when the paper molecules become polarized by the nearby rubbed piece of plastic, this polarization should not represent the main aspect responsible for the attraction of the small piece of paper. In this description presented by most textbooks it is implicitly assumed that the bits of paper behave as insulators. However, most kinds of paper and the majority of light substances usually attracted by a rubbed piece of amber or by a rubbed piece of plastic behave as conductors.

Moreover, the textbooks do not discuss the nature of the support on which the paper bits are located initially. That is, they do not mention if this support behaves as a conductor or insulator.

4.1.2 Our Explanation of the Amber Effect

We now present our description of the main phenomena in the amber effect. Figure 4.2 (a) illustrates the small piece of paper represented by the letter C, indicating that it is a conductor. We are here assuming that it rests on an insulating surface I.

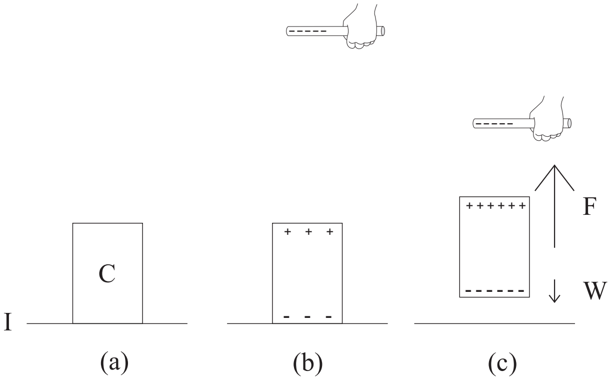


Figure 4.2: (a) Conducting bit of paper C on an insulating surface I. (b) Macroscopic polarization of the conductor due to the presence of a nearby electrified piece of plastic. (c) When the plastic comes even closer, the amount of polarized charges on the paper increases. If the attractive force F exerted by the electrified plastic on the macroscopically polarized conducting paper is greater than the weight W of the paper, it will be attracted towards the plastic.

In this configuration, the main effect which takes place when a rubbed plastic comes close to these conducting materials is their macroscopic polarization. That is, a real separation of charges over the whole volume of the material. Instead of a simple polarization of the molecules of the paper, the presence of the nearby electrified piece of plastic creates a macroscopic separation of electrified particles over the whole piece of paper. Figure 4.2 (b) illustrates qualitatively this macroscopic polarization of a piece of paper when it is supported on an insulating surface I. We did not present in this figure the polarized molecules of the insulating surface. When the plastic comes even closer, the amount of polarized charges on the paper increases. If the attractive force F exerted by the electrified plastic on the macroscopically polarized conducting paper is greater than the weight W of the paper, it will be attracted towards the plastic, Figure 4.2 (c).

Suppose two bodies of the same size, weight and shape. One of them is a conductor and the other an insulator. They are at rest on an insulating table, far away from one another. Assume, moreover, that an electrified plastic moves towards these bodies, coming at the same small distance d from both bodies. When it is at this distance d from the insulating body, the molecules of the body will become polarized. This microscopic polarization will yield an effective polarization of the whole insulating body. When, on the other hand, the electrified plastic is at this same distance d from the conducting body, it will cause a macroscopic polarization of the conductor. This macroscopic polarization of the conductor will be greater than the effective polarization of the insulator. Figure 4.1 (c) illustrates the polarization of the piece of paper as presented in the textbooks. They consider, erroneously, the piece of paper as an insulator. The effective polarization of this piece of paper is represented by three positive charges on the upper portion of the paper and three negative charges on its lower portion, while the positive and negative charges on its interior essentially cancel one another. Figure 4.2 (c), on the other hand, illustrates qualitatively the real polarization of the paper by considering it as a conducting material. It is represented by six positive charges on its upper portion and six negative charges on its lower portion. This polarization is larger than the effective polarization of the insulating material represented in Figure 4.1 (c). As this macroscopic polarization of a conducting material is larger than the effective polarization of an insulating material, the net attractive force F exerted by the rubbed plastic on the polarized paper is represented in Figure 4.2 (c) by a vector of larger magnitude than the attractive force F represented in Figure 4.1 (c).

However, the most common attractive behavior observed in the amber effect takes place when a conducting light body rests on a conducting support C, Figure 4.3 (a).

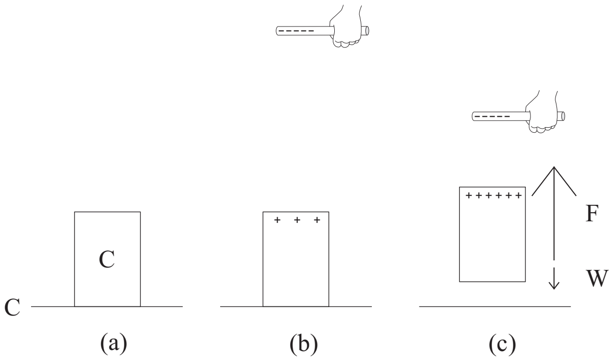


Figure 4.3: (a) Conducting bit of paper C on a conducting surface C. This paper is initially grounded. (b) When an electrified straw comes close to the paper, it acquires a net charge of opposite sign to that of the straw. (c) When the plastic comes even closer, the amount of charges on the paper increases. If the attractive force F is larger than the weight W of the paper, it moves towards the straw.

Examples of this configuration: Bits of paper on the ground, on a wood table (the wood material here should not be varnished), on a metal surface, etc. When a conducting bit of paper is on a conducting support, the paper is grounded. Therefore, when an electrified piece of plastic comes close to the paper, it will acquire a net charge having an opposite sign to that of the electrified plastic. This configuration is represented in Figure 4.3 (b). In this image we did not represent the net charges on the conducting surface. When the plastic comes even closer, the amount of charges on the paper increases. If the attractive force F is larger than the weight W of the paper, it moves towards the straw, Figure 4.3 (c).

The net or total force F exerted by the electrified plastic on the bit of paper which was on a conducting surface, Figure 4.3 (c), is larger than the net force represented in Figure 4.2 (c).

Figures 4.1 (c), 4.2 (c) and 4.3 (c) assume that the plastic straw is equally electrified in all cases. Moreover, it is always drawn at the same distance d from a specific bit of paper which is moving towards it. The size of the arrows indicate the magnitude of the force F exerted by the electrified straw on the paper. The force F of Figure 4.2 (c) is larger than the force of Figure 4.1 (c) because the polarization of a conductor is larger than the effective polarization of an insulator. The force F of Figure 4.3 (c) is larger than the force of Figure 4.2 due to the fact that the paper of Figure 4.3 (c) has a net charge different from zero, while the paper of Figure 4.2 (c) is only polarized, having no net charge.

It is an erroneous prejudice widely spread in the textbooks and in the heads of many teachers and students to assume that materials like paper, wood, glass and rubber always behave as insulators. This behavior may take place at low voltages. However, it usually does not take place in electrostatic experiments dealing with potential differences ranging typically from 1,000 V up to 10,000 V. When we apply these high voltages between the ends of a piece of paper, wood, glass or rubber, usually this material will behave as a conductor. These high voltages are very common in experiments similar to the amber effect. For this reason we were careful when presenting a detailed description of this effect in Volume 1 of this book, showing several didactic figures.[2]

The first experiment presented in Volume 1 of our book presented the amber effect. The last experiment of Volume 1 presented an analogous phenomenon. With this last experiment we could test the net charge acquired by the attracted piece of paper. Moreover, Volume 1 discussed several instruments made of paper in which the paper behaved as a conductor. We also utilized in these instruments analogous conducting substances like cardboard and tissue paper. We can mention, in particular, the electric pendulum and the electroscope.[3] This organization of the book was made on purpose. We thought carefully about it. It is very simple to perform an experiment analogous to the amber effect. However, it is complex to describe correctly many important factors associated with this phenomenon.

---

[2] Section 8.3 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[3] Sections 2.1, 2.2, 4.4, 6.1, 6.5 and 7.15 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

4.1.3 It is Important to Present a Detailed Explanation of the Amber Effect

Subsection 4.1.1 presented the explanation of the textbooks related to the amber effect. Our own explanation of this effect was presented in Subsection 4.1.2. Our description is very different from what appears in the usual textbooks. We consider important to correct the textbooks for several reasons:

- The amber effect is the oldest experiment of electricity. Modern textbooks should not present a wrong explanation of this old phenomenon.

- Most people performed an analogous experiment during high school, just for fun, as a children's play. They rubbed a plastic straw or acrylic ruler in hair and attracted bits of paper resting on a table. Sometimes this fun activity will be one of the rare physics experiments they will ever perform in their lives, especially for those who drop out their studies after high school or for those who follow human sciences or biological sciences at University level. Therefore, it is important to present a clear and correct picture of this effect.

- The explanation of Subsection 4.1.1 may be considered simpler than the description presented in Subsection 4.1.2. Even if this occurs, it is better to present a careful and complex description which is essentially correct, than to present a simple but wrong explanation. The simpler explanation is not always the best one. We learn many important aspects when we think carefully on what is taking place in such an apparently simple phenomenon. We realize many relevant aspects which should be considered in order to describe it correctly.

- Even some apparently simple and everyday phenomena can hide relevant surprises and subtleties, as is the case with the amber effect.

- The correct description of this phenomenon requires the understanding of what conductors and insulators are, together with some of their main properties. When we understand these aspects we begin to have a more complete picture of what is taking place in this phenomenon. We can then consider these extremely important aspects when analyzing other more complex phenomena of nature.

- With the correct explanation we learn that the light bodies (like bits of paper, feathers or a cotton thread) attracted by the rubbed plastic normally behave as conductors in electrostatic experiments.

- With the correct explanation we also learn that the surface where the light bodies rest before the attraction (surfaces made of metal or wood, for instance) normally behaves as a conducting and grounded surfaces in electrostatic experiments.

These two last items are very important aspects which should be learned by everyone. By understanding these two facts we are then able to explain many other curious phenomena related to electricity.

4.2 Conductors and Insulators in the Experiment of the Attraction of a Stream of Water

Many people have already performed or at least observed a simple experiment described in many textbooks on electricity showing the attraction of a stream of water coming out of a tap, as in Experiment 3.7. Assume that a plastic straw has become negatively electrified by friction. Bring it close to the stream of water. The water bends towards the straw, Figure 3.8. This attraction represents the observed phenomenon. In Volume 1 of this book we presented a detailed description of the origins of this attraction of the stream of water.[4] We wish to emphasize here that this description is different from the explanations found in most didactic textbooks.

4.2.1 Explanation of the Attraction of a Stream of Water in the Textbooks

Most textbooks dealing with this phenomenon mention that water is composed of polar molecules. Due to the difference in electronegativity between the bonded oxygen and hydrogen atoms, there is a permanent dipole moment in each molecule. The oxygen atom is negatively electrified, while the hydrogen atoms are positively electrified. This imbalance results in a molecular dipole moment, pointing from the negative oxygen atom to a positive region between the two hydrogen atoms. Therefore, even when there is no external influence, each water molecule has permanently a positive side and a negative side of equal magnitude. The explanation of the bending of the stream in the textbooks is based essentially on this property of the water molecules. Initially each water molecule points in an arbitrary direction. They mention that when an electrified body comes close to the stream, these polar molecules are oriented by this body. Consider a negative straw close to the stream. Due to the electric force exerted by the electrified plastic on the electrified portions of each molecule, the polar water molecules will turn. In particular, the positive side of each molecule will point towards the negative straw, becoming closer to it, while the negative side of each molecule will point away from it, becoming slightly farther away from the straw. The electric force decreases with increasing distance between the interacting bodies. Therefore, the positive portion of each oriented molecule will be attracted by the straw with a force slightly larger than the repulsive force acting on the negative portion of each molecule. There would remain a net attractive force on each water molecule pointing towards the electrified straw.

---

[4] Sections 2.5 and 7.11 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

According to the textbooks, this would be the explanation for the bending of the stream, as represented qualitatively in Figure 4.4.

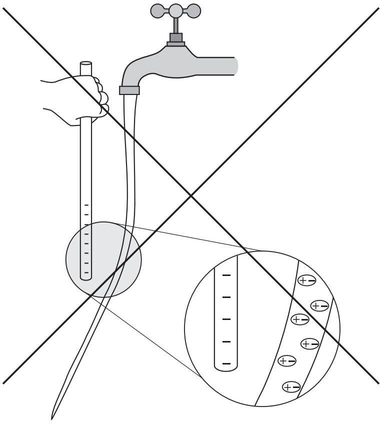


Figure 4.4: Wrong explanation of the bending of the stream due to the orientation of the water polar molecules when a rubbed straw comes close to the water.

We believe that this is not the correct explanation for this phenomenon. For this reason we draw a large × symbol on Figure 4.4. Textbooks assume implicitly that water is an insulator. If this were the case, it would have no free charges that could move along the whole volume of water. The electrified straw could only orientate polar molecules. We do not doubt that water molecules are polar and can get, indeed, oriented by the electrified straw. However, that is not the main mechanism responsible in causing the stream to bend.

4.2.2 Our Explanation of the Attraction of a Stream of Water

We present now our description of this phenomenon. The main difference between our description and the explanation of the textbooks is that we consider tap water as a good conductor in electrostatic experiments. After all, it discharges an electrified electroscope, as shown in Experiment 3.5, Figure 3.6. Of course, tap water is composed mostly of polar H_2O molecules. But it also contains salts, various impurities, H_3O^+ and OH^-, along with other ions, etc. These substances make water behave as a conductor.

Consider first a dripping faucet, Figure 4.5 (a).

A negatively electrified straw bends the trajectory of the nearby water drops, Figure 4.5 (b). Assume that the straw is far away from the faucet and that it may have an affect only on the nearby drops of water. Suppose the water behaves as a conductor. When a negative straw comes close to the drops, they become polarized. There is a real separation of charges in each drop. The closest portion of the drop becomes positively electrified, while the farthest portion becomes negatively electrified, Figure 4.6.

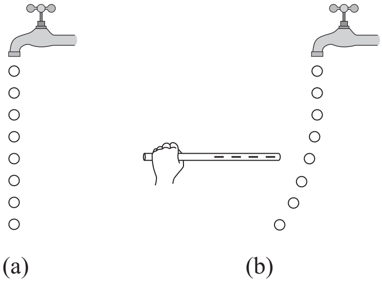


Figure 4.5: (a) A dripping faucet. (b) A negatively electrified straw attracts drops of water.

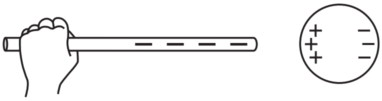


Figure 4.6: A drop of water polarized by the negative straw.

The magnitude of the electric force increases when the distance between the interacting bodies decreases. Therefore the positive portion of the drop is attracted by the straw with a stronger force than the repulsive force acting on the negative portion of the drop. This imbalance of forces produces a total attractive force acting on the drop. It then moves towards the straw.

Consider now a continuous stream of water. When a negative straw moves toward the stream, the water bends. The portion of the stream closer to the straw becomes positively charged while the portion farther from the straw becomes negatively charged. Supposing a continuous stream, its portion farther from the negative straw becomes neutralized due to the electrified particles which can be exchanged between water and the Earth. After all, it is a grounded stream, as the conducting falling water is in contact with the water in the tap, pipes, water box, etc. The stream of water becomes then positively electrified on its side close to the negative straw.[5] There will be an attraction between the negative straw and the positive stream, bending the water towards the plastic. Figure 4.7 illustrates qualitatively the distribution of charges in the water stream.

Once more, there is an erroneous prejudice to assume that tap water is an insulator. If this were the case, its polar molecules would be aligned by an external electric force. The aligned molecules would be then attracted by the external charged body. But in reality, fresh water contains many salts, minerals, and impurities which abound in electrically charged particles, also called ions, like H_3O^+ and OH^-. In the presence of high potentials differences, these electrified ions can move in water, so that water acquires a conducting behavior. A mass of water can then be macroscopically polarized when an

---

[5] Sections 2.5 and 7.11 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

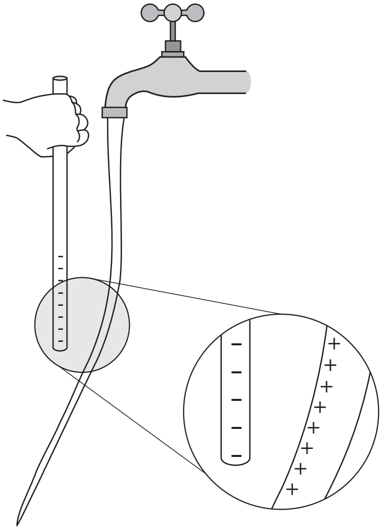


Figure 4.7: Electrification of the grounded conducting water stream when an electrified body is brought close to it.

external electrified body is brought close to it. When this volume of water is electrically grounded, it will acquire a net charge with an opposite sign to that of the electrified body nearby. The effects caused by this macroscopic polarization or by this net charge accumulated in the volume of water will be much more relevant than any effect arising only from the orientation of its polar molecules.[6] One of these effects may be the bending of the stream. The magnitude of the bending for a conducting liquid like water is much larger than the bending of an insulating liquid like oil, assuming both liquids at the same distance from the same electrified straw, Figures 3.8 and 3.9

Feynman, Leighton and Sands are some of the rare modern authors considering tap water as a conductor.[7]

4.2.3 It is Important to Present a Detailed Explanation of the Attraction of a Stream of Water

Subsection 4.2.1 presented the explanation of the textbooks related to the experiment of the deflection of a stream of water by a nearby electrified straw. Our own explanation of this effect was presented in Subsection 4.2.2. Our description is very different from what appears in the usual textbooks. We consider important to correct the textbooks for several reasons. Beyond the reasons quoted in Subsection 4.1.3 we can mention:

---

[6] For a discussion of this topic see [WB11], [Jec12], [BW12d], together with Sections 2.5 and 7.11 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[7] [FLS64, p. 9-8].

- The experiment of the attraction of a stream of water is one of the simplest phenomena of electricity, appearing in many textbooks. Modern manuals should not present a wrong explanation of this simple phenomenon.

- Most people saw this experiment described on the Internet and may have even performed it themselves at home or at school. They deserve a clear and correct picture of this effect.

- With the correct explanation we learn that water behaves as a conductor in electrostatic experiments. This is a very important aspect which should be learned by everyone. By understanding this fact we are then able to explain many other curious phenomena related to electricity. We become aware, in particular, of the crucial role of water and humidity in these experiments.

4.3 Differences between Old and Modern Glasses

Electric phenomena were first described by the ancient Greeks, the famous amber effect, Section 1.1. During the XVII and XVIIIth centuries people usually replaced the amber by a glass tube in order to perform these experiments. As regards their electric behavior, there are three main differences between the old and modern glasses. By old glasses we mean the glass tubes, spheres and cylinders utilized by Francis Hauksbee (c. 1666-1713), Stephen Gray (1666-1736), Charles Du Fay (1698-1739), Jean Antoine Nollet (1700-1770) and Benjamin Franklin (1706-1790), for instance. By modern glasses we mean the common types of glass found in everyday life at home (e.g. drinking cup, bottle, food pot, window pane, mirror, lamp bulb, etc.) or in retail shops (beaker, test tube, culture tube, lens, microscope slide, prism, etc.)

These differences may be due to the internal composition of these glasses and also to the fabrication processes of these materials. Gray, in particular, performed most of his experiments electrifying a flint-glass tube, which is a special kind of glass containing lead in its composition.[8] Flint glass was developed by George Ravenscroft (1632-1683) around 1662, being the precursor to English lead glass or crystal, commonly called crystal (although it is an amorphous material lacking a crystalline structure).

It is important to emphasize here these differences not only due to the historical aspects associated with the original experiments of these early scientists, but also due to their modern pedagogic and didactic aspects. After all, when we try to reproduce some of the early experiments with modern glasses, many activities simply don't work as originally described. The desired phenomena may also take place only with a very small intensity or amplitude, that is, with a very small degree not easily observable or detectable. The next three Subsections discuss the main differences between old and modern glasses, beginning with the most relevant ones.[9]

---

[8] [Chi54], [Hau], [RR57, pp. 570 and 584-585], [Hom81, p. 13] and [Hei99, pp. 235-236].

[9] [Bos11, Section 2.5] and [BAC12, Section 4.5, pp. 93-100]. See also Chapter 1, Sections

4.3.1 Conducting or Insulating Behavior

Stephen Gray rubbed his flint glass tube with his bare hand, as mentioned in his paper of 1707-1708.[10] After the glass tube was rubbed, he held it in his hand during the experiments. Other researchers of this period like Hauksbee, Du Fay and Nollet also rubbed glass tubes. These tubes were made with the common glasses of that period. Most figures and paintings of that period picturing electrical experiments show the researchers holding the rubbed tubes with their bare hands. These tubes were not discharged by grounding, that is, through the contact with the hands of the scientists.

This fact means that the old glass tubes behaved like excellent insulators. The electrified tubes were not discharged through the hands of the grounded researchers. In contrast, many kinds of common modern glass behave as good conductors for electrostatic experiments. This is the main difference between old and modern glasses.

The conducting behavior of many kinds of modern glasses is easily verified through Experiment 3.4 of Section 3.1. That is, when a piece of glass held in the hand touches the cardboard of a charged electroscope, it discharges quickly. Although this conducting behavior takes place with many types of modern glass, some kinds of glass still present an insulating behavior. The conducting or insulating property of any piece of glass depends on its internal constitution, on the behavior of its surface and on its fabrication process.

Therefore it is difficult to electrify many kinds of modern glass utilizing Gray's procedure. Hold, for instance, a glass cup by hand and rub it with the hair or with a cotton tissue. If we then move this rubbed cup towards bits of paper on the table, no attraction will be observed. Even when there is an attraction, usually it will have low intensity, not easily perceptible. This lack of attraction can be understood due to the conducting behavior of modern glass. Regardless of the amount of charge it acquires during friction, most of it is neutralized by the charges of the ground through our body and hands, as soon as the friction is over. After all, the glass cup is grounded through the hand.

According to Bossa and collaborators, the electric conductivity of glasses can change greatly depending on its chemical composition.[11] For this reason, as regards electrostatic experiments, it is easy to find nowadays glasses which behave as conductors and other glasses which behave as insulators. It is easy to electrify by friction insulating materials held in the hand. Conducting materials, on the contrary, can only become electrified by friction when they are insulated from the ground through an insulating handle. Therefore, before trying to reproduce any old experiment utilizing modern glasses, test their electrical behavior. This test is very important. If they behave as insulators, there is a good chance to succeed with the replication of the old experiment, yielding similar results while holding the glass tube in the hand. If they behave as conductors, on the con-

---

5.1 and 6.3, together with Appendix B, Section B.1 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[10] [Chi54, pp. 34 and 37].

[11] [Bos].

trary, then the glass must be insulated from the ground before performing the experiment. The glass should be fixed to an insulating handle. The hand should touch only this handle and not the glass, in order to prevent its discharge. The glass tube can then be rubbed against another material. Afterwards this rubbed, electrified and insulated piece of glass can be utilized in different experiments.

Many kinds of glass can change their electric behavior by a small amount of heating. A conducting piece of glass may become insulating by simply warming it by the fire or in a microwave.

Handling leaves sweat on the glass surface. This humidity should be avoided due to the high conductivity of water when compared with the conductivity of glass. Some glasses behave as conductors due to the humidity or water vapor accumulated over their surface. When the glass is heated, this water is evaporated and they can behave as insulators. That is, this warming procedure increases the amount of charge which the glass can hold on its surface after being rubbed. Glass is an hygroscopic material, absorbing air humidity and thereby increasing its conducting property.[12] The glass conductivity depends on its composition and on the state of its surface. Warm glass is usually more insulating than glass at room temperature.

Another factor which may increase the insulating property of glass is to increase its length, as discussed in Subsection 3.3.4. Suppose a glass tube held by the hand in one extremity and rubbed in the other end. There will be a reasonable amount of dry glass between these two regions, resulting in a good degree of insulation. Moreover, longer tubes have greater electrical resistance than shorter tubes. Therefore, longer tubes will preserve for a longer time any charges acquired by friction. Gray, in particular, usually worked with a glass tube 1 m long.

4.3.2 Density of the Surface Charges Acquired by Friction

Consider a modern glass which behaves as an insulator due to its chemical composition, fabrication process or when previously warmed. Even in this case, there is an important difference between this glass and the old glasses. Stephen Gray and other early scientists could produce huge effects with their tubes electrified by friction. These effects were easily perceived at large distances. They might, for instance, attract light bodies 10 or 20 cm away from the tubes. They succeeded also in transmitting the electric virtue or attractive power to very long conducting cords which were insulated from the ground. Some of these cords were more than 100 m long. The electrified glass tube touched one end of the cord or was kept close to it. The other end of the long cord (or a conducting body attached to this other end of the cord) could then attract light bodies placed close to it, like leaf brass. Gray was then able to create a strong polarization of the cord due to the large amount of charge accumulated on the surface of his rubbed glass tube. His tube acquired a large amount of electrical charges during the rubbing process. Moreover, Gray could easily

---

[12] [WB09].

produce sparks or electric discharges when moving his electrified glass tube close to other conducting bodies.

It is difficult to reproduce some of these effects with the same magnitude (or at these distances) utilizing modern materials rubbed manually. To perform these experiments, an insulator should be electrified by friction. This insulator can be, for instance, a previously heated piece of glass, a plastic straw, an acrylic ruler or a PVC tube. Even when we reproduce some of the phenomena described by Gray, the order of magnitude of the observed effects are usually smaller than those phenomena mentioned by Gray. Measure, for instance, the critical distance at which a rubbed straw or PVC tube begins to attract small pieces of paper. This distance is usually smaller than the critical distance at which Gray succeeded in attracting light bodies with his rubbed tube. We can also polarize the ends of an insulated and conducting metal wire which is close to a rubbed acrylic ruler or plastic straw. However, the amount of this polarization of the metal wire is usually smaller than the amount of polarization of the cords obtained by Gray which were close to his rubbed glass tube. Place bits of paper close to one end of a metal wire and bring the rubbed PVC tube close to its other end. Measure the maximum length of this wire with which it attracts the bits of paper. It is usually smaller than the length of Gray's cords attracting light bodies when his rubbed glass tube was close to the other end of the cord. It is difficult nowadays to produce visible sparks or electric discharges after rubbing an insulator in the hand and then bringing it close to another conducting body. Even when we produce these sparks, they take place only at very small distances between the electrified plastic straw and the nearby conductor. Gray, on the other hand, could produce large and visible sparks with his electrified tube 10 or 20 cm away from a nearby conducting body.

The explanation of this different behavior, or the cause of these different orders of magnitude, lie in the densities of the surface charges acquired by friction. Gray's tube was not only an excellent insulator, but could also acquire a large surface charge density by friction. The density of charges which he obtained is usually much larger than the density of surface charges obtained nowadays in our insulators, even when we utilize good insulators like a plastic straw, an acrylic ruler or a PVC tube. As we obtain only small amounts of surface charge by friction, it is difficult to reproduce some experiments performed by Gray yielding effects with the same order of magnitude or with the same intensity.

4.3.3 The Sign of the Charges Acquired by Rubbed Glass

The third difference between old and modern glasses is related to the type of electric charges acquired by the material when it is rubbed by human skin.[13]

Du Fay discovered the two kinds of electricity. He also proposed the rule according to which bodies electrified with charges of the same type repel one another, while bodies electrified with charges of opposite sign attract one another. These discoveries were published in 1733.[14] He found that glass, rock-crystal,

---

[13] Sections 5.2 to 5.4 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[14] [DF33b], [DF] and [BC07].

precious stones, hair of animals and wool acquired electricity of the first type when rubbed with his skin or with silk. Amber, copal, gum-lack, silk cloth, thread and paper, on the other hand, acquired electricity of the second type when rubbed with his skin or with another silk cloth. Accordingly he named *vitreous electricity* the first kind of electricity and *resinous electricity* the second kind.

Twenty years after publication of these results, some new effects were discovered. It was observed, in particular, that roughened or unpolished glass could be charged vitreously by rubbing with flannel, or resinously by rubbing with oiled silk. This effect also happened with other materials. That is, the same material might acquire electricity of the first or second kind, depending on the material against which it was rubbed. This discovery led to the creation of the so-called triboelectric series, the first ones being published in 1757 and 1759.

In a triboelectric series the symbol + is followed by many bodies, ending with the symbol $-$. When body I is rubbed against body II, the positively charged one will be the body which is closer to the symbol +, while the other body becomes negatively charged.

Du Fay's terminology lost its meaning and was replaced by other terms. Since then it has been defined by convention to replace the terms vitreous and resinous electricities by *positive and negative electricities*, respectively. Other similar expressions used nowadays are *positive and negative electric charges*, or *positively and negatively charged bodies*.

We can now explain the third difference between the old and modern glasses. It is related to the kind of electrification acquired by a piece of glass when rubbed with human skin. Modern glasses are very close to the skin in the triboelectric series.[15] In particular, some kinds of glass will be closer to the symbol + in a triboelectric series than human skin. Call these glasses A. Other kinds of glass will be closer to the symbol $-$ in a triboelectric series than human skin. Call these glasses B, Table 4.1.

+
glass of kind A
human skin
glass of kind B
$-$

Table 4.1: Triboelectric series for modern glasses.

When glass A is rubbed on the skin, the glass will become positively charged. On the other hand, when glass B is rubbed on the skin, it will become negatively charged. In order to know if any specific piece of glass is of kind A or B, rub it on the skin. Test its acquired charge. Detect, for instance, if this piece of glass will be attracted or repelled by another body previously charged positively.

---

[15] Section 5.4 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

Experiments of this kind will then allow us to classify this specific piece of glass as being of kind A or B.

In conclusion, modern glasses can acquire positive or negative electrification when rubbed against the human skin. Old glasses utilized by Gray and other researchers of that period, on the other hand, usually acquired only positive electrification when rubbed against the skin.

4.3.4 The Glass in Modern Textbooks and the Importance to Correct What They Say

Most modern textbooks begin the study of electricity with the amber effect. The experiment is usually described with a glass tube replacing the amber. These textbooks also utilize electrified glass tubes in order to present the two kinds of electricity, positive and negative. In these two cases the authors assume explicitly or implicitly that glass is an insulator for electrostatic experiments.

The figures or pictures in these modern textbooks usually show the rubbed tube held by a bare hand. They replace the amber by an electrified glass tube. They discuss the attraction of light bodies on a table, the attraction and repulsion exerted by this electrified glass tube on a nearby electric pendulum, its effect on a nearby electroscope, etc. We believe that in most cases modern authors are just copying from other textbooks the *hypothetical* outcome of these experiments. That is, probably they did not perform the experiments themselves. Our guess is based on some details. In the first place, it is not easy to find a glass rod at home or in a usual retail shop. In any event, even if we try these experiments with a glass cup or with a test tube, the described effects usually will not take place or will only happen with a very small magnitude, not easily perceived with the naked eyes. After all, most modern glasses behave as conductors. Therefore, while held in the hands, they will not preserve any charge acquired during friction due to the grounding effect.

Another experiment described in many textbooks is related to the two kinds of charge, positive and negative. Sometimes they mention that a glass tube becomes positive when rubbed with silk, while a rubber rod becomes negative due to friction with an acrylic cloth. The force of repulsion between two positively electrified glass tubes is illustrated with one of these tubes suspended by a thread, while the other tube is held by a bare hand, Figure 4.8 (a). Sometimes this *hypothetical* experiment is also illustrated with two tubes suspended by threads, Figure 4.8 (b).

By replacing one of the suspended positive glass tubes with a suspended negative rubber rod, the textbooks illustrate the attractive forces between oppositely electrified bodies.

Once more the textbooks are assuming explicitly or implicitly that glass behaves as an insulator. They are here supposing that the glass tube remains electrified when held by a bare hand. They are also making the same assumption by supposing that it remains electrified when suspended by a thread. After all, they do not specify the material of this thread and do not discuss if this thread is a conductor or insulator.

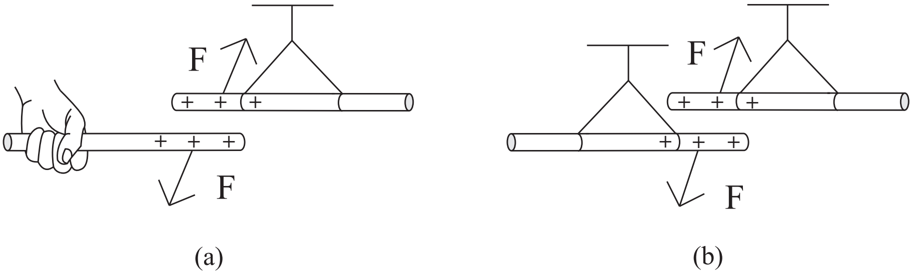


Figure 4.8: (a) Forces of repulsion between a glass tube held by a bare hand while the other is suspended by a thread. (b) Forces of repulsion between two glass tubes suspended by threads.

If a student tries to repeat this experiment with a glass tube or cup, probably he will not observe any repulsion. The reason, as stated before, is that modern glass usually behaves as a conductor. Therefore, a rubbed glass will not remain electrified when held by a bare hand. It will also not remain electrified when suspended by most kinds of thread (cotton, linen, copper, ...) as these threads behave as conductors. The student may become frustrated. He can also conclude that the problem is with himself, namely, that he has no ability or skills in physics. He may even loose any interest he might have before in this subject.

Obviously some textbooks present real experiments performed with modern glass tubes yielding the effects discussed in the figures. In these cases they were working with insulating electrified glasses even while held in their hands. But even when this was really the case, they should call attention to the fact that the described experiments would not work with most glasses found at home due to their conducting behavior.

In conclusion, before performing experiments with glasses, it is crucial to test in advance if they behave as conductors or insulators.

4.4 The ACR Mechanism

Volume 1 of this book discussed the so-called ACR mechanism discovered by Du Fay in 1733.[16] This phenomenon usually takes place when a light conductor, electrically insulated from the ground, is attracted by an electrified body. It touches this body and is then repelled by it. Sometimes the light body does not need to touch the electrified body, as repulsion can take place after they come very close to one another. Heilbron designated by the letters ACR this simple rule of attraction, communication of electricity, and repulsion (i.e., Attract, Communicate, Repel).[17] These letters A, C and R are sometimes utilized as coming from the words Attraction, Contact and Repulsion.

---

[16] Sections 4.2 and 4.8 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[17] [Hei99, pp. 5 and 255-258].

Experiments 4.1, 4.2 and 4.3 show simple situations illustrating this mechanism.

Experiment 4.1 - *Floating a few strands of cotton*

Consider initially an object like a down feather or a few strands of cotton. The important factor is that the object selected should take a long time to fall to the ground in air, e.g., some 10 seconds to cover a distance of 2 meters of fall. It is even better if it falls slower than this. On the other hand, if it falls much faster than this, it will not be possible to observe the effects described here.

Rub a plastic straw or acrylic ruler with hair. Hold the rubbed straw or acrylic ruler horizontally. Release the feather or piece of cotton a little above the straw. The object is attracted by the straw and sticks to it, Figure 4.9 (a) and (b).

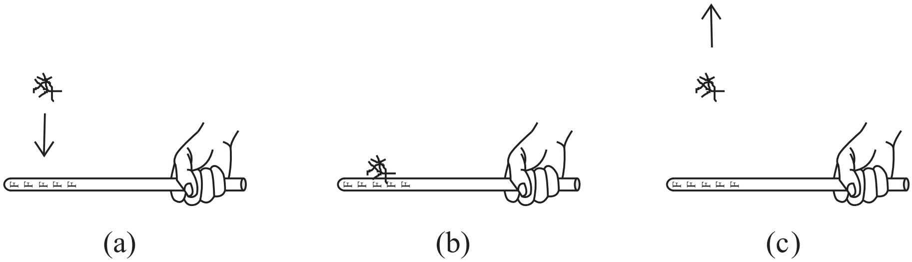


Figure 4.9: (a) A piece of cotton is initially attracted by a rubbed plastic straw. (b) The cotton touches the rubbed portion of the straw. (c) After contact, the cotton is repelled by the straw. It can then be kept floating above the straw despite the gravitational attraction of the Earth!

If we look closely at the object, we can see its strands stretching, as if they wanted to move away from the straw. Sometimes the object actually jumps upward after contact, moving away from the rubbed straw. If this does not happen immediately, we can induce the object to release by tapping on the straw, or by blowing on the object softly. After the object is free from the straw and begins falling, place the rubbed straw below the falling object. The object is then repelled by the straw and moves upward. Sometimes this does not happen at once, since the object must touch the rubbed straw two or three times and be freed after each touch before it can clearly be repelled by it. The more electrified the straw, the more quickly the object will be repelled after touching it, Figure 4.9 (c).

By placing the rubbed straw slowly below the object, move it to any place inside a room. If the object comes very close to our body or to any other item in the room, it is attracted to our body or item and sticks to it. To prevent this from happening, utilize the rubbed straw to propel the object away from these bodies. In this case the object can easily be kept floating for some time at a distance of 10 to 20 cm above the straw, depending upon how well electrified the straw is. To keep the object floating, the rubbed straw must be kept moving constantly below it, following the motion of the object, in order to guide its motion.

Experiment 4.2 - *Floating a dandelion seed*

Figure 4.10 illustrates a similar experiment made with a dandelion seed. The dandelion seed falls naturally very slowly, so it is suitable for this experiment. It is easy to keep it floating above a plastic straw rubbed with hair.

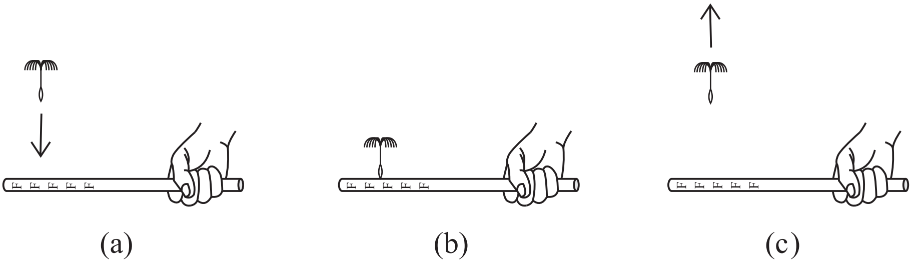


Figure 4.10: Experiment 4.9 can easily be performed with a dandelion seed floating above a plastic straw rubbed with hair.

With a dandelion seed the procedure is normally easier than with a few strands of cotton. When the dandelion seed is first released in the air above the rubbed straw, it is attracted by the straw, touches it and is immediately repelled by it.

Experiments 4.1 and 4.2 are very simple, but extremely curious. No one who performs it forgets what he or she sees. O. v. Guericke (1602-1686), Stephen Gray and Du Fay performed experiments like these. They had a great historical importance. A very interesting video showing a modern reproduction of the levitation of a thin gold leaf has been made by Blondel and Wolff,[18] "La danse des feuilles d'or."

Experiment 4.3 - *Repulsion between an electrified body and the paper disk of an electric pendulum*

Utilize a classical electric pendulum composed of a small disk made of paper or aluminum foil with a diameter on the order of 1 or 2 cm tied to the lower free end of a thread made of silk, nylon or polyester, Figure 2.10. Electrify a plastic straw or acrylic comb by rubbing it briskly with hair, in a napkin or in a cotton tissue. Bring it near the pendulum. The disk is attracted by the straw, touches it, and is then repelled by the straw, Figure 4.11.

Sometimes the paper disk is not immediately repelled by the rubbed plastic after contact, remaining in touch with it for a few seconds. Observe the repulsion in these cases by tapping on the straw to release the disk. You can also move

---

[18] [BW12b] and [BW12c].

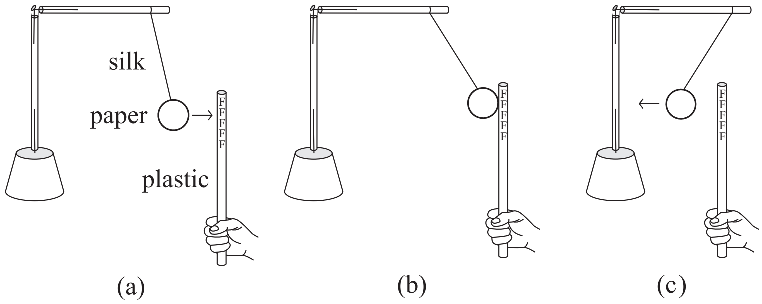


Figure 4.11: (a) The paper disk is initially attracted by the rubbed plastic, (b) touches it and afterward (c) is repelled by the straw.

the straw up and down to release the paper, or blow on it lightly. After release, the paper disk is normally repelled by the rubbed plastic. In some cases 2 or 3 attractions of the disk by the rubbed straw are required, always allowing their contact in each attraction, before you can observe their repulsion.

To begin this whole process again, the disk must be discharged. To this end, touch the paper disk with the finger. It is not necessary to hold the paper disk, a touch is enough. It is then discharged by grounding. After this discharge, once more bring the electrified straw close to the pendulum. The paper disk will be attracted again by the straw. It will touch the straw and will be repelled by it.

4.4.1 Explanation of the ACR Mechanism

There is a simple explanation for this behavior. We illustrate the explanation of the ACR mechanism utilizing Experiment 4.3. Assume that the straw or plastic ruler is negatively electrified and that the paper disk is initially neutral when far away from the plastic. A disk made of paper or aluminum foil behaves as a good conductor. It is supported by an insulating thread made of silk, nylon or polyester. When the electrified straw is brought close to the disk, it becomes polarized. The portion of the disk which is closer to the rubbed straw acquires a charge of opposite sign to that on the straw, while the opposite portion of the conductor acquires a charge of the same sign as the charge on the straw, Figure 4.12 (a).

The distance between the positive portion of the disk and the negative straw is smaller than the distance between the negative portion of the disk and the straw. The electric force is attractive between bodies electrified with charges of opposite signs and repulsive between bodies electrified with charges of the same sign. Moreover, the intensity of these forces increases by decreasing the distance between the electrified bodies. Therefore, the attraction exerted by the negative straw on the positively electrified portion of the disk is larger than the repulsion exerted on the opposite portion of the conductor which is negatively electrified. These opposite forces of different magnitudes yield a net attractive force acting

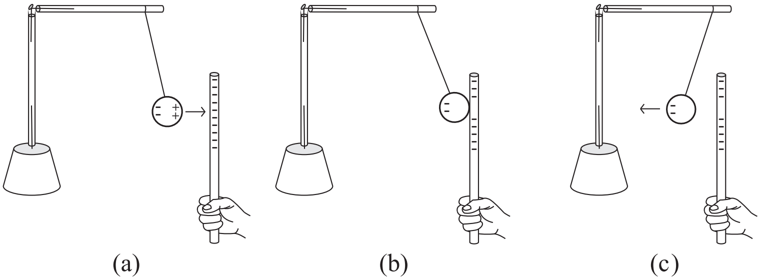


Figure 4.12: (a) The conducting disk becomes polarized due to a nearby electrified straw. There is a net attraction between them. (b) During contact, there is an exchange of electrified particles. As a result of this exchange, the disk becomes electrified with a net charge of the same sign as that of the straw. (c) The electrified disk is then repelled by the straw.

on the disk. When the disk touches the straw, there is an exchange of electrified particles between them, neutralizing the portion of the disk close to the straw and also the points of the straw which touched the disk, Figure 4.12 (b). We exaggerate in this image the neutralized region of the straw. Plastic behaves as an insulator. Therefore, the negative particles of the other electrified regions of the straw do not move. After contact, the disk and the straw become both negatively electrified. There is then a net repulsion between them, Figure 4.12 (c).

4.4.2 Situations where the ACR Mechanism Does Not Take Place

Experiment 4.4 - *Attraction between an electrified body and a paper disk attached to a cotton thread*

Repeat Experiment 4.3 utilizing in this case a grounded conducting disk. To this end, replace the insulating thread by a conducting thread tied on a conducting support. The paper disk can then be tied to the lower end of a cotton thread, which is tied to a wood skewer or metal wire. Hold one end of the skewer with the hand, while its other end supports the cotton thread. This instrument is analogous to Gray's pendulous thread described in Section 2.5.

Slowly bring a rubbed piece of plastic near this conducting pendulum. The pendulum inclines toward the straw, touches it, remaining stuck to the electrified straw, Figure 4.13.

Repeat this process many times. The ACR mechanism does not take place. That is, even when the disk touches the electrified straw many times, the mechanism of attraction, contact and repulsion does not happen.

Experiment 4.5 - *Attraction between an electrified body and a plastic disk*

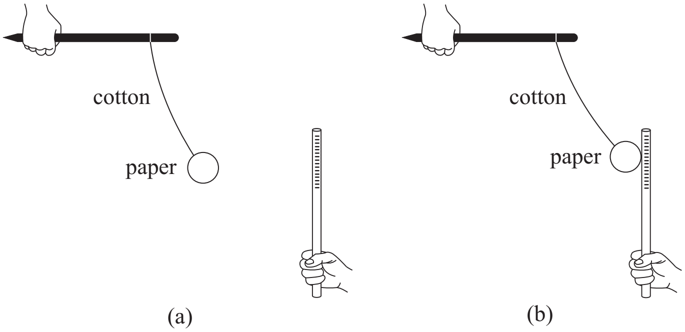


Figure 4.13: (a) The grounded conducting disk is attracted by an electrified straw. (b) The disk touches the straw and remains stuck to it after contact.

Repeat Experiment 4.3 utilizing in this case an insulating disk of a plastic electric pendulum of Figure 2.12.

Slowly bring a rubbed piece of plastic near the plastic disk of this pendulum. The pendulum inclines toward the straw, Figure 4.14 (a).

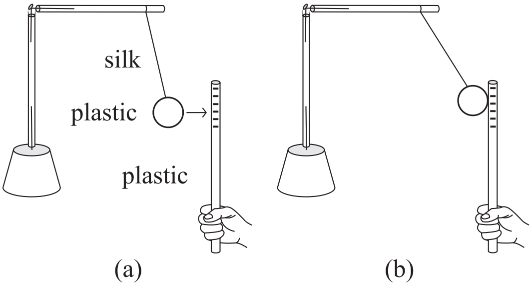


Figure 4.14: (a) The insulating disk of a plastic pendulum is attracted by a rubbed straw, (b) touches it and remains stuck to it.

If we allow the contact between the plastic disk and the rubbed straw, normally they remain stuck to one another, Figure 4.14 (b).

These activities indicate that in order for the ACR mechanism to take place, the conductor (paper disk) must be electrically insulated from the ground (by air and by an insulating thread), as was the case of Experiment 4.3. When the conductor is grounded as in Experiment 4.4, the ACR mechanism will not take place, even allowing contact between the conductor and the electrified straw.

This behavior can also be justified. Observe first that the only insulators in this last Experiment were air and the electrified plastic straw. All other bodies behaved as conductors, namely, the paper disk, cotton thread, wood skewer and the hand connected to the ground. Assume that the straw was negatively electrified. When it approaches the disk, the disk tends to get polarized. However, as it is a grounded conductor, its negatively electrified particles become neutralized due to the grounding. Consequently the disk becomes positively electrified close to the straw, Figure 4.15 (a).

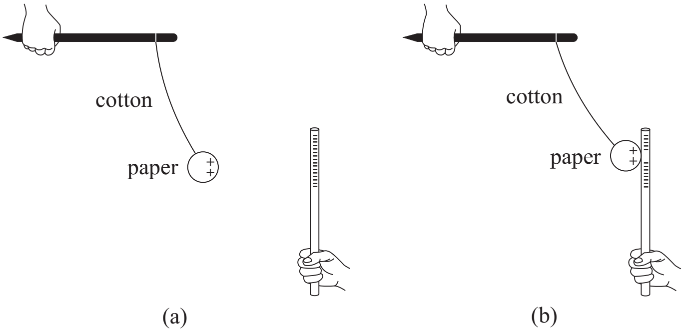


Figure 4.15: (a) The grounded disk positively electrified close to the negative straw. (b) The grounded conductor remains positively electrified close to the straw, being attracted by the negative regions of the insulating straw.

When the paper disk touches the straw, there is an exchange of electrified particles between them, tending to neutralize the disk and the points of the straw which touched it. As the straw is an insulator, its other electrified particles do not move, remaining in their places. These negative particles which remained in the electrified straw continue to exert an attractive force on the free electrified particles of the conducting disk. These attractive forces tend to polarize the disk once more, leaving it positive in the region of contact and negative on its opposite side. Due to the grounding, the opposite side of the disk becomes neutral. There remains only the positive region close to the negative straw, Figure 4.15 (b). In this figure we exaggerate the neutral region of the straw which is in contact with the disk.

It should be emphasized that the ACR mechanism also does not take place for a small insulator which is being attracted by an electrified body, as observed in Experiment 4.5. The plastic disk can be slightly attracted by the electrified straw and may even touch it. However, the disk will remain stuck to the electrified straw after contact, even after repeating this procedure a few times.[19]

4.5 The Importance of Stephen Gray's Discovery of Conductors and Insulators

The oldest reference of the so-called amber effect appears in the work *Timaeus* of Plato (circa 428-348 B.C.).[20] For two thousand years little more was discovered

---

[19] Section 7.6 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[20] [Pla52, Sections 79 to 80, pp. 470-471], [Pla09, Sections 79 to 80, pp. 163-165] and Section 2.2 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

about electricity. Essentially people knew only that amber and a few other substances had the power of attracting light bodies after being rubbed. In 1729 Stephen Gray realized that there are two groups of bodies, called conductors and insulators nowadays. He also obtained some of the main properties of conductors and insulators. He published his results in 1731 in one of the most important works in the history of electricity.[21] Volume 1 of this book discussed Gray's paper in detail.[22]

Gray's fundamental discovery allowed the control of electric phenomena. He identified the grounding or earthing mechanism to discharge an electrified conductor. He succeeded in electrifying metals, water and the human body. To this end, these materials were insulated from the ground. He was able to transmit electricity (or the power of attracting light bodies) to places far away from where rubbing was taking place. To this end, he utilized conducting strings and wires insulated from the ground. When an electrified glass tube was kept in contact with, or close to, the end of this conducting string, the free end of the string (or a conductor attached to it) would also attract light placed near it. He was also the first to show how to store electricity, that is, to show how to increase the amount of time a body remains electrified. He created the first electrets (dielectric materials with a permanent electrostatic dipole polarization, or with a permanent electrification), as discussed in Section 13.4. The materials with a permanent dipole polarization are also called the magnets of electricity.[23] He was also one of the first scientists to perform experiments related to the conservation of electric charges.[24]

Du Fay, following Gray's footsteps, recognized repulsion as an electric phenomenon and discovered the ACR mechanism.[25] When he observed an anomaly in this mechanism (that is, a situation in which this rule did not work), he was convinced of the existence of two kinds of electricity, which he called vitreous and resinous electricities.[26] Until then only one kind of electricity was known. Nowadays these two kinds of electricity are called positive and negative electricities, respectively. Other analogous expressions are *positive and negative electric charges*, or *bodies electrified positively and negatively*.

The development of electricity has been vertiginous after Gray's discovery. What made possible all these new discoveries was the knowledge about these two kinds of bodies in nature, namely, conductors and insulators, together with their main properties. This knowledge seems trivial nowadays. In any event, it was the ignorance about the existence of these two essentially different materials which prevented for two thousand years the advance in the study of electricity. In 2012 we published a commented and complete Portuguese translation of Gray's papers related to electricity, together with a reproduction of his main

---

[21] [Graf], [Bos11, Chapter 6] and [BAC12, Chapter 7, pp. 127-169].

[22] Appendix B of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17]. See also [RP13a], [RP13b], [RP13c], [Rai15], [RP15b], [RP15a] and [RP16].

[23] [Net94], [Sil10b], [Sil10a], [Bos11, Chapter 8, pp. 226-248] and [BAC12, Chapter 19, pp. 373-392].

[24] Section 6.10 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[25] Section 4.8 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[26] [DF33b], [DF] and [BC07].

experiments utilizing low cost materials.[27]

---

[27] [BAC12].

Chapter 5

Electrification of Adhesive Tapes

This Chapter describes experiments relating to a curious subject, namely, the electrification of adhesive tapes.[1]

5.1 Insulating or Conducting Behavior of the Tape

Experiment 5.1 - *Insulating along its length*

Begin with a spool of a common adhesive tape 1 or 2 cm wide. It can be a PSA office tape, magic tape, invisible tape, sticky tape, cellophane tape, etc. Analyze its conductive or insulating properties. The gluey, sticky or gummy side will be represented by the initial letter G of the word "glue", while the slick or smooth side will be represented by the letter S. First charge an electroscope, Figure 5.1 (a).

Consider a strip of tape about 10 to 20 cm long. Hold its ends with the hands. Touch the smooth side on the edge of the charged electroscope. The strip of the electroscope remains raised, Figure 5.1 (b). The same happens when the sticky side of the tape touches the edge of a charged electroscope, Figure 5.1 (c).

This experiment shows that both sides of an adhesive tape behave as insulators along their length. Although the tape is grounded by the hand, the electroscope is not discharged.

Experiment 5.2 - *The tape conducts through its side*

Begin the experiment again with a charged electroscope, Figure 5.2 (a).

---

[1] [Jef59], [Bea96], [CS02, Chapter 14], [Mor04b], [Mor04a] and [Vas05].

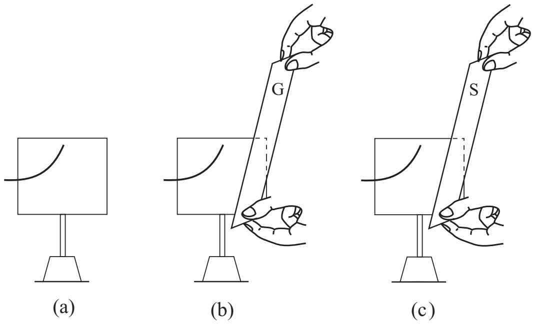


Figure 5.1: (a) Charged electroscope. (b) The smooth side of an adhesive tape touches the edge of the electroscope. The strip remains raised. (c) It also remains raised when the sticky side of the tape touches the cardboard.

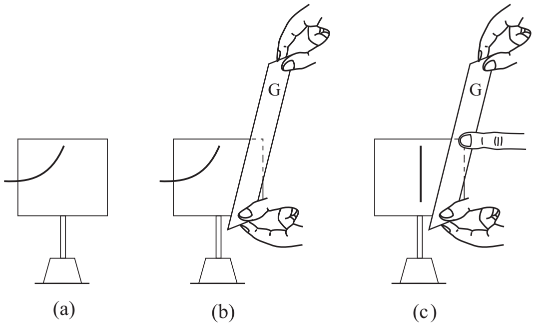


Figure 5.2: (a) Charged electroscope. (b) The smooth side of the tape touches the edge of the cardboard and the strip remains raised. (c) A finger touches the other side of the tape and the strip drops.

Hold an adhesive tape by both ends. Touch the center of the smooth side of the adhesive tape on the edge of the electroscope. Its strip remains raised, Figure 5.2 (b). Then another person touches one finger on the center of the other side of the tape. The tape should remain between the edge of the cardboard and the finger. The finger should not touch the cardboard. In this case the strip drops in a few seconds, Figure 5.2 (c).

The strip of a charged electroscope also drops when the sticky side of the tape touches the edge of the cardboard and a finger touches the smooth side of the tape.

The electroscope is then discharged when one side of an adhesive tape touches the edge of the cardboard and a finger touches the other side of the tape. Therefore the side of an adhesive tape behaves as a conductor for electrostatic experiments, although the tape behaves as an insulator along its length.

Experiment 5.3 - *Several superimposed tapes*

Overlap several layers of tape superimposing strips of the same length. Stick a 10 to 20 cm long strip of tape on the surface of a desk. Stick above it as many layers as desired, all of the same length. Then repeat Experiment 5.2 with this multilayer strip. Touch one side of the multilayer strip on the edge of a charged electroscope. A finger then touches the opposite side of this multilayer strip. Measure the time interval to discharge the electroscope. Table 5.1 presents a typical outcome.

Number of overlapping layers	Discharge time interval
1	1-5 s
5	5 s
10	10 s
15	15-20 s
20	25-60 s

Table 5.1: Approximate time intervals to discharge the electroscope.

According to Definition 3.5, we then conclude that 20 superimposed layers of a tape can be considered an insulator in a direction orthogonal to these layers. This situation is represented in Figure 5.3.

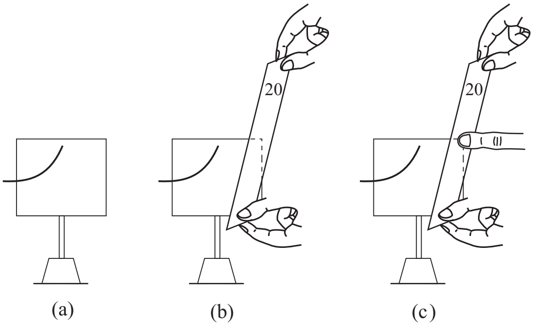


Figure 5.3: (a) Charged electroscope. (b) One side of a 20 multilayer tape touches the border of the cardboard and the strip remains raised. (c) The strip remains raised when a finger touches the outer side of this multilayer tape.

This experiment illustrates once more the subject discussed in Subsection 3.3.4. That is, the conducting or insulating property of a body depends not only on its nature, but also on its length or thickness. In the present experiment, the thicker the multilayer tape, the more it will behave as an insulator.

Experiment 5.4 - *Other kinds of tape*

Repeat Experiments 5.1 and 5.2 with other kinds of adhesive tape.

A surgical or medical tape, for instance, behaves as conductors not only through its side, but also along its length. While a normal office tape is made of an insulating plastic material, a surgical tape is normally made of cotton, a conducting material.

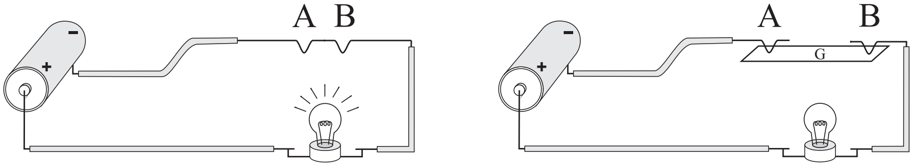
An electrical tape (also called an insulating tape), on the other hand, behaves like most adhesive tapes. That is, insulating along its length and conducting through its side. Its standard color is black. It is made of vinyl or PVC.

By increasing the number of superimposed layers of electrical tape we also increase its insulating behavior orthogonally to its sides. A tape with 15 or 20 layers can be considered a good insulator through its thick side, as illustrated in Figure 5.3.

Experiment 5.5 - *Insulating behavior along its length for low voltages*

The behavior of the electrical tape in Experiment 5.4 may surprise many people. After all, this tape is usually called "insulating tape". However, through its side it behaves as a conductor in electrostatic experiments (the electroscope is discharged through its side). We perform two new experiments in order to understand this nomenclature.

Repeat Experiment 3.9. The light bulb turns on when the conducting ends A and B are directly connected with one another, Figure 5.4 (a). The same happens when A and B are connected through a metal wire.



(a) (b)

Figure 5.4: (a) The bulb turns on when conductors A and B touch one another. (b) The bulb does not turn on when A and B, separated by 2 or 5 cm, touch two central points on the sticky side of the tape.

Place now a 2 to 5 cm long tape between the conducting points A and B, with these points touching the center of the sticky side of this tape. Adhesive tape, surgical tape and electrical tape behave as insulators in this experiment, as shown in Figure 5.4 (b). The same happens when A and B touch two points of the smooth side of the tape separated by 2 or 5 cm.

All these tapes behave as insulators along their lengths for low voltages.

Experiment 5.6 - *Insulating behavior through its side for low voltages*

Test how these tapes behave through their sides. First connect A and B directly to verify that the lamp turns on and that all electric connections have been correctly made, Figure 5.5 (a).

Then place a piece of tape in a vertical plane, with point A touching the center of one side of this tape and point B touching the center of the other side

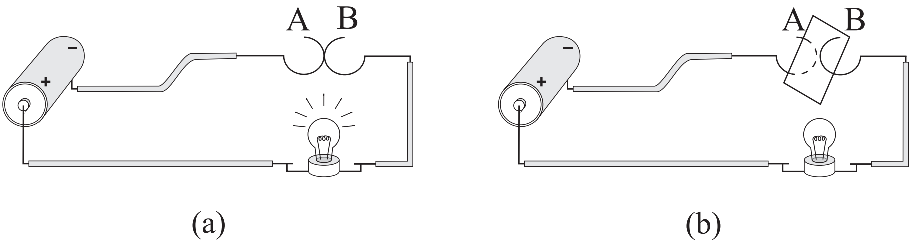


Figure 5.5: (a) The bulb turns on when conductors A and B touch one another. (b) The bulb does not turn on when A touches one side of the tape while B touches the other side of the tape.

of this tape. The bulb does not turn on for all kinds of tape (adhesive, surgical or electrical), Figure 5.5 (b).

Experiment 5.4 shows that electrical tape behaves as a conductor through its side in electrostatic phenomena in which there is a potential difference of 1,000 V or higher between the two sides of the tape. Experiment 5.6, on the other hand, shows that electrical tape behaves as an insulator through its sides for low voltages of a few Volts. This tape is also a good insulator when the voltage through its side goes up to some 300 Volts. For this reason it received the name of *insulating* or *electrical* tape.

These Experiments also illustrate the topic discussed in Subsection 3.3.2. That is, the conducting or insulating behavior of a body depends not only on the intrinsic properties of the body, but also on the external potential difference applied to this body.

5.2 Electrification of the Tape

To standardize the experiments and their results, the strip to be tested should always be removed from another strip below it, called a base tape and represented by the letter B. Stick a 10 to 20 cm long strip of tape onto a smooth flat surface of a table. This base tape should be smoothed down with the finger. Another strip of the same length should be stuck on top of the base tape. It will be called the upper tape and represented by the letter U, Figure 5.6.

Figure 5.6: Upper tape U on top of the base tape B.

Fold one end of it to facilitate manipulation. The upper tape should be also smoothed down with the finger.

Experiment 5.7 - *Tape attracting light bodies*

A discharged electroscope is kept on the table, Figure 5.7 (a).

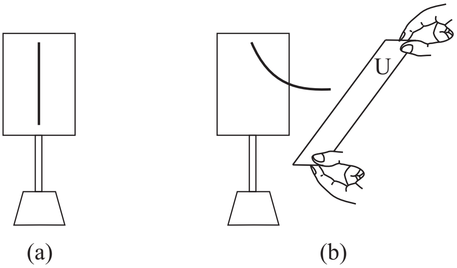


Figure 5.7: (a) Discharged electroscope. (b) Upper tape U attracting the strip of the electroscope.

The B and U tapes should be prepared, Figure 5.6. Hold the folded end of the upper tape and *quickly* pull it up and off the base tape. The base tape should remain stuck to the table. Hold the U tape by its ends and move it near the lower portion of the tissue paper strip of the electroscope. The strip is attracted by the tape, Figure 5.7 (b).

This upper tape also orientates a metal versorium when brought close to it. Hold the tape vertically by its ends and move it near one leg of the versorium. The versorium will turn, pointing its closest leg towards the tape. When the tape is moved around the versorium, it will turn accompanying the position of the tape.

This experiment shows that the upper tape has become electrified when it was quickly removed from the base tape. These attractive phenomena are analogous to the amber effect, Section 1.1. This experiment also illustrates that the tape behaves as an insulator along its length. After all, although grounded while held in the hands, it was not discharged.

Experiment 5.8 - *Tape being attracted by initially neutral conductors*

Pull another U tape *quickly* off the base tape. Hang one of its ends from a pencil, pen or from the edge of a table. The tape should hang vertically, Figure 5.8 (a) and (b).

Bring a finger near the lower portion of the hanging tape, in a direction orthogonal to the plane of the tape. The tape is attracted by the finger, Figure 5.8 (c). The tape should not touch the finger. This attraction takes place not only when the finger moves close to the gluey G side of the tape, but also when it moves close to the smooth S side.

This experiment also shows that the adhesive tape has become electrified when quickly pulled up and off the base tape. This phenomenon is the opposite to the amber effect. It illustrates the principle of action and reaction.[2] In the amber effect an electrified body attracts light objects which were initially neutral. There is a strong attraction when these light objects behave as conductors.

---

[2] Section 3.5 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

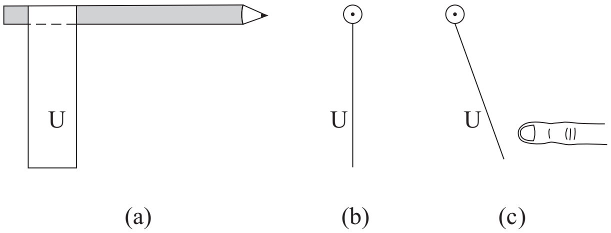


Figure 5.8: (a) Side view of a hanging upper tape. (b) End view. (c) The tape is attracted by a nearby finger.

In the opposite phenomenon being observed here, an initially neutral body (the finger) attracts electrified objects (like the hanging U tape) which are close to it. When the attraction takes place, the finger is no longer neutral. It has now an electrical charge of opposite sign to that on the electrified tape.

Try Experiments 5.7 and 5.8 with different kinds or brands of adhesive tapes, always utilizing the same kind of tape for each pair BU. The brand which becomes more electrified should be utilized in the next experiments.

These experiments work well on dry weather.

Probably the upper tape has become electrified on the gluey side G when it was pulled up and off the base tape. After all, before it was removed from the base tape, it had been smoothed down with a conducting finger.

The experiments of Section 5.1 showed that an adhesive tape behaves as a conductor through its side. Therefore, after it is removed from the base tape, an exchange of electrified particles can take place between the gluey and smooth sides of the charged upper tape. It may happen that a few seconds after being pulled up and off the base tape, both sides of the upper tape become equally electrified. In any event, we will not test in this book if the tape has become electrified only on the sticky side or on both sides.

Experiment 5.9 - *Discovering the sign of the charges on the electrified tape*

Electrify two electroscopes with opposite charges. This opposite electrification can be obtained by induction, for instance.[3] These charged electroscopes should stay on a table separated from one another, with raised strips. Take notice of which one is positively electrified and which one is negative.

Quickly pull another U tape up and off the base B tape. Hold it horizontally by its ends and bring it close to the lower portion of the strips of both electroscopes, without touching them. It attracts one strip and repels the other. By knowing the sign of the charge of the electrified electroscopes, determine the sign of the charges on the U tape. In the majority of the experiments which we performed, most brands produced *negatively* electrified upper tapes. These tapes repelled the strip of the negative electroscope and attracted the strip of the positive electroscope.

---

[3] Section 7.5 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

Depending on the brand of the adhesive tape, the upper tape may become positively electrified.

5.3 Neutralization of the Tape

This Section describes how to neutralize an electrified tape.

Experiment 5.10 - *Discharge of the tape over time*

Suppose an upper tape which has become electrified as described in Section 5.2. Hang it vertically from an appropriate support, Figure 5.8 (a) and (b).

The simplest way to discharge it, is to let the tape hanging at rest for a few minutes in the open air. Afterwards, when a finger is brought near the lower portion of the tape, it no longer attracts the tape. Likewise, when this tape is brought near the lower portion of a strip belonging to a discharged electroscope, the strip is no longer attracted by the tape. Similarly, a metal versorium is not oriented by this tape.

Experiment 5.11 - *Discharging the tape through its smooth side*

We present now another procedure to discharge an upper tape. Pull a new U tape up and off the B tape. Hang it vertically from the edge of a table or from a pencil, as in Figure 5.8 (a) and (b). Hold the bottom of the tape and slowly rub a finger back and forth along the *smooth* side of the tape, Figure 5.9.

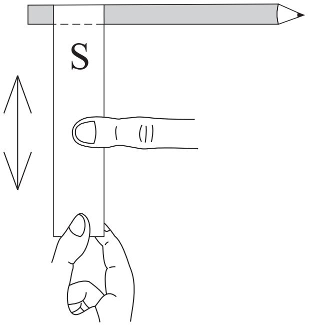


Figure 5.9: Rubbing the *smooth* side of the tape.

Afterwards test its electrification as in Experiments 5.7 and 5.8. Normally this tape no longer attracts the strip of a discharged electroscope, it does not orientate a versorium and is not attracted by a finger.

Experiment 5.12 - *It is difficult to discharge the tape through its sticky side*

Begin the experiment again with a hanging electrified tape. Repeat the procedure of Experiment 5.11, but this time rub the finger along the *sticky* G

side of the tape. Afterwards test its electrification as in Experiments 5.7 and 5.8. Observe that this time the tape remains electrified.

Experiments 5.11 and 5.12 are a little surprising. After all, the *U* tape should initially have been electrified on the sticky side when pulled up and off the base tape. Therefore, we might expect to discharge it by rubbing a finger along the *G* side. However, the neutralization does not take place in this case. One of the reasons why it remained electrified might be connected with the adhesive itself, which prevents the finger from sliding smoothly along the *G* side. Therefore, we can neither touch nor ground all points along this side of the tape. Maybe it becomes neutralized only in the few points where the finger touches the adhesive, remaining electrified in the other points. Moreover, the finger separating from the glue may recharge the tape.

Experiment 5.11, on the other hand, indicated that it can be discharged by sliding a finger along the smooth side of the tape. One of the reasons why this neutralization takes place in this case is connected to Experiment 5.2 which indicated that the tape behaves as a conductor through its side. Therefore, by sliding a conducting finger along the smooth side, the electrified particles located on both sides of the tape are neutralized. Moreover, the finger can slide along the whole area of the smooth side, touching most points of the tape. This general grounding did not take place on the sticky side, as the adhesive prevented the sliding motion of the finger.

Experiment 5.13 - *Discharging half of a tape*

Prepare a new electrified *U* tape approximately 20 cm long. Hang it by one end and rub the finger slowly along its smooth side, as in Figure 5.9, but only along the lower half of the tape. Remove the finger.

Once more bring a finger close to the center of the rubbed portion of the tape, approximately at 5 cm from the lower free end. The tape is no longer attracted by the finger. The tape can also be held horizontally. When the center of the rubbed portion of the tape is brought close to the lower end of the strip of a discharged electroscope, no attraction takes place. This rubbed portion of the tape does not interact as well with a nearby metal versorium.

Bring the center of the portion of this tape which was not rubbed close to the lower end of the strip of a discharged electroscope. The strip is attracted by the tape. This portion of the tape also orientates a nearby versorium. Hang the tape again by its other end, this time with the rubbed portion above. Bring a finger close to the center of the lower portion of the tape which was not rubbed. This unrubbed portion of the tape is attracted by the finger.

This experiment demonstrates several facts. We started with a tape electrified along its entire length and rubbed only half of it. By sliding a finger along the smooth side of this electrified tape, we neutralized this region. The other half of the tape on which the finger did not slide was not discharged. This fact shows again that the adhesive tape behaves as an insulator along its length. That is, only half of the tape remains electrified along its length. The electrified particles of this portion are not able to move longitudinally towards the other half of the tape.

5.4 Electrifying Tapes with Opposite Charges

Prepare another set of tapes, this time with 3 tapes on top of one another. The lower base tape B should be 10 to 20 cm long, stuck onto a smooth flat surface. Smooth it down with the finger. Stick a second strip of tape onto the base tape. Fold one end and smooth this second tape down along its length. Stick a third strip of tape onto the second tape. Fold one end and smooth this third tape down along its length. The second strip is called the lower tape and represented by the letter L which should be written on its end. The third strip is called the upper tape and represented by the letter U which should be written on its end. The folded ends of the L and U tape should be on top of one another. Figure 5.10 illustrates this set of 3 tapes.

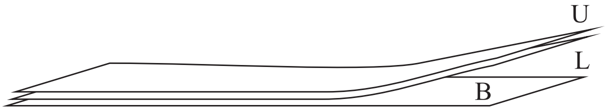
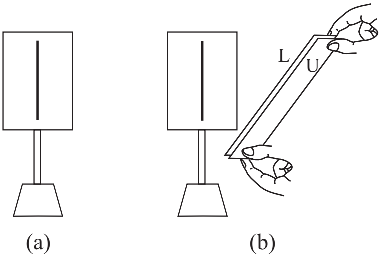


Figure 5.10: The U tape lies on top of the L tape, which lies on top of the B tape.

Experiment 5.14 - *Neutrality of a superimposed pair of tapes*

The U and L tapes should be *slowly* lifted together up and off the base tape. The B tape should remain stuck to the table. Hang the double layer of tape vertically from an appropriate support. Pass this double layer a few times between two fingers, discharging the pair.

Then bring this LU tape pair close to the strip of a discharged electroscope. The strip is not attracted, Figure 5.11.



(a) (b)

Figure 5.11: (a) Discharged electroscope. (b) The neutral LU tape pair does not attract the strip of a discharged electroscope.

Hang the LU tape pair vertically from an appropriate support, Figure 5.12 (a) and (b). Bring a finger close to the lower portion of this pair. No attraction takes place, Figure 5.12 (c).

Sometimes the pair, after being lifted up and off the base tape and smoothed down between two fingers, attracts the strip of a discharged electroscope and

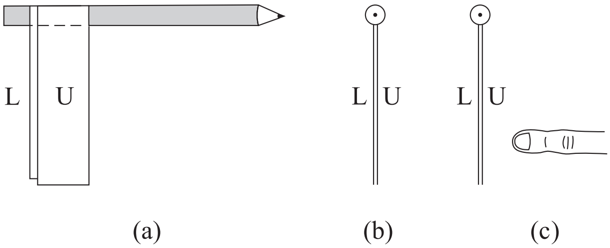


Figure 5.12: (a) Side view of a hanging LU tape pair. (B) End view. (c) The pair is not attracted by a nearby finger.

is attracted by another finger. If these interactions take place, the pair should be neutralized before continuing the experiments. In order to neutralize the pair, hang it vertically and wait a few minutes. Or pass it slowly a few more times between two fingers. The pair can also hang vertically by one end in an appropriate support. Slowly rub a finger back and forth along the smooth side of the U tape, as shown in Figure 5.9.

From now on, assume that the LU pair is neutral. That is, it no longer attracts light bodies and is not attracted by grounded conductors.

Experiment 5.15 - *Attraction and repulsion between electrified tapes*

Begin with a neutral LU tape pair, like that of Experiment 5.14. Hold the folded end of the L tape with one hand and the folded end of the U tape with the other hand. Then *quickly* pull the U tape up and off the L tape. Hang each tape vertically in an appropriate support, with the two supports separated from one another.

Verify that each tape has become electrified by performing procedures analogous to those of Experiments 5.7 and 5.8.

Follow the same procedure with a new neutral LU tape pair and prepare another electrified L tape and another electrified U tape.

Bring one horizontal pencil laterally near the other pencil, each pencil carrying an U tape. The pencils can even touch one another. Observe that the tapes repel one another, Figure 5.13 (a). Two electrified L tapes also repel one another, Figure 5.13 (b). However, a lower tape attracts an upper tape, Figure 5.13 (c).

Conclude that the U and L tapes are now oppositely electrified, one positive and the other negative.

Decreasing the distance between the horizontal pencils carrying U tapes, increases the angle of inclination of the tapes relative to the vertical. This fact illustrates that the force of repulsion between bodies electrified with charges of the same sign increases when the distance between the interacting bodies decreases. The same happens by decreasing the distance between two L tapes, or between a lower tape and an upper tape.

Experiment 5.16 - *Discovering the sign of the charge on each tape*

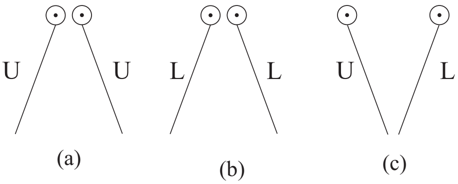


Figure 5.13: (a) Repulsion between two U tapes. (b) Repulsion between two L tapes. (c) Attraction between a lower tape and an upper tape.

Hang an electrified lower tape vertically from an appropriate support and an electrified upper tape from another appropriate support. These two supports should be separated from one another. Rub a plastic straw in hair or on a piece of paper so that it becomes negatively electrified. Bring it horizontally near the lower portion of both tapes. In most tapes with which we worked, the upper tape was repelled by the straw while the lower tape was attracted by it.

A straw acquires a large enough amount of positive charge when rubbed between two hard rubber hoses or between two PVC tubes.[4] Bring this positive straw near the two electrified tapes. It repels the lower tape and attracts the upper tape.

You can then conclude that normally the upper tape becomes negatively electrified, while the lower tape becomes positively electrified, Figure 5.14.

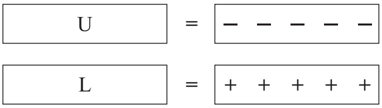


Figure 5.14: Upper tape negatively electrified and lower tape positively electrified.

5.5 Electric Dipoles

An electric dipole consists of two equal and oppositely electrified particles separated by a certain distance. A body with zero total charge having an equal amount of positive and negative charges separated along its volume is also called an electric dipole. In this Section we show how to make electric dipoles and some phenomena which can be observed with them. The interaction between two electric dipoles has many properties analogous to the interaction between two magnets.

Experiment 5.17 - *Electric dipole made with adhesive tapes*

Prepare now an electric dipole beginning with a plastic versorium, as described in Subsection 2.3.3. Assume that each leg of this versorium is approximately 5 cm long. Suppose as well that both legs are initially neutral. This

---

[4] Section 5.3 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

fact can be tested when a finger is brought close to each leg. If the versorium is not oriented by the finger, the legs can be considered neutral. Prepare a set of 3 superimposed tapes (called B, L and U), as in Figure 5.10, each 4 cm long. Tapes L and U are then oppositely electrified as in Experiment 5.15. Stick the L tape onto one leg of the versorium and the U tape on the other leg, Figure 5.15 (a).

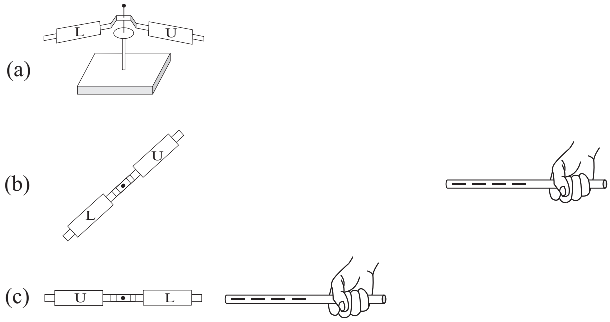


Figure 5.15: (a) Plastic versorium with an electrified L tape on one leg and an electrified U tape on the other leg. (b) Top view with the versorium in an arbitrary orientation when the electrified straw is far away from it. (c) The versorium is oriented toward the electrified straw which is placed near it.

When the negative straw is brought close to any leg, the versorium turns and points towards the straw. Moreover, the U leg is repelled by the straw while the L leg is attracted by it. In equilibrium the versorium is oriented as indicated in Figure 5.15 (c).

This electric dipole has opposite charges of the same magnitude in different legs of the versorium. It is analogous to an ordinary magnetic compass and can be called an *electric compass*.[5] The interaction between two polarized plastic versoria behaves as the interaction between two magnetic compasses.

However, while an ordinary compass is oriented by the Earth and by a nearby magnet, this electric dipole is oriented not only by another electric dipole, but also by a straw electrified with a single kind of charge (positive or negative). There is no magnet similar to an electrified straw. That is, we don't know any material in nature containing a single kind of "magnetic charge." For instance, there is no substance containing only a North pole. When we break a bar magnet in the middle, each half will have a North and a South pole, Figure 5.16.

This experiment does not work properly when the adhesive tapes are fixed on a metal versorium. There are two reasons for this fact. (a) The first reason is that this versorium is a conductor. The adhesive tape also behaves as a conductor through its side. Therefore, the electrified particles on both tapes can neutralize one another through the conducting versorium.

(b) There is a second reason which makes the realization of this experiment difficult with a metal versorium (even when this neutralization does not take

---

[5] [Net94] and [CS02, p. 466].

Figure 5.16: (a) Bar magnet. (b) By breaking the magnet, we form two new magnets. Each small magnet has a North pole and a South pole.

place, with the two tapes maintaining their opposite charges). A metal versorium is a conductor. Therefore, when an electrified straw is brought close to one of its legs, this leg will acquire an induced charge of the opposite sign. It will then be attracted by the straw, trying to orientate the versorium. There will be a strong attractive force between this leg and the straw. Eventually, this attractive force can be larger in magnitude than the force acting between each tape and the straw. If this happens, both sides of the versorium will be attracted by the straw, although with total forces of different magnitudes. Suppose, for instance, that the straw is negative, the tape on the left leg is positive and the tape on the right leg is negative. When the straw is brought close to the left leg, the tip of this leg will become positive. Therefore the straw will attract this metal leg and also the tape fixed on it. Bring the straw close to the right leg. The tip of this leg will also become positive. Now the straw will attract this metal leg due to the charges induced on it, while it will repel the negative tape fixed on it. The total attractive force acting on the left leg will be larger than the resultant attractive force acting on the right leg, assuming the same distance between the straw and each leg. This fact will complicate a little the analysis of the rotation of this metal versorium.

Experiment 5.18 - *Other kinds of electric dipoles*

Experiment 5.17 had an electric dipole made with adhesive tapes. The present experiment describes other kinds of electric dipoles.

The triboelectric series, Table 1.1, shows that a plastic straw becomes negatively electrified when rubbed with hair, on the skin, with paper or cotton. It acquires a large enough amount of positive charge when rubbed between two hard rubber hoses or between two PVC tubes. To this end, place one end of the straw between these well compressed pieces and pull it quickly away from the rubber hoses.

Begin with a neutral straw in the shape of an upside down letter V. Hang it by a silk thread passing through its center. Rub half of this straw with a paper napkin. This first half of the straw becomes negatively electrified. Pull quickly the other half of the straw, moving it away from two compressed rubber hoses. This second half of the straw becomes positively electrified. The straw is then polarized by this procedure, although the two legs may acquire charges of different magnitude, as represented in Figure 5.17 (a). In this situation the straw has a total, net or resultant charge different from zero. An electric dipole is formed when the two legs are equally electrified with opposite charges, Figure 5.17 (b).

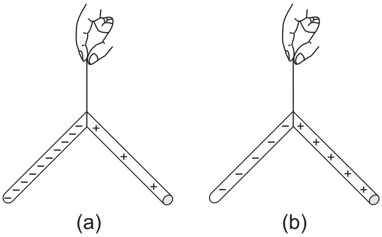


Figure 5.17: (a) Negative leg more electrified than the positive leg. (b) Legs equally electrified with opposite charges.

You can orientate this dipole when a negative acrylic ruler is brought close to any of its legs.

Make another kind of electric dipole utilizing an Styrofoam bar or parallelepiped having, for instance, 2 × 2 × 7 cm or 0.5 × 0.5 × 5 cm.[6] The exact size is not so crucial. Utilizing the triboelectric series, Table 1.1, we know that Styrofoam becomes negative when rubbed with hair, on the skin or with paper. It becomes positive when rubbed with a plastic bag or against a rigid acrylic plate. Rub one end of the Styrofoam bar on a piece of paper. Rub the other end of the bar on a rigid acrylic plate. The bar is then supported by a silk thread passing through its center. It will be analogous to an electric pendulum, with the bar replacing the paper disk of Figure 2.10. Figure 5.18 illustrates this electric dipole assuming equal and opposite charges on both ends.

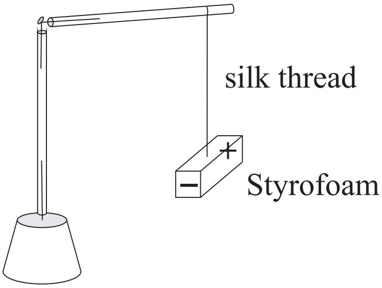


Figure 5.18: Polarized Styrofoam bar.

A negative straw repels the negative end of this bar and attracts the positive end.

Two of these polarized bars placed side by side orientate one another. One bar will not only exert a torque on the other, but also a net force. In equilibrium the ends facing one another will have opposite polarities.

---

[6] [Ferb, Corpo com duas cargas diferentes, p. 11; e Pêndulo de isopor, p. 30].

Make an electric dipole utilizing a plastic versorium. Choose two appropriate materials to rub its legs. These materials should be located on opposite sides of the triboelectric series relative to the plastic material of the versorium. That is, one material should be located between the plastic and the positive charge, while the other material should be located between the plastic and the negative charge. Electrify one leg negatively and the other leg positively. An electric dipole is formed when both legs are equally electrified with opposite charges, Figure 5.19.

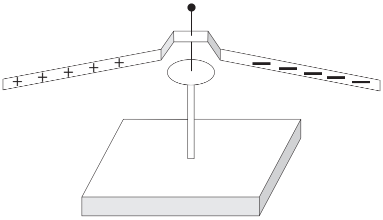


Figure 5.19: Polarized plastic versorium.

The negative leg is repelled by a negative straw and attracted by a positive straw. The positive leg is repelled by a positive straw and attracted by a negative straw.

5.6 General Aspects Related to Adhesive Tapes

Adhesive substances have been known for thousands of years. Adhesive tapes were invented around 1845 by the surgeon Horace Day. He created surgical tapes by applying a rubber based adhesive to strips of fabric. Commercial adhesive tapes were introduced in the beginning of the XXth century. Electrical tapes were created in the early 1930s. They were referred to as "friction tapes", being made of cloth tape impregnated with an adhesive material manufactured using Gutta-percha. In the 1940s the cloth paper was replaced with vinyl plastic tape.

Most adhesive tapes utilize a pressure sensitive adhesive, PSA. That is, the degree of bond between two surfaces is influenced by the amount of pressure which is used. Nowadays most tapes are made of vinyl, PVC or plastic strips with a rubber adhesive applied on one side and a non-stick layer applied on the other side. This last layer prevents the adhesive from sticking on the smooth side when the spool is wound or unwound.

Chapter 6

The Electrophorus

6.1 The Instrument

This Section presents a device which had a great importance in the history of electricity, namely, the electrophorus or electrophore. It is composed of two parts: (a) an insulating electrified base, together with (b) a charge collector. This charge collector is composed of a conductor connected to an insulating handle, Section 2.6. The insulating base is also called a dielectric plate or cake. It can be charged by friction or by any other means. Figure 6.1 represents a positively charged insulating plate, together with the charge collector of the electrophorus.

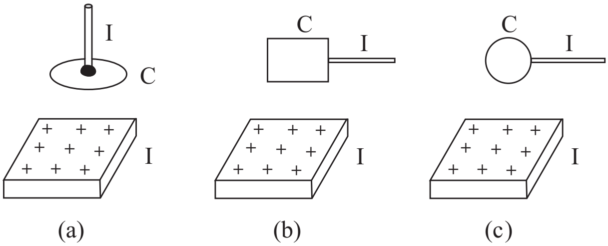


Figure 6.1: Examples of electrophorus composed of an insulating plate I positively charged, together with its charge collector, namely, a conductor C with an insulating handle I.

Normally the insulating base and the conductor are plane, although this aspect is not essential. They should have the same shape allowing a large area of contact. The insulating or dielectric base has the same size or is larger than the conductor. It can be a plastic sheet, a Styrofoam plate, the plastic cover of a CD, a PVC plate, an acrylic slab, etc. It can be electrified by rubbing it briskly against a paper napkin, wool, cotton tissue or another appropriate material.

Some authors utilize the name electrophorus when referring only to its part (b), namely, the conductor with an insulating handle. This portion (b) works as a charge collector.

The charge collector of Figure 6.1 (a) may represent, for instance, the metal cover of a food can or an aluminum pizza pan connected to a PVC tube. This charge collector may also represent Coulomb's proof plane, namely, a conducting disk made of thin cardboard connected to a plastic straw with modeling clay.[1] It can also be a light aluminum plate connected to the end of a horizontal plastic fork by means of adhesive tape. The charge collector of Figure 6.1 (b) may represent, for instance, a typical electroscope like the ones utilized in this book but without its strip made of tissue paper. In this case it is simply a rectangular cardboard connected to a plastic straw. The charge collector of Figure 6.1 (c) may represent, for instance, a ball made of aluminum paper connected at the end of a plastic straw, or a metal sphere at the end of a PVC tube.

A particular electrophorus with which we obtained a good electrification utilizes a pizza pan with 30 cm diameter with an insulating handle at its center. The insulating base of this electrophorus can be a square PVC plate with sides of 40 cm. This insulating base is electrified by rubbing it briskly against a paper napkin or a cotton tissue. Cláudio Furukawa of the University of São Paulo gave us this electrophorus as a gift.[2]

The electrophorus was invented by the Swedish physicist Johan Carl Wilcke (1732-1796). He published his main results in 1762.[3] He had published the first triboelectric series in 1757. The electrophorus was improved and popularized by Alessandro Volta around 1775. The name "electrophorus" is due to Volta. It is derived from the Greek words "amber or elektron" and "to carry or pherein", that is, a purveyor or bearer of electricity.[4] This instrument is usually called "Volta's electrophorus", although it was invented by Wilcke.

The German scientist Georg Christoph Lichtenberg (1742-1799) built in 1777 a very large electrophorus. Its charge collector was a metal disk 2 m in diameter. This metal plate was raised and lowered using a pulley system, producing sparks up to 40 cm long. He utilized this electrophorus to produce the famous Lichtenberg figures, namely, branching electric discharges on the surface of insulating materials.[5]

6.2 Operation of the Electrophorus

Experiment 6.1 - *Electrifying the charge collector of an electrophorus*

This Section describes how to operate the electrophorus. Figure 6.2 (a) represents a Styrofoam plate negatively electrified on its surface by friction against a paper napkin. The charge collector of this electrophorus can be a disk of thin cardboard having a plastic straw as its handle, or a metal disk having

---

[1] Section 2.6.

[2] [MF].

[3] [Hei99, pp. 418-419].

[4] [Hei99, pp. 416-417].

[5] [Lic56], [Har67, p. 89], [BJ92], [Beu92] and [Ach96, Chapter 5].

a PVC tube as its handle. Figure 6.2 (b) shows the disk on the electrified insulating base. In Figure 6.2 (c) a finger touches anywhere on the upper side of the metal disk. Remove the finger, Figure 6.2 (d). Finally raise the charge collector by its handle, Figure 6.2 (e). Do not touch its conducting disk.

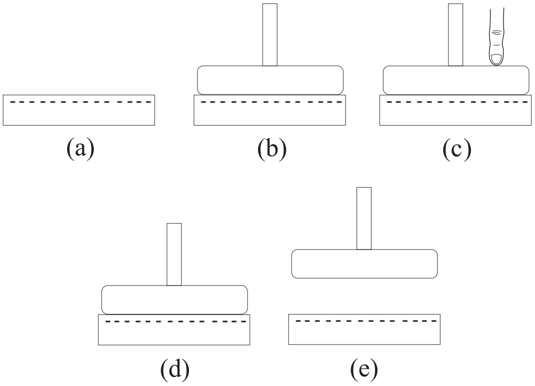


Figure 6.2: Operation of the electrophorus.

Charge two electric pendulums, one positively and the other negatively. They should be kept separated from one another. Slowly bring the charge collector of the electrophorus near each one of these pendulums. Observe that it repels the positive pendulum and attracts the negative pendulum. We conclude that the electrophorus has become positively electrified in this operation.

There is a simple explanation for this electrification based on electric induction or polarization, Figure 6.3.

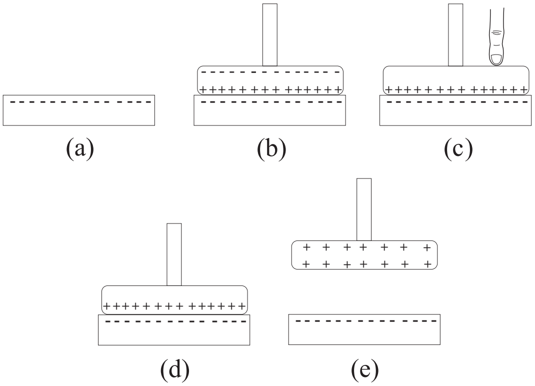


Figure 6.3: Electrification of the charge collector with a net charge of opposite sign to that of the base.

When the conducting disk is placed on the electrified insulating plate, it becomes polarized. When a finger touches its upper side, the conducting disk is grounded. Its upper side is neutralized but its lower side remains electrified due to the presence of the nearby electrified insulating plate. When the finger is removed, nothing changes on the disk. When the disk is lifted by its handle, there is a redistribution of the net charge of the disk between its upper and bottom sides. At the end of the process, the electrophorus becomes electrified with a net charge of opposite sign to that of the electrified base.

Figure 6.4 illustrates the situation in which the charge collector is composed of a metal sphere with an insulating handle. It touches a positively electrified insulating plate, becoming negatively charged at the end of the process.

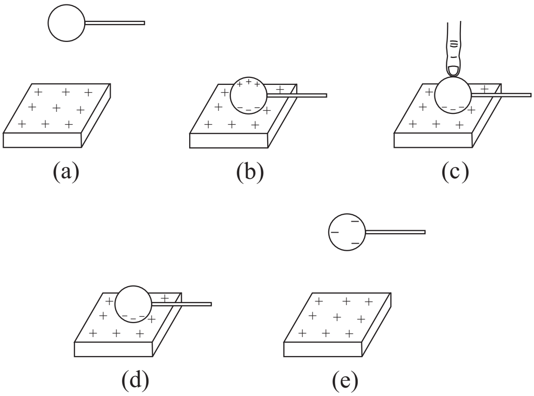


Figure 6.4: Spherical conductor touching a positive insulating plate.

Experiment 6.1 shows that the charge collector becomes electrified with a charge of opposite sign to that of the base. The electricity stored in the charge collector can be easily transported to any place when the collector is held only through its insulating handle. It can then be partially transferred to another conductor which is insulated from the ground when the electrified charge collector touches this conductor. When this conductor is much larger than the charge collector, it will acquire most of the electricity initially stored in the collector.

It is very easy to electrify and to manipulate an electrophorus. *But its main advantage is that all this electrification process can be repeated many times without causing the electrified base to lose its charge appreciably.* Suppose that in each operation cycle we transfer all collected charge to another conductor. After many cycles, we transfer an amount of charge having a magnitude much larger than the amount of charge spread on the electrified base. This remarkable fact has a simple explanation. In each cycle the charge collector touches the electrified base in just a few points of contact. Only these points will be neutralized. The other regions of the electrified base are not neutralized in this process. After all, it is an insulator which does not allow the motion of its electrified particles. Moreover, the charges acquired by the collector in each cycle are not supplied by the electrified slab. They are supplied by the Earth during the grounding with a finger. The importance of the electrified base is to polarize the conductor of the charge collector. The charge collector acquires a net charge through grounding.

As the surface area of the conducting Earth is enormously larger than the area of the charge collector, the Earth has an almost inexhaustible amount of free charges which can be supplied to the charge collector in many operation cycles.

In any event, the electrified base slowly discharges. One reason is the small amount of electrified particles exchanged with the charge collector in the contact points. Another reason is the small conductivity of air due to the presence of mobile ions. Moreover, it also loses some of its electrified particles to the ground. After all, although it is insulating, there are no perfect insulators in nature. Styrofoam, plastic, acrylic and other insulating materials always present a small conductivity. But normally these electrification losses are very small and are not easily perceived on dry weather. Normally you can operate the electrophorus for a few minutes, repeating many times the charging cycle, without noticing the loss of electrification of its base. Moreover, even when the amount of electricity of the base decreases in time or with the operation cycles of the electrophorus, you can simply rub once more the insulating base in order to restore its original electrification. You can then produce a whole new series of charging cycles.

The charge collector of an electrophorus can be electrified many times without discharging appreciably its base. For this reason Volta called this device an *elettroforo perpetuo*, that is, an inexhaustible purveyor of electricity. Its dielectric cake preserved almost indefinitely its electricity during many operation cycles:[6]

> [...] electrified but once, briefly and moderately, never loses its electricity, and although repeatedly touched, obstinately preserves the strength of its signs.

Experiment 6.2 - *Charging an electroscope in contact with an electrified base*

In this experiment the rectangular electrified insulating base or plate of the electrophorus remains fixed relative to the ground in a vertical plane, Figure 6.5 (a).

The charge collector will be a rectangular thin cardboard with 7 by 10 cm sides connected to a plastic straw. A single thin strip of tissue paper is glued on the outer side of this charge collector, that is, on the same side on which the straw is located. Hold the charge collector by its straw and place the cardboard on the electrified plate, touching it. The strip moves away from the cardboard, Figure 6.3 (b). Ground the cardboard while it is touching the electrified base. This grounding process can be performed, for instance, by touching the cardboard with a finger. The strip drops, sticking to the rectangle, Figure 6.3 (c). The strip remains down when the grounding is removed, Figure 6.3 (d). Remove the electrophorus from the electrified plate while holding its insulating handle. The strip rises again, Figure 6.3 (e). Place the positively electrified insulating slab in a horizontal orientation. Bring it close to the cardboard, its strip moves towards the plate, Figure 6.5 (f). This fact indicates that the collector has become electrified with a charge of opposite sign to that of the electrified plate.

---

[6] [Hei99, p. 416].

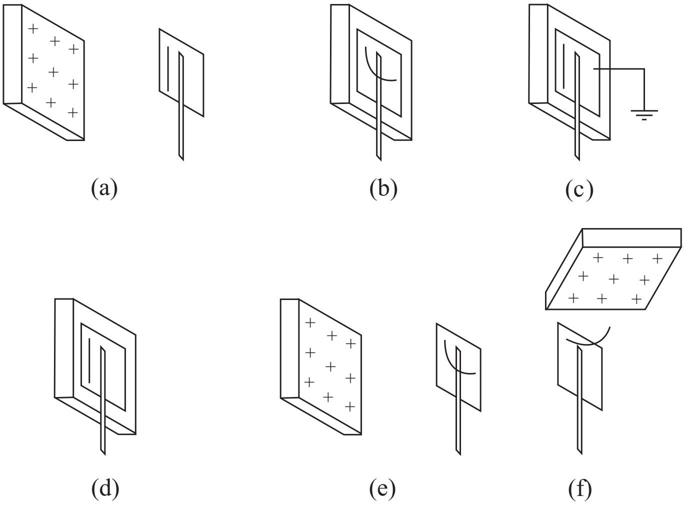


Figure 6.5: (a) Electrified base and charge collector of the electrophorus having a strip of tissue paper. (b) The strip raises when the cardboard touches the electrified plate. (c) The strip drops during grounding. (d) It remains down when the grounding is removed. (e) It raises when the collector comes out of the base. (f) Strip attracted by the electrified plate.

This behavior can be explained with the charge distribution of Figure 6.3, reversing the signs of all charges.

Experiment 6.3 - *The electric snake*

Perform the experiment of the electric snake.[7] The charge collector of the electrophorus will be the disk of Figure 6.1 (a). Place bits of paper (or small pieces of aluminum foil or bits of tissue paper) on the disk, on the same side on which the insulating handle was fixed. The charge collector is electrified as in Experiment 6.1. When the charge collector comes out of the electrified base, some paper bits jump off the disk. Move now a finger near the upper side of the disk. The remaining pieces of paper are attracted by the finger, touch it and fall back to the disk.

This experiment does not work properly when the paper bits are replaced by small pieces of an insulating material like a plastic bag.

This experiment is related to the amber effect, showing an opposite phenomenon. In the amber effect a rubbed straw comes close to small pieces of paper and they jump to the rubbed plastic. Although the paper bits are initially neutral, they become polarized by the nearby electrified straw. When the paper bits rest on a conducting surface, they acquire a net charge of opposite

---

[7] [FR08, p. 86].

sign to that of the nearby straw.[8]

In the present experiment, on the other hand, the disk of the electrophorus and the pieces of paper which are located on the disk become electrified with charges of the same sign when we separate the charge collector from the electrified base. Due to the repulsion exerted by the electrified disk on the electrified pieces of paper, some of the paper bits jump off the disk when the disk comes out of the base. When a finger is brought near the disk, the remaining paper bits are attracted by it. The finger is a grounded conductor. It is initially neutral when it is far away from the electrified disk. When it gets close to the electrified disk, the tip of the finger becomes electrified with a charge of opposite sign to that of the disk. Now the electrified finger attracts the oppositely charged paper bits. As the remaining paper bits are also repelled by the electrified disk, they move toward the finger. When the small pieces of paper touch the finger, they acquire a net charge of the same sign as that of the finger due to the ACR mechanism. They are now repelled by the finger and attracted by the disk, falling back on the disk.

This experiment and the amber effect illustrate the principle of action and reaction. In the amber effect an electrified straw attracts paper bits which were initially neutral. Here, on the other hand, electrified paper bits are attracted by a finger which was initially neutral.

6.3 A Personal Account

I quote here a particular experience which may be useful to other people. During my physics undergraduate studies at the University of Campinas—UNICAMP (1980-1983), I read about the electrophorus and decided to build this instrument. As charge collector I utilized the circular lid of a metal can. I sawed 20 cm of a wood broomstick as my insulating handle. With a nail I fixed the handle to the disk. I utilized several insulating bases like a plastic bag, an acrylic slab or a PVC plate. To electrify this base, I rubbed it with a paper napkin, cotton tissue and other materials.

I tried some simple experiments as described in the textbooks but always failed. That is, I could not reproduce with my electrophorus the electric phenomena described in the textbooks. Initially I supposed that the base had not received a large enough amount of electricity. I changed the material of the base plate, but nothing changed. I changed the substances utilized to rub the plate, once more nothing changed. Finally I decided to change the friction methods. Nothing worked. Eventually I gave up this experiment and others related to electricity. I concluded that it was my fault, my lack of ability with experimental physics. This frustrating experience was one of the reasons why I decided to dedicate myself to theoretical physics.

---

[8] As discussed in Subsection 4.1.2. See also Section 8.3 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

In the early 1990's I discovered the works of Norberto Ferreira.[9] I then finally discovered the correct explanation for my failure. It was not lack of manual ability. My mistake was that I had employed a wood handle as an insulating material. At that time I believed that this handle was an insulator simply due to the fact that it was made of wood. After all, this was the implicit message found in most didactic textbooks. They mentioned that wood, glass, rubber, water and many other substances were insulators, presenting even their dielectric constants. Metals and the human body, on the other hand, were considered as conductors. During my undergraduate studies I never imagined that a piece of wood might behave as a conductor. Therefore I never tried to test its conducting behavior and did not consider replacing it by a PVC tube or another material.

With the works of Norberto Ferreira I discovered that most materials behave as conductors for electrostatic experiments. These conducting materials include many kinds of wood, glass, rubber, tap water, etc. This aspect was the most important lesson that I learned from his works. That is, instead of saying that a certain body *is* a conductor or an insulator, it is more correct to mention that this material *behaves as* a conductor or an insulator, *depending on internal and external conditions applied to it*. In particular, when we apply a high voltage between the ends of a body, a certain material which behaves usually as an insulator for low voltages, may now behave as a conductor. As in electrostatics we normally deal with high voltages, ranging typically from 1,000 V up to 10,000 V, most materials behave as conductors.

Probably the wood handle which I utilized in the charge collector of my electrophorus behaved as a conductor. For this reason I could not collect any charges with this instrument and the experiments failed. By replacing the wood broomstick by a PVC tube or by another insulating handle, the simple experiments described in the textbooks can be easily repeated.

My original failure or frustration illustrates the importance of always testing the conducting behavior of materials before beginning any experiment. To this end, the best procedure in order to know if a substance behaves as a conductor or an insulator, is to utilize the electroscope test described in Section 3.1. Norberto Ferreira also taught me how to build simple and cheap electroscopes and many other devices which work perfectly well. This was the second important lesson which I learned with him.

---

[9] [Fer78], [FM91], [Fera], [Ferb], [Ferc], [Ferd], [Fer06], [Fer01c], [Fer01d], [Fer01b] and [Fer01a].

Chapter 7

Distribution of Charges in a Conductor

This book presents several experiments with hollow conductors. Normally it will be a cylindrical shell made of paper, cardboard or metal (like a cup or food can). Sometimes this cylindrical shell will be called a cylinder. It will have no lids above and/or below, so that you can see what is taking place inside it. You can also utilize a cylindrical metal net. When necessary, the cylinder can be insulated from the ground by supporting it on vertical straws fixed with adhesive tape. The cylindrical shell is also insulated when it rests on a Styrofoam plate or acrylic CD cover. The thicker the plate, the better will be its insulation. A good insulation for these experiments can be achieved with 2 to 5 cm thick plates.

7.1 Distribution of Charges in Conductors

7.1.1 Experiments with Electroscopes

Experiment 7.1 - *Electrifying a cylindrical shell*

Prepare the cylindrical shell of Figure 7.1 (a). This shell will be utilized as a curved electroscope. The internal and external strips of tissue paper will indicate the surface charge densities located on the internal and external walls.

Cut a rectangle made of paper or thin cardboard with 10 by 20 cm sides (or 10 by 30 cm). A plastic straw is fixed with adhesive tape in such a way that a portion of it remains outside the strip. Close the rectangle by making a cylindrical shell. The touching borders of the paper can be glued together or fixed with a stapler. This cylindrical shell will sometimes be simply called a cylinder. Cut very small strips of tissue paper, from 1 to 3 mm wide and 5 to 9 cm long. Their upper ends should be glued inside and outside the cylinder. The vertical straw is then fixed on an appropriate support, like the support made of thin plastic coffee cup, gypsum and paper fastener, Figure 7.1 (a).

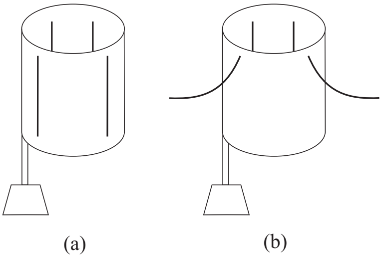


Figure 7.1: (a) Cylindrical shell made of paper and insulated from the ground. (b) Electrified cylindrical shell with raised external strips. The greater the electrification of the cylinder, the higher its strips.

Electrify a plastic straw or acrylic ruler by rubbing it with hair or a paper napkin. Scrape the rubbed straw a few times on the upper edge of the cylinder until it becomes electrified, as indicated by its raised strips. The cylinder may also be electrified utilizing an electrophorus, like the one made with a cardboard fixed to a plastic straw, Figure 6.1 (b). To electrify the paper shell, touch the upper edge of the cylinder with the electrified electrophorus. This process should be repeated a few times, always electrifying the electrophorus before touching it on the cylinder. When the cylinder acquires a large enough amount of electricity, observe that only its external strips remain raised, away from the cylinder. Its inner strips, on the other hand, remain low, attached to the cylinder even when it is electrified, as indicated in Figure 7.1 (b).

Moreover, the external strips raise little by little. That is, they increase their elevation angle every time the electrified straw is scraped on the cylinder or each time an electrified electrophorus touches its upper edge. They go up until they reach a certain degree of saturation. After reaching this maximal deflection, you can scrape the cylinder with the electrified straw or touch it with an electrified electrophorus, that the strips do not go higher.

Experiment 7.2 - *Electrifying a paper rectangle*

Cut a rectangle made of paper or thin cardboard with 7 by 20 cm sides (or 10 by 30 cm). Fix two or three straws with adhesive tapes in such a way that a portion of each straw should remain outside the strip. The strip should remain vertical with the straws fixed on appropriate supports. Cut two thin strips of tissue paper 6 cm long and 1 to 3 mm wide. The upper end of one strip should be glued on the center of one side of the paper, while the upper end of the other strip should be glued on the center of the other side of the paper, as indicated in Figure 7.2. This instrument will be like a wider electroscope, with a tissue paper strip on each side. It is insulated from the ground by the plastic straws.

Scrape an electrified straw on the upper border of the rectangle. The strips on both sides raise, Figure 7.3. The rectangle can also be electrified by touching its upper border with the charge collector of an electrified electrophorus.

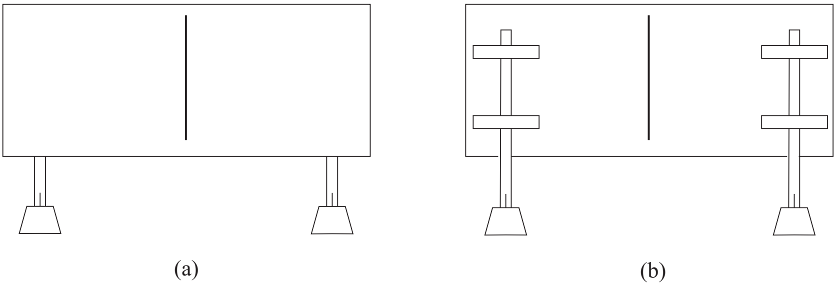


Figure 7.2: (a) Paper rectangle seen face on. (b) Back view.

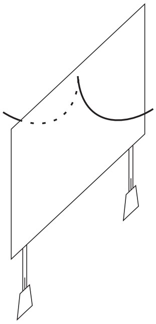


Figure 7.3: Electrified rectangle.

This charging process can be repeated a few times. The more electrified the rectangle is, the higher the angle of elevation of its strips.

Experiment 7.3 - *Bending an electrified rectangle*

Call A one side of the rectangle and B the other side. Hold the electroscope of Experiment 7.2 by its plastic straws or by the bases made of coffee cups, gypsum and paper fastener, without touching the rectangular paper. It is then deformed in the shape of a cylindrical shell.[1] As we close the circle, the inner strip on side B goes down, while the outer strip on side A goes up, Figure 7.4 (a). When we close the circle, the inner strip drops. Moreover, the outer strip is higher in this configuration of Figure 7.4 (a) than the strips on both sides of Figure 7.3.

Open the circular strip, returning to the rectangle. Make another cylindrical shell by bending the rectangle towards the other side. The tissue paper strip on side B which was down in Figure 7.4 (a) is now raised, being located on the outer side of the new circle, Figure 7.4 (b). The tissue paper strip on side A which was up in Figure 7.4 (a) is now down, being located on the inner side of the new circle, Figure 7.4 (b).

---

[1] [FM91, pp. 74-75], [Ferb, Gaiola de Faraday, p. 45] and [FR08, pp. 89-90].

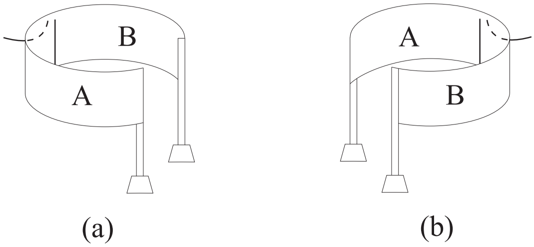


Figure 7.4: Electrified circular strip. (a) and (b): The inner strips drop, while the outer strips go up.

Experiment 7.4 - *Separating the two parts of an electrified conductor*

An analogous experiment utilizes an instrument composed of two independent parts which can be separated from one another.[2] The first part of this instrument is a simple electroscope composed of a rectangular cardboard connected to two plastic straws fixed on two appropriate supports. There are two thin tissue paper strips glued on this electroscope, one on each side, as in Figure 7.2. The second part of this instrument is a cylindrical strip made of paper or thin cardboard. The straws and cardboards of both parts should have the same height. This cylindrical strip is also connected to two straws fixed on appropriate supports. Initially the borders of both parts touch one another. The tissue paper strips on both sides of the electroscope should be down.

Electrify the system scraping the upper border of the electroscope with a rubbed straw. The system can also be charged by touching the cardboard with an electrified electrophorus. With this procedure the external tissue paper strip goes up, while the internal tissue paper strip remains down, Figure 7.5 (a).

Separate both parts of this instrument while holding only the supports or the straws, without touching the cardboards. The external strip goes a little down, while the inner strip of Figure 7.5 (a) goes up, as indicated in Figure 7.5 (b).

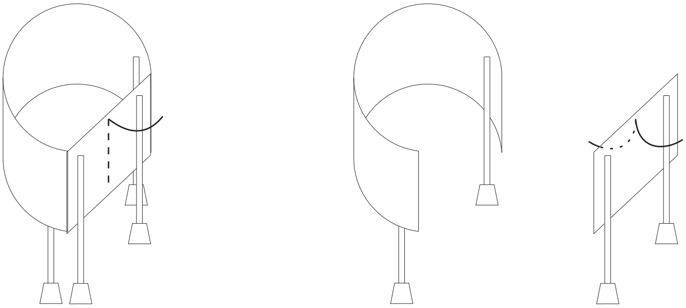
7.1.2 Collecting the Charges Located on the Internal and External Walls of an Electrified Conductor

The previous experiments analyzed only the behavior of the thin tissue paper strips. The next experiments show how to collect directly a portion of the electrified particles spread on the internal and external walls of an electrified cylindrical shell.

Experiment 7.5 - *Trying to collect charges on the internal wall of an electrified cylindrical shell*

---

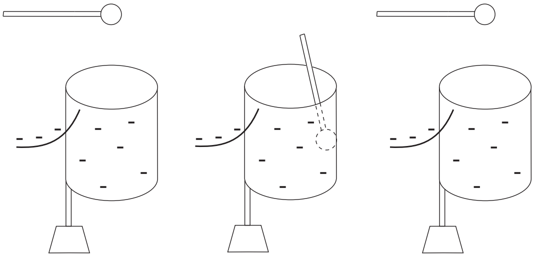
[2] [Fer78, Section 4.10.9, pp. 89-90].



(a) (b)

Figure 7.5: (a) Electrified system with the two cardboards touching one another. Only the external tissue paper strip goes up. (b) When both parts are separated, the external strip goes a little down, while the inner strip goes up.

Utilize now the cylindrical shell of Experiment 7.1 without the internal strips and with a single external tissue paper strip. This cylinder is insulated from the ground by the plastic straw. Scrape a negatively charged rubbed straw on its upper edge, until its tissue paper strip goes up, Figure 7.6 (a). The shell becomes negatively electrified.



(a) (b) (c)

Figure 7.6: (a) A discharged collector and a negatively electrified cylindrical shell. (b) Touch the ball of aluminum foil on the internal wall of the cylindrical shell. (c) By removing the charge collector, verify that it remains discharged.

The charge collector will be a ball of aluminum foil connected to the end of a plastic straw, Figure 2.15 (b). This collector should be initially discharged, Figure 7.6 (a).

Holding the collector by its straw, touch the ball of aluminum foil on the *internal* wall of the electrified cylinder, Figure 7.6 (b). Remove the collector and test its electrification. To this end, bring it close to a discharged electric pendulum or to a metal versorium. Observe that the electric pendulum and the metal versorium do not move. We conclude that the collector did not acquire any net charge by touching the internal wall of the electrified cylinder, Figure

7.6 (c).

Experiment 7.6 - *Collecting the charges on the external wall of an electrified cylindrical shell*

Repeat Experiment 7.5 beginning again with a discharged collector and a negatively electrified cylindrical shell, Figure 7.7 (a).

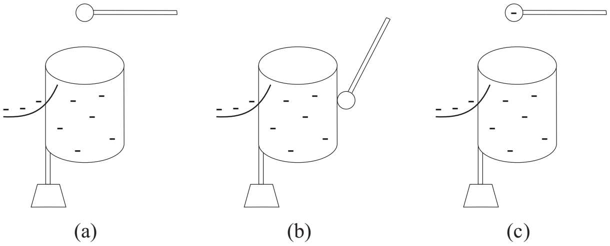


Figure 7.7: (a) A discharged collector and a negatively electrified cylindrical shell. (b) Touch the ball of aluminum foil on the external wall of the cylindrical shell. (c) Remove the charge collector and test its charge, verifying that it is negatively electrified.

Touch the ball of aluminum foil on the *external* wall of the electrified cylinder, Figure 7.7 (b). Test its charge by moving it towards a neutral pendulum or metal versorium. The pendulum and the versorium are attracted by the ball, indicating that it is now electrified. Bring the electrified ball close to two electrified pendulums separated from one another, one positive and the other negative. The ball attracts the positive pendulum and repels the negative pendulum, showing that the charge collector has become negatively electrified, Figure 7.7 (c).

Experiment 7.7 - *Trying to collect charges on the internal wall of an electrified cylindrical shell utilizing a small electroscope*

Experiment 7.5 can also be performed with another charge collector, namely, a square cardboard connected to a straw. The small square can have sides of 5 cm. The upper end of a thin strip of tissue paper can be glued on this cardboard in order to indicate when it is charged. This collector will be utilized as an usual electroscope, but now with the upper end of the strip of tissue paper glued on the opposite side of the cardboard, as indicated in Figure 7.8 (a). Scrape its cardboard with a rubbed straw or touch it with a charged electrophorus. This collector is electrified, as indicated by its lifted strip, Figure 7.8 (b).

The collector should be initially discharged, with its tissue paper strip vertical. Begin the experiment again with a negatively charged cylindrical shell, Figure 7.9 (a).

While holding the collector by its straw, touch an edge of the cardboard on the internal wall of the electrified cylindrical shell, Figure 7.9 (b). The strip of

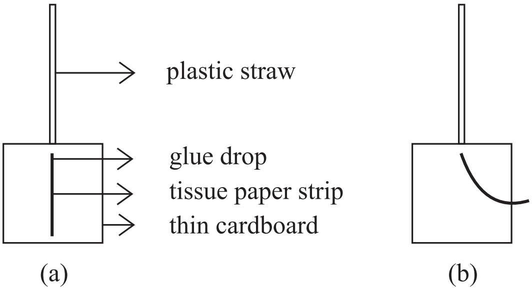


Figure 7.8: (a) Discharged collector of charges. (b) Electrified collector.

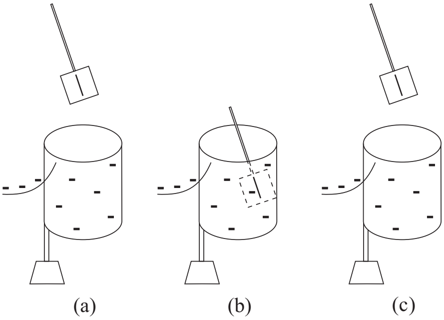


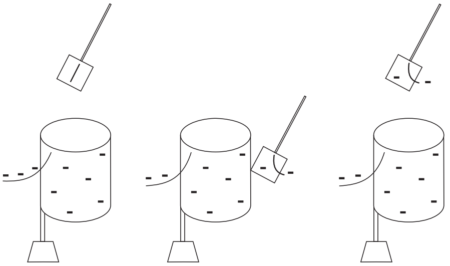
Figure 7.9: (a) A discharged collector and a negatively electrified cylindrical shell. (b) Touch the edge of the cardboard on the internal wall of the electrified cylindrical shell. (b) By removing the charge collector, verify that it remains discharged.

the collector remains down. Its strip remains attached to the cardboard when the charge collector comes out of the shell, Figure 7.9 (c). This fact indicates that the charge collector remains discharged.

Experiment 7.8 - *Collecting charges on the external wall of an electrified cylindrical shell utilizing a small electroscope*

Begin Experiment 7.7 again with a discharged collector and a negatively electrified cylindrical shell, Figure 7.10 (a).

Touch an edge of the cardboard on the external wall of the electrified cylindrical shell. The strip of the collector goes up, Figure 7.10 (b). Observe that sometimes the external strip of the charged electroscope lowers a little bit. When the collector is removed, its strip remains lifted. You can test its charge when it is brought close to a positively charged pendulum and then close to a negatively charged pendulum. It attracts the positive pendulum and repels the negative pendulum, showing that the collector is negatively electrified, Figure 7.10 (c).



(a) (b) (c)

Figure 7.10: (a) A discharged collector and a negatively electrified cylindrical shell. (b) Touch the edge of the cardboard on the external wall of the electrified cylindrical shell. (b) By removing the charge collector, verify that it is now negatively electrified.

7.1.3 Gray, Franklin and the Distribution of Charges on Electrified Conductors

Experiments of Subsections 7.1.1 and 7.1.2 show that in a hollow electrified conductor the charges spread only on its *external* surface. Stephen Gray was the first scientist to arrive at this conclusion, in 1731, when he performed another kind of experiment.[3] He suspended two oak cubes at the ends of a conducting string (his communication line). They had the same size, but one of them was hollow and the other solid. The string was insulated from the ground, suspended by silk cords (his hair-lines). Thin brass leaves were placed below the cubes. He brought an electrified glass tube close to the center of the conducting string and observed that both cubes attracted the same amount of leaves at the same height, as illustrated in Figure 7.11.

Below we present Gray's words describing his experiment (our words in square brackets and our emphasis in italics in his conclusion):[4]

> *Some time after, at Mr. Wheler's, we made the following experiment, in order to try whether the electrick attraction be proportional to the quantity of matter in bodies.*
>
> There were made two cubes of oak, of about six inches square [15 cm^2], the one solid, the other hollow: These were suspended by two hair-lines, nearly after the same manner as in the experiment above-mentioned; the distance of the cubes from each other, was by estimation, about fourteen or fifteen feet [4.6 m]; the line of communication being tied to each hair-line, and the leaf-brass placed under the cubes, the [glass] tube was rubbed and held over the middle of the [communication] line, and as near as could be guessed, at equal distances from the cubes, when both of them attracted and repelled the leaf-brass at the same time, and to the same hight; *so that it seemed to be no more attraction in the solid than in the hollow*

---

[3] Section B.8 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[4] [Graf, p. 35], [Bos11, pp. 160-161] and [BAC12, pp. 154-155].

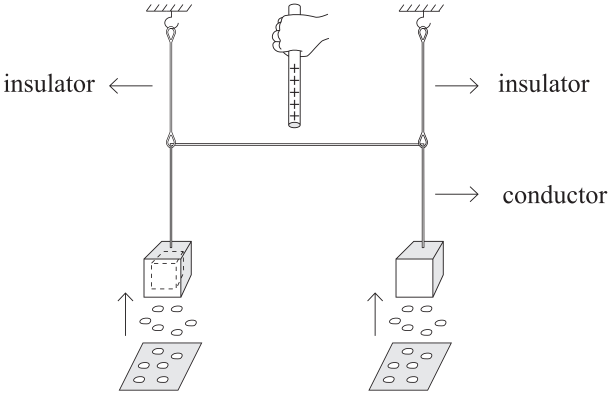


Figure 7.11: Two oak cubes, one hollow and the other solid, attract brass leaves with the same intensity.

> *cube; yet I am apt to think that the electrick effluvia pass through all the interior parts of the solid cube, though no part but the surface attracts*; for from several experiments it appears, that if any solid body touches that which attracts, its attraction ceases till that body be removed, and the other be again excited by the tube.

Benjamin Franklin was the first scientist to perform in 1755 an activity analogous to Experiments 7.5 and 7.7, although he could not explain his findings (our words in square brackets):[5]

> I electrified a silver pint cann, on an electric stand [that is, on an insulating stand], and then lowered into it a cork ball, of about an inch diameter, hanging by a silk string, till the cork touched the bottom of the cann. The cork was not attracted to the inside of the cann as it would have been to the outside, and though it touched the bottom, yet, when drawn out, it was not found to be electrified by that touch, as it would have been by touching the outside. The fact is singular. You require the reason: I do not know it.

In 1775 Joseph Priestley (1733-1804) utilized Franklin's experiment to conclude that the electrical attraction varies as the inverse square of the distance between the interacting bodies, in analogy with what happens with the gravitational attraction:[6]

> May we not infer from this experiment that the attraction of electricity is subject to the same laws with that of gravity, and is therefore according to the squares of the distances; since it is easily demonstrated that were the earth in the form of a shell, a body in the inside of it would not be attracted to one side more than another.

---

[5] [Fra69, Letter 24, pp. 326-327] and [Hei99, p. 464].

[6] [Pri75, pp. 372-374], [Pri66, pp. 372-374], [Whi73a, pp. 53-54] and [Hei99, p. 464].

Priestley was here referring to two famous theorems due to Isaac Newton (1642-1727), Figure 7.12.

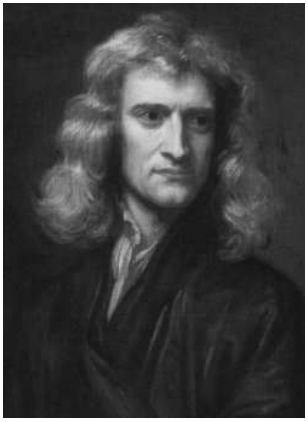


Figure 7.12: Isaac Newton (1642-1727). This is the most famous portrait of Newton. It was made by Godfrey Kneller (1646-1723) in 1689. Newton appears with his natural hair, at the peak of his scientific career, two years after the publication of the *Principia*.

These theorems were included in Section XII of book I of his work *Mathematical Principles of Natural Philosophy*:[7]

> *Section 12: The attractive forces of spherical bodies.*
>
> *Proposition 70. Theorem 30: If to every point of a spherical surface there tend equal centripetal forces decreasing as the square of the distances from these points, I say, that a corpuscle placed within that surface will not be attracted by those forces any way.*
>
> [...]
>
> *Proposition 71. Theorem 31: The same things supposed as above, I say, that a corpuscle placed without the spherical surface is attracted towards the centre of the sphere with a force inversely proportional to the square of its distance from that centre.*

Newton's theorems are valid for a spherical shell. They are not valid for a cylindrical shell with an uniform surface mass density. Franklin, on the other hand, showed that an electrified can does not exert a force on a neutral cork ball placed anywhere inside the can. There is a difference between the gravitational and electrical configurations. In a conducting can the electrified particles are free to move. In equilibrium they arrange themselves in such a way that all portions of the electrified can acquire the same electrostatic potential. In this equilibrium configuration the surface charge density changes from point to

---

[7] [New34, p. 193], [New90, p. 221], [Ass13, pp. 9-10] and [Ass14, pp. 10-11].

point. Moreover, in equilibrium the electrified conducting can will not polarize a neutral conductor placed anywhere inside the can, except close to its open lid. As the internal conductor is not polarized by the electrified can, it will not be attracted toward any side of the can, even when it gets close to this specific side.

7.1.4 Electrified Conductors Touching the Internal and External Walls of Another Conductor

In Experiments 7.5 to 7.8 we began with an electrified cylindrical shell and a discharged collector. Reverse this procedure. Begin with an electrified collector which will touch an initially discharged cylindrical shell.

Experiment 7.9 - *Electrifying a cylindrical shell by touching its internal wall with an electrified charge collector*

Utilize the cylindrical shell of Experiment 7.1 without internal strips and with a single external tissue paper strip. The cylinder is insulated from the ground by the plastic straw. It can also be insulated when supported on a Styrofoam plate. It should be initially discharged, with its tissue paper strip vertical. Utilize a charge collector composed of a conducting spherical shell connected to an insulating handle, as in Figure 2.15 (b). In particular, suppose a ball of aluminum foil on the end of a straw. It will be utilized as the charge collector of an electrophorus, being charged by the procedure shown in Figure 6.4. That is, a rectangular insulating plate is initially electrified by friction against a paper napkin or with a cotton tissue. Hold the charge collector by its handle, touch the bottom part of the aluminum ball on the electrified plate, put a finger on the top of the ball, remove the finger and finally remove the ball by raising its straw. The charge collector becomes electrified by this procedure. This can be verified moving it close to a discharged electric pendulum and observing the attraction of the disk of the pendulum.

Hold the electrified charge collector by its straw. Touch the electrified aluminum ball on the internal wall of the cylindrical shell. Repeat this procedure many times, always electrifying the collector of the electrophorus before each contact. Observe that the external tissue paper strip of the cylindrical shell raises little by little on every touch of the electrified ball. By analyzing the charge of the cylinder, conclude that it becomes electrified with a charge of the same sign as that of the ball. This fact can be visualized when the ball of the charge collector is electrified again and it is brought close to the external raised strip. Observe their repulsion.

Electrify once more the ball of the charge collector. Touch it again on the internal wall of the electrified cylinder. Remove the ball and test its charge when it is moved close to a discharged electric pendulum. Observe that there is no attraction between them, indicating that the ball has been *completely discharged* when the internal wall of the cylinder was touched with the ball. No matter if the cylinder is totally discharged or if it has an initial charge, the electrified ball is totally discharged when it touches the internal wall of the cylindrical shell, Figure 7.13.

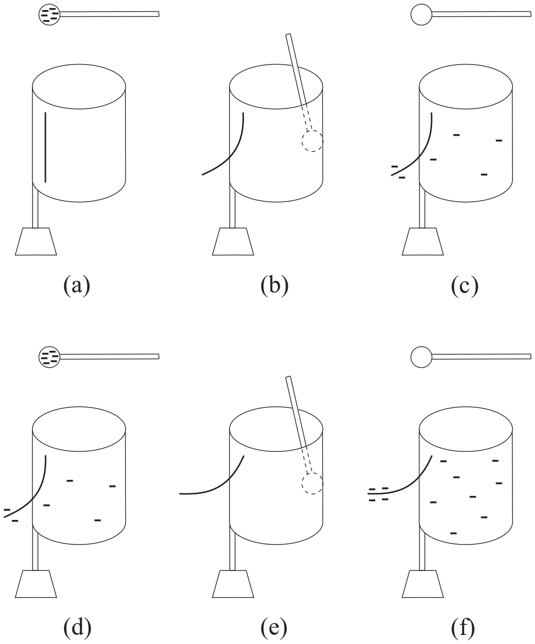


Figure 7.13: (a) Cylinder discharged and electrified collector. (b) Touch the charged collector on the internal wall of the cylinder. This procedure may be repeated many times. (c) to (f): The collector always becomes totally discharged after each contact, while the cylinder becomes more and more electrified.

Experiment 7.10 - *Bringing a neutral or electrified ball close to the external strip of a cylindrical shell*

Observe other facts in Experiment 7.9. Suppose the cylindrical shell is discharged. Electrify the charge collector of the electrophorus. Bring the electrified ball of the collector close to the external tissue paper strip of the cylindrical shell, not allowing them to come into contact. Observe that the tissue paper strip is attracted by the electrified ball. This attraction is due to the polarization of the cylindrical shell produced by the presence of the nearby electrified ball.

Repeat Experiment 7.9 electrifying the cylindrical shell. To this end, touch the electrified ball on the internal wall of the shell, repeating this procedure many times until the shell has a large enough amount of electrification, as indicated by its raised strip.

Electrify once more the ball of the charge collector of the electrophorus and bring it close to the raised strip. Observe in this case a repulsion of the strip. This repulsion indicates that the ball and strip are electrified with charges of the same sign.

Touch the electrified ball once more on the internal wall of the electrified cylinder. This procedure discharges totally the ball, as seen in Experiment 7.9. Remove the discharged ball and bring it close to the raised strip, not allowing them to come into contact. Observe once more the strip being attracted by the ball. This time the attraction is due to the polarization of the conducting ball caused by the electrification of the cylinder and of its raised strip. The ball is insulated from the ground by its straw.

Experiment 7.11 - *Cylindrical shell with internal and external strips*

Experiment 7.9 can also be performed when the cylindrical shell has internal and external thin tissue paper strips. Begin with a discharged shell having vertical strips. In this case, when the electrified ball of aluminum foil enters the cylindrical shell, the internal strip is attracted by it. Allow their contact and separate them. Observe that the internal strip drops after this contact. When it is vertical again, it is no longer attracted towards the ball it has just touched. Remove the charge collector. Test its electrification. Conclude that it has been completely discharged when the internal strip was touched with the ball.

Repeat this procedure many times. The internal strips are always attracted, touch the electrified ball and drop again. The external strips, on the other hand, become every time more inclined relative to the external surface of the shell. Moreover, whenever we test the electrification of the ball after contact with the internal strip, we conclude that it becomes completely discharged.

Experiment 7.12 - *Electrifying a cylindrical shell by touching its external wall with an electrified charge collector*

Perform a variation of Experiment 7.9. This time the electrified ball of aluminum foil touches only the external wall of the cylindrical shell. After each contact the ball is electrified again by the electrophorus. Observe that the external strip of tissue paper raises more and more after each contact. The internal strip, on the other hand, remains always vertical, regardless of how many times the electrified ball touches the cylinder. Test also the electrification of the ball after each contact with the external wall of the cylinder. Observe that it always remains a little charged. This fact can be verified when this ball is brought close to another discharged electroscope. Observe that it attracts its strip of tissue paper. This fact can also be verified when this ball is brought close to the external strip of the electrified cylinder it has just touched. Observe that this raised strip is repelled by the ball, indicating that it has not been completely discharged when it touched the external wall. The cylindrical shell, on the other hand, is more and more electrified on every touch with the electrified ball, Figure 7.14.

Experiment 7.13 - *Repeating these experiments with a small electroscope*

Experiments 7.9 and 7.12 can be repeated utilizing the charge collector of Experiment 7.7, Figure 7.8. This collector should be initially electrified, as indicated by its raised strip.

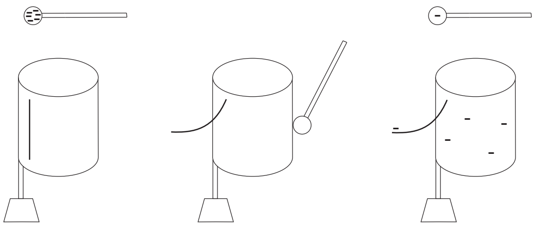


Figure 7.14: (a) Discharged cylinder and electrified collector. (b) The collector touches the external wall of the cylinder. (c) The collector loses some of its charge while the cylinder becomes a little electrified.

Hold the electrified charge collector by its straw and touch a border of the cardboard on the internal wall of an initially discharged cylindrical shell. The collector is immediately discharged, as indicated by its vertical strip. The external strip of the cylinder, on the other hand, raises a little. Repeat this process many times, always electrifying the collector before each contact. It is then possible to electrify significantly the cylinder, as indicated by its higher and higher strip. Every time the electrified collector touches the internal wall of the cylinder, it loses almost all its charge. Sometimes its strip remains a little inclined relative to the cardboard, indicating that it did not lose all its charge. It would only lose completely all of its charge if the cylinder were completely closed, with bottom and top lids. As at least one of these lids must be absent to allow the passage of the collector, sometimes the collector maintains a little amount of its charge even after touching the internal wall of the cylinder. But even when this fact takes place, observe that it will lose almost all of its electrification, regardless of the amount of charge already acquired by the electrified cylindrical shell.

Suppose now that the electrified charge collector touches the external wall of an initially neutral insulated cylindrical shell. The strip of the charge collector drops a little, remaining inclined relative to its cardboard. The external strip of the cylinder raises a little relative to the cylindrical shell. Repeat this procedure many times, always charging the collector before each contact. The external strip of the cylindrical shell raises little by little. The strip of the charge collector never drops completely after each contact, remaining always a little inclined relative to its cardboard.

After a certain amount of electrification of the cylinder, you reach a saturation point. Touch the external wall of the electrified cylinder with the charged collector. Observe that nothing takes place. That is, the charge collector remains electrified and the raised strip of the cylinder does not change its angle of inclination relative to the cylinder. There is no longer an exchange of charges between these two electrified conductors, as both strips keep their inclination angles relative to their cardboards.

7.1.5 Distribution of Charges in Open and Closed Conductors

The previous experiments indicate that in a curved conductor the charges are located on the outside, as indicated by the inclination of the strips of Figure 7.4. Moreover, as the external strips of Figure 7.4 are higher than both strips of Figure 7.3, we conclude that the charges which were located on one side of the rectangle moved to the other side when we deformed it into a circular strip.

Figure 7.15 (a) illustrates a qualitative distribution of charges on the rectangular cardboard of Figure 7.3 as seen from above.

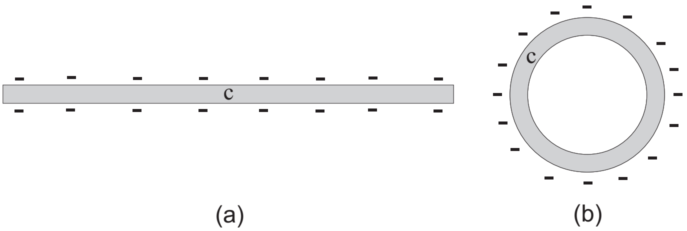


Figure 7.15: (a) Qualitative representation of the charges spread on the rectangular cardboard of Figure 7.3 as seen from above. (b) Distribution of charges on the cylindrical shell of Figure 7.4 as seen from above.

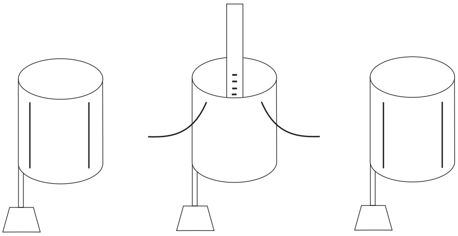
The letter "c" indicates the conductor, namely, the cardboard. We exaggerate its thickness in order to indicate the distribution of charges on its external surface. When it assumes the shape of a cylindrical shell, as in Figure 7.4, the charges which were located in one side of the rectangle flow to the other side. When the system reaches a new state of equilibrium, there will be no charges located inside the cylindrical shell, all charges will be located on the outside, Figure 7.15 (b).

7.2 Charges Induced on the Internal and External Walls of a Hollow Conductor

Experiment 7.14 - *Electrified ruler inside the cylindrical shell*

Utilize a conducting cylindrical shell with thin tissue paper strips on the outside. The cylinder is insulated from the ground when it is supported on plastic straws or above a Styrofoam plate. It should be initially discharged, with its strips vertical, Figure 7.16 (a).

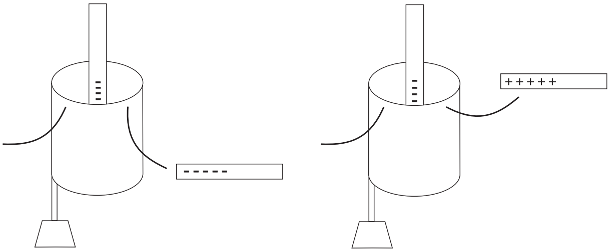
Electrify negatively a plastic ruler by rubbing it with hair or with a paper napkin. Bring it inside the cylindrical shell, not allowing it to touch its wall. The strips move away from the cylinder, Figure 7.16 (b). When the ruler comes out, the strips return to their original vertical orientation along the cylindrical shell, Figure 7.16 (c).



(a) (b) (c)

Figure 7.16: (a) Discharged and insulated cylindrical shell. (b) When an electrified ruler is placed inside the shell, without touching it, the strips raise. (c) When the electrified ruler comes out, the strips drop.

Repeat this experiment. This time, while the electrified ruler is inside the cylinder, bring a second negatively electrified ruler close to one of the raised strips, not allowing them to come into contact. Observe that the raised strip is repelled by the electrified ruler, as it tends to move away from it, inclining towards the cylinder, Figure 7.17 (a). When, on the other hand, a positively charged ruler comes close to this strip, observe their attraction, Figure 7.17 (b).



(a) (b)

Figure 7.17: (a) Strip repelled by a negatively charged ruler. (b) Strip attracted by a positively charged ruler.

This experiment illustrates electric polarization. The cylindrical shell is insulated from the ground. When the negative ruler goes inside it, the internal wall of the cylinder becomes positively electrified, while the external wall becomes negatively electrified.

Experiment 7.15 - *Grounding the cylindrical shell while the electrified ruler is inside it*

Repeat Experiment 7.14. Figure 7.18 (a) illustrates a discharged cylindrical shell insulated from the ground.

Figure 7.18 (b) shows the behavior of the strips when a negative ruler goes inside the shell. This time, when the negatively electrified ruler is inside the cylinder, ground the shell. Its strips drop, as indicated in Figure 7.18 (c).

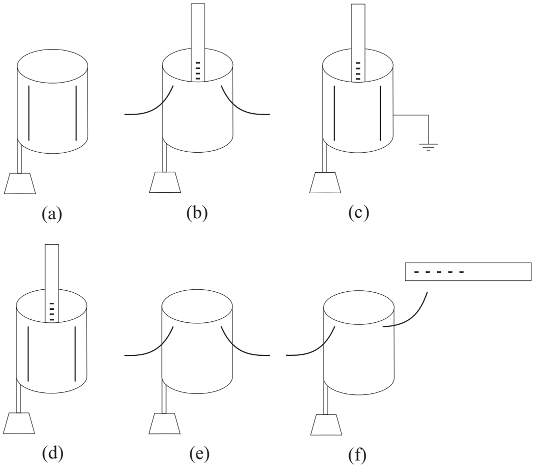


Figure 7.18: Electrification of the cylindrical shell by induction.

Remove the grounding while the electrified ruler remains inside the cylinder. Its strips remain down, Figure 7.18 (d). By removing the ruler, the strips rise again, remaining inclined relative to the cylinder, Figure 7.18 (e). Bring the negatively electrified ruler close to the cylinder. It attracts the strips, Figure 7.18 (f).

This experiment illustrates electrification by induction. At the end of this procedure the cylinder becomes electrified with a charge of opposite sign to that of the ruler. When the negatively electrified ruler penetrates the cylinder, there is a polarization of its charges. In particular, the internal wall becomes positively electrified while the external wall becomes negatively electrified, Figure 7.19 (a).

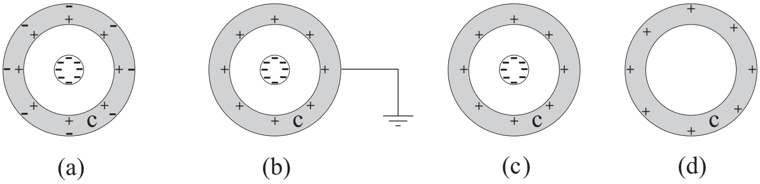


Figure 7.19: (a) Hollow conductor c insulated from the ground and polarized due to the presence of a negatively charged body inside it. (b) Grounded conductor with the neutralization of its external wall. (c) The distribution of charges does not change by removing the grounding. (d) By removing the internal body, there is a redistribution of the charges. They are now located only on the external wall.

By grounding the shell, we neutralize the electricity of the external wall. The internal wall remains positively electrified due to the attraction exerted by the negative charges of the ruler, Figure 7.19 (b). When the grounding is removed, nothing changes in the distribution of charges, Figure 7.19 (c). By removing the ruler, there is a redistribution of charges on the cylinder. The positive charges are now spread only over its external wall, Figure 7.19 (d).

7.3 Actions Exerted by a Hollow Electrified Conductor on Internal and External Bodies

Experiment 7.16 - *Action of an electrified cylindrical shell on an internal electric pendulum*

Begin with a conducting cylindrical shell insulated from the ground by straws or when it is supported on an insulating plate. It should be initially discharged. The shell can be made of paper or cardboard. It can also be a can of soda. The upper end of a thin tissue paper strip is glued on the external wall. Utilize also an electric pendulum composed of a small paper disk attached to a silk thread. This pendulum should also be initially neutral. The disk of the pendulum is then placed inside the cylindrical shell, close to its wall but without touching it, between its upper and lower edges, Figure 7.20 (a).

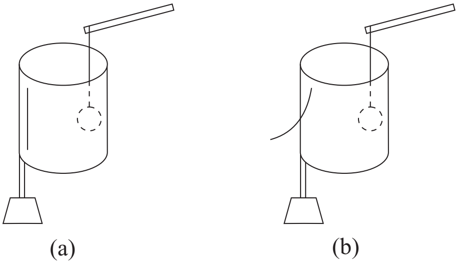


Figure 7.20: (a) Insulated cylindrical shell with an internal electric pendulum. (b) The paper disk is not affected when the cylindrical shell is electrified.

The electric pendulum should remain inside the shell, without touching it. Electrify the shell scraping a rubbed straw on its upper edge. It can also be electrified by touching its upper edge with an electrified charge collector of an electrophorus. The electrification of the shell is indicated by its raised strip. The internal pendulum is not affected by the electrification of the cylindrical shell. That is, it is not attracted nor repelled by its wall, Figure 7.20 (b).

Experiment 7.17 - *Action of an electrified cylindrical shell on an external electric pendulum*

Repeat Experiment 7.16, this time beginning with the pendulum outside the cylindrical shell. The disk should be close to the wall, without touching it, Figure 7.21 (a).

Electrify the shell scraping a rubbed straw on its upper edge or touching it with an electrified electrophorus. The disk of the paper is then attracted by

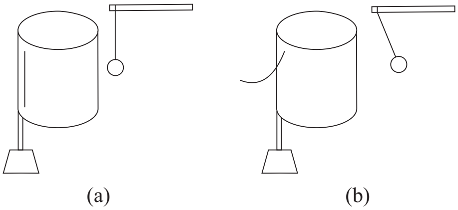

(a) (b)

Figure 7.21: (a) Conducting cylindrical shell insulated from the ground with an electric pendulum outside it. (b) When the shell is electrified, the paper disk is attracted, touches it and is then repelled by the cylinder through the ACR mechanism.

the shell. It moves towards it and sticks to its wall. Sometimes it is released immediately, being repelled by the electrified wall through the ACR mechanism. Other times this repulsion only takes place when the shell has been more significantly electrified. Other times we need to tap on the straw, or to blow the disk softly, in order to release it from the wall. Then observe its repulsion. Normally you can observe this repulsion when there is a large enough amount of electrification of the cylindrical shell, as indicated in Figure 7.21 (b).

7.4 Faraday's Ice Pail Experiment

Michael Faraday (1791-1867) performed in 1843 an activity analogous to Experiment 7.9. He utilized a metal ice pail 27 cm high and 18 cm diameter insulated from the ground.[8] His charge collector was a round brass ball suspended by a 90 to 120 cm long silk thread. In Figure 7.22 the ice pail is represented by letter A, the brass ball by letter B, while the insulation of the pail and ball are represented by letters I. The external wall of the pail was connected by a conducting wire to a delicate gold-leaf electrometer E.

When the ice pail was discharged, the leaves of the electroscope remained vertical. When a positively electrified ball was introduced into the pail, without touching it, the leaves of the electroscope diverged from one another, indicating that the outer wall of the pail had been electrified. By studying the charge of the electroscope, Faraday concluded that it was also positively charged. By taking away the electrified ball, the leaves of the electroscope collapsed. By introducing the electrified ball slowly, he found that the divergence of the electroscope increased until the sphere was around 7.6 cm below the surface of the pail, remaining with a constant opening for any greater depression. This fact indicated to Faraday that all inductive action of the sphere was exerted on the internal wall of the pail and not upon external objects. When the electrified ball was made to touch the bottom of the pail, he observed that the sphere was completely discharged. He concluded that the charge induced by the electrified

---

[8] [Far43a].

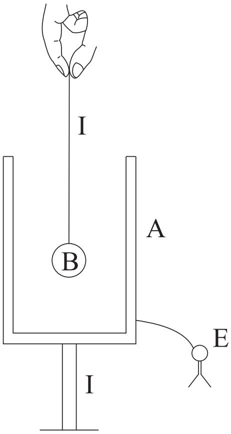


Figure 7.22: Faraday's ice pail experiment.

ball on the outside of the pail had the same value and sign as the charge originally located on the ball. Likewise, the charge induced on the internal wall of the pail had the same magnitude as that of the ball, but opposite sign. When the electrified ball touched the bottom of the vessel, there was a neutralization between the charges of the ball and those located on the internal wall of the recipient.

He replaced the bronze ball by electrified pieces of shellac, an insulating material. They acted exactly as the metallic carriers, producing the same effects. There was only one exception, namely, their charge was not communicated to the metallic vessel when they got in touch with one another.

Moreover, he observed that the internal electrified metal ball might be placed near any side of the vessel without affecting the divergence of the electroscope. This fact indicated to Faraday that the distribution of charges on the external wall of the bucket was not affected by the position of the electrified body inside it. This conclusion is illustrated in Figure 7.23.

Figure 7.23 (a) shows a positively charged body B at the center of an insulated bucket A. The charges induced on the bucket are symmetrically distributed on the internal and external walls. Figure 7.23 (b) shows B closer to one side of the bucket. In this case there is a redistribution of charges only on the internal wall. The charges on the outer wall are not affected. In this figure we also represented the redistribution of charges on the conductor B. Figure 7.23 (c) illustrates the neutralization which takes place when B touches the bucket. Its charges are neutralized with the equal and opposite charges which were spread on the inner wall of the ice pail. Once more the charges on the external wall are not affected.

James Clerk Maxwell (1831-1879), Joseph John Thomson (1856-1940) and James H. Jeans (1877-1946) utilized this experiment in order to quantify the

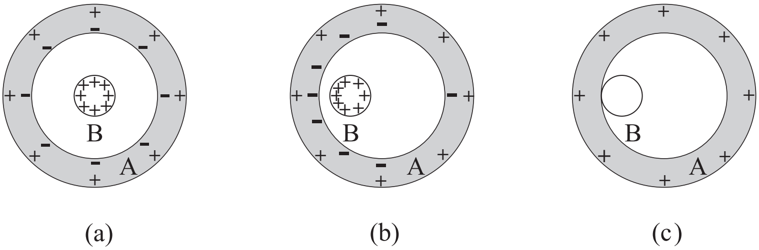


Figure 7.23: (a) Insulated ice pail A polarized due to the presence of an electrified body B at its center. The charges spread on the internal and external walls of the bucket have the same magnitude as that of B. (b) Redistribution of the charges spread on the internal wall of the bucket when B is close to one of its sides. (c) When B touches the bucket, there is a neutralization between its charge and those spread on the internal wall of the ice pail.

charge concept.[9] The opening angle of the leaves of the electroscope would be an indicator of the amount of charge on the body located inside the pail. Suppose that body A produces an opening angle θ_A when it is alone inside the pail. Suppose that body B produces an opening angle θ_B when it is alone inside the pail. When $\theta_A = \theta_B$, we say bodies A and B have charges of the same magnitude. Two bodies would have equal and opposite charges if, when introduced simultaneously into the pail, they produce no divergence of the electroscope. By following this procedure, we might also define positive and negative charges, as well as multiples of any charge. For instance, suppose that a body C produces an opening angle θ_C when it is alone inside the pail. If θ_C is equal the opening angle of the electroscope when only A and B are located together inside the pail, with A and B having charges of the same magnitude and equal sign, we say that the charge of C is twice the charge of body A. And so on.

---

[9] [Max54a, articles 27-36, pp. 32-41], [Tho21, pp. 5-6] and [Jea27, pp. 7-10].

Chapter 8

Electric Shielding

8.1 Placing a Conductor or an Insulator between an Electrified Body and a Light Body

Experiment 8.1 - *Trying to attract bits of paper with an electrified ruler when there is a metal strainer between them*

Repeat the experiment of the amber effect. Rub a straw or acrylic ruler in hair, in a paper napkin or in a cotton tissue. Assume that the rubbed acrylic ruler attracts bits of paper on a table when their distance is equal to or smaller than 5 cm.

Place a metal strainer above the pieces of paper. Bring the rubbed ruler above the strainer. This time the bits of paper do not move towards the ruler, even when the distance between the ruler and the pieces of paper is smaller than 5 cm.

Experiment 8.2 - *Trying to attract bits of paper with an electrified ruler when there is a plastic strainer between them*

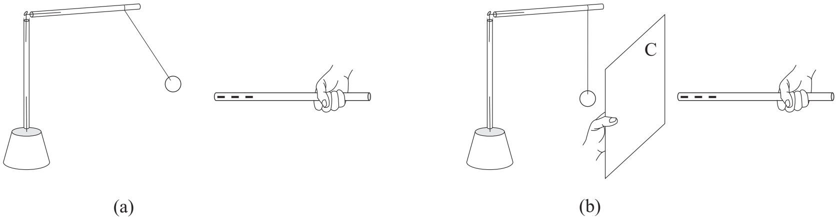
Utilize now a plastic strainer. Verify initially that the strainer net really behaves as an insulator. That is, it should not discharge an electrified electroscope. From now, assume that it is an insulator. We cover the paper bits with this plastic strainer. Bring a rubbed acrylic ruler above the strainer. The paper bits are attracted by the rubbed ruler when their distance is equal to or smaller than 5 cm. Sometimes the attraction is a little smaller than in the situation without the plastic strainer, so that now the distance between the ruler and the paper bits must be smaller than 5 cm to produce a perceptible attraction.

Definition 8.1

These experiments show that by placing a grounded conductor between an electrified body and bits of paper, the bits of paper remain at rest even when the electrified body is close to them. This phenomenon is called *electrostatic shielding*, *electric shielding*, *electrostatic screening* or *electric screening*.
The shielding no longer takes place by replacing the grounded conductor with an insulator. This time the bits of paper will move towards the electrified body when they are close to one another.

Experiment 8.3 - *Trying to attract the paper disk of an electric pendulum with an electrified ruler when there is a sheet of paper between them*

Utilize a classic electric pendulum composed of a paper or aluminum foil disk suspended by a silk thread. It should be initially discharged. A rubbed straw or plastic ruler is brought near the pendulum. The paper disk begins to move towards the rubbed straw when their distance is approximately 10 cm, Figure 8.1 (a).



(a) (b)

Figure 8.1: (a) A rubbed plastic attracting the paper disk of a nearby electric pendulum. (b) The attraction disappears by placing a conducting sheet of paper C between the pendulum and the rubbed plastic.

Do not allow the contact between the paper disk and the rubbed straw. However, sometimes they touch one another and the pendulum begins to be repelled by the straw due to the ACR mechanism. If this happens, discharge the pendulum by contact with the finger.

Begin once more with a discharged pendulum. This time, hold a sheet of A4 paper between the pendulum and the rubbed straw. The paper should be vertical and should not touch the disk, with its center at approximately 5 cm from the disk of the pendulum. Slowly bring the rubbed straw or plastic ruler close to the pendulum, with the paper between them. There is no motion of the disk toward the rubbed straw even when their distance is equal to 10 cm or even less, Figure 8.1 (b). Sometimes the sheet of paper is attracted by the rubbed straw. Even when this attraction takes place, the pendulum remains vertically at rest on the other side of the paper.

There will be zero net force on the paper disk by replacing the sheet of paper with a metal screen of the same size. The disk of paper will remain at rest when there is a grounded conductor between the disk and the rubbed plastic on the other side. This grounded conductor does not need to be continuous. It can have holes as a typical net, provided these holes are not very large.

Experiment 8.4 - *Trying to attract the paper disk of an electric pendulum with an electrified ruler when there is a plastic sheet between them*

Replace the sheet of paper by a transparent plastic sheet of the same size. Hold a rubbed straw or acrylic ruler on the other side of the plastic sheet. The disk of the pendulum is now attracted by the rubbed straw when they are close to one another, Figure 8.2.

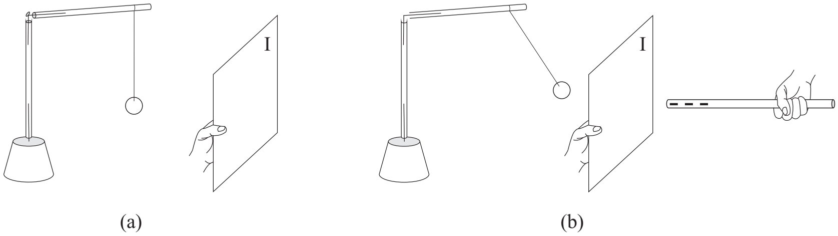


Figure 8.2: (a) An insulating sheet of plastic I close to a discharged pendulum. (b) The disk is attracted by a nearby rubbed straw on the other side of the plastic sheet.

Experiment 8.5 - *Trying to attract the paper disk of an electric pendulum with an electrified ruler when the pendulum is inside a cup made of platic or glass*

We can make another simple and interesting experiment utilizing two transparent cups of the same size and shape, one made of plastic and the other of glass. Suppose we have cups with 6 to 8 cm diameter and 7 to 10 cm height. The plastic must behave as a good insulator and the glass as a good conductor. Before beginning the experiment, the insulating and conducting properties of the plastic and glass materials should be tested with the procedure of Section 3.1. Charge an electroscope. Hold the plastic cup in your hand and touch it on the cardboard. If the electroscope remains electrified for more than 20 seconds, this plastic cup can be utilized in the experiment. Repeat the procedure with the glass cup. If the electroscope discharges in less than 3 seconds after contact, this glass cup can be utilized in the experiment.

The experiment should begin with the plastic cup. Fix a small paper disk on the extremity of a 5 cm long silk thread. Fix the free extremity of the thread in the interior of the cup. Utilize glue or a small piece of adhesive tape to fix it in the bottom of the cup. The thread should hang at 1 or 2 cm from one side of the cup, that is, it should not be located at the center. The cup is then placed on a table upside down. The pendulum hangs vertically and the paper disk should not touch the table nor the cup. Electrify an acrylic ruler by friction. When the electrified ruler is far away from the cup, the pendulum remains vertical,

Figure 8.3 (a). Bring the electrified ruler close to the cup, at the same height as the paper disk. The pendulum moves towards the ruler, touching the side of the cup, Figure 8.3 (b). By removing the ruler, the pendulum returns to the vertical, Figure 8.3 (c).

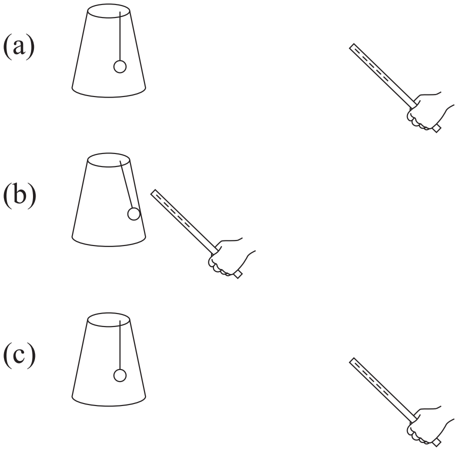


Figure 8.3: Plastic cup upside down with an electric pendulum inside it. (a) Electrified ruler far away from the pendulum. (b) When the ruler comes close to the cup, the disk is attracted and touches the side of the cup. (c) By removing the ruler, the pendulum returns to the vertical.

When this experiment was successful, we can continue. Repeat this procedure with the glass cup. This time the pendulum remains at rest vertically, no matter if the electrified ruler is close or far away, Figure 8.4.

The pendulum also remains at rest by replacing the glass cup with a metal net having the same size and shape of the cup. In this case, the hand should move slowly when bringing the electrified ruler close to the net, to avoid disturbances of the pendulum by air currents. Sometimes there is a little motion of the pendulum when the electrified ruler comes to the net, although it does not touch the side of the net, as it happened in Figure 8.3 (b).

8.1.1 Some Old Research on Screening

Girolamo Cardano (1501-1576) presented a catalog of differences between electric and magnetic phenomena in his book of 1550. He observed that lodestone attracts iron across interposed objects, while rubbed amber does not attract light bodies across interposed objects.[1] William Gilbert discussed these phenomena in his book of 1600:[2]

> In all bodies everywhere are presented two causes or principles whereby

---

[1] [Hei99, p. 174].

[2] [Gil78, p. 30], [Gil00, pp. 52-53] and [Hei99, p. 174].

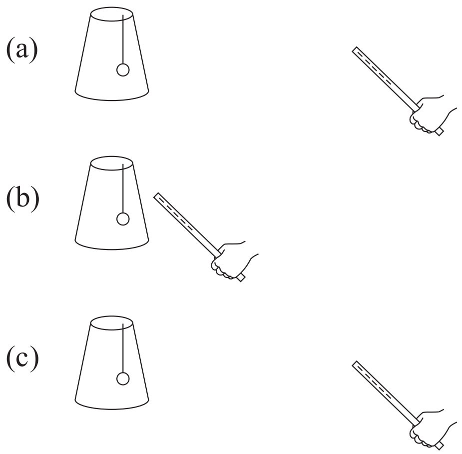


Figure 8.4: Glass cup upside down with an electric pendulum inside it. (a) Electrified ruler far away from the pendulum. (b) When the ruler comes close to the cup, the pendulum remains vertical. (c) By removing the ruler, the pendulum remains at rest vertically.

> the bodies are produced, to wit, matter (*materia*) and form (*forma*). Electrical movements come from the *materia*, but magnetic from the prime *forma*; and these two differ widely from each other and become unlike—the one ennobled by many virtues, and prepotent; the other lowly, of less potency, and confined in certain prisons, as it were; wherefore its force has to be awakened by friction till the substance attains a moderate heat, and gives out an effluvium, and its surface is made to shine. Moist air blown upon it from the mouth or a current of humid air from the atmosphere chokes its powers; and if a sheet of paper or a linen cloth be interposed there is no movement. But loadstone, neither rubbed nor heated, and even though it be drenched with liquid, and whether in air or water, attracts magnetic bodies, and that, though solidest bodies or boards, or thick slabs of stone or plates of metal, stand between.

Honoré Fabri (1607-1688) and the scientists of the Accademia del Cimento (Academy of Experiment) developed these experiments between 1657 and 1667:[3]

> The motive for the investigation of screens was, the Diarist says, to discover 'the resistance sufficient to impede the attraction of amber.' The academicians began by interposing sheets of paper punctured first with a fine needle, then with the points of scissors, finally with a large nail. The holes grew; the attraction did not.

Fabri and the other scientists investigated also the shielding of liquids. They mentioned that rubbed amber loses its electricity when moistened with water, retaining it when covered with oil.[4]

---

[3] [Hei99, p. 201].

[4] [Hei99, pp. 195-196 and 200-201].

Stephen Gray mentioned in 1731 an important experiment of his friend Granville Wheler (1701-1770). A rubbed glass tube attracted a thread (probably a cotton or linen thread, that is, a conducting material) across five superposed layers of glass.[5] It should be emphasized once more that the glass objects utilized by Gray and collaborators behaved as good insulators.

Gianfrancesco Cigna (1734-1790) mentioned in his doctoral thesis of 1757 that attractions occur between charged bodies immersed in oil. This fact was also discussed by Alessandro Volta.[6]

All these important facts were persuasive arguments against theories of effluvia emitted by rubbed amber. These facts also undermined the supposed existence of atmospheres around electrified bodies.[7]

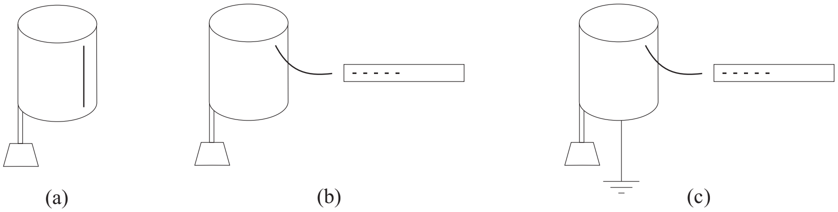
These experiments were totally understood only after the discovery of conductors and insulators, of the existence of two kinds of electricity, and the knowledge about the effects of electric polarization in conductors and insulators. Water, for instance, behaves as a conductor in electrostatics. Oil, on the other hand, behaves as an insulator.

8.2 Experiments with Hollow Conductors

Perform now some experiments with hollow conductors as those described in Section 7.2.

Experiment 8.6 - *Trying to attract the external strip of a cylindrical shell with an electrified ruler*

Begin with an insulated and discharged cylindrical shell. It should have one or more thin tissue paper strips with their upper ends glued on the external wall of the cylinder, Figure 8.5 (a).



(a) (b) (c)

Figure 8.5: (a) Discharged cylindrical shell. (b) The external strip is attracted by a nearby rubbed acrylic ruler. (c) By grounding the cylinder, the attraction remains.

A straw or plastic ruler is negatively electrified by friction in hair, in a paper napkin or in a cotton tissue. The rubbed straw is brought close to the cylinder. For the time being it should not touch the cylinder nor its strips. The nearby

---

[5] [Grae, p. 399], [Bos11, pp. 253-255], [BAC12, pp. 194-199] and [Hei99, p. 249].

[6] [Hei99, pp. 406, 413 and 415].

[7] [Hei99, Chapters V and XVII].

strip is attracted by the rubbed straw, Figure 8.5 (b). Even when the cylinder is grounded (touching its upper edged with a finger, for instance), the strip remains attracted by the rubbed straw, Figure 8.5 (c).

The tissue paper strip is also attracted by the straw when reversing this procedure. That is, first ground the cylinder. Then bring the rubbed straw close to it.

Experiment 8.7 - *Trying to attract the internal strip of a cylindrical shell with an electrified ruler*

Repeat Experiment 8.6, but now with the strips glued on the internal wall of an insulated cylindrical shell, Figure 8.6 (a).

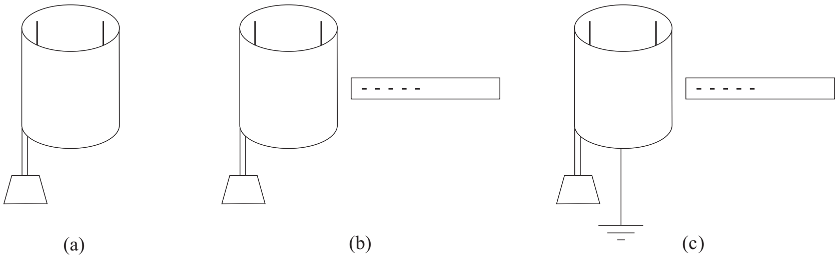


Figure 8.6: (a) Discharged cylindrical shell. (b) The internal strips remain at rest when a rubbed straw or acrylic ruler is brought close to the cylinder. (c) They remain vertical when the cylinder is grounded.

Bring a rubbed straw or acrylic ruler close to the cylinder. Its internal strips remain vertically at rest, Figure 8.6 (b). They remain at rest when the cylinder is grounded, Figure 8.6 (c).

The internal strips remain at rest when the procedure is reversed. That is, ground the cylinder and then bring the rubbed straw close to it.

Experiment 8.8 - *Trying to attract an electric pendulum inside a cylindrical shell*

Utilize a conducting and insulated cylindrical shell initially discharged. The conducting paper disk of an electric pendulum is placed inside it, close to its wall but without touching it, between its upper and lower edges. A rubbed straw or acrylic ruler is brought close to the disk from the outside. The disk does not move towards the rubbed straw even when they are close to one another, Figure 8.7 (a). Sometimes the upper edge of the cylinder attracts lightly the silk thread of the pendulum. Even in this case, observe that the attraction acts on the thread and not on the internal paper disk.

By grounding the cylindrical shell, the pendulum remains vertically at rest, Figure 8.7 (b).

Experiment 8.9 - *Trying to attract an electric pendulum outside a cylindrical shell*

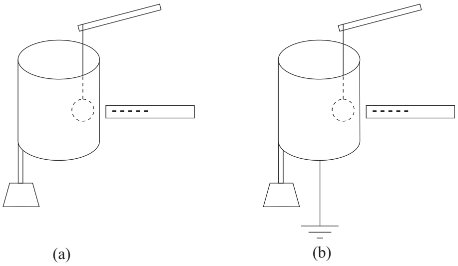


Figure 8.7: (a) The paper disk of an electric pendulum does not move towards a nearby external rubbed straw or acrylic ruler. (b) By grounding the cylinder, the pendulum remains vertically at rest.

Repeat Experiment 8.8, but now with the pendulum outside the shell. The cylinder must be initially discharged and insulated from the ground. The pendulum should be very close to the shell, but without touching it. The paper disk should be located midway between the upper and lower edges. A negatively rubbed straw or acrylic ruler is slowly brought close to the other side of the cylinder with its rubbed part at the same height as the paper disk. When it is very close to the shell, without touching it, the disk is attracted by the shell, touches it and is then repelled through the ACR mechanism, Figure 8.8.

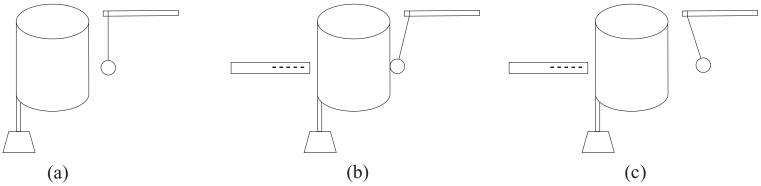


Figure 8.8: (a) An external electric pendulum close to a cylindrical shell. (b) and (c): Bring a rubbed straw or acrylic ruler close to the other side of the cylinder. The disk is attracted by the cylinder, touches it and is then repelled.

By studying the charge of the electrified disk, we discover that it has the same sign as the charge of the electrified ruler. Sometimes the disk remains attached to the cylinder after contact. You can induce it to release by tapping on the straw supporting the cylinder, or by blowing on the disk softly. It can also be released by removing the rubbed straw and bringing it back close to the other side of the cylinder.

On the other hand, when the cylindrical shell is initially grounded, the ACR mechanism does not take place. Bring the rubbed acrylic ruler close to the shell. Observe that the pendulum close to the other side remains vertically at rest, Figure 8.9.

Experiment 8.10 - *Electrified ruler inside a cylindrical shell and electric pendulum outside it*

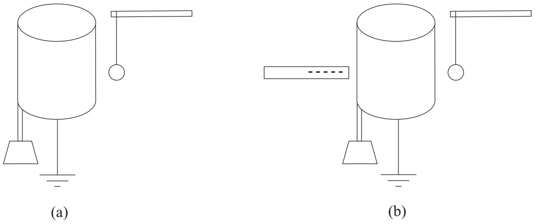

(a) (b)

Figure 8.9: The ACR mechanism does not take place when a rubbed acrylic ruler is brought close to the other side of an initially grounded cylindrical shell.

Utilize once more a conducting cylindrical shell. It is insulated and initially discharged. The rubbed part of a negatively charged plastic ruler is placed inside the shell. It should be close to the wall but without touching it. The disk of the electric pendulum should be outside the shell, far away from it and at the same height as the electrified ruler, Figure 8.10 (a).

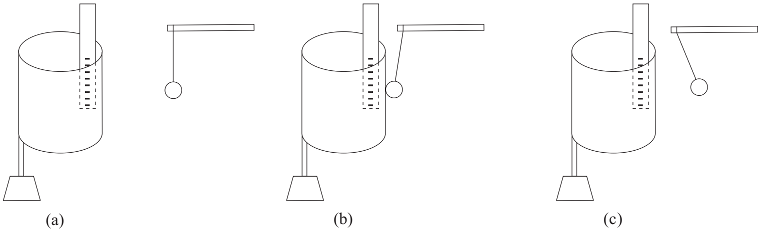

(a) (b) (c)

Figure 8.10: (a) Electric pendulum far away from an insulated cylindrical shell with an internal electrified acrylic ruler. (b) and (c): When the pendulum is brought close to the ruler, it is attracted towards the shell, touches it and is then repelled.

Hold the pendulum by its support or straw, bringing it slowly close to the cylinder. When it is very close to the shell, its disk is attracted towards the rubbed acrylic ruler, touches the shell and is then repelled by it through the ACR mechanism, Figure 8.10 (b) and (c). By studying its charge, we obtain that it is now electrified with charges of the same sign as those of the internal ruler.

Repeat this experiment but now with the cylindrical shell initially grounded. Bring the pendulum close to the rubbed acrylic ruler. Observe that the pendulum remains vertical. That is, its disk does not experience the ACR mechanism, Figure 8.11.

8.3 Sufficient Conditions for Effective Shielding

This Subsection discusses some situations in which there is effective shielding and other situations in which there is no effective shielding.

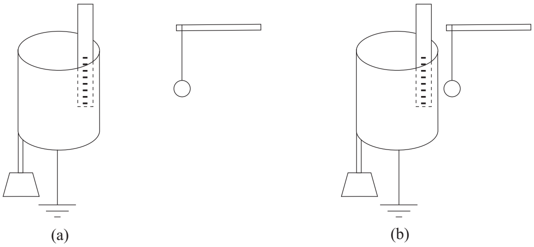


Figure 8.11: (a) Electric pendulum far away from a grounded cylindrical shell with an internal electrified acrylic ruler. (b) When the pendulum is brought close to the ruler, it is not attracted towards it.

Experiment 7.15 utilized an insulated and conducting cylindrical shell. Figure 7.18 (b) showed that when an electrified ruler was placed inside it, the strips located outside the cylinder lifted. However, when the cylinder was grounded, the strips dropped, despite the presence of the internal electrified ruler, Figure 7.18 (c). Therefore, a closed and grounded conductor shields externally the effects which would be produced by the internal electrified body if the shell were insulated from the ground.

The same behavior can be observed in Experiment 8.10 by comparing Figures 8.10 and 8.11. A closed conductor has an internal charge. When the conductor is insulated, it affects the disk of a pendulum which comes close to it, producing the ACR mechanism. However, when the conductor is grounded, the ACR mechanism will not take place, even when the electric pendulum is close to the cylinder.

In Experiment 8.6, Figures 8.5 and 8.6, there is a conducting cylindrical shell with an external charge (the rubbed acrylic ruler). When the electrified ruler comes close to the cylinder, the external tissue paper strips are affected by it, no matter if the cylinder is insulated or grounded. The internal strips, on the other hand, are not affected, no matter if the cylinder is insulated or grounded.

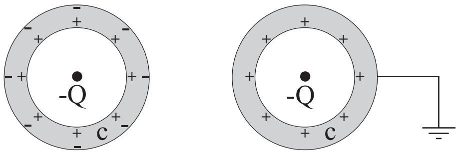
This behavior can also be observed with the electric pendulum of Experiment 8.8. We have a conducting cylindrical shell with the rubbed acrylic ruler outside it. The electric pendulum is inside the cylinder. Its disk is close to one of its sides, without touching it, located midway between the upper and lower edges. Even when the electrified ruler is brought close to the cylinder, there is no net force on the disk, as it remains at rest, Figure 8.7. No matter if the cylinder is insulated or grounded, there is no net force on the internal disk.

In Experiment 8.9 the rubbed acrylic ruler is outside an insulated conducting shell. It affects an external electric pendulum located on the other side of the cylinder. When the rubbed ruler is brought close to the cylinder, the disk of the pendulum follows the ACR mechanism, Figure 8.8. For a grounded cylindrical shell, on the other hand, the ACR mechanism does not take place, Figure 8.9.

We conclude by saying that there are no net effects on externally electrified bodies when there are charges located inside a closed and grounded conductor (by net effect we mean a resultant or total effect). In this situation an effective electric shielding takes place. There are also no net effects on internal charges when there are electrified bodies outside a closed conductor, no matter if the conductor is insulated or grounded.

However, there are net effects on external charges when there are electrified bodies inside an insulated and closed conductor.

These behaviors can be explained by the distributions of charges spread on the internal and external surfaces of hollow conductors. Consider initially the shielding taking place on the outside of a closed and insulated conductor with an internal charge. Consider the conductor as a hollow sphere initially discharged and insulated from the ground. Suppose a net negative charge $-Q$ located inside the shell. The presence of this charge polarizes the shell. Its internal wall becomes positively electrified, while its external wall becomes negatively electrified, Figure 8.12 (a). By grounding the conductor, we neutralize the distribution of charges on its external wall, Figure 8.12 (b).



(a) (b)

Figure 8.12: (a) Insulated conductor c polarized due to the presence of an internal negative charge $-Q$. (b) Grounded conductor with neutralized external wall.

Assume the presence of a body electrified positively with charge q and located outside the grounded conductor of Figure 8.12 (b). Assume that $q << Q$ and neglect the polarization of charges induced on the conductor due to the presence of this external charge q. There are two forces acting on the external body, namely, the attractive force F_A exerted by the internal body electrified with charge $-Q$ and the repulsive force F_R exerted by all charges spread on the internal wall of the conductor. These two forces have the same magnitude but act in opposite directions. They cancel one another, Figure 8.13.

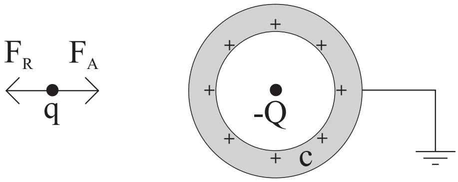


Figure 8.13: Attractive and repulsive forces, F_A and F_R, acting on the body electrified with charge q.

Important: It is only the *net or resultant force* acting on charge q located outside the grounded conductor that goes to zero. Despite this fact, the presence of the conductor does not eliminate the attractive force F_A exerted by the internal charge $-Q$. When the conductor is grounded, there will also exist a repulsive force F_R due to the positive charges spread on the internal wall of the spherical shell. These two forces have the same magnitude but opposite directions, canceling one another.

Figure 8.14 (a) shows the attractive force F_A exerted by $-Q$ on q separated by a distance d when there are no other bodies between these charges. When there is a grounded conductor around $-Q$, as in Figure 8.14 (b), the attractive force exerted by $-Q$ on q remains exactly the same as before, with the same magnitude and direction, provided $-Q$ and q remain at the same distance d. However, the *resultant force* acting on q goes to zero in the last situation due to the presence of the repulsive force F_R exerted by the positive charges spread on the internal wall of the conductor. This repulsive force F_R was not represented in Figure 8.14 (b). The reaction force exerted by q on $-Q$ is given by $-F_A$, where F_A has been represented in Figure 8.14 (a) and (b). The reaction force $-F_A$ has not been represented in this figure.

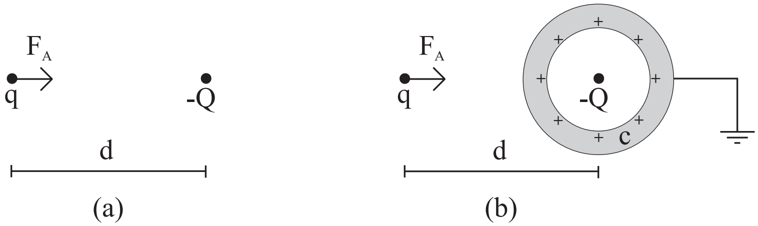


Figure 8.14: (a) Attractive force F_A exerted by $-Q$ on q separated by a distance d when there are no bodies between them. (b) The attractive force F_A exerted by $-Q$ on q remains the same when there is a grounded conductor around $-Q$, provided $-Q$ and q remain separated by the same distance d.

Consider the shielding that occurs inside a closed conductor when there is an electrified body outside it, the conductor itself being insulated or grounded. Assume once more a spherical conductor initially discharged and insulated. We consider the situation in which a body negatively electrified with a charge $-Q$ is located outside the shell. This external body polarizes the external wall of the insulated shell, Figure 8.15 (a). By grounding the shell, we neutralize the charges initially spread on the external wall close to the grounding position. Moreover, the other charges remaining on the surface of the shell are now rearranged (compared with the previous distribution of charges on the insulated sphere), Figure 8.15 (b).

Assume now the presence of a body electrified with a positive charge q inside the conductor of Figure 8.15 (a). Once more we suppose $q << Q$ and neglect the polarization induced in the shell by the presence of this internal charge q. There are three forces acting on the positive body electrified with charge q, namely, the attractive force F_A pointing to the left and exerted by the external

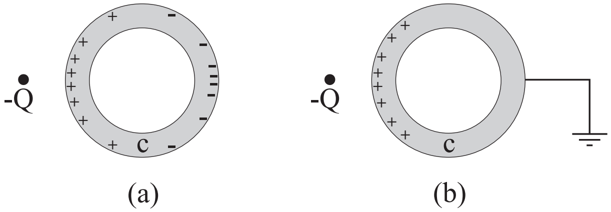


Figure 8.15: (a) Insulated conductor c with its polarized external wall due to the presence of the negative body $-Q$ outside it. (b) Grounded conductor showing the neutralization of charges close to the grounding location and a redistribution of the remaining charges.

negative body electrified with charge $-Q$, the repulsive force F_1 pointing to the right and exerted by the positive charges spread on the external wall of the conductor, together with the attractive force F_2 pointing to the right and exerted by the negative charges spread on the external wall of the conductor. These three forces equilibrate one another, such that $|\vec{F}_A| = |\vec{F}_1 + \vec{F}_2|$, yielding no resultant force on the internal charge q, Figure 8.16 (a).

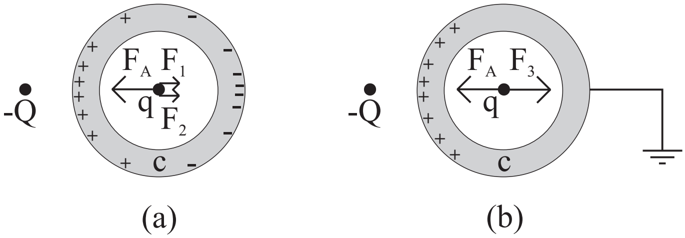


Figure 8.16: (a) Forces acting on the charge q located inside the insulated conductor of Figure 8.15 (a), $|\vec{F}_A| = |\vec{F}_1 + \vec{F}_2|$. (b) Forces acting on the charge q located inside the grounded conductor of Figure 8.15 (b), $|\vec{F}_A| = |\vec{F}_3|$.

As regards the grounded conductor of Figure 8.15 (b), there are two equal and opposite forces acting on the internal charge q, namely, the attractive force F_A pointing to the left and being exerted by the external charge $-Q$, together with the repulsive force F_3 pointing to the right and being exerted by the positive charges spread on the external wall of the conductor, Figure 8.16 (b). These two forces have the same magnitude but opposite directions, canceling one another, $|\vec{F}_A| = |\vec{F}_3|$.

The *net or resultant force* acting on the internal charge q goes to zero in both situations of Figure 8.16. However, it is important to emphasize here that the attractive force exerted by $-Q$ on q always remains the same, regardless of the presence or absence of the conductor around q. The attractive force F_A exerted by $-Q$ on q always has the same value, regardless of the distribution of charges on the external wall of the conductor. The conductor may be insulated or grounded, it does not matter. The attractive force between $-Q$ and q always remains the same. The presence of the conductor does not eliminate this attractive force exerted by $-Q$ on q. However, the presence of the conductor allows a redistribution of charges on its outer wall. The force exerted by these surface charges on q have the same magnitude as the force exerted by $-Q$ on q, but act in opposite direction, so that they cancel one another.

Figure 8.17 (a) shows the attractive force F_A exerted by $-Q$ on q separated by a distance d when there are no other bodies between them. This force remains the same when there is an insulated conductor around q, Figure 8.17 (b). The attractive force F_A exerted by $-Q$ on q also remains the same as before when there is a grounded conductor around q, Figure 8.17 (c). This figure does not show the forces acting on q due to the charges spread on the external wall of the conductor. The reaction force exerted by q on $-Q$ is given by $-F_A$ in situations (a), (b) and (c) of Figure 8.17. This reaction force is also not represented in this figure.

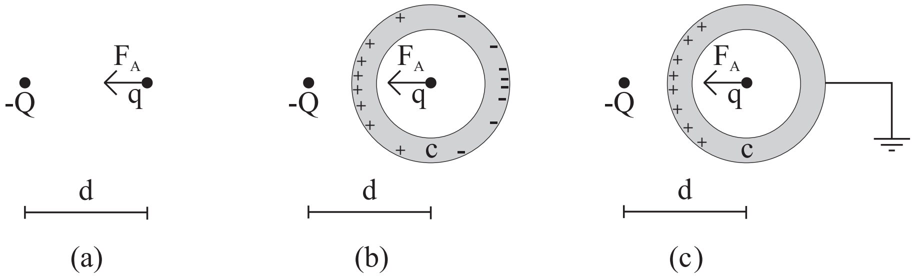


Figure 8.17: (a) Attractive force F_A exerted by $-Q$ on q separated by a distance d when there are no other bodies between them. (b) This force remains the same when there is an insulated conductor around q. (c) This force remains exactly the same when there is a grounded conductor around q.

Figures 8.13 and 8.14 show that the presence of a grounded conductor yields an *effective shielding*. There is no *net or resultant force* acting on an electrified particle located outside a grounded conductor when there is an electrified body inside it. However, there is no *real shielding* of the force exerted by the internally electrified body acting on the external body. This force always remains the same, no matter if the grounded conductor is present or absent. The same conclusion can be drawn comparing Figures 8.16 and 8.17. In this last situation there is also an *effective shielding*, as the *net or resultant force* acting on a body inside a grounded conductor goes to zero. However, once more there is no *real shielding* of the force exerted by the external charge acting on the internally electrified body. This last force always acts with the same intensity, no matter if the grounded conductor is present or absent.[8]

---

[8] [Roc89].

8.4 Faraday Cage

Michael Faraday performed some very interesting experiments utilizing an apparatus which is popularly known as a *Faraday cage*. It is a hollow conductor. Here are his words describing his observations:[9]

> 1173. I carried these experiments on with air to a very great extent. I had a chamber built, being a cube of twelve feet. A slight cubical wooden frame was constructed, and copper wire passed along and across it in various directions, so as to make the sides a large network, and then all was covered in with paper, placed in close connexion with the wires, and supplied in every direction with bands of tin foil, that the whole might be brought into good metallic communication, and rendered a free conductor in every part. This chamber was insulated in the lecture-room of the Royal Institution; [...]
>
> 1174. I put a delicate gold-leaf electrometer within the cube, and then charged the whole by an *outside* communication, very strongly, for some time together; but neither during the charge or after the discharge did the electrometer or air within show the least signs of electricity. I charged and discharged the whole arrangement in various ways, but in no case could I obtain the least indication of an absolute charge; or of one by induction in which the electricity of one kind had the smallest superiority in quantity over the other. I went into the cube and lived in it, and using light candles, electrometers, and all other tests of electrical states, I could not find the least influence upon them, or indication of anything particular given by them, though all the time the outside of the cube was powerfully charged, and large sparks and brushes were darting off from every part of its outer surface. The conclusion I have come to is that non-conductors, as well as conductors, have never yet had an absolute and independent charge of one electricity communicated to them, and that to all appearance such a state of matter is impossible.

The experiments of Section 8.1 are related with these phenomena observed by Faraday. In particular, there are no *net*, *total* or *resultant effects* inside a closed conductor due to the presence of charges on the surface of the conductor or located outside the conductor.

---

[9] [Far38, paragraphs 1173-1174, pp. 442-443].

Chapter 9

The Power of Points

There are several electric effects which are more intense in the pointed regions of conductors than in the blunt or less sharp regions. Some of these effects receive a generic denomination, namely, *the power of points*. We list here a few of these phenomena:

1. Electrified particles accumulate with a higher surface density in the pointed regions of electrified or polarized conductors.
2. Light bodies located on the pointed regions of conductors are attracted with a greater force by another electrified body.
3. The pointed regions of conductors are attracted or repelled with greater intensity by other electrified bodies.

We illustrate these properties with some simple experiments.

9.1 Illustrating the Power of Points with Electroscopes

You can visualize the power of points utilizing simple electroscopes made of thin cardboard. Their shape should be like a tennis racket, a kitchen cutting board or a pointed clown hat.[1] We suggest a specific size here, although the most important aspect for these experiments is the asymmetric shape of the cardboard and not its size. The cardboard is attached to a plastic straw with two pieces of adhesive tape, just like a simple electroscope. Cut two very small strips of tissue paper, from 1 to 3 mm wide and 6 to 9 cm long. They should have the same size and thickness. Glue the upper ends of these strips on the electroscope. One of them is glued on the pointed region of the cardboard and the other in its larger region, Figure 9.1.

---

[1] [FM91, pp. 60-61], [Ferb, Poder das pontas, p. 39] and [Gas03, pp. 239-243].

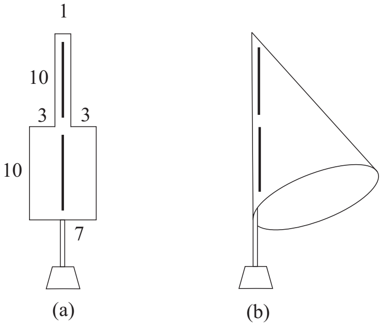


Figure 9.1: (a) Electroscope with the shape of a cutting board. Approximate dimensions in centimeters. (b) Electroscope with the shape of a clown hat.

Experiment 9.1 - *Charging an asymmetric electroscope*

Briskly rub a straw or an acrylic ruler in hair or in a sheet of paper. Scrape the rubbed straw a few times on the upper edge of these electroscopes until they acquire a large enough amount of electrification, as indicated by the raised strips. Move the rubbed straw away from the electroscope. Observe that the tissue paper strips located on the pointed regions of the electroscopes get higher than the other strips. That is, they acquire higher angles of inclination relative to their cardboards than the other strips located on the same electroscopes, Figure 9.2.

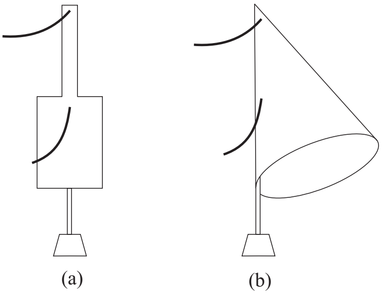


Figure 9.2: Charged electroscopes. The strips on the pointed regions are more inclined than the other strips.

Volume 1 of this book showed that the inclination angle of the tissue paper strip of an electroscope is a qualitative indicator of the electrification of the electroscope, that is, of its surface charge density.[2] The more electrified it is, the higher will be its raised strip.

From the present experiment we conclude that the surface charge density on the pointed region of a charged electroscope is higher than the surface charge

---

[2] Experiment 6.9 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

density on the blunt region, as indicated in Figure 9.3.

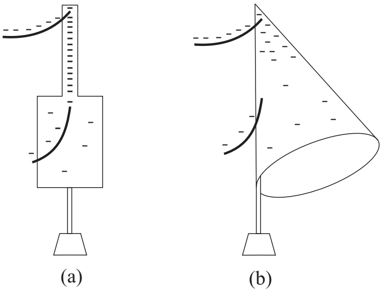


Figure 9.3: Charges concentrated on the points of electrified electroscopes.

Experiment 9.2 - *Charging a long rectangular paper strip*

Cut a 10 cm wide and 1 to 2 m long cardboard. Instead of the cardboard, you can also utilize rectangles of A4 paper 10 cm wide stapled together in order to reach a length of 1 to 2 m. Straws should be fixed on this long rectangle with adhesive tapes in such a way that half of the lengths of the straws remain outside the rectangle. The straws are then fixed on appropriate supports so that the cardboard remains on a vertical plane. Glue the upper ends of some thin tissue paper strips along the length of the cardboard, as indicated in Figure 9.4.

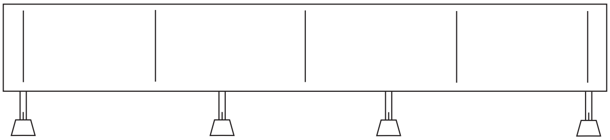


Figure 9.4: Cardboard rectangle 10 cm wide and 1 m long with several thin tissue paper strips.

Electrify this rectangle scraping a rubbed plastic ruler several times on the upper edge of the cardboard. After the ruler has been removed, observe that the strips on the borders of the rectangle are higher than the middle strips, Figure 9.5 (a). This fact is an indication that there is a higher concentration of charges on the borders of the rectangle, Figure 9.5 (b).

9.2 Collecting and Comparing the Surface Charge Densities

Experiment 9.3 - *Collecting the surface charges of an asymmetric electroscope*

You can compare more straightforwardly the amounts of surface charge densities located on different regions of a charged electroscope by utilizing appropriate charge collectors. An example is the Coulomb's proof plane represented in

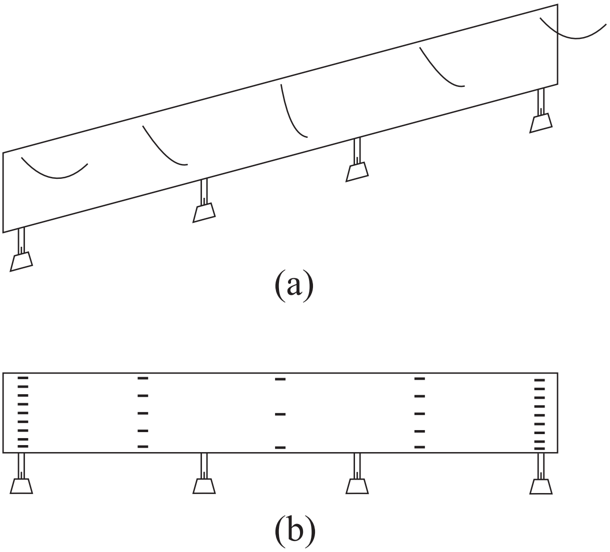


Figure 9.5: (a) The strips on the borders are higher than those on the middle of the rectangle. (b) Qualitative distribution of charges on the rectangle.

Figure 2.17 of Section 2.6. It can be a 1 cm diameter cardboard disk with a 4 cm long plastic straw connected at its center with glue or modeling clay. Estimate qualitatively the amount of charge collected by the proof plane by comparing the smallest required distance it must be brought to, in order to affect the raised strips of two other electroscopes, one charged positively and the other negatively. These two electroscopes should be separated from one another, being also removed from the asymmetric insulated and electrified conductor. After collecting charges from different regions of this asymmetric conductor, slowly bring the proof plane close to the raised strips of the electroscopes. Estimate the critical distance at which these strips begin to be attracted or repelled by the proof plane. The larger these critical distances, the more electrified is the proof plane.

As an asymmetric conductor, utilize the cutting board electroscope of Figure 9.1 (a). Remove its tissue paper strips, as in Figure 9.6 (a).

Another example of an asymmetric conductor is a 10 cm wide and 60 cm long paper rectangle supported by three or four plastic straws fixed on appropriate supports. Paste or fix the two borders of this flexible strip in order to give it a drop format, Figure 9.6 (b).

Electrify the cutting board electroscope by scraping its cardboard with a rubbed acrylic ruler or straw. First collect charges from the handle of this electroscope utilizing the proof plane, as in Figure 9.7 (a). Hold the charged proof plane only through its insulating straw. Then bring it close to a positively charged electroscope. Measure the critical distance between the charged proof plane and this electroscope in order to affect its raised strip. Repeat this pro-

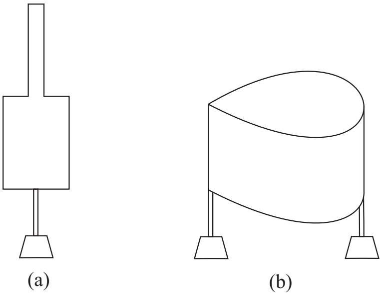


Figure 9.6: Asymmetric conductors insulated from the ground by plastic straws.

cedure, but now bringing the charged proof plane close to a negatively charged electroscope.

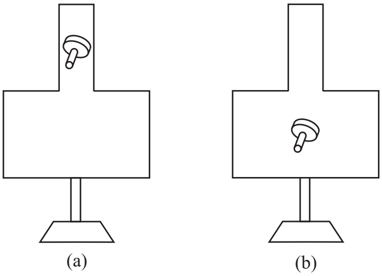


Figure 9.7: (a) Collecting charges from the handle of an asymmetric conductor. (b) Collecting charges from the center of the board.

Collect now charges from the center of the board, as in Figure 9.7 (b). Bring the charged proof plane close to positively and to negatively charged electroscopes, measuring once more the critical distances required to affect their raised strips.

Compare the critical distances in the first situation (charge collected from the handle of the electroscope) and in the second situation (charge collected from the center of the board). Verify that the critical distances in the first situation are larger than in the second situation. This fact indicates that there is a larger surface charge density on the handle of the electroscope than on its board, as indicated in Figure 9.3 (a).

The same conclusion takes place with the tear drop asymmetric conductor. That is, the amount of charges collected from the pointed region of the drop is larger than the amount collected from the blunt portion, Figure 9.8. The surface charge density is larger on the pointed region of the drop than on its blunt portion.

Experiment 9.4 - *Collecting the surface charges of a long strip of paper*

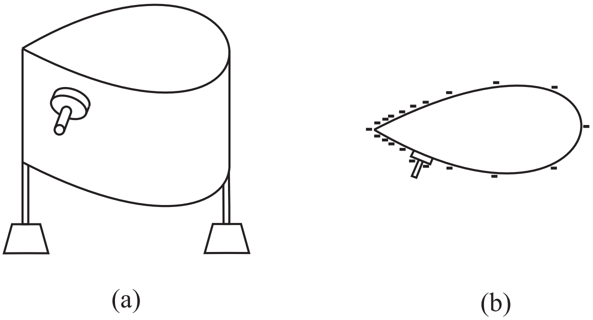


Figure 9.8: (a) Proof plane on an asymmetric conductor. (b) Qualitative distribution of charges on this conductor.

The proof plane can also collect directly charges from different regions of the 10 cm wide and 1 to 2 m long rectangle of Experiment 9.2. The thin tissue paper strips of this rectangle hinder the collection of charges. To avoid this problem, eliminate all of the tissue paper strips. You can also eliminate only half of the strips, namely, those located on the right side of the rectangle where the collector will be placed. Maintain the strips on the left side of the rectangle to indicate when the rectangle acquired a large enough amount of electrification. After collecting charges from any region of the rectangle, bring the collector close to a positively charged electroscope and measure the smallest required distance in order to affect the strip of this electroscope. This procedure can also be repeated with a negatively charged electroscope. Compare these critical distances for charged proof planes coming from different regions of the rectangle. Conclude that the electrified collectors coming from the borders of the rectangle acquired a larger amount of charge than those coming from the central regions of the electrified rectangle, Figure 9.5 (b).

Sometimes the outcome of these experiments are not very clear. In the first place, the surface charge densities of several regions of the same asymmetric conductor may not be so different from one another. Moreover, it is not easy to measure precisely the critical distance between the charged proof plane and an electrified electroscope in order to attract or repel its raised strip. In order to facilitate the measurement of this distance, move the charged collector slowly to and fro in front of the raised strip of the charged electroscope. You can then observe more easily when the coordinated forward and backward motions of the raised strip takes place.

9.3 Gray and the Power of Points

Stephen Gray presented in 1731 the first description of the so-called *power of points.*[3] He laid thin brass leaves on three different places, namely, on the ground, on a 30 cm diameter and 30 cm high wood cylinder, and also on the top of a conic stand 30 cm high, with 7.6 cm upper diameter and 11.4 cm lower diameter. He tried to attract these brass leaves with an electrified glass tube brought close to them. When the brass leaves were laid on this conic stand, he found that they were attracted to a much greater height than when laid on a table, and at least three times higher than when laid on the floor of a room. Figure 9.9 represents a qualitative description of this experiment.

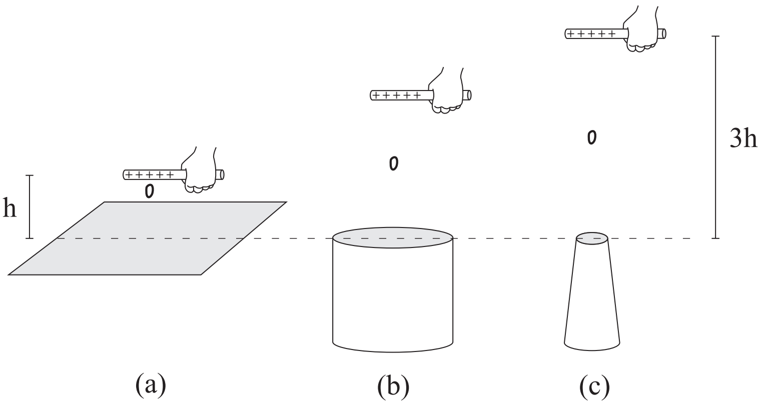


Figure 9.9: (a) A light leaf-brass is attracted to a height h from its initial position on the floor. (b) It rises higher when laid on a table or on a conducting cylinder 30 cm in diameter. (c) When it is on the top of a conical conductor, it is attracted three times higher than when it is on the floor.

Experiment 9.5 - *Reproducing Gray's experiment*

Gray's experiment can be easily reproduced. Bring a rubbed acrylic ruler close to bits of paper and measure the critical distance at which the pieces of paper are attracted by the ruler. In the first situation they are laid on the center of an A4 sheet of paper. In the second situation they are laid on the center of a 4 cm diameter and 10 cm high cylinder made of paper. In the third situation they are laid on the top of a 6 cm base and 10 high paper cone. Cut the tip of the cone, replacing it with a small horizontal paper disk having an approximate diameter of 0.5 cm. This disk is glued on the cone. You can then lay the paper bits on the flat top of this cone in order to perform the experiment. The cone and the cylinder should be made from the same A4 paper as the plane sheet of paper of the first situation. The sheet of paper of the first situation should be

---

[3] Section B.9 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

laid above three or four paper columns or above three or four paper cylinders. In order to begin the experiment, this sheet of paper, the upper side of the cylinder and the upper portion of the cone should be at the same height, that is, located in the same horizontal plane. These three supports should be separated from one another.

Rub an acrylic ruler and bring it slowly above the bits of paper laid on the plane sheet of paper. The ruler should be in a horizontal position. Notice that they begin to move towards the ruler when it is approximately 2 cm above the sheet of paper. When the bits of paper are laid on the cylinder, they begin to move when the ruler is at 4 cm from the top side of the cylinder. When the bits of paper are located on the cone, they begin to move at a critical distance of some 6 cm between the ruler and the tip of the cone.

These distances are only approximate. They depend on the degree of electrification of the ruler, on air humidity and also on the shape, size and weight of the bits of paper. In any event, this experiment shows clearly that the motion of the paper bits takes place at larger distances when they are laid on pointed surfaces. When they are laid on a planar sheet of paper, on the other hand, the rubbed acrylic ruler must be brought much closer to them in order to produce the motion of the paper bits. In these three situations the paper bits were laid on supports made of the same material, namely, a conducting A4 sheet of paper. The different values of the critical distances required to produce motion can only be due to the different shapes of these supports.

Experiment 9.6 - *Electrified ruler placed below a sheet, a cylinder and a cone made of paper*

Support three plastic sheets (the size of an A4 sheet of paper) on 3 or 4 paper cylinders 10 cm high. The three sheets of plastic should be at the same height above the ground. Lay the three supports of Experiment 9.5 (namely, the sheet of paper, the paper cylinder and the paper cone) on these three plastic sheets, so that their bases are at the same height, Figure 9.10.

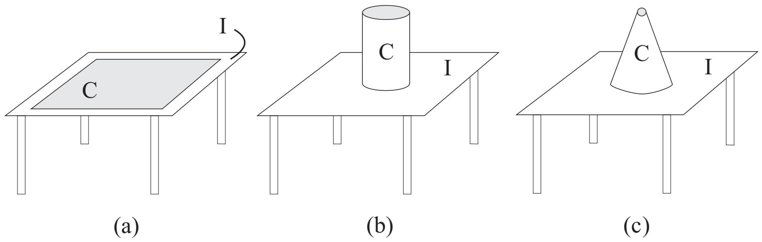


Figure 9.10: (a) A conducting sheet of paper C laid on an insulating sheet of plastic I. (b) A conducting cylinder C on an insulating sheet I. (c) A conducting cone C on an insulating sheet I.

Place bits of paper on the center of these three paper supports. Rub the acrylic ruler and bring it below the first plastic sheet. Move it slowly upwards, always in a horizontal orientation. The bits of paper do not move, even when the rubbed acrylic ruler gets very close to the plastic sheet. The bits of paper located on the upper side of the cylinder also do not move when the rubbed ruler located below the cylinder comes close to it. On the other hand, when the rubbed ruler located below the cone comes close to its base, the paper bits located on its tip are thrown off the cone, Figure 9.11.

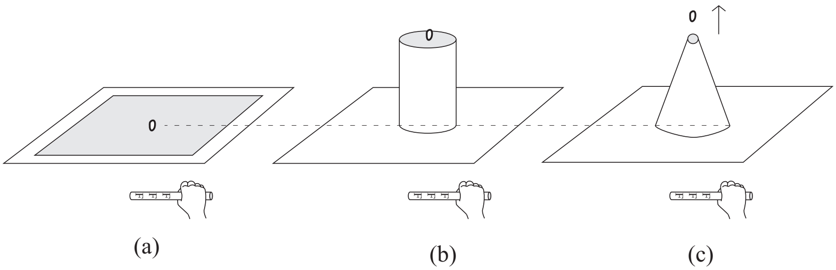


Figure 9.11: (a) An electrified ruler below a sheet of paper. (b) Below a paper cylinder. (c) Below a paper cone. The bits of paper do not move in (a) and (b), but are thrown off the cone in situation (c).

Experiments 9.5 and 9.6 can be explained assuming that electrified particles accumulate with higher surface densities on the tips of conductors. Assume that the rubbed acrylic ruler is negatively electrified. Paper behaves as a conductor for electrostatic experiments, while plastic behaves as an insulator. Consider the paper bits which were thrown off the cone in Experiment 9.6. The cone is polarized by the electrified ruler below it, becoming positive on its lower portions and negative on its upper portions, Figure 9.12 (a).

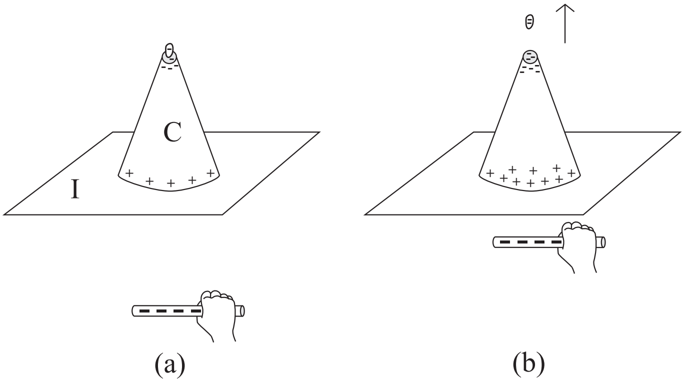


Figure 9.12: (a) A conducting cone C on an insulating support I. The cone is polarized due to the presence of a negative body below it. There is a larger surface charge density on the tip than on the base. (b) When the ruler is brought even closer to the insulating support, the paper bit is thrown off the cone.

The magnitude of the surface charge densities is larger on the tip of the cone than on its base. A small bit of paper located on the tip of the cone becomes negatively electrified. It is repelled by the negative ruler, is attracted by the positive charges on the base of the cone, and is also repelled by the other negative charges located on the tip of the cone. The net electric force acting on it points upward. The main component of this force is due to the repulsive action exerted by the other nearby negative charges located on the tip of the cone. In the situation of Figure 9.12 (a) this net repulsive force is smaller than the weight of the paper bit, so that it is not thrown off the cone. When the ruler is brought even closer to the base of the cone, the magnitude of its polarization increases. There are more positive charges on its base, more negative charges on its tip, and also more negative charges on each paper bit. Therefore, the net upward electric force acting on the paper bit also increases. Beyond a critical distance of the ruler, the net repulsive electric force acting on the paper bit will be larger than its weight. It is then thrown off the cone, Figure 9.12 (b). Although the negative paper bit is repelled by the negative ruler, the main component of the force throwing it off the cone arises from the repulsion exerted by the other negatively electrified particles located on the tip of the cone. These negative charges are much closer to the paper bit than the negative ruler.

Consider the cylinder of Figure 9.11 (b). Even when the ruler was brought close to its base, the bit of paper was not thrown off. The reason for this behavior is that the surface charge density at the top of the cylinder had not the same magnitude as the surface charge density at the top of the cone of Figure 9.11 (c) when the ruler was at the same distance to its base. Therefore, the repulsive force acting on the negatively electrified bit of paper was not great enough to overcome its weight.

The situation was different for Experiment 9.5. Now the paper cone was grounded due to its contact with the floor. When the electrified ruler comes close to it, the cone tends to be polarized. As it is grounded, part of its polarized charge is neutralized. It then acquires a net charge of opposite sign to that on the ruler, Figure 9.13 (a).

This electrification concentrates at the top of the cone and, consequently, at the bits of paper located on the tip of the cone. A positively electrified bit of paper is then under the action of two forces, namely, an attractive force exerted by the negative ruler and a repulsive force exerted by the other positive portions of the top of the cone. These two forces point upwards, while the weight of the paper bit points downwards. As the negative ruler comes closer to the cone, its tip becomes more and more positive. The same happens with the paper bits located on its tip. Below a certain critical distance, the two upward forces overcome the downward weight of the paper bit. It then moves towards the ruler, Figure 9.13 (b).

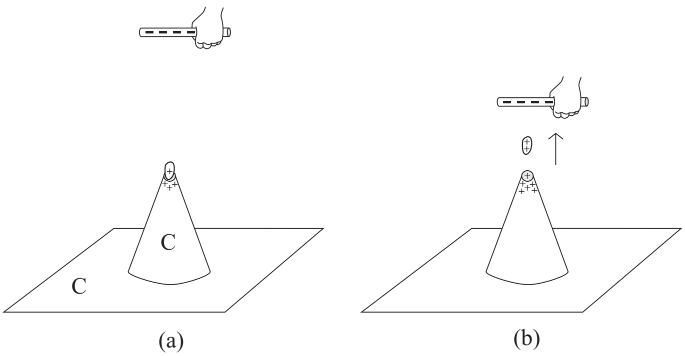


Figure 9.13: (a) A conducting cone C suppoted on a conducting surface C, grounding the cone. The positive paper bit is attracted by the negative ruler and repelled by the positive tip of the grounded cone. (b) When the ruler gets closer to the cone, the amount of positive charges on the paper increases, the same happening with the amount of positive charges on the tip of the cone. The piece of paper moves towards the ruler.

9.4 Intensifying the Amber Effect

The oldest experiment of electrostatics is the so-called amber effect, analogous to Experiment 1.1. There are several procedures which can increase its magnitude. These procedures are deduced from what was seen in Volume 1 of this book and in the previous experiments of this Volume 2. We list here some of these procedures which can make this effect more visible, reaching greater distances or happening with a larger intensity, namely:

- To perform the experiment in a cold and dry weather.
- The material which will be rubbed in other to attract light bodies should be an insulator. In this way it will not be discharged while it is contact with the hands. When this material is a conductor, it should be insulated to avoid the loss of the acquired charge due to the grounding with the hands. It might, for instance, be previously fixed on an insulated handle. We would then hold the material only through this handle, avoiding to touch the material directly with the hands.
- Test several different insulating materials. Rub in hair, for instance, a plastic straw, an acrylic ruler, a PVC tube, a Styrofoam plate, etc. Identify which body, after being rubbed, will attract a larger amount of paper bits.
- Test different substances utilized to rub each one of these bodies. Rub a PVC tube, for instance, in hair, in a paper napkin, in a plastic bag, in a cotton tissue, etc. Identify the substance which will produce a greater electrification of the body.

- Increase as much as possible the magnitude of the surface charge density of the material which will be rubbed. To this end, the most important aspect is to rub it briskly in hair or in a sheet of paper. The faster it is rubbed, the greater will be the magnitude of its acquired surface charge density.[4]

- The light bodies to be attracted should, preferably, behave as conductors. Examples of conducting bodies for electrostatic experiments are bits of paper, small pieces of aluminum foil, a cotton thread, etc. Consider an electrified plastic ruler attracting two light bodies of the same weight, shape and size, namely, a conductor and an insulator. The force exerted by the ruler on the conductor is much larger than the force exerted by the ruler on the insulator, supposing both of them at the same distance to the ruler. This stronger attraction can be observed by noticing that the conductor is more accelerated than the insulator when both of them are released at rest. Moreover, the electrified plastic must be brought closer to the insulator than to the conductor in order to make each one of them begin to move towards the rubbed plastic.

- The bodies which will be attracted by the rubbed plastic should, preferably, be located on a conducting surface. After all, a small piece of paper is attracted with a greater force when above a conductor than when above an insulator.

- The light bodies should be initially located on a pointed support. A small piece of paper is attracted with a greater force when above a pointed support than when above a blunt support.

---

[4] [SGS31] and [Hei99, p. 451, note 6].

Chapter 10

Electrical Equilibrium and the Instrument which Indicates Potential Difference

10.1 Conductor in Electrical Equilibrium

The bodies of nature can be divided or classified in two basic groups which are called conductors and insulators. The main difference between these bodies is that conductors have mobile electrified particles which can move through the conductor and along its surface. Insulators, on the other hand, do not have free electrified particles which can move through the whole volume of the material. Their mobile particles can move only inside the molecules composing the insulator. Therefore the insulators do not allow the passage or flow of electrified particles through their bodies nor along their surfaces. We remind the reader once more that the conducting or insulating behavior of any body depends not only on its nature or chemical composition, but also on the potential difference which may be applied to its ends.

Suppose a conductor C at rest relative to the ground. It can be electrically insulated from the ground or from other conductors. Alternatively, it can be connected by conducting substances to the ground or to other conductors. The conductor can have a positive net charge, a negative net charge or zero net charge. It can be alone or it can be under the action of other nearby electrified bodies (it might be, for instance, be polarized due to a nearby charged body). This Section presents the definition of the electric equilibrium for this conductor, valid in all these situations:

Definition 10.1

Consider an electrified conductor at rest relative to the ground, being either subject to electrical action from other bodies, or entirely isolated. When the distribution of its charge remains constant in time, the electricity upon it is said to be *in equilibrium* and the conductor is said to be in *electric equilibrium* or *electrical equilibrium*. When, on the other hand, its distribution of charge changes in time, the electricity upon it is said to be *in disequilibrium*, *imbalanced* or *unbalanced*, while the conductor is said to be in *electric disequilibrium*, *electrical disequilibrium*, *electrically imbalanced* or *electrically unbalanced*.

William Thomson (1824-1907), or Lord Kelvin, presented a similar definition in 1848:[1]

> *Electrical Equilibrium.*
>
> 66. When a body held at rest is electrified, and when, being either subject to electrical action from other bodies, or entirely isolated, the distribution of its charge remains permanently unaltered, the electricity upon it is said to be in equilibrium.

The surface charge density on each point of a conductor can be indirectly indicated by a thin tissue paper strip connected at this point. The higher the strip's deflection, the greater is the surface charge density. When the angles of inclination relative to the vertical of all strips connected to the body remain constant in time, we say that it is in electric equilibrium. When, on the other hand, the inclination of any strip varies as a function of time, we say that the conductor is in electric disequilibrium or that it is imbalanced.

Examples of electric disequilibrium:

- When a conductor is being charged. Consider, for instance, an initially discharged electroscope. It is in electric disequilibrium while an electrified plastic ruler is being scraped on the border of the cardboard and its tissue paper strip is raising.

- When a conductor is being discharged. Consider, for instance, an initially charged electroscope. Touch its cardboard with a finger. The electroscope discharges due to grounding. It is imbalanced while its strip is dropping.

- Consider a conductor insulated from the ground. The conductor is polarized by the presence of a nearby electrified body. The degree or amount of this polarization varies in time while the electrified body is approaching or moving away from the conductor. The conductor is in disequilibrium during these motions of the nearby electrified body.

- When two electroscopes are connected by a bad or imperfect conductor, as in Experiments of Section 3.3. Suppose, for instance, two initially discharged electroscopes connected by an imperfect conducting wire. When

---

[1] [Tho84d, p. 46, §66].

a rubbed plastic is scraped on the border of the cardboard of one electroscope, its strip raises almost immediately, while the strip of the other conductor raises slowly.

- Consider an electroscope initially electrified and insulated from another electroscope initially discharged. Connect their cardboards by an imperfect conducting wire. Both electroscopes will be imbalanced while the strip of the first electroscope is dropping and that of the second electroscope is rising.

10.2 The Electric Potential of a Conductor

Temperature is the magnitude which characterizes equilibrium in thermal physics or in thermology. The instrument which measures temperature is called thermometer. As regards the statics of liquids, gases and fluids, the magnitude characterizing the mechanical equilibrium is called pressure. Atmospheric pressure is measured by a barometer, while a manometer measures pressures in general.

As regards electrostatics, the magnitude characterizing equilibrium is called *electric potential* or *electrostatic potential*. It will be represented by the Greek letter ϕ. We can then present another definition:

Definition 10.2

All points in the interior and along the surface of a homogeneous conductor in electrical equilibrium are at the same electric potential, represented by the letter ϕ. Moreover, this electric potential is constant in time for a conductor in equilibrium.

Here we present some brief information related to the potential.[2] The concept of electric potential was introduced by Cavendish (1731-1810) in 1771, although he did not utilize the name "potential." The potential function was introduced as a mathematical concept in gravitation by Lagrange (1736-1813) in 1777. Laplace (1749-1827) obtained in 1782 the equation satisfied by this potential function in empty space, publishing his results in 1785. Poisson (1781-1840) introduced the potential function in electromagnetism in 1811. In 1813 he generalized Laplace's equation, obtaining a more general equation which was also valid for regions containing matter and free charges. The name "potential" was introduced by Green (1793-1841) in 1828.

This book analyses the instrument which can indicate the equality or difference of potential between two conductors. It also discusses the practical aspects associated with the operation of this instrument. This book will not consider the mathematical properties of the potential function.

---

[2] [Tho84b, p. 367], [Max54a, article 16, p. 15], [Whi73a, pp. 54-55 and 61], [Roc89], [Ass92a, p. 18], [Hei99, pp. 449 and 498-500] and [Ass15a, p. 22].

10.3 Electroscope with Conducting Case

This Section presents an instrument which indicates when two conductors are at the same electrostatic potential or when they are at different potentials.[3] When this device is adequately calibrated, it also allows the measurement of this potential difference.

Suppose two conductors C_1 and C_2 insulated from one another and from the ground. Suppose, moreover, that each conductor is in electrical equilibrium at potentials ϕ_1 and ϕ_2, respectively. Which instrument is able to indicate that $\phi_1 = \phi_2$ or that $\phi_1 \neq \phi_2$? The electroscope utilized in Volume 1 of this book, represented in Section 2.2, Figures 2.2 and 2.3, indicates surface charge density. It does not indicate electric potential. The greater the surface charge density at the location of the thin tissue paper strip, the higher will it be relative to the cardboard. A dropped or vertical strip indicates zero or very low surface charge density.

Chapter 7 analyzed the distribution of charges on the internal and external walls of a hollow conductor. It was an indirect analysis by means of thin tissue paper strips. The higher the strip's deflection, the greater was the surface charge density at its location. Chapter 7 presented also a direct analysis of surface charge densities. We collected part of the electricity located on the internal and external walls of a conductor. To this end, charge collectors or proof planes were utilized.

In the case of Experiment 7.1, Figure 7.1, for instance, the charges distribute themselves only on the external wall of an electrified cylindrical shell. There were no charges located on the internal wall. This electrified conductor made of paper or cardboard was in equilibrium. Their internal and external walls were in electrical contact through the paper itself. Despite the existence of this conducting material connecting the internal and external walls, there was no surface charge density on the internal wall, while the external wall had a charge density different from zero. Which instrument might indicate that the internal and external walls were at the same potential?

This important instrument has two conducting parts, A and B, insulated electrically from one another, Figure 10.1.

Normally parts A and B are made only of conducting materials. The instrument will indicate the potential difference between its parts A and B. Part A contains the indicator of potential difference. Part B is a conducting envelope, cage or case around part A.

The indicator of potential difference located on part A is normally the opening angle between two mobile leaves or strips. It can also be the opening angle between a fixed part of the instrument and a mobile leaf or strip. Part A in this last configuration can be, for instance, the usual electroscope of Figures 2.2 and 2.3. The potential difference between parts A and B will be indicated by the opening angle of the thin tissue paper strip relative to the fixed cardboard.

This instrument will be called here an *electroscope with conducting case.*

---

[3] [Tho84a], [Tho84c], [Per44] and [TP11].

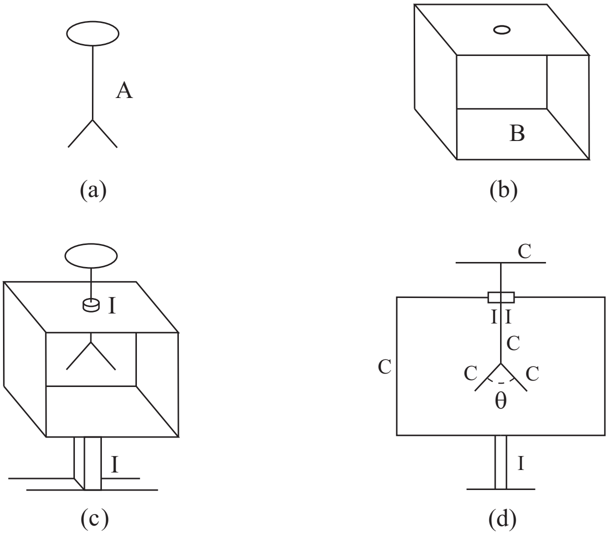


Figure 10.1: Electroscope with conducting case. (a) Conducting part A. (b) Conducting part B. (c) Perspective view. There is an insulator I between parts A and B. There is another insulator I between part B and the ground. (d) Instrument seen in profile. Letters C indicate the conductors, letters I the insulators, while letter θ indicates the opening angle between the mobile leaves.

Figure 10.1 illustrates one model of this instrument. Part A of the instrument is represented in Figure 10.1 (a). It has a horizontal disk, a vertical rod or axis, together with two mobile leaves which can open. Part B of the instrument is represented in Figure 10.1 (b). It is a conducting case with a hole on the upper lid. Parts A and B are made only of conducting materials. Figure 10.1 (c) represents the built instrument. It has an insulator I which connects part A to part B, maintaining their electric insulation. There is another insulator I which insulates electrically part B from the ground. Figure 10.1 (d) illustrates the instrument seen in profile. Letters C indicate the conductors, letters I the insulators, while letter θ shows the opening angle indicated by this electroscope.

The experiments of Chapters 7 and 8 present the principles justifying the working mechanism of this device. It is an appropriate instrument to indicate the potential difference between its parts A and B.

Figure 10.2 illustrates an electroscope with conducting case built with the simple electroscopes of Figures 2.2 and 2.3. The envelope is a conducting cylindrical strip made of paper or cardboard, supported on insulating straws. The insulator between parts A and B of this electroscope is simply air. Both parts are insulated from the ground by plastic straws.

Figure 10.3 represents another electroscope with conducting case built utilizing the simple electroscope of Figures 2.2 and 2.3. The envelope now is a shoe box made of conducting cardboard. Two and a half sides of the box were

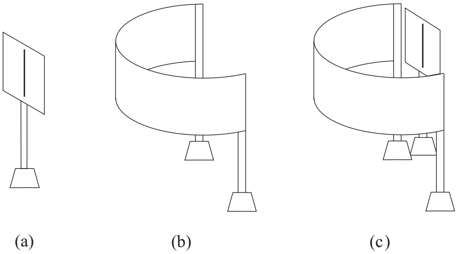


Figure 10.2: Electroscope with conducting case. (a) Part A is a simple electroscope made with a tissue paper strip glued on a cardboard. It is supported by a plastic straw. (b) Part B is an open cylindrical shell made of paper or cardboard. It is supported by plastic straws. (c) Mounted electroscope.

eliminated. There is air insulating part A from part B. Part A is insulated from the ground by the plastic straw, while part B is insulated by a Styrofoam plate.

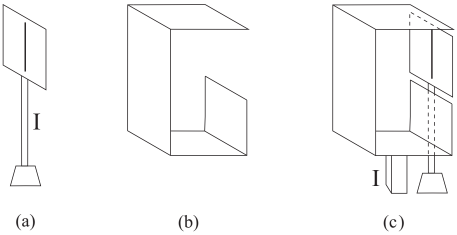


Figure 10.3: Another example of an electroscope with conducting case. (a) Part A is a simple electroscope with a tissue paper strip glued on a cardboard. It is supported by a plastic straw I. (b) Part B is a shoe box without two and a half sides. (c) Mounted electroscope supported by an insulating plate I.

Figure 10.4 illustrates another electroscope with conducting case. Letter C indicates the conductors, I the insulators and θ the opening angle.

Figure 10.5 (a) and (b) represents a classic electroscope with conducting case. It has two mobile leaves or strips. Figure 10.5 (c) and (d) illustrates an electroscope with conducting case which has a single mobile strip. The conductors are represented by letters C, the insulators by letters I, while the opening angle is indicated by letter θ.

The insulator between parts A and B can be air, a piece of Styrofoam, plastic or PVC. Some textbooks mention a wine stopper connecting parts A and B. This is not a good choice, after all cork behaves as a conductor in electrostatics, as discussed in Section 3.1. Any substance connecting parts A and B of this electroscope should be tested in advance. Only insulators should be employed. Many kinds of rubber, for instance, behave as conductors and should not be utilized as an insulator in this device.

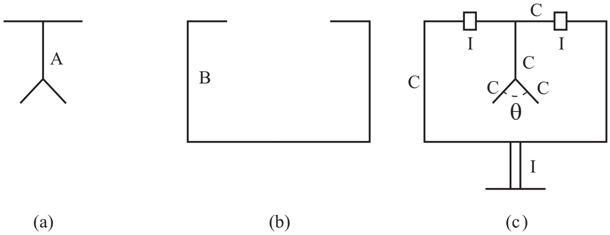


Figure 10.4: Electroscope with conducting case seen in profile. (a) Conducting part A. (b) Conducting part B. (c) Mounted instrument. The conductors are represented by letters C, the insulators by letters I, while the opening angle is indicated by θ.

In many commercial or educational electroscopes the conducting portions are made of metal. In this book the instrument will be made with paper, cardboard and tissue paper strips.

In a precise instrument, part B should envelop or cover part A almost totally. However, in order to see the opening angle, there must be a hole or opening in part B. Ideally the size of this hole should be small, so that it will not affect the potential difference indicated by the instrument. In this book we will utilize this device only as a qualitative indicator of potential differences, not worrying about quantitative measurements. Therefore the electroscopes can have large openings on part B.

Normally there are two conducting electrodes connected to parts A and B of any electroscope with conducting case. The so-called principal electrode, PE, connects part A with a certain conductor C_1, while the so-called secondary electrode, SE, connects part B with another conductor C_2, Figure 10.6.

In this example the opening angle θ of part A will indicate the potential difference between conductors C_1 and C_2. When $\theta = 0$, conductors C_1 and C_2 will be at the same potential. When $\theta \neq 0$, conductors C_1 and C_2 will be at different potentials. The greater the value of θ, the larger will be their potential difference. Ideally parts A and B of the electroscope should have small areas compared to the areas of conductors C_1 and C_2. When this is the case, they will not affect significantly the potentials which are to be measured.

These two electrodes can also be connected to different portions of a single conductor in order to verify that all points of this conductor are at the same potential.

In many situations conductor C_2 will be the Earth itself, so that the conducting case of the electroscope will be grounded. When this is the case, the opening angle will indicate the potential difference between conductor C_1 and the ground. The potential of the Earth is usually defined as zero. Part B may be grounded by the secondary electrode, as in Figure 10.7 (a). When part B is supported on a conducing plate connected to the Earth, it will be automatically grounded. The secondary electrode will be no longer necessary, as indicated in Figure 10.7 (b).

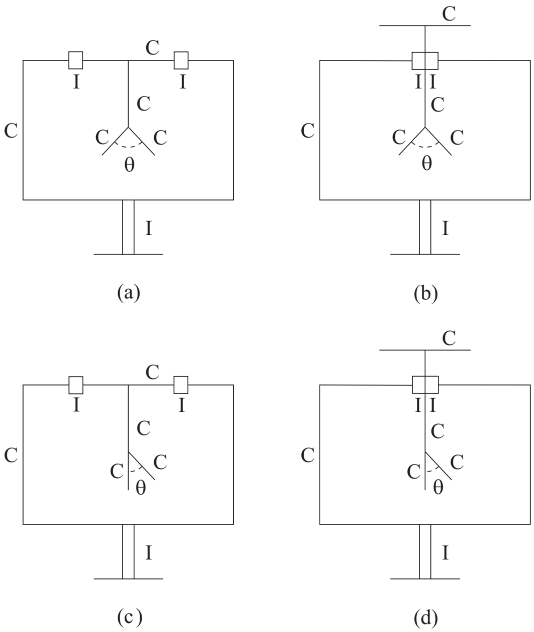


Figure 10.5: Electroscope with conducting cases. (a) and (b): Electroscope with two mobile leaves. (c) and (d): Electroscope with a single mobile strip which can open relative to a fixed portion.

Normally the electrodes connecting the electroscope with conductors C_1 and C_2 are metal wires. We need to manipulate them in order to perform these connections. To this end, the electrodes must be insulated from the ground, in order to avoid the discharge of the conductors. The insulation of common stranded copper wires sold at electric shops is normally made of polyethylene or PVC. They behave as good insulators for potential differences up to some 300 V. In electrostatic experiments, on the other hand, we deal with voltages reaching 1,000 V or 10,000 V. These flexible plastics around copper wires are not good insulators for electrostatic experiments. Therefore, when utilizing these insulated wires as electrodes, do not touch them directly with the hands. Be careful to manipulate these electrodes. Ideally, fix a portion of these wires with an acrylic ruler or PVC tube. Coil, for instance, a portion of the wire on the plastic ruler, as in Figure 10.8 (a). The hand would touch only the ruler or PVC tube, but not the wire. Connect in this way part A of the electroscope with conductor C_1 without discharging this conductor.

You can also manipulate these electrodes utilizing another procedure. To this end, utilize conducting coiled wires, like springs, which can be compressed or stretched. Fix the end of this wire to an acrylic ruler or PVC tube,[4] as indicated in Figure 10.8 (b).

---

[4] [Per44, Fig. 1277, p. 1421].

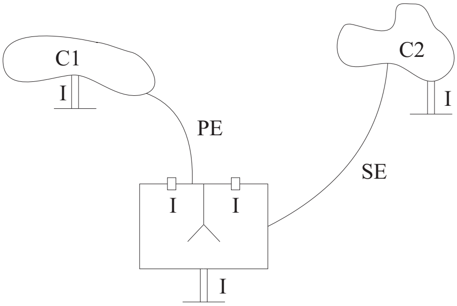


Figure 10.6: The principal electrode PE connecting part A of the electroscope with conductor C_1, while the secondary electrode SE connects part B with the conductor C_2.

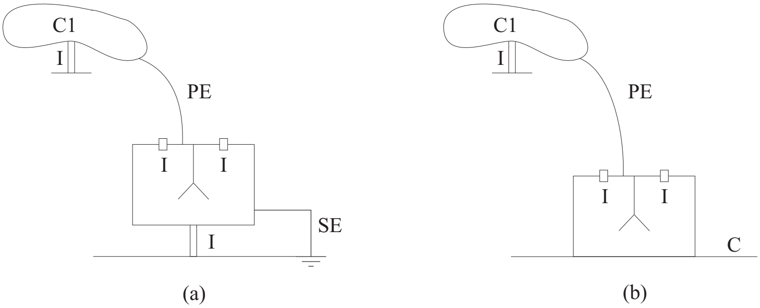


Figure 10.7: Electroscope with grounded case. (a) Secondary electrode connected to the Earth. (b) Case on a conducting plate C connected to the ground.

In order to transform this electroscope into an electrometer, it would be necessary to calibrate it, so that each opening angle would correspond to a known potential difference. In this book we will not deal with this problem. The electroscope will be utilized only to know if two points are at the same potential or at different potentials. It will also indicate qualitatively the amount of the potential difference by the size of the opening angle. A large angle indicates a great potential difference, while a small angle indicates little potential difference.

10.4 Experiments Utilizing the Electroscope with Conducting Case

10.4.1 The Electroscope Shows that All Portions of a Conductor in Equilibrium Are at the Same Potential

This Subsection describes some experiments related to the equality of potential between different portions of a single electrified conductor in equilibrium. The

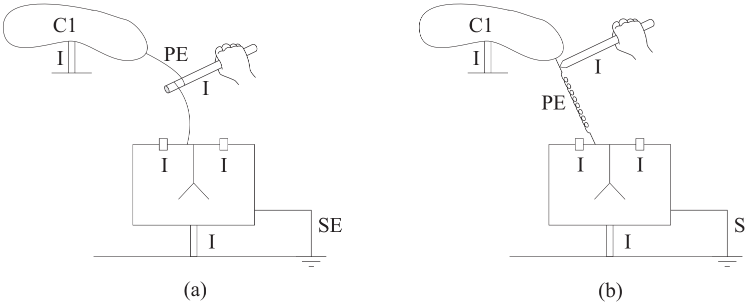


Figure 10.8: Electroscope with a grounded case and with the principal electrode connected to an insulating tube. (a) Conducting wire coiled around the tube. (b) Conducting spring connected to the tube.

experiments which we performed utilized the simple electroscope surrounded by an open conducting cylindrical shell like that of Figure 10.2, or the simple electroscope surrounded by a conducting shoe box like that of Figure 10.3. The potential difference was indicated qualitatively by the opening angle between the tissue paper strip and the cardboard of the electroscope. However, the images of the experiments of this Section were made with the electroscope of Figure 10.6. This last electroscope has two mobile leaves while the one utilized by us had a single mobile strip. In any event, it is easier and more didactic to represent the results of the experiments with the electroscope of Figure 10.6 than with that of Figure 10.3.

We first perform some experiments showing that this instrument indicates that two arbitrary portions of a single electrified conductor in equilibrium are really at the same potential. Later on we show some experimental conditions which make the potential of part A of the electroscope to be different from the potential of its part B.

Experiment 10.1 - *Touching the internal and external walls of an electrified cylindrical shell*

Begin with an electrified cylindrical shell like that of Figure 7.1 (b). The net charges spread only on the external surface of the cylinder, as indicated by the raised tissue paper strips. This fact is also indicated when a proof plane touches its internal and external surfaces. You can then test the charge acquired by this collector. Assume in the present experiment that there are no tissue paper strips on the internal wall of the cylindrical shell and a single strip on its external wall. When the shell is electrified, this strip raises. Connect the principal electrode of the electroscope of Figure 10.6 to the internal wall of the electrified cylinder, while the secondary electrode is connected to the external wall. The tissue paper strips of part A of the electroscope remain down, with $\theta = 0$. Therefore the internal and external walls of an electrified cylindrical shell are at the same potential, Figure 10.9.

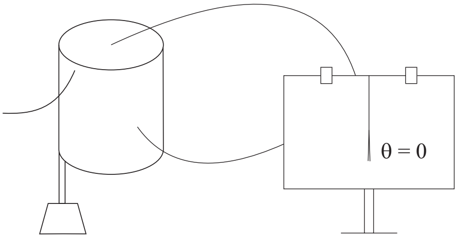


Figure 10.9: Part A of the electroscope connected to the internal wall of an electrified cylindrical shell and part B connected to the external wall. There is no opening angle of the electroscope, indicating that these two walls are at the same potential.

This fact can also be shown with the grounded electroscope of Figure 10.7. To this end, connect the principal conductor with the internal wall of the electrified cylinder and observe the opening angle θ_1 of the strips of part A, Figure 10.10 (a). Then connect the principal electrode with the external wall of the electrified cylinder and observe the opening angle θ_2 of the strips of part A, Figure 10.10 (b). After performing this experiment, it is found that $\theta_1 = \theta_2 \equiv \theta$.[5] Therefore the internal and external walls of the electrified cylinder are at the same potential relative to the ground. There is no potential difference between the internal and external walls, that is, $\theta_1 - \theta_2 = 0$. They are then in electric equilibrium.

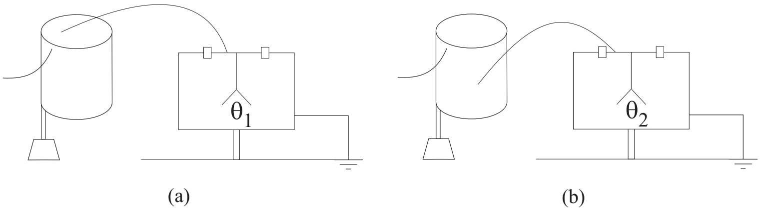


Figure 10.10: (a) Grounded electroscope with its part A connected to the internal wall of an electrified cylindrical shell. Opening angle θ_1. (b) The same configuration with part A connected to the external wall. Opening angle θ_2. There is the same opening in both situations, that is, $\theta_1 = \theta_2$.

You can also show this fact in another way. To this end, reverse the electrode which is grounded. Ground part A through the principal electrode. The secondary electrode is first connected to the internal wall of the electrified cylindrical shell. Observe the opening angle θ_1, Figure 10.11 (a). The secondary electrode is then connected to the external wall of the shell. Observe the opening angle θ_2, Figure 10.11 (b). By comparing these two angles, we conclude that in both situations there is the same opening angle, namely, $\theta_1 = \theta_2 = \theta$. Therefore the internal and external walls are in equilibrium at the same potential, because

---

[5] The symbol "≡" indicates a definition.

we find that $\theta_1 - \theta_2 = 0$.

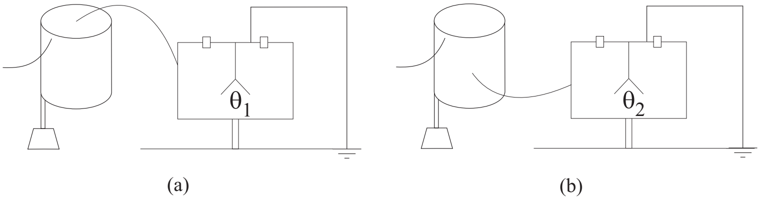


Figure 10.11: (a) Electroscope grounded by part A, while part B is connected to the internal wall of an electrified cylindrical shell. Opening angle θ_1. (b) The same configuration with part B connected to the external wall. Opening angle θ_2. In both situations there is the same opening angle, that is, $\theta_1 = \theta_2$.

The configuration of Figure 10.11 is very interesting. It shows an opening angle $\theta \neq 0$ for the mobile strips of part A even when this part A is grounded, provided part B has a potential different from that of part A. Although the grounded part A is at zero potential, part B of the electroscope is connected to an electrified cylindrical shell which is at a potential different from zero.

Experiment 10.2 - *Touching different points of an asymmetric conductor*

Another experiment of this kind utilizes an asymmetric conductor strip, like the drop like conductor of Figure 9.6 (b). When this conductor is electrified, there will be a gradient of surface charge densities along its surface, larger in the pointed regions and smaller in the blunt regions, as shown by a proof plane, see Figure 9.8. Glue the upper end of a single tissue paper strip on the external wall of this conductor in order to indicate when it is electrified. After being charged, this strip raises. Connect the principal electrode of a grounded electroscope in any point of the external wall of the conductor, observing always the same opening angle θ. The surface charge densities σ are different at points 1, 2 or 3, namely, $\sigma_1 \neq \sigma_2 \neq \sigma_3$. Despite this fact, there is the same opening angle in all these points, namely, $\theta_1 = \theta_2 = \theta_3 \equiv \theta$, Figure 10.12.

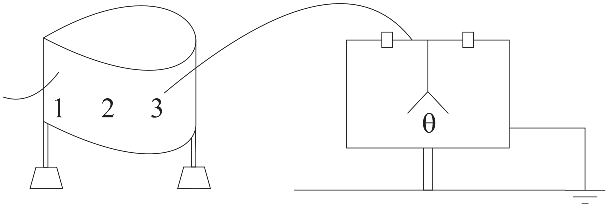


Figure 10.12: Grounded electroscope indicating the same opening angle θ, no matter if the principal electrode is connected to point 1, 2 or 3 of the electrified drop conductor.

Experiment 10.3 - *Touching different points of a long electrified strip*

Perform a similar test utilizing the electrified rectangle of Experiments 9.2 and 9.4, Figure 9.4. First get the rectangle highly electrified, with visibly raised tissue paper strips. There is a higher surface charge density at the borders of the rectangle than on its central region, Figure 9.5. Connect the principal electrode of a grounded electroscope to any point of the rectangle. Observe that there will always be the same opening angle θ of the electroscope, regardless of the location where the electrode is connected. This fact indicates that all these points are at the same electric potential. There is a gradient of surface charge densities, larger at the borders of the rectangle and smaller at its central regions. But the electric potential is the same on all points, Figure 10.13.

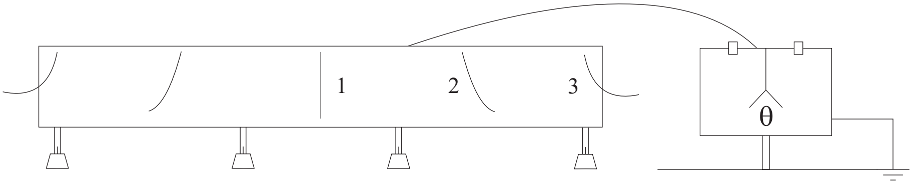


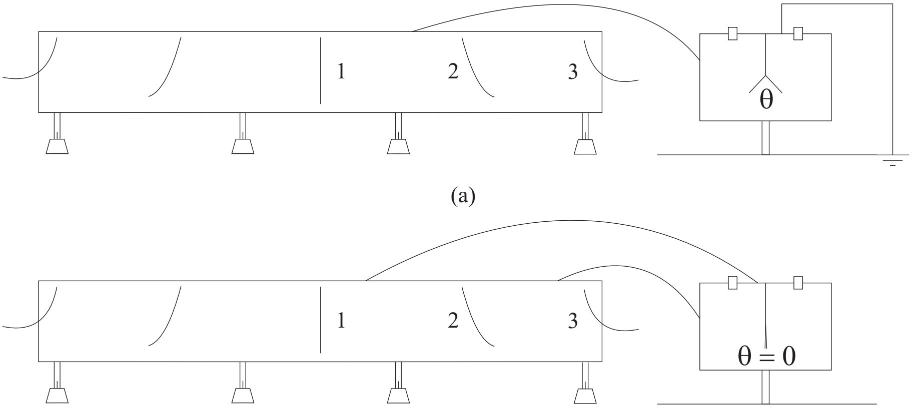
Figure 10.13: Grounded electroscope indicating always the same opening angle θ, no matter if its electrode touches points 1, 2 or 3 of the electrified rectangle.

This procedure can also be reversed. Ground part A of the electroscope and connect the secondary electrode to points 1, 2 or 3 of the electrified rectangle. The opening angle θ will be always the same, regardless of the location where the secondary electrode is connected, Figure 10.14 (a).

Insulate this electroscope from the ground. Connect its part A to a specific point of the electrified rectangle, while its part B is connected to any other point of the rectangle. Observe that the leaves of the electroscope remain closed, $\theta = 0$, Figure 10.14 (b). This fact indicates that all points of the electrified rectangle are at the same potential. Despite this fact, there are different surface charge densities in different points of the rectangle, as indicated by its raised strips or by collecting charges from different regions of the rectangle utilizing a proof plane.

10.4.2 Procedures which can Change the Potential of One Conductor Relative to the Potential of Another Conductor

This Subsection describes some experiments related to the equality or difference of potential between two insulated electrified conductors. Up to now we have seen how an electroscope with conducting case indicates that two portions of a single conductor in equilibrium are at the same potential. This Subsection describes how to change the potential of one conductor relative to the potential of another conductor. It shows also some procedures to change the potential of part A of this electroscope relative to the potential of its part B.



(a)

(b)

Figure 10.14: (a) Electroscope grounded by part A indicating always the same opening angle θ, regardless of the location where the secondary electrode is connected. (b) Insulated electroscope with its part A connected to one point of the electrified rectangle, while its part B is connected to another point of the rectangle. There is no opening angle of the electroscope.

Experiment 10.4 - *Bringing an electrified body close to one of the parts of the electroscope*

Begin with an electroscope with conducting case grounded by its part B. Initially part A should also be at zero potential, in such a way that there is no opening angle of its strips, Figure 10.15 (a). Electrify negatively a plastic ruler by rubbing it in hair, on a piece of paper or in a cotton tissue. The rubbed acrylic ruler is then brought close to part A of the grounded electroscope. There is now an opening θ_1 of its strips, indicating that part A is at a potential different from zero, Figure 10.15 (b). The closer the ruler, the greater will be this opening angle.

By removing the ruler, the opening angle goes to zero.

Ground part A of the electroscope. When parts A and B are at zero potential, the strips of the electroscope remain down, with no opening angle, Figure 10.16 (a). Bring the same rubbed acrylic ruler close to part B of the electroscope. There is now an opening angle θ_2 of its strip, indicating that part B is once more at a potential different from zero, while part A remained at ground potential, Figure 10.16 (b). The closer is the rubbed ruler from part B, the greater will be the opening angle.

Experiment 10.5 - *Bringing an electrified body close to one of the parts of the electroscope, assuming parts A and B connected by a conducting wire*

Suppose now an electroscope with conducting case insulated from the ground. Connect its parts A and B by a conducting wire. When the rubbed acrylic ruler

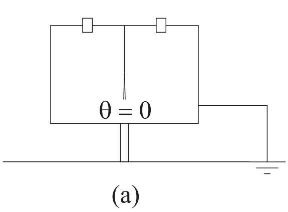


Figure 10.15: Electroscope grounded by part B. (a) Parts A and B initially at zero potential. (b) When a rubbed acrylic ruler is brought close to part A, the strips raise.

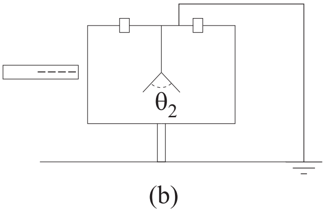


Figure 10.16: (a) Electroscope grounded by part A. Initially parts A and B are at zero potential. (b) When a rubbed acrylic ruler is brought close to part B, the strips raise.

is brought close to part A, the strips of the electroscope remain closed, Figure 10.17 (a). There is also no opening angle when the rubbed ruler is brought close to part B, Figure 10.17 (b).

This behavior can be justified. When the rubbed acrylic ruler is brought close to the electroscope, the potentials of the connected parts A and B increase equally relative to the zero potential of the ground. That is, when the rubbed ruler is close to the electroscope, $\phi_A \neq 0$ and $\phi_B \neq 0$, although $\phi_A - \phi_B = 0$, regardless of the position or distance of the ruler relative to the electroscope.

Experiment 10.6 - *Electrifying one of the parts of the electroscope*

Experiment 10.4 showed how to create a potential difference between parts A and B of an insulated electroscope when an electrified body is brought close to one of its parts. A potential difference can also be created electrifying separately part A or part B. Begin with an electroscope insulated from the ground. Its parts A and B should be initially discharged. There will be no opening angle in the electroscope. Electrify part A. This can be done, for instance, scraping a rubbed acrylic ruler on the border of the cardboard of the electroscope of part A, as in Figure 10.2 (a). You can also electrify part A by touching its cardboard with a rectangular charge collector electrified as an electrophorus. When part A is electrified, its strip raises, as in the electroscope with a single mobile strip

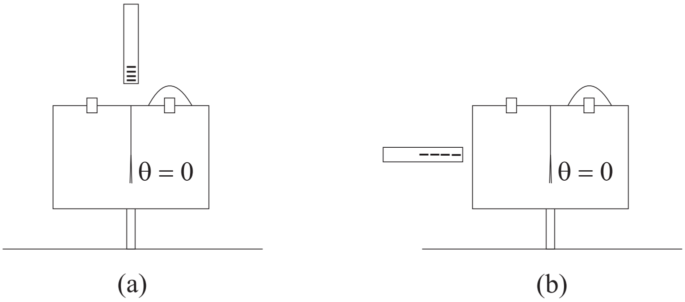


Figure 10.17: Electroscope insulated from the ground with parts A and B connected through a conducting wire. (a) Its strips remain closed when a rubbed acrylic ruler is brought close to its part A. (b) There is also no opening angle when the rubbed ruler is brought close to part B.

of Figure 10.18 (a), or its leaves open, as in the electroscope with two mobile leaves of Figure 10.18 (b).

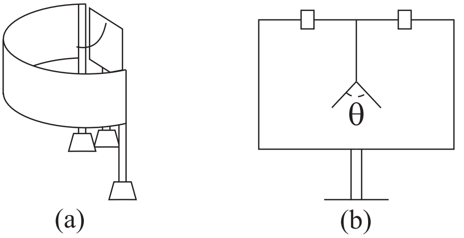


Figure 10.18: Electroscope insulated from the ground. Electrify only part A. (a) When the electroscope has a single mobile strip, it raises. (b) When the electroscope has two mobile leaves, they open.

Discharge the cardboard of the electroscope, so that both parts A and B have zero charge and are at zero potential. Electrify only part B. This can be done scraping a rubbed acrylic ruler on its cylindrical cardboard of Figure 10.2 (b), or by touching this cylindrical cardboard with an electrified electrophorus. The electrification of part B can be indicated by a raised external strip, Figure 10.19 (a). When there is an electroscope with a single internal mobile strip on part A, it raises, as in Figure 10.19 (b). When the electroscope has two mobile leaves, they open, as in Figure 10.19 (b).

Although part A has not been electrified in this last experiment, its internal strip raised (or its two leaves opened). This opening angle is due to the fact that when only part B was electrified, a potential difference was created between parts A and B of this electroscope.

Experiment 10.7 - *Electrifying one of the parts of the electroscope, assuming parts A and B connected by a conducting wire*

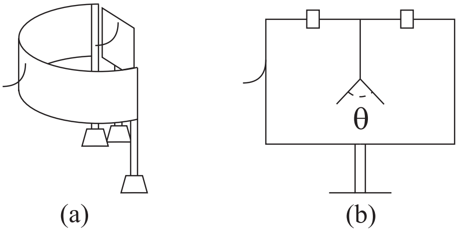


Figure 10.19: Electrify only part B. (a) The external strip of part B raises, indicating that this part has been electrified. The internal strip of part A also raises, indicating a potential difference between parts A and B. (c) The mobile strips of part A open in another model of electroscope.

Suppose now that parts A and B are connected by a conducting wire and that the electroscope is insulated from the ground. When this electroscope is electrified, its internal strip remains down, as in Figure 10.20 (a), or its two strips remain closed, as in Figure 10.20 (b). The raised strips on the external walls of the electroscopes of Figure 10.20 (a) and (b) have been drawn only to indicate that this insulated electroscope has been electrified as a whole.

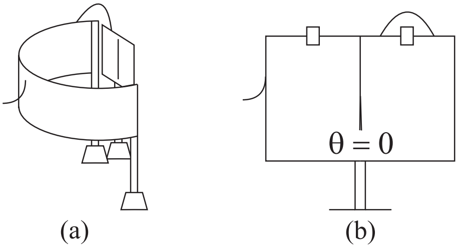


Figure 10.20: Insulated electroscope with its parts A and B connected by a conducting wire. (a) Charge the electroscope and its internal strip remains down. (b) Electrify another model of electroscope and its two internal leaves remain closed.

10.5 Kelvin and the Electrometer to Measure Potential Difference

In 1860 Kelvin specified clearly that an electroscope or electrometer with conducting case is an instrument appropriate to indicate the equality or the difference of potential between two conductors:[6]

> Two conducting bodies are said to be of the same electric potential when, if put in conducting communication with the two electrodes of an electrometer, no electric effect is produced. When, on the other hand, the

---

[6] [Tho84a, Note on p. 192].

> electrometer shows an effect, the amount of this effect measures the difference of potentials between the two bodies thus tested. [...]

The "effect" mentioned here by Kelvin is normally the opening angle between the two leaves of part A of the electrometer with conducting case. The principal electrode connects part A with the first conducting body, while the secondary electrode connects part B of the electrometer with the second conducting body.

We quote here from another work of Kelvin from 1860, our words in square brackets:[7]

> 336. *Interpretation of measurement by electrometer.*—Every kind of electrometer consists of a cage or case containing a moveable and a fixed conductor, of which one at least is insulated [electrically from the ground] and put in metallic communication, by what I shall call the principal electrode passing through an aperture in the case or cage, with the conductor whose electricity is to be tested. In every properly constructed electrometer, the electric force experienced by the moveable part in a given position cannot be electrically influenced except by changing the difference of potentials between the principal electrode and the uninsulated conductor or conducting system in the electrometer. Even the best ordinary electrometers hitherto constructed do not fulfil this condition, as the inner surface of the glass of which the whole or part of the enclosing case is generally made, is liable to become electrified, and inevitably does become so when any high electrification is designedly or accidentally introduced, even for a very short time; the consequence of which is that the moving body will generally not return to its zero position when the principal electrode is perfectly disinsulated. Faraday long ago showed how to obviate this radical defect by coating the interior of the glass case with a fine network of tinfoil; and it seems strange that even at the present day electrometers for scientific research, as, for instance, for the investigation of atmospheric electricity, should be constructed with so bad and obvious a defect uncured by so simple and perfect a remedy. When it is desired to leave the interior of the electrometer as much light as possible, and to allow it to be clearly seen from any external position with as little embarrassment as possible, a cage made like a bird's cage, with an extremely fine wire on a metal frame, inside the glass shade used to protect the instrument from currents of air, etc., may be substituted with advantage for the tinfoil network lining of the glass. It appears, therefore, that a properly constructed electrometer is an instrument for measuring, by means of the motions of a moveable conductor, the difference of potentials of two conducting systems insulated from one another, of one of which the case or cage of the apparatus forms part. It may be remarked in passing, that it is sometimes convenient in special researches to insulate [from the ground] the case or cage of the apparatus, and allow it to acquire a potential differing from that of the earth, and that then, as always, the subject of measurement is the difference of potentials between the principal electrode and the case or cage, while in the ordinary use of the [grounded] instrument the potential of the latter is the same as that of the earth. Hence we may regard the electrometer merely as an instrument for measuring differences of potential

---

[7] [Tho84c, pp. 258-259].

> between two conducting systems mutually insulated; and the object to be aimed at in perfecting any kind of electrometer (more or less sensitive as it may be, according to the subjects of investigation for which it is to be used), is, *that accurate evaluations in absolute measure, of differences of potential, may be immediately derivable from its indications.*

Kelvin was here referring to Faraday's work of 1838 in which he utilized Coulomb's torsion balance as an electrometer. He made an improvement in this device, namely, he coated the interior of the glass case with a grounded conducting material. This glass case was originally put around the bodies which were attracting or repelling one another in order to prevent disturbances from air currents. By coating it with a conducting material, Faraday was able to avoid the influence of external electrified bodies on the internal bodies:[8]

> That the inductive action within the electrometer might be uniform in all positions of the repelled ball and in all states of the apparatus, two bands of tinfoil, about an inch wide each, were attached to the inner surface of the glass cylinder, going entirely round it, at the distance of 0.4 of an inch from each other, and at such a height that the intermediate clear surface was in the same horizontal plane with the lever and ball. These bands were connected with each other and with the earth, and, being perfect conductors, always exerted a uniform influence on the electrified balls within, which the glass surface, from its irregularity of condition at different times, I found, did not.

---

[8] [Far38, article 1180, p. 444].

Chapter 11

Electric Discharges in Air

In Chapter 9 we described the so-called power of points, namely, some effects associated with the points of electrified conductors. There are some other extremely important effects of these points associated with electric discharges and sparks in air. Some of these phenomena will be discussed in this Chapter:

1. Air is more easily ionized close to the pointed regions of electrified conductors than close to its blunt portions. When it is ionized, air behaves as a conductor.

2. It is then easier to electrify a conductor through the ionized air close to its points. Bring an electrified body close to a pointed region of an insulated conductor. The body and the conductor do not need to touch one another. The exchange of their electrified particles happens through the conducting air between them.

3. It is also possible to discharge an initially electrified conductor though its pointed regions when these points are close to a grounded conductor. That is, the electrified conductor does not need to touch the grounded conductor in order to be discharged.

11.1 Sparks

Perform some extremely simple and interesting experiments by fixing a needle, pin or metal wire on a simple electroscope.[1] The needle or wire can be fixed on the back side of the electroscope with adhesive tape. A small portion of it, 1 to 2 cm, should protrude from the cardboard, Figure 11.1.

Experiment 11.1 - *Electrifying an electroscope at a distance*

---

[1] [FM91, p. 62], [Ferb, Pára-raios: Igrejinha, p. 40], [Gas03, pp. 239-243] and [LSB08].

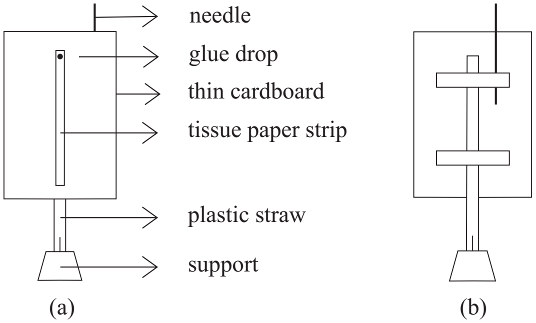


Figure 11.1: (a) Electroscope seen face on with a needle fixed on its back side. (b) Back view.

Electrify negatively a plastic straw or acrylic ruler by rubbing it in hair, in a paper napkin or in a cotton tissue. Hold it horizontally some centimeters above the tip of the needle. Nothing happens. When it comes even closer to the electroscope, at approximately 1 cm from the tip, the thin tissue paper strip of the electroscope rises. By removing the straw, the strip drops.

Repeat this procedure with the electroscope initially discharged, Figure 11.2 (a).

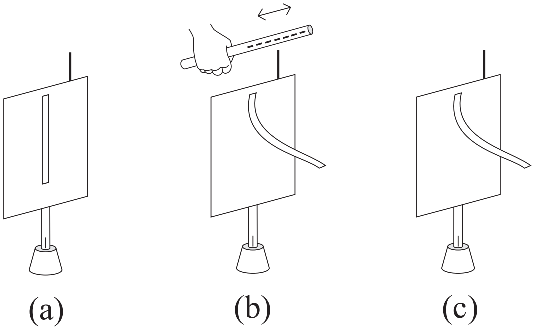


Figure 11.2: (a) A discharged electroscope with a needle on its back side. (b): Rubbed straw very close to the tip of the needle, moving to and fro horizontally. The strip lifts from the electroscope. (c) By removing the straw, the strip remains away from the cardboard!

This time the electrified straw should be brought even closer to the needle, being at a distance of 1 to 3 mm from its tip, *without touching it*. The tissue paper strip will rise. The rubbed straw should be moved horizontally to and fro above the tip of the needle, always remaining very close to it, Figure 11.2 (b). Moreover, the straw should be rotated or turned around its longitudinal axis during the oscillatory motion, presenting different regions of its surface to the needle. Remove the straw far away from the electroscope. The strip remains away from the cardboard of the electroscope, Figure 11.2 (c).

The strip remains away from the cardboard after the rubbed straw has been removed. This fact proves that the electroscope has become electrified by this procedure. *This phenomenon presents something new, namely, the electrification of the electroscope without contact with another electrified body!*

We did not discuss this charging mechanism in Volume 1 of this book. Up to now we had only considered three other means of charging, namely: (I) By friction, as in the amber effect, Section 1.1. (II) By contact of a conductor with another electrified body, as in the *ACR* mechanism, Section 4.4. (III) Electrification by induction or by polarization.[2]

Experiment 11.2 - *Discovering the sign of the charge acquired by the electroscope*

Consider the electroscope charged by the procedure of Experiment 11.1. Bring the same rubbed straw slowly close to the lifted strip of this charged electroscope. The rubbed straw should be horizontal, at the same height of the lower end of the raised strip. The motion of approach should be very slow, in order to prevent them from coming into contact. Observe attentively the direction in which the strip tries to move, that is, whether it moves toward the rubbed straw or away from it. By performing this experiment carefully, conclude that the strip moves toward the cardboard, that is, it moves away from the approaching rubbed straw.

The strip can move to and fro with the rubbed straw. To this end, move the straw toward the strip and away from it. The strip will move in consonance with the straw, toward the cardboard and away from it. If you wish to observe this oscillatory motion of the strip, the amplitude or magnitude of the motion of the rubbed straw should be low. That is, use movements of small magnitude. Avoid also bringing the rubbed straw very close to the strip, Figure 11.3.

This behavior of the strip shows that the electroscope with a needle has become electrified with a charge of the same sign as that of the rubbed straw, as there is repulsion between them. You can then represent the charges of the electrified electroscope as having the same sign as the charges of the rubbed plastic. In the present example, these charges would be negative.

Experiment 11.3 - *Discharging an electroscope at a distance*

Reverse Experiment 11.1 utilizing once more an electroscope with a needle on its back side. Begin with a charged electroscope, as indicated by its lifted tissue paper strip, Figure 11.4 (a).

Hold by hand a horizontal wood skewer or metal wire. Bring it slowly very close to the charged electroscope, at a distance of 1 to 3 mm from the tip of the needle, *without touching it*. In a few seconds the strip drops, becoming vertical and touching the cardboard, Figure 11.4 (b) and (c). By removing the skewer or wire, the strip remains down, Figure 11.4 (d).

---

[2] As discussed in Section 7.5 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

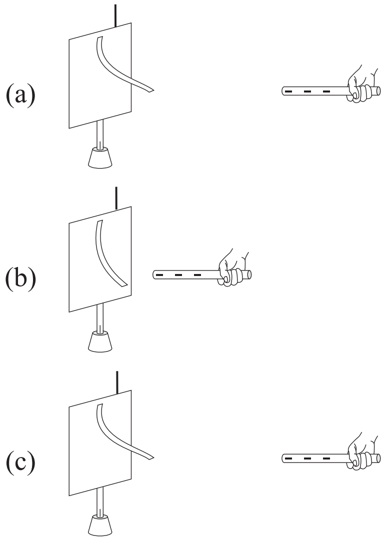


Figure 11.3: Repulsion between the negatively charged straw and the electroscope charged by this rubbed plastic. (b) When the straw is moved near the electroscope, the strip drops. (a) and (c): When the plastic is moved away from the electroscope, the strip raises.

In this experiment the electroscope was discharged at a distance, without contact. It was only necessary to bring a grounded conductor (wood skewer or metal wire held in the hand) very close to the tip of the needle.

Experiment 11.4 - *Influence of the number of needles in the required time interval to discharge an electroscope*

Compare the time interval required to discharge an electrified electroscope as a function of the presence or absence of the needle on its back side. We consider two electroscopes of the same size and shape. The first one is the usual electroscope, without a needle. The second electroscope has a needle on its back with the tip protruding out of the cardboard.

The two electroscopes should be separated from one another. Scrape a rubbed straw or acrylic ruler on their cardboards. They should be equally electrified. The same amount of electrification will be indicated when both strips raise by equal angles θ relative to their cardboards. Remove the rubbed straw and measure the discharge times of both electroscopes. That is, the time interval required for the strips to drop until they touch their cardboards. It is easy to observe that the electroscope with a needle discharges faster than the other electroscope.

Perform this experiment with a third electroscope containing two or three needles. One of the needles might come out vertically upwards and the other two sideways, one to the right and the other to the left, for instance. Electrify

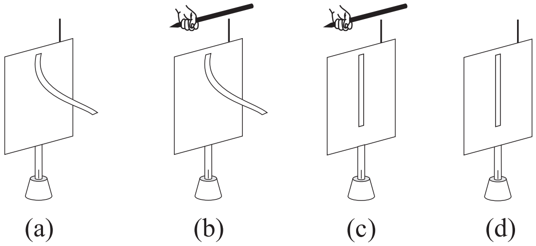


Figure 11.4: (a) A charged electroscope. (b) and (c): When a wood skewer or metal wire is brought very close to the tip of the needle, without touching it, the strip drops. (d) By removing the skewer, the strip remains down.

equally the three electroscopes and measure their discharge times. The higher the number of needles it possess, the faster it will discharge.

Experiment 11.5 - *Transfer of charges between two conductors separated from one another*

Utilize two empty cans of soda, A and B. Glue the upper end of a thin tissue paper strip on each one of them. A pin or needle should be fixed horizontally in one of these cans by passing the pin through a hole in its body. It should be fixed on the can with adhesive tape. The tip of this horizontal needle should come out of the can. Each can should be supported on an insulating Styrofoam plate. The pin sticking out of can A should be very close to the center of can B, with its tip at 1 or 2 mm from B. Initially both cans should be discharged, as indicated by their dropped strips, Figure 11.5 (a).

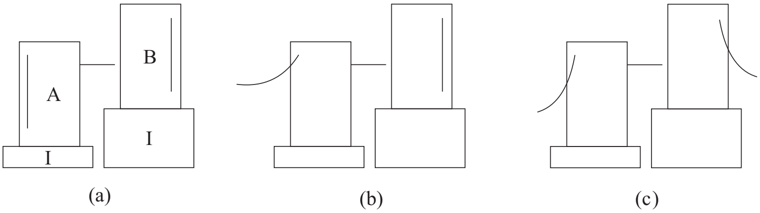


Figure 11.5: (a) Two discharged conducting cans insulated from the ground by Styrofam plates I. There is a horizontal pin sticking out of one can with its tip very close to the other can. (b) Electrify only can A scraping a rubbed plastic on its body. (c) After some time, both cans become electrified as indicated by their raised strips.

Electrify only can A scraping its upper edge a few times with a rubbed acrylic ruler, Figure 11.5 (b). Remove the rubbed acrylic ruler. After a while, both cans become electrified, Figure 11.5 (c).

This experiment shows that we could electrify can B at a distance from the electrified can A.

Experiment 11.6 - *Another example of this transfer of charges at a distance*

Reverse the procedure of Experiment 11.5. Electrify can B scraping a rubbed acrylic ruler on its upper edge, Figure 11.6 (b). Remove the rubbed ruler. After a while, both cans become electrified, Figure 11.6 (c).

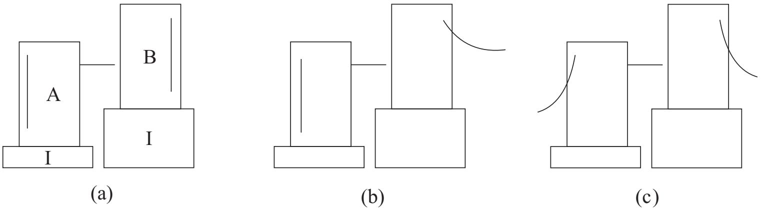


Figure 11.6: (a) Two discharged and insulated cans, with a pin in one of them. (b) Electrified can B. (c) After a while both cans become electrified.

In this experiment we electrified can A, which has a pin, without contact with the electrified can B.

11.2 Comments on These Experiments

Experiments of Section 11.1 are extremely interesting.

Experiment 11.1 utilized a discharged electroscope with a metal pin sticking out of it. A rubbed straw was brought very close to the tip of the pin. After a while the electroscope has become electrified. There was no contact between the electrified straw and the point of the needle. Therefore, the electrification took place through the intervening air. Dry air normally behaves as an insulator for electrostatic experiments. This conclusion can be drawn by the fact that a simple electroscope containing no needle can remain electrified for a few minutes, although it is surrounded by air. In Experiment 11.1, on the other hand, air around the pointed needle behaved as a conductor. Many of its molecules are ionized or electrified. As these ions are mobile, it was possible for the exchange of electrified particles between the electrified straw, the ions of the air, and the electroscope.

Experiment 11.3 utilized an initially charged electroscope with a metal pin sticking out of it. A grounded conductor was brought very close to the tip of the pin. After a while the electroscope was discharged. The grounded conductor was a wood skewer or a metal wire. The electroscope was discharged without the usual grounding mechanism which takes place by contact. In this experiment, on the other hand, the wood skewer was brought close to the tip of the needle, without touching it. Air around the tip behaved as a conductor when the wood skewer was brought close to the tip. This wood skewer or metal wire was grounded through contact with the hand holding it. When it was brought very close to the tip of the needle, the conducting air around it allowed the discharge of the electroscope.

Experiment 11.4 showed that the presence of points on an electrified conductor, insulated from the ground, facilitates its discharge through the air around it. Once more it is the air around the points of electrified conductors which behaves as a conductor, facilitating the discharge of the electroscope.

This changing behavior of air, from insulator to conductor, is a complex phenomenon which depends on several factors. We will not explain in this book how air can change its behavior, from insulator to conductor. We will only describe some of its main properties. This transition is neither slow nor gradual—it takes place in the blink of an eye. It is called *corona discharge*. Given two points in air, when the potential difference between them is smaller than a certain critical value, air behaves as a good insulator. Beyond this critical value, on the other hand, it behaves as a good conductor. The maximum electric field (voltage difference per unit distance) that an insulator can withstand under ideal conditions without breaking down, that is, without experiencing failure of its insulating properties, is called *dielectric strength* of the material. This critical value depends on many factors. For air, in particular, it depends on the atmospheric pressure. The dielectric strength of air at normal pressure ($P = 1\ atm = 1 \times 10^5\ N/m^2$) is approximately $3 \times 10^6\ V/m = 3,000\ volts/mm$.[3]

Consider, for instance, Experiment 11.1. Suppose that the electroscope can be charged when there is a 2 mm distance between the electrified straw and the tip of the needle. In this case there will be a potential difference of approximately 6,000 V between the straw and the electroscope.

From experiments like this one, or from the measurement of the distance between two conducting spheres in Kelvin's water dropper experiment required to produce a spark, we conclude that in the usual electrostatic experiments we deal with potential differences ranging typically from 1,000 V up to 10,000 V.[4] Although these potential differences are much larger than the potential differences available in ordinary batteries (a few Volts), the amount of electric charges involved in electrostatic experiments is usually very small.

It should be emphasized here that sparks in air are not due the extraction of electrons from the electrodes. In order to remove electrons from metal surfaces at low temperatures, we need forces per unit charge of the order of $10^8\ V/m$. This phenomenon is known as *field electron emission*, *field emission*, *electron field emission* or *cold emission*. This value of $10^8\ V/m$ is two orders of magnitude larger than the critical electric field of $3 \times 10^6 V/m$ required to ionize air at atmospheric pressure.[5]

11.3 Lightning Rods

Experiments 11.1 and 11.3 show that it is possible to charge or discharge an electroscope at a distance. Experiment 11.4 shows that air around an electrified

---

[3] [TM09, pp. 91 and 125].

[4] [Tho], [Llo80], [Cam06], [CA08] and Sections 6.6, 7.11 and 7.12 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[5] [Sav, p. 249], [Sil10c], [Sil11] and [Sil16].

pointed region of a conductor behaves as a conductor. This conducting behavior of air close to electrified pointed conductors is the working principle of lightning rods. This working mechanism can be illustrated with some simple experiments.

Experiment 11.7 - *Simulation of a lightning rod*

Cut a thin cardboard in the shape of a simple house. It can be fixed in the ground by a gap or slot in a wooden board or plate. Glue the upper end of a thin tissue paper strip on the house in order to indicate possible electric effects. A 20 or 30 cm long metal wire is fixed vertically next to the house. It should be insulated from the house by pieces of Styrofoam or rigid plastic. The lower end of the wire should penetrate on the wooden board. This device will represent a lightning rod, Figure 11.7 (a), in which the letter *I* represents insulating materials.

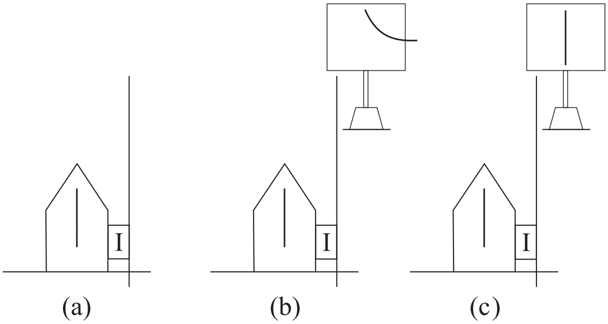


Figure 11.7: (a) The lightning rod is a conducting wire insulated from the house or building which is being protected by it. Its lower end penetrates into the ground. (b) Bring the lower edge of a charged electroscope very close to the upper end of the wire. (c) The electroscope is discharged by the lightning rod. The house and its thin tissue paper strip are not affected by the discharge.

Our model of an electrified cloud will be a simple electroscope supported by an insulating straw. Electrify this cloud scraping a rubbed acrylic ruler on the upper edge of the cardboard. The degree of inclination of its tissue paper strip indicates the amount of electrification of this cloud. Hold it through its insulating straw. Bring the lower edge of the cardboard close to the upper end of the metal wire, avoiding their contact, up to a small distance of 1 to 3 mm, Figure 11.7 (b). The electroscope is then discharged without contact with the metal wire, Figure 11.7 (c). Moreover, the house is not affected by this discharge. That is, its tissue paper strip is not affected during this whole process, remaining always vertical.

This experiment illustrates the working mechanism of a lightning rod and its protective role. The lightning rod is a conducting wire with its lower end penetrating the ground. Its upper end goes vertically beyond the house or building which it is protecting. It is insulated from this building by an insulating material I. Suppose an electrified cloud passes above the lightning rod. The upper tip of the rod becomes electrified with a charge of opposite sign to that on the cloud. When there is a high voltage between the cloud and the ground, the air around the tip of the rod will behave as a conductor. This conducting channel can discharge the cloud through the lightning rod.

11.4 Lightning Rod Insulated from the Ground

The lightning rod intended to protect buildings from the discharge of a cloud must be grounded.

On the other hand, when the metal wire is insulated from the ground, we have the so-called *test rod* or *lightning rod insulated from the ground*. It is used to collect part of the electricity accumulated in clouds or in the atmosphere. We can then test or verify the sign of this collected charge, its magnitude at different altitudes or locations of the rod, its magnitude as a function of the local weather, at different hours or at different months along the year. It is extremely dangerous to perform real experiments with test rods in the open air in order to study the electricity of clouds. In this book we will perform some didactic experiments utilizing small metal wires as test rods. The electrified clouds will be simulated by charged electroscopes insulated from the ground.

Experiment 11.8 - *Removing the charges of an electroscope*

A metal wire is fixed vertically on a thick Styrofoam plate. The lower end of this wire should be located at the center of the plate and cannot touch the ground. This wire will be insulated from the Earth. The upper end of this wire will be outside the plate, in the open air. An insulated electroscope initially discharged is supported above the wire with the lower edge of its cardboard close to the upper end of the wire, 1 to 3 mm distant from its tip. A metal versorium is located close to the center of the vertical wire, pointing in an arbitrary direction, Figure 11.8 (a).

The electroscope is then electrified scraping its upper edge with a rubbed straw. Its strip lifts immediately, Figure 11.8 (b). Remove the rubbed straw. After a while, the lifted strip drops a little bit and the versorium points towards the vertical wire, Figure 11.8 (c).

This experiment is not related with electrostatic induction. That is, the orientation of the versorium is not due to the polarization of the wire, which takes place when a charged electroscope is close to the wire. Suppose the electroscope is negatively charged. The upper end of the insulated wire will be positively electrified by induction, while its lower end will be negatively electrified. This induction takes place almost immediately, being simultaneous with the electrification of the electroscope.

The orientation of the versorium, on the other hand, only takes place a few seconds after the electrification of the electroscope. This orientation is due to the gradual electrification of the wire as a whole, which takes place due to air

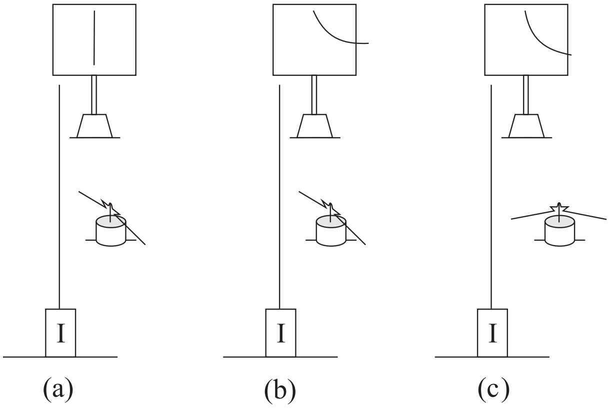


Figure 11.8: (a) Vertical test wire insulated from the ground. A nearby versorium close to its center points in an arbitrary direction. The electroscope is initially discharged. (b) A charged electroscope. (c) After a while, the strip drops a little and the electrified wire orientates the versorium towards it.

ionization around the upper tip of the wire. As the wire becomes negatively electrified, it causes a redistribution of charges in the nearby versorium, orientating it towards the wire.

This experiment can also be performed with a horizontal metal wire supported on two Styrofoam cups. The versorium should be placed in the same plane of the wire, close to it and pointing in an arbitrary direction, Figure 11.9 (a). The charged electroscope is then brought very close to the wire, with its center in the plane of the wire. The tip of the wire should be at a distance of 1 to 3 mm from the vertical border of the cardboard. After a while, the versorium is oriented towards the wire, Figure 11.9 (b).

11.5 Sparks in the ACR Mechanism

The ACR mechanism was discussed in Section 4.4. In this phenomenon an insulated and light conductor is attracted by a charged body, there is communication of electricity, followed by the repulsion of the conductor. Experiment 4.3 showed an example of this mechanism. A small conducting disk initially neutral and insulated from the ground was attracted by an electrified insulator, touched it and was then repelled by it. The disk acquired a charge of the same sign as that of the electrified insulator. The attraction took place due to the polarization of the disk. This polarization was induced by the nearby electrified plastic. Normally the communication of electricity in the ACR mechanism takes place during the contact between the small conductor and the nearby charged body.

However, this contact is not always necessary. That is, the ACR mechanism may take place without contact between the charged body and the insulated conductor. Sometimes when the small conductor is sufficiently close to the

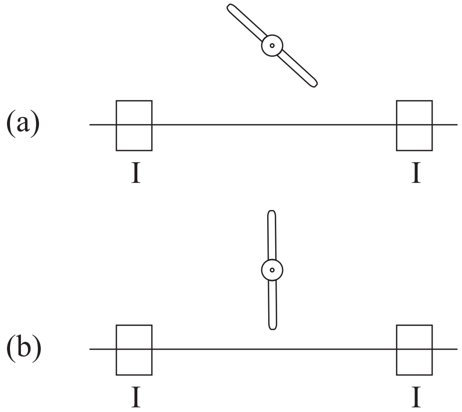


Figure 11.9: (a) Horizontal test rod insulated from the ground. A nearby versorium close to its center points in an arbitrary direction. (b) After the wire has been electrified, it orientates the versorium, making it point towards the wire.

electrified insulator, there is a transfer of charges between them and the surrounding air, electrifying the conductor. In this process the small conductor acquires a charge of the same sign as that of the nearby electrified body. When this communication of charges takes place, there is a repulsion between the small conductor and the electrified body, although they never touched physically one another. What takes place in this case is that when they are very close to one another, the air between them can behave as a conductor. There is then a small spark through the air, with an exchange of electrified particles between the small conductor, the ions of the air and the electrified insulator. After a while, the small conductor becomes electrified and is then repelled by the insulator.

Du Fay himself, who discovered the ACR mechanism, was aware that contact was not necessary for a repulsion to take place. Sometimes the small conductor would acquire a net charge of the same sign as that of the electrified body by simply coming very close to it, without contact.[6]

11.6 Neon Lamp

It is easy to buy in electric shops a so-called *neon lamp* or *neon glow lamp*, Figure 11.10.

It is a gas discharge lamp used as an indicator in electronic equipment, voltage testers, etc. In electrostatic experiments it can be utilized to indicate not only if a body is electrified or discharged, but also the sign of its charge, that is, if the body is positive or negative.

Experiment 11.9 - *Scraping a neon lamp on a negatively charged ruler*

---

[6] Section 4.8 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

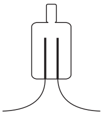


Figure 11.10: Neon lamp.

Hold by hand one of the legs of a neon lamp and touch the other leg in a neutral acrylic ruler. The lamp does not turn on, Figure 11.11 (a).

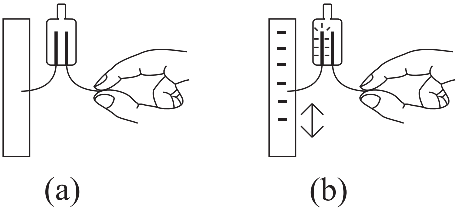


Figure 11.11: (a) A neon lamp remains turned off when it touches a neutral acrylic ruler. (b) Scrape one of its legs on a negatively electrified ruler. Observe that only the electrode connected to the ruler blinks.

An acrylic ruler is negatively electrified by rubbing it in hair, in a paper napkin or in a cotton tissue. Hold one leg of the neon lamp with a finger and touch its other leg on the electrified portion of the ruler, scraping it along the ruler in a darkened room. Only the electrode connected to the negative ruler blinks, Figure 11.11 (b).

Experiment 11.10 - *Touching a neon lamp on positively and negatively charged electroscopes*

Electrify two electroscopes, one positively and the other negatively. This electrification can be obtained scraping a positively electrified plastic ruler on the upper edge of the cardboard of one electroscope and a negative plastic ruler on the edge of the cardboard of the other electroscope. These opposite electrifications of the electroscopes can also be easily obtained by induction or polarization.[7] The charged electroscopes are then separated from one another.

Hold one leg of the neon lamp and touch its other leg on the positive electroscope in a darkened room. It discharges almost immediately. During the discharge, only the electrode connected to the hand blinks, Figure 11.12 (a).

Repeat the same procedure when touching the negatively charged electroscope. Observe that the lamp also blinks during the discharge. However, in this case, only the electrode connected to the electroscope blinks, Figure 11.12 (b).

This experiment can be repeated with electrophori.[8] When the charge collector of the electrophorus is negatively electrified, only the electrode touching

---

[7] Section 7.5 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[8] [Ferb, Lâmpada de néon, p. 32; Lâmpada fluorescente, p. 34; e Eletróforo de Volta, p. 38].

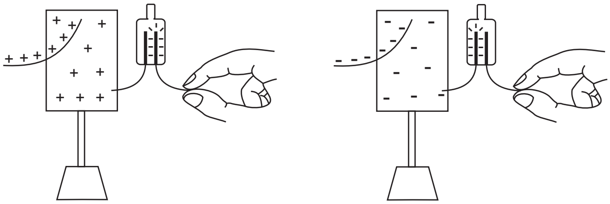

(a) (b)

Figure 11.12: The lamp blinks when one of its legs touches a charged electroscope while its other leg is held in the hand. (a) Only the electrode connected to the hand blinks when the electroscope is positively electrified. (b) Only the electrode connected to the electroscope blinks when the electroscope is negatively electrified.

it will blink. When, on the other hand, the leg of the neon lamp touches a positively charged electrophorus, only the electrode connected to the hand of the person holding the lamp will blink.

The neon lamp is then a very useful device. In the first place, it can indicate if a certain conductor is charged or discharged. When the conductor is initially electrified, the neon lamp will also indicate if it is positively or negatively charged.

11.7 Gray, Franklin, the Power of Points and the Electric Nature of Lightning

Some early scientists noticed several analogies between the small sparks and electric discharges they produced in their electrostatic experiments and lightning observed in thunderstorms. They suggested that these two classes of phenomena might be the same effect but with a huge difference in magnitude. One of these researchers was Stephen Gray. In a letter sent to the Secretary of the Royal Society in 1734, published in 1735, he described several experiments related with sparks and lights he was able to produce with his electrified glass tube and also when pointed conductors were placed very close to electrified bodies. We quote here from the final section of his paper, with our figures and our words in the footnotes and between square brackets:[9]

> **8.** I then took a wooden dish, and placed it upon the stand[10] first empty; then applying the tube, [that is, a rubbed glass tube,] and the finger[11] near the dish, there appeared a light, but no pushing of the finger nor snapping: I then filled the dish with water, and the tube being held over the surface of the water, there appeared a greater light than when the

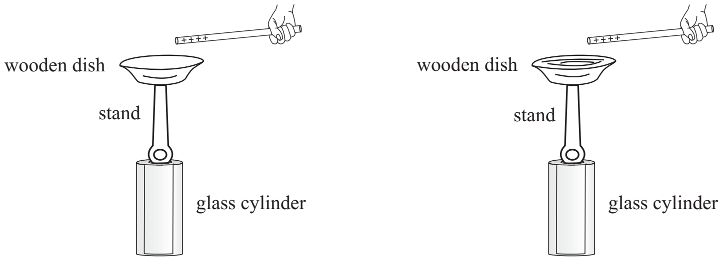
---

[9] [Grac, p. 24], [Bos11, Chapter 10] and [BAC12, Chapter 11, pp. 221-238].

[10] In this paper Gray mentioned that this stand was set upon a cylindric glass. His glass cylinder behaved as an insulator.

[11] "*Fin-*" in the original. Probably he was referring to a finger.

> finger had been applied to the empty dish, but no snapping,[12] till by holding the tube after it had been well rubbed, within two or three inches of the finger that was held near the surface of the water, and then the finger was pushed, and a snapping noise heard, as when the experiment was made with the pewter plate.[13]



(a) Glass cylinder, stand and an empty wooden dish.

(b) Glass cylinder, stand and a water filled wooden dish.

Figure 11.13: Glass cylinder, wood support and dish.

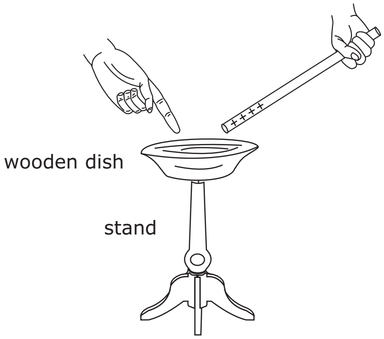


Figure 11.14: A finger held near the surface of the water. When a well rubbed glass tube was held within 2 or 3 inches of the finger, the finger was pushed and a snapping noise heard.

Gray continued his description of the experiment with the following words:

> By these experiments we see, that an actual flame of fire, together with an explosion, and an ebullition of cold water,[14] may be produced by communicative electricity; and altho' these effects are at present but in *minimis*,

---

[12] Figure 11.13 illustrates how this experiment might look.

[13] Figure 11.14 illustrates how this experiment might look.

[14] Probably this "flame of fire" refers to the spark or light emitted by the objects, the "explosion" refers to the snapping noise heard, while the "ebullition of cold water" refers to the water droplets collected at the surface of the tube when it was held close to the surface of water.

> it is probable, in time there may be found out a way to collect a greater quantity of it; and consequently to increase the force of this electric fire,[15] which, by several of these experiments (*Si licet magnis componere parva*)[16] seems to be of the same nature with that of thunder and lightning.[17]

Gray described several other experiments relating the power of points with sparks in air. He also made several experiments related to the conservation of electric charges.[18] These experiments will not be discussed in this book.

Benjamin Franklin (1706-1790) was a self-taught man who worked in many different areas. During 1743 and 1753 he devoted himself to electric experiments after hearing some public talks on this subject.[19] He received as a gift a glass tube which might be easily electrified by friction and which behaved as a good insulator. He also acquired some of the main electric instruments of his age. He informed his European colleagues of his experiments performed in Philadelphia through letters which were widely read and discussed. They were collected and published in book format in London in 1751. This work was enlarged and published in several editions up to 1774, being known by its title: *Experiments and Observations on Electricity*.[20] This book had a great impact, being translated into several languages. He coined a number of scientific terms in electricity like "plus and minus" or "positive and negative", "battery", etc. He gave an explanation for the working mechanism of a Leyden jar, spread the use of a parallel plate capacitor, emphasized enormously the power of points, being also one of the main scientists responsible for the establishment and utilization of the law of conservation of electric charges.[21] He called the electrified particles by several names like "electric fire", "electric matter" and "electric fluid". He worked with the conception of a single electric fluid. He believed there was a normal amount or density of this fluid contained in all substances. When a body had more electric fluid than this normal amount, it would be "positively electrified". Likewise, if it had less electric fluid than this normal amount, it would be "negatively electrified". Nowadays people utilize his nomenclature but with a different meaning, namely, assuming the existence of two kinds of electricity or two kinds of electric charge.

With his conception of the conservation of electric charges, Franklin emphasized that electricity was not created, generated nor produced during the friction between two substances, nor in any other process of electrification. The only thing happening during friction or in any other electrification process, was

---

[15] Later experiments with the Leyden jar confirmed Gray's predictions, see Chapter 12. It was then possible to collect electricity and store it for a long time. It was also possible to increase the size and power of the electric sparks produced experimentally.

[16] This quotation comes from a poem of the Roman poet Virgil (70-19 b.C.), *Georgics*, 4.176. Free translation: If we may compare small things with great.

[17] Gray's suggestion was confirmed during the 1750's with the experiments performed following the ideas of Benjamin Franklin.

[18] [Bos11] and [BAC12]; see also Section 6.10 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[19] [Hei99, Chapter 14], [SP06], [SP08] and [MB17].

[20] [Fra69], [Fra41] and [Mor04b].

[21] [Coh66], [Coh96] and [Hei99, Chapter 14: Benjamin Franklin].

a redistribution or transference of charge. That is, one of the bodies receives exactly the same amount of electric fluid lost by the other body.

In his first letter of 1747 Franklin described "the wonderful effect of pointed bodies, both in *drawing off* and *throwing off* the electric fire." He first presented an experiment in which a grounded and pointed conductor extracted the electric fluid from another electrified conductor which was insulated from the ground, our words in the footnotes:[22]

> Place an iron shot of three or four inches diameter on the mouth of a clean dry glass bottle.[23] By a fine silken thread from the ceiling, right over the mouth of the bottle, suspend a small cork-ball, about the bigness of a marble; the thread of such a length, as that the cork-ball may rest against the side of the shot. Electrify the shot, and the ball will be repelled to the distance of four or five inches, more or less, according to the quantity of electricity.
>
> When in this state, if you present to the shot the point of a slender sharp bodkin, at six or eight inches distance, the repellency is instantly destroy'd, and the cork flies to the shot. A blunt body must be brought within an inch, and draw a spark, to produce the same effect. To prove that the electrical fire is *drawn off* by the point, if you take the blade of the bodkin out of the wooden handle, and fix it in a stick of sealing-wax, and then present it at the distance aforesaid, or if you bring it very near, no such effect follows; but sliding one finger along the wax till you touch the blade, and the ball flies to the shot immediately.[24]

His first description of a pointed conductor emitting the electric fluid:[25]

> To shew that points will *throw off*[26] as well as *draw off* the electrical fire; lay a long sharp needle upon the shot, and you cannot electrify the shot, so as to make it repel the cork-ball.[27]

This experiment utilized again an iron shot insulated from the ground, as it was supported on a glass bottle. Despite this fact, it was not possible to electrify the shot, as any acquired electric fluid is lost to the air through the long sharp needle.

---

[22] [Fra69, pp. 3-4], [Coh96, pp. 23-24], [Hei99, pp. 327-328] and [MB17].

[23] This glass bottle behaves as an insulator.

[24] Sealing-wax is an insulator. In this experiment the metal blade is no longer grounded initially, as the sealing-wax behaves here as a handle insulating the blade from Franklin's hand. The blade is only grounded when the finger touches it. At this moment, the discharge of the iron shot takes place.

[25] [Fra69, p. 5] and [Coh96, pp. 23-24].

[26] This power of points to *throw ff* the electrical fire, was first communicated to me by my ingenious friend Mr. *Thomas Hopkinson*, since deceased, whose virtue and integrity, in every station of life, public and private, will ever make his Memory dear to those who knew him, and know how to value him.

[27] This was Mr. *Hopkinson*'s experiment, made with an expectation of drawing a more sharp and powerful spark from the point, as from a kind of focus, and he was surprized to find little or none.

He presented a similar experiment illustrating the emission of the electric fluid, namely:[28]

> Or fix a needle to the end of a suspended gun-barrel, or iron-rod, so as to point beyond it like a little bayonet; and while it remains there, the gun-barrel, or rod, cannot by applying the tube to the other end be electrified so as to give a spark, the fire continually running out silently at the point.

Once more the conducting point prevents the accumulation of charges on the metal rod.

The previous experiment in which Franklin extracted the electric fluid from an insulated electrified conductor through another pointed and grounded conductor inspired him. By reasoning analogously, he suggested how to test the idea that lightning might be a similar effect, only on a huge scale. In a letter of 1750, published in 1751, he proposed the sentry box experiment in order to test the electrification of clouds, our words in square brackets:[29]

> 21. To determine the question, whether the clouds that contain lightning are electrified or not, I would propose an experiment to be try'd where it may be done conveniently. On the top of some high tower or steeple, place a kind of sentry-box (as in Fig. 9 [see Figure 11.15]) big enough to contain a man and an electrical stand [that is, an insulating stand]. From the middle of the stand let an iron rod rise and pass bending out of the door, and then upright 20 or 30 feet, pointed very sharp at the end. If the electrical stand be kept clean and dry, a man standing on it when such clouds are passing low, might be electrified and afford sparks, the rod drawing fire to him from a cloud. If any danger to the man should be apprehended (though I think there would be none) let him stand on the floor of his box, and now and then bring near to the rod the loop of a wire that has one end fastened to the leads, he holding it by a wax handle [that is, by an insulating handle]; so the sparks, if the rod is electrified, will strike from the rod to the wire, and not affect him.

Franklin did not perform this experiment. It was first realized in May 1752 at the city of Marly, in France, inspired by Franklin's letter. It was performed by the French translator of his book, T. F. D'Alibard (1709-1778). The description of the experiment was published soon afterwards, our words in square brackets:[30]

> M. D'Alibard chose, for this purpose, a garden situated at Marly, where he placed upon an electrical body [that is, upon an insulator] a pointed bar of iron, of 40 feet high. On the 10 of May, 20 minutes past 2 in the afternoon, a stormy cloud having passed over the place where the bar stood, those, that were appointed to observe it, drew near, and attracted from it sparks of fire, perceiving the same kind of commotions as in the common electrical experiments.

---

[28] [Fra69, p. 5] and [Coh96, p. 24].

[29] [Fra69, p. 66], [Coh96, p. 70], [Hei99, pp. 340-341] and [SP06].

[30] [Fra69, p. 107], [Coh96, pp. 127-130] and [Hei99, pp. 349-351].

Fig IX.

Figure 11.15: Franklin's suggested sentry-box experiment.

> M. De Lor, sensible of the good success of this experiment, resolved to repeat it at his house in the Estrapade at Paris. He raised a bar of iron 99 feet high, placed upon a cake of resin [insulator], two feet square, and 3 inches thick. On the 18 of May, between 4 and 5 in the afternoon, a stormy cloud having passed over the bar, where it remain'd half an hour, he drew sparks from the bar. These sparks were like those of a gun, when, in the electrical experiments the globe is only rubb'd by the cushion [of a frictional electric generator], and they produced the same noise, the same fire, and the same crackling. They drew the strongest sparks at the distance of 9 lines, while the rain, mingled with a little hail, fell from the cloud, without either thunder or lightning; this cloud being, according to all appearance, only the consequence of a storm, which happen'd elsewhere.

D'Alibard included a representation of the Marly experiment in the second edition of the French translation of Franklin's book, Figure 11.16. The main aspect to take notice in this experiment is that the conducting iron bar was insulated electrically from the ground. This insulation was provided by the silk cords tying up the bar and also by the empty glass bottles of wine located between the small bench and the wooden board on which the lower end of the bar rested.

Due to the power of points, when there was a high voltage between the electrified cloud and the iron bar, the air close to the upper end of the bar behaved as a conductor. The insulated conducting bar collected then a small portion of the electricity of the cloud. When a grounded conductor was brought close to the bar, sparks were produced. These sparks had the same properties as the usual discharges obtained in electrostatic experiments. These experiments were the first ones which proved the identity of lightning with electricity. Some earlier scientists like Stephen Gray had already presented this conjecture, but Franklin was the first person to propose a specific experiment to test this suggestion. D'Alibard made his experiment directly influenced by Franklin's pre-

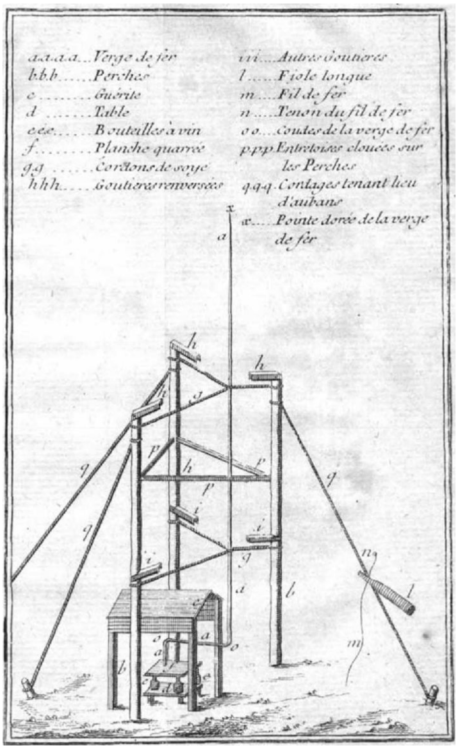


Figure 11.16: Iron bar insulated from the ground.

diction. Similar experiments were soon performed in several countries utilizing conducting bars insulated from the ground.

Experiments 11.1, 11.2 and 11.8 are similar to the Marly experiment, although on much smaller scales. We did not produce sparks in these experiments. However, the electrification of an electroscope and the orientation of a versorium by the test wire indicate some effects which take place in an insulated conductor which has one of its ends close to another electrified body.

Obviously there is a great danger in performing experiments like those of Marly in the open air utilizing conducting bars insulated from the ground. In 1753 the Russian scientist of German descent G. W. Richmann (1711-1753) died in Saint Petersburg through a sudden discharge of his insulated bar while performing experiments of this kind in a thunderstorm.[31]

In 1752 Franklin also suggested an experiment with a kite to test the electricity of clouds. Experiments of this kind were soon performed by several scientists.[32]

---

[31] [Coh96, pp. 5-6, 84-85, 113, 135 and 157], [Hei99, pp. 352, 390, 391 and 460] and [Lom17].
[32] [Coh96, pp. 5, 28, 67-70, 97, 125 and 130], [Hei99, p. 351] and [SP06].

Franklin was completely sure about the identity between lightning and the usual sparks, even before this conjecture was confirmed in 1752 by the Marly experiment. In a letter of 1750 addressed to his friend Peter Collinson (1694-1768) and published soon afterwards, he proposed the construction of lightning rods as a means of protecting buildings from electric discharges. There is a great difference between protective lightning rods and test rods, as discussed in Sections 11.3 and 11.4. Lightning rods are grounded, while test rods are insulated from the Earth. Test rods can be used to collect a small amount of electricity from clouds or from the atmosphere. Lightning rods are not intended to collect electricity, but to protect buildings. Franklin's first suggestion of a protective lightning rod:[33]

> ... may not the knowledge of this power of points be of use to mankind, in preserving houses, churches, ships, &c. from the stroke of lightning, by directing us to fix on the highest parts of those edifices, upright rods of iron made sharp as a needle, and gilt to prevent rusting, and from the foot of those rods a wire down the outside of the building into the ground, or down round one of the shrouds of a ship, and down her side till it reaches the water? Would not these pointed rods probably draw the electrical fire silently out of a cloud before it came nigh enough to strike, and thereby secure us from that most sudden and terrible mischief?

Experiment 11.7 illustrates in small scale the working mechanism of a lightning rod. The electrified electroscope is discharged through a grounded wire close to it. The discharge does not affect a nearby house which is insulated from the wire.

The first lightning rods were built in Europe and North America in 1752, soon after the Marly experiment.[34] The invention of the lightning rod brought great fame to Franklin, motivated the study of atmospheric electricity not only in stormy weather but also on dry weather, being one of the first practical applications in large scale of the research in electricity.

11.8 Applications of the Power of Points

The power of points has been applied in many situations. Some examples:

- In this book the power of points was utilized every time an electroscope was charged with a rubbed straw scraping the border of the cardboard. We obtain a more efficient electrification scraping the straw on the border of the cardboard than on its blunt parts. After all, the border is sharper than the body of the cardboard rectangle. During the scraping process, the transfer of electrified particles can take place not only during the contact between the rubbed straw and the cardboard, but also when the straw and the cardboard are very close to one another, without contact.

---

[33] [Fra69, pp. 65-66] and [Coh96, p. 83].

[34] [Coh96, pp. 29, 67, 74, 82-83, 91 and 109].

In this last situation the electrification takes place when the air between the sharp border and the electrified straw becomes ionized. Ionized air behaves as a conductor, facilitating the exchange of electrified particles.[35]

- Lightning rods.
- An important application happens in field emission microscopes, a device invented in 1936 by the physicist Erwin Wilhelm Müller (1911-1977).
- It is utilized in electrostatic motors and in phenomena associated with the so-called *electric wind*.[36]
- In photocopy machines.
- In van der Graaff generators.
- In atomic force microscopes.
- Etc.

---

[35] [FM91, p. 61].

[36] [Jef71b], [Jef71a], [JW71] and [Jef73].

Chapter 12

The Leyden Jar and Capacitors

12.1 Building a Capacitor

This Section shows how to build a very important electric device called a *condenser* or *capacitor*. It stores charges and electrical energy. The first device of this kind, the so-called Leyden jar was built in 1745, being discussed in Section 12.5.

A capacitor is a device composed essentially of two conductors separated by an insulator. Usually the insulator is thin and the conductors have parallel faces, almost superimposed on one another. It can have several shapes: parallel plates, cylindrical, a bottle or jar, etc. Before beginning the construction, test if the material which will be utilized as an insulator really behaves in this way. This test is very important. To this end, utilize the procedure indicated in Figure 3.4. If this material does not discharge an electrified electroscope when touching it during some 30 seconds, then it can be considered a good insulator. From now on we will utilize as insulators dishes, bottles and jars made of plastic or Styrofoam.

The simplest condenser is the parallel plate capacitor. It was invented by people connected to Benjamin Wilson (1721-1788), being popularized by Benjamin Franklin.[1] Franklin utilized a glass plate as his insulator. In this book the insulator will be a rigid plastic lamina, like a birthday party dish, or a thin Styrofoam plate. A rectangle (or disk) of aluminum foil should be glued on each side of the plastic rectangle (or plastic disk). The conducting foils should be slightly smaller than the plastic and cannot touch one another, Figure 12.1.

A very common device, usually called a Leyden jar, can be built with a 200 or 300 ml plastic bottle of water.[2] A strip of aluminum foil should be glued on the outer side of the bottle, covering some three quarters of the lateral side,

---

[1] [Hei99, p. 317, note 31 and pp. 333-334, note 29].

[2] [MF].

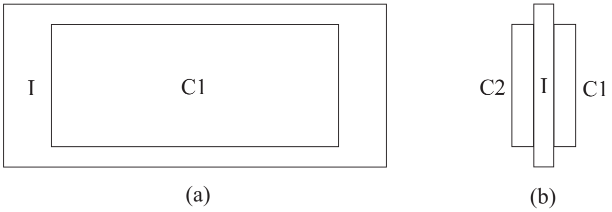


Figure 12.1: (a) A rectangular parallel plate capacitor seen from above: conductor $C1$ above insulator I. There is another conductor $C2$ below the insulator (not shown in the left figure). (b) System seen in profile.

making a full revolution around the bottle. Make a hole on the center of the plastic cap. Pass a metal wire, nail or long screw through this hole. Ideally the screw should have a rounded head above the lid in order to prevent losses through the power of points when the system is electrified. The head can be spherical, like a metallic ball, or like a hook. The internal conductor can be simply tap water. Alternatively, the jar can be filled with aluminum foil or steel wool. The metal wire, nail or screw should penetrate the water, aluminum foil or steel wool, Figure 12.2.

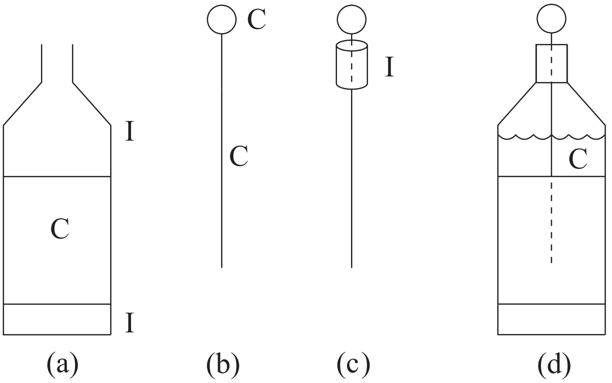


Figure 12.2: (a) Insulating plastic bottle I surrounded by a conducting strip C on the outer side. (b) Conducting screw C with a rounded head. (c) Screw passing through a hole in the center of the insulating cap I. (d) Mounted capacitor filled with a conducting material C (water, aluminum foil or steel wool).

Many other kinds of capacitors can be similarly made. A few examples:[3] (a) Utilizing plastic yogurt pots with aluminum foil on the outside. The pot is filled with aluminum foil. (b) Utilizing small cylindrical plastic pots (like those of vitamin C or dental floss). An aluminum foil is glued on the outside, with steel wool inside. (c) A plastic straw with aluminum foil inside and outside, etc.

---

[3] [FM91, pp. 76-83], [Ferb, Garrafa de Leyden, p. 31] and [Ferc, pp. 73-79].

The internal conductor is connected to the outside world by a nail, metal wire, bracket or paper clip passing through the center of the plastic cover or lid.

The capacitor is a device which stores electric charge and energy. We can make the following definitions:

Definition 12.1

The capacitor is said to be *charged*, *energized* or *electrified* when there is an electric charge $Q \neq 0$ on the internal conductor and an electric charge $-Q$ on the external conductor. A capacitor is *discharged* when there are no charges on the internal conductor nor on the external one, that is, when $Q = -Q = 0$.

In the first situation $Q \neq 0$, while $Q = 0$ in the second situation. In both situations there is no net charge on the whole system, $Q + (-Q) = 0$, no matter if the capacitor is charged ($Q \neq 0$) or discharged ($Q = 0$). The difference between these two situations is that when the capacitor is charged, there is an electric energy stored in the system which can produce many effects (sparks, electric shocks, etc.) As there is no total charge in both situations, it would be more appropriate to say that the capacitor is *electrically polarized* in the first situation. However, as it is usually said that the capacitor is *electrically charged* in the first situation, we will keep this nomenclature. In any event, it should be kept in mind that in both situations there is no net charge in the system as a whole, even when the capacitor is said to be charged.

12.1.1 Do Not Utilize a Glass Bottle in Order to Insulate the Internal Conductor from the External Conductor

It should be emphasized here once more that most kinds of modern glasses behave as conductors in the usual experiments of electrostatics, Section 4.3. We know some people who tried to build Leyden jars utilizing glass bottles and were unable to reproduce some simple experiments. The expression "jar" suggests a glass bottle. Many people believe that glass, wood and water are insulators, as the textbooks present their dielectric constants. However, most modern materials made of glass or wood behave as conductors. If we utilize a conducting glass bottle to build a Leyden jar, it will not accumulate opposite charges on its internal and external portions. Therefore, the experiments performed with these conducting bottles will not work, see also Section 6.3.

In order to utilize a glass bottle to build a capacitor or Leyden jar, we must first test its conducting behavior. Only the specific kinds of glass which behave as good insulators can be utilized in these devices. The conducting behavior of any material can be tested with the simple electroscope, Section 3.1, Experiment 3.3, Figure 3.4.

12.2 Experiments with the Capacitor

Experiment 12.1 - *Charging and discharging a capacitor*

Utilize a small cylindrical capacitor made with a plastic pot, like those of dental floss, with some 5 cm height and 3 cm diameter. A strip of aluminum foil is glued on the outside, with the cylinder filled with steel wool, Figure 12.3 (a). This steel wool must be in contact with the nail passing through the center of the plastic lid, with the nail's head on the outside, Figure 12.3 (b).

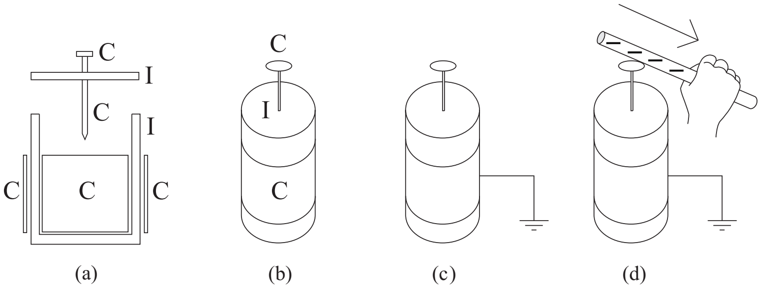


Figure 12.3: (a) Cylindrical capacitor made with conductors C and insulators I. (b) Mounted system. (c) Grounded capacitor. (d) Scraping an electrified straw on the nail's head.

Electrify a straw or acrylic ruler by rubbing it in hair, in a napkin or in a cotton tissue. Ground the capacitor. To this end, hold the cylinder while touching the external strip of aluminum foil, Figure 12.3 (c). Scrape the rubbed straw with the other hand on the head of the nail, Figure 12.3 (d). This procedure should be repeated several times, charging the capacitor.

From now on, assume that the capacitor has been charged or electrified. Hold the aluminum foil strip of the cylinder by hand. The conducting hand is represented by the letter C in Figure 12.4 (a). Bring a finger close to the nail's head. When they are very close to one another, we feel a small shock. Sometimes we can see a spark in a darkened room, hearing a snapping noise during the discharge, Figure 12.4 (b).

Experiment 12.2 - *Discharging a capacitor without taking shock*

It is possible to perform Experiment 12.1 without feeling shocks.[4] One end of a conductor should be fixed on the strip of aluminum foil. The other portions of the conductor should be far away from the nail's head. This conductor can be a copper wire, a paper fastener or a metallic bracket, as in Figure 12.5 (b).

From now on, assume that the capacitor has been charged. Hold an acrylic ruler by hand with its free end touching the conductor connected to the strip of aluminum foil. Move the head of the paper fastener towards the nail's head.

---

[4] [Ferc, p. 73].

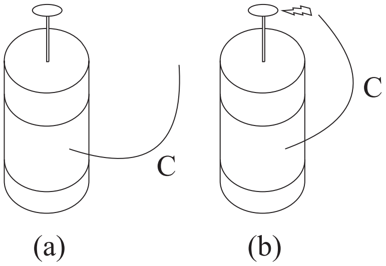


Figure 12.4: (a) Charged capacitor with a conducting hand C connected to the aluminum foil strip. (b) A spark takes place when a finger is brought close to the nail's head.

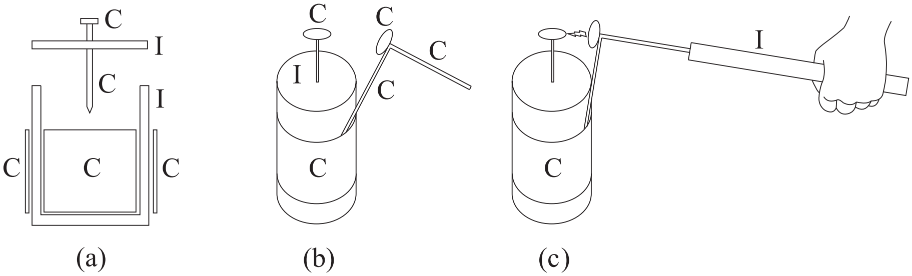


Figure 12.5: (a) Cylindrical capacitor made of conductors C and insulators I. (b) Mounted system with a paper fastener connected to the strip of aluminum foil. The head of the paper fastener is far away from the head of the nail. (c) A spark takes place when the head of the paper fastener becomes very close to the head of the nail.

When they are very close to one another, a spark takes place and we don't feel any shock, Figure 12.5 (c).

Experiment 12.3 - *Charging a capacitor with an electrophorus*

Experiment 12.1 can be more easily performed utilizing an electrophorus to charge the capacitor. While holding the cylinder by its external aluminum foil strip, touch the head of the nail several times with the electrified charge collector of an electrophorus. When the system is well charged, we can feel a shock by simultaneously touching the same hand in the strip of aluminum foil and in the head of the nail.

Experiment 12.4 - *Charging and discharging a Leyden jar*

This Experiment shows how to obtain larger effects with greater intensity utilizing a Leyden jar composed of a 200 or 300 ml plastic bottle. Utilize an electrophorus to charge this capacitor. The charge collector of this electrophorus will be a 30 cm diameter pizza pan with an insulating handle at its center.

Electrify the charge collector of the electrophorus. It is represented by the electrified metal disk next to the Leyden jar in Figure 12.6 (a). This charge collector should be manipulated only through its insulating handle. Hold the external strip of aluminum foil by the hand, grounding it, as indicated in the figure.

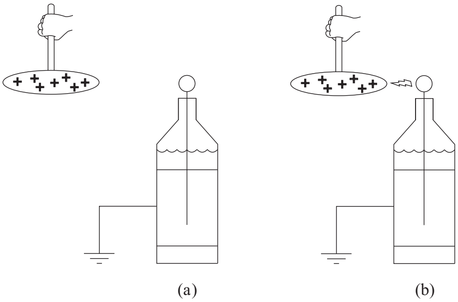


Figure 12.6: (a) A discharged and grounded Leyden jar. There is an electrified electrophorus far away from it. (b) You can charge the capacitor when the electrophorus is brought very close to the head of the screw.

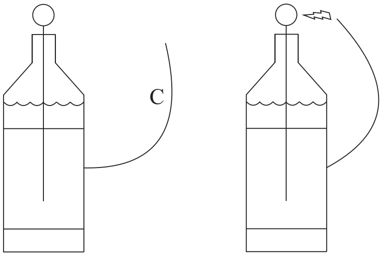
Electrify several times the Leyden jar utilizing this charge collector. To this end, it is not necessary a contact between the charge collector and the rounded head of the screw in the bottle. Normally when they come very close to one another, we can hear a cracking noise followed by a spark, especially when an edge of the pizza pan is brought close to the head of the screw, Figure 12.6 (b). This charging procedure should be repeated 5 or 10 times.

From now on, assume that the capacitor is well charged, with a large enough amount of positive electricity in one of its conductors. It can be grounded or insulated from the Earth. Touch a finger on the external strip of aluminum foil, grounding it, Figure 12.7 (a). We can then feel a good shock by simultaneously touching one finger to the aluminum foil strip of the bottle and another finger to the head of its screw. Sometimes this last contact is not necessary. It is enough to bring a finger very close to the head of the screw in order to feel the shock and see the spark, Figure 12.7 (b).

Figure 12.8 (a) shows how to obtain a spark without feeling electric shock. The Leyden jar is initially charged. Consider a 20 or 30 cm long flexible copper wire. Coil one portion of it around an insulating acrylic ruler. Coil another portion around another acrylic ruler. The free ends of the wire should extend beyond the rulers.

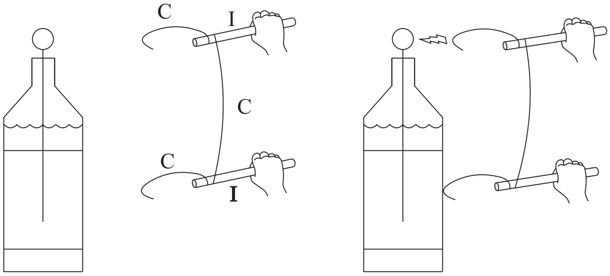
Hold each ruler with a hand. Touch one free end of the copper wire in the aluminum foil strip. When the other free end of the wire is brought close to the screw's head, there is a spark and snapping noise, Figure 12.8 (b). We do not experience any shock during this discharge process.

Experiment 12.5 - *Charging a cylindrical capacitor by its lateral conducting strip*



(a) (b)

Figure 12.7: (a) Charged Leyden jar held in the hand by the conducting aluminum foil. (b) When a finger is brought close to the head of the screw, there is a spark, discharging the capacitor.



(a) (b)

Figure 12.8: (a) Charged Leyden jar. A single copper wire C coiled around two acrylic rulers I. (b) Discharging the jar by connecting its external conductor with the free end of a copper wire and bringing the other end of the wire very close to the screw's head.

The capacitors of Experiments 12.1 and 12.3 can also be charged scraping the rubbed straw on the aluminum foil strip glued on the outside of the cylinder. In order to obtain a large enough amount of electrification, the capacitor should be grounded by its inner conductor. To this end, touch the nail with a finger, Figure 12.9 (a). While the capacitor is grounded, scrape a rubbed acrylic ruler on the external aluminum foil strip of the capacitor, Figure 12.9 (b). This process should be repeated some 5 or 10 times.

From now on, suppose that this capacitor has a large enough amount of electrification. Touch a finger on its inner conductor, Figure 12.10 (a). When another finger comes close to the aluminum foil strip, we feel a shock and sometimes perceive a spark, Figure 12.10 (b).

The capacitor can also be charged through its external strip utilizing an electrophorus. Initially the capacitor should be grounded through its internal conductor. This grounding can be achieved when a finger touches the head of the nail. While it is grounded, bring the charge collector of an electrophorus

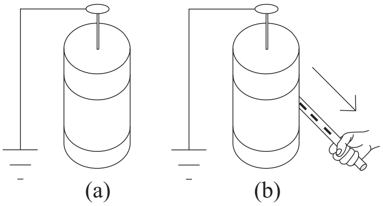


Figure 12.9: (a) Discharged capacitor grounded by its internal conductor. (b) Charge the capacitor while it is grounded, scraping a rubbed acrylic ruler on its external strip of aluminum foil.

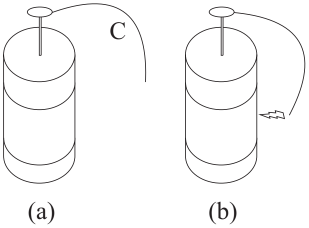


Figure 12.10: (a) Charged capacitor with a conductor C touching the nail. (b) When the free end of this conductor is brought close to the aluminum foil strip, a spark is produced, we feel a shock and the capacitor is discharged.

close to the external strip of aluminum foil. When an edge of the electrified charge collector is very close to the external strip, a spark is produced. This charging procedure should be repeated 5 or 10 times.

Suppose that the capacitor has been electrified. It can then be easily discharged when the same hand touches the head of the nail and the aluminum foil strip.

Experiment 12.6 - *Grounding any one of the two conductors of an electrified capacitor without discharging it*

Charge the capacitors as in Experiments 12.1 and 12.3. To this end, the capacitors should be grounded during the charging process. Remove the hand from the external strip of aluminum foil. The electrified capacitor should rest on a table. The lower part of the capacitors utilized in this book are made of plastic, as in Figures 12.2 and 12.3 (b). Therefore, when these charged capacitors rest on a table, they are insulated from the ground. When there is any portion of the external strip of aluminum foil on the lower face of the cylinder, then the capacitor should rest on an insulator (like on a Styrofoam plate) before proceeding with this experiment.

When a finger touches the head of the nail or screw of this charged and insulated capacitor, we do not feel any shock. This is a relevant observation. A charged capacitor insulated from the ground is not discharged when a finger touches its internal conductor. That is, it is not discharged by grounding its internal conductor.

Remove the finger from the nail or screw. We can now touch only on its external strip of aluminum foil. Once more we will not feel any shock from this charged capacitor. This is another relevant observation. A charged capacitor insulated from the ground is not discharged when a finger touches its external conductor. That is, it is not discharged by grounding its external conductor.

However, when we touch simultaneously the head of the nail and the strip of aluminum foil, we will feel a shock.

Experiment 12.7 - *Comparing the charges acquired by a grounded capacitor and by another capacitor which is not grounded*

In this experiment, electrify the capacitor without grounding it during the charging process. Begin with a discharged Leyden jar resting on a table. Electrify it utilizing the charge collector of an electrophorus. Assume that this charge collector is a conducting disk with an insulating handle on its center. Electrify this charge collector and manipulate it only through its handle. An edge of its electrified disk is then brought close to the head of the nail or screw of the capacitor. A spark can be observed when they are very close to one another.

Compare the spark produced in this Experiment with that produced in Experiments 12.3 and 12.4 in which the jar was grounded. The first observation which can be made is that now the spark and snapping noise are smaller than the spark and snapping noise produced with the grounded jar.

Five times bring the electrified disk of the charge collector of an electrophorus close to the head of the nail of the insulated capacitor. After this charging process, discharge it by simultaneously touching the aluminum foil strip and the head of the nail, feeling a shock during this discharge. However, this shock is smaller than the shock produced by following the same procedure with a grounded capacitor. That is, suppose a capacitor which is initially discharged and grounded through its strip of aluminum foil. Five times bring the electrified disk of the charge collector of an electrophorus close to the head of the nail of this grounded capacitor. After this charging process, discharge it by simultaneously touching the aluminum foil strip and the head of the nail, feeling a large shock during this discharge.

Repeat this charging procedure with an insulated capacitor. That is, five times bring the electrified disk of the charge collector of an electrophorus close to the head of the nail of the insulated capacitor. Ground now this capacitor through its nail by touching its head with a finger. We feel only a small shock and the capacitor becomes completely discharged.

Repeat once more this charging procedure with an insulated capacitor. Place the back of a hand close to the strip of aluminum foil of this charged and insulated capacitor. Sometimes we feel the hairs of our hand being attracted by this strip. When we touch the strip, we feel a small shock. However, the jar is not completely discharged by this grounding procedure (the grounding here takes place through the external strip of aluminum foil). In order to discharge completely this electrified capacitor, we must touch simultaneously its strip and the head of the nail, feeling a small shock during this discharge.

12.3 Working Mechanism of the Capacitor

This Section describes these experiments utilizing the fact that there is an insulator between the conductors of the capacitor. Ideally this insulator prevents the exchange of electrified particles between the internal and external conductors of a Leyden jar.

Consider the situation in which the jar is being charged while its external conductor is grounded, that is, while we hold its aluminum foil strip with the hand. Suppose that we are scraping a positively electrified straw on the head of the screw. Alternatively, bring a charge collector positively electrified close to the head of the screw, producing a spark when they are very close. In these situations the internal conductor of the capacitor becomes positively electrified. As the external strip is grounded, there is an exchange of electrified particles with the ground. This strip becomes negatively electrified. The positive charges of the internal conductor are distributed essentially along the portion of its surface which is close to the external conductor. Likewise, the negative charges of the external conductor are distributed essentially along the portion of its surface which is close to the internal conductor.

Figure 12.11 illustrates electrified capacitors of several shapes. Their two conductors are represented by $C1$ and $C2$, while the intervening insulator is represented by I.

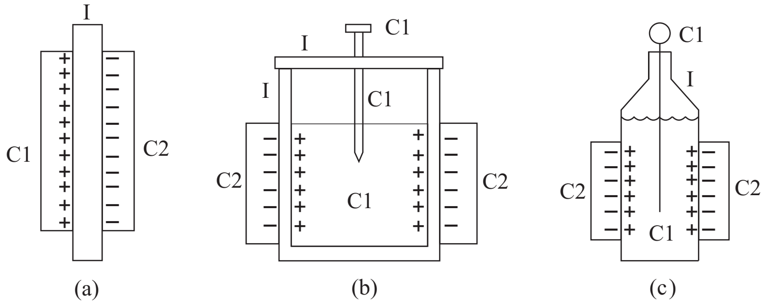


Figure 12.11: Charged capacitors. (a) Parallel plate. (b) Cylindrical capacitor. (c) Leyden jar.

Figure 12.11 (a) illustrates a parallel plate capacitor seen in profile, Figure 12.11 (b) shows a cylindrical capacitor, while Figure 12.11 (c) represents a Leyden jar. We exaggerate the thicknesses of the external strips of aluminum foil to emphasize the fact that their charges are essentially located along their internal faces. These three distributions of charge are only qualitative.

When we ground only one of the conductors of a charged Leyden jar, keeping the jar insulated from the ground, it is not discharged. The opposite charges remain in their locations due to the attraction between particles of different sign.

On the other hand, the capacitor is discharged when both conductors $C1$ and $C2$ are connected to a third conducting wire.

12.4 Gray, Du Fay and the Electrification of Water

Stephen Gray (1666-1736) discovered conductors and insulators in 1729, publishing his findings in 1731 in one of the most important papers in the history of electricity.[5] Volume 1 of this book presented a detailed description of Gray's work.[6] He described the following insulating substances in his experiments: a silk thread, horse-hair fishing-lines, a cake of resin, warmed glass, cakes of beeswax, sulfur and shell-lack. His electrical generator was simply a flint-glass tube, that is, a heavy brilliant glass that contains lead oxide. He rubbed his tube with his bare hand. He held the rubbed glass tube in his hand during the experiments. As the tube was not discharged by contact with his hands, this fact means that the tube acted like a very good insulator, contrary to what happens with most modern glasses found at home. Moreover, his glass tube acquired a great surface charge density. He transmitted the attractive virtue of this electrified tube to several conductors. In order to obtain this effect, the conductor was electrically insulated from the ground, being supported on insulating materials or hanging by silk cords. When his electrified tube was brought close to one end of this insulated conductor, he observed that the other end of the conductor acquired the property of attracting light bodies placed near it. In this way he succeeded in transmitting this attractive virtue to metals, to wood, to the human body and to many other conducting substances. He also transmitted this attractive virtue to water, our words in square brackets:[7]

> March the 23d [1730], I dissolved soap in the Thames water, then I suspended a tobacco-pipe by a hair line [an insulated thread probably made of silk or horse-hair], so as that it hung nearly horizontal, with the mouth of the bowl downwards; then having dipped it in the soap-liquor, and blown a bubble, the leaf-brass laid on a stand under it, the [glass] tube being rubbed, the brass was attracted by the bubble, when the tube was held near the hair-line. Then I repeated the experiment with another bubble, holding the tube near the little end of the pipe, and the attraction was now much greater, the leaf-brass being attracted to the hight [sic] of near two inches.

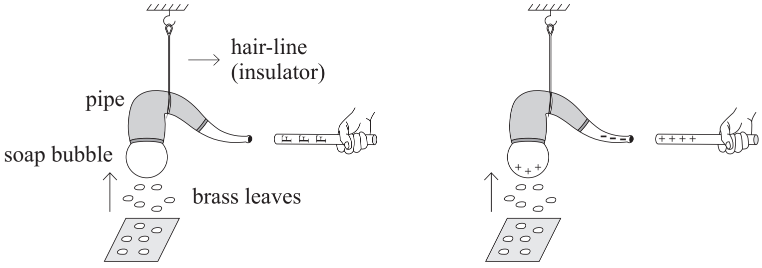
Figure 12.12 (a) illustrates this experiment. It shows that soapy water behaves as a conductor. Figure 12.12 (b) presents the qualitative distribution of charges in Gray's experiment.

---

[5] [Graf], [Bos11, Capítulo 6] and [BAC12, Chapter 7, pp. 127-169].

[6] Appendix B of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[7] [Graf, pp. 38-39], [Bos11, pp. 165-166] and [BAC12, pp. 162-163].



(a) (b)

Figure 12.12: (a) An insulated bubble attracting small pieces of leaf-brass when a rubbed glass tube is brought near the little end of the pipe. (b) Qualitative distribution of charges on the tube, pipe and bubble.

Gray had succeeded in transmitting the attractive virtue to several kinds of conductors, making them attract light bodies placed in their neighborhood. Insulators, on the other hand, could not attract light bodies with the same force when the rubbed glass tube was brought close to them. Suppose two bodies of the same shape and size, a conductor and an insulator, both of them insulated from the ground and far away from one another. Bring a rubbed glass tube close to the conductor, polarizing it. Bring the rubbed glass tube at the same distance to the insulator, polarizing it. The observed polarization acquired by the conductor is much larger than the effective polarization acquired by the insulator.[8]

Here we present the modern interpretation of Gray's experiment. The pipe and the bubble behaved as conductors, while the hair-line behaved as an insulator. Suppose the glass tube positively electrified. When it is brought near the little end of the pipe, there is a polarization of charges on the system pipe-bubble. The far away bubble becomes positively electrified, while the little end of the pipe becomes negatively electrified. The electrified bubble then attracts the light pieces of conducting brass placed below it.

In 1731 Gray electrified the water through another process. He fixed a wooden plate on an insulating support made of glass. The plate was filled with fresh water. A rubbed glass tube was then moved very close to the surface of the water, without touching it. He then removed the tube. By performing some tests, he verified that the water had been electrified by this process. We now quote from his work, our words in the footnotes:[9]

> I. In the former account of my experiments, I described the manner of communicating an attraction to a bubble of soaped water; but I have now found, that even *a body of water receives an attractive virtue, and also a repelling one, by applying the excited tube near it, after the same manner*

---

[8] See Sections 7.3, 7.6, 7.7, 7.9 and 8.3 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[9] [Grab, pp. 227-228], [Bos11, pp. 211-214] and [BAC12, Chapter 8, pp. 172-174], [DF33a, pp. 34-35] and [Hei99, p. 253].

as solid bodies do.[10] To perform this experiment, I caused a wooden dish to be turned, with a screw-hole at the bottom, but no so far as to come through the wood: This was screwed on the upper end of one of the stands I have mentioned in the other experiments, the other top being taken off. The dish was about four inches diameter, and one inch deep. Then the stand was set on a cake of rosin, or a plate of glass, or the brims of a drinking-glass, or of a cylindrick one, such as are used for water glasses. The glass must be first warmed,[11] then the dish being filled with water, the tube rubbed, and moved both under the dish and over the water three or four times, without touching them.[12] After it has been excited, not only the dish, but the water also, becomes electrical;[13] and if a small piece of thread,[14] or a narrow slip of thin paper, or a piece of sheer-brass, commonly called tinsel, be held over the water in an horizontal position, within about an inch or some times more, any of the said bodies[15] will be attracted to the surface of the water, and be repelled, but not so often as by solids.[16] If a pendulous thread be held at some distance from the outside of the dish, it will be attracted and repelled by it many times together with a very quick motion,[17] but not at so great a distance as

---

[10] Italics in the original. Gray had found that a solid conductor can acquire attractive and repulsive virtues when a rubbed glass tube was brought close to them. He now found that the same virtues could be transmitted to a body of water.

[11] By this procedure the wooden dish was fixed on an insulating support, namely, a cake of resin or a warmed glass.

[12] Figure 12.13 illustrates this procedure.

[13] Figure 12.14 illustrates how Gray may have concluded that the water dish had become electrified by this procedure.

[14] Probably a cotton or linen thread. These materials behave as conductors in electrostatic experiments.

[15] The bodies mentioned by Gray were a [cotton] thread, a narrow paper slip and a piece of sheer-brass. All these materials behave as conductors.

[16] As Gray is talking about attraction and repulsion, he may have observed something analogous to the ACR mechanism. If this was the case, then probably one end of the thread, paper or tinsel was fixed to an insulating handle, while their free ends were above the water in an horizontal position.

[17] Gray did not specify the material of his "pendulous thread". We believe it was similar to the electric pendulum which he described in 1720 [Graa, p. 107]. That is, a wooden stick had a silk thread fixed on its end. A down feather was tied to the free end of this thread. The stick was held by his bare hands. Although the wooden stick behaves as a conductor in this experiment, this aspect is not crucial. The main properties of this pendulum: the silk thread behaves as an insulator, while the down feather behaves as a conductor.

Obtain a sequence of attractions and repulsions with this electric pendulum. To this end, the down feather must be located between a rubbed straw and a grounded conductor, as described in Experiment 4.15 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17]. In Gray's specific experiment, the down feather of his electric pendulum was held, by the silk thread to which it was tied, at the same height as the electrified water dish. The down feather should be located between this electrified dish and a grounded body. Assume that this grounded body was one of Gray's hands. When the pendulum was placed close to the electrified dish, the down feather was attracted by the dish, touched it and acquired a net charge of the same sign as that of the dish. After their contact, the feather was repelled by the dish. It then touched Gray's finger on the opposite side. The feather was discharged by this grounding process. It could then be attracted again by the electrified dish, touched it, being afterwards discharged by the finger. This process might be repeated many times, producing a vibratory motion of attraction and repulsion. In principle it might take place many times, until the water dish was completely discharged. Figure 12.14 illustrates this ACR mechanism.

when the dish is empty.

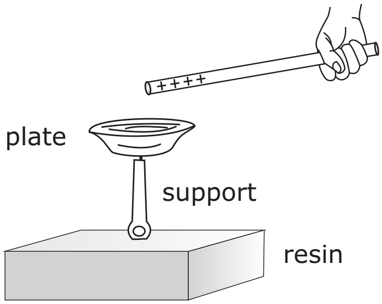


Figure 12.13: Water dish fixed on a support which is on an insulating cake of resin. The electrified tube is moved under and over the dish, without touching the water and the dish.

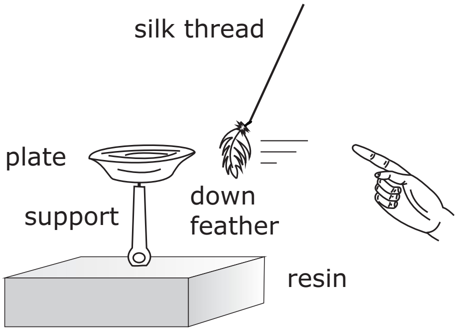
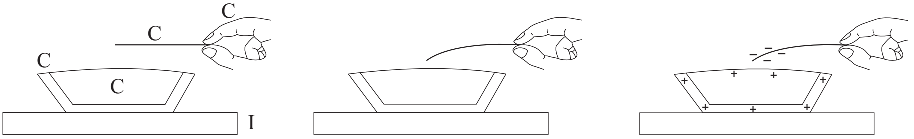


Figure 12.14: After the dish has been electrified, a conducting feather tied to an insulating thread is placed between the plate and a finger. The feather is attracted by the plate, touches it and is then repelled. It is electrified during the contact with the dish and discharged when touching the finger. This ACR mechanism can be repeated many times.

Probably the support in this experiment was made of wood. Only the cake of resin and the surrounding air were insulators. All other bodies were conductors, namely, the water, the plate and the support. Therefore, it is possible that the glass tube electrified not only water, but also all conductors in contact with the water. Probably the electrification was obtained through sparks or small electric discharges between the electrified glass tube and the water. Supposing that this electrification process took place, then the plate and water were electrified with a charge of the same sign as that of the glass tube. In the earlier experiment there was a polarization of the system pipe-bubble. In the present experiment, on the other hand, the system of conductors received a net charge different from zero. Figure 12.15 illustrates how Gray may have concluded that the water was electrified.



(a) (b) (c)

Figure 12.15: (a) Conductors represented by the letter C, while the insulator is represented by I. Neutral water, no attraction. (b) Electrified water attracting a conducting strip brought close to it. (c) Distribution of charges in this experiment.

The water plate is supported on an insulating material I. Figure 12.15 (a) shows the situation when the system is not electrified. In this case a horizontal strip of paper can be brought close to the plate without being attracted. The electrified glass tube is then moved over and under the water plate, very close to the system but without touching it. Remove the glass tube. Figure 12.15 (b) shows what happen when a horizontal strip of paper is brought close to the system. It is attracted by the electrified water. Figure 12.15 (c) presents the qualitative distribution of charges in this experiment.

In 1733 Du Fay continued these researches of Gray. He concluded that most bodies initially neutral might be electrified by this process. It was only necessary to bring them in contact, or very close, to another electrified body.[18] In order to electrify the initially neutral body, it should be insulated from the ground. An example of this electrification process takes place in the ACR mechanism described in Section 4.4, Figure 4.11.[19] In this process the charge acquired by the body which was initially neutral has the same sign as the charge of the electrified insulator which comes in contact with it. The so-called "*rule of Du Fay*" established that the body to be electrified by this process had to be properly insulated, that is, had to rest upon an insulating support of sufficient thickness. He described this electrification process as follows, our words in square brackets and in the footnote:[20,21]

> We have seen in the first part of this Memory,[22] that the liquids might become electrified; the only way to succeed in electrifying [liquids] by the approach of the [electrified] tube is to put them in a little glass, porcelain or faience jar, and to place the jar on a wax or a glass support, one would try in vain using a platform made of wood or metal; [...]

---

[18] [DF33a], [DF33c] and [Hei99, pp. 252-253].

[19] Section 4.8 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[20] [DF33c, p. 84] and [Hei99, pp. 252-253].

[21] Nous avons vû dans la premiére partie de ce Mémoire, que les liqueurs pouvoient devenir électriques; la seule maniére d'y réüssir par l'approche du tuyau, est de les mettre dans un petit vase de verre, de porcelaine ou de fayence, & de poser ce vase sur un guéridon de verre ou de cire d'Espagne, car on le tenteroit en vain sur un de bois ou de métal; [...]

[22] See [DF33a, pp. 33-34].

The support of wax or glass behaved here as insulators.

When this precaution was taken, most bodies could be electrified either by contact or by close approach of an electrified insulator. By following this procedure, Du Fay succeeded in electrifying water, as Gray had done before him. In the first place a water dish rested upon an insulating material. It could then be electrified when a charged tube is moved over and under the dish.

Du Fay also succeeded in electrifying water by contact. To this end, a water dish rested upon an insulating material. A conducting thread was fixed on a glass tube. He electrified the tube by rubbing it against an appropriate material. With this electrification of the tube, the thread connected to it was polarized. The free end of the thread was then brought into contact with the insulated water. After the thread was removed, some tests showed him that the water had become electrified. His description of this experiment, with our words in square brackets and in the footnote:[23],[24]

> In another volume of the *Transactions Philosophiques* of the last year, number 422,[25] Mr. Gray showed that water can be electrified. This experiment can be made as follows. A small wood écouelle [that is, a two-handled soup or porridge bowl made of wood], or a porcelain saucer, is filled with water, it is then placed on one of these small pedestals, or on a very dry and a little heated wood dish; for having rubbed this tube, one brings it close to the bowl, passing it twice or three times under and on its sides, without touching it, this procedure will be enough in order to communicate a very sensitive electric virtue [that is, the property of attracting light bodies] to the bowl, or saucer, and to the water inside it, this [electrification] can be recognized when a [single] hair, or delicate thread, is brought horizontally close to the water surface, we then see this thread approaching the water until it is immersed into it. I succeeded in this experiment following this procedure, and with as much ease, by the following way. I connected a cork with a piece of string [or rope] at the end of my [glass] tube, the tube was electrified by friction, I then immersed the end of the string into the water filled bowl, which was supported on a heated piece of glass, this procedure communicated the [electric] virtue

---

[23] [DF33a, pp. 34-35] and [Hei99, p. 253].

[24] Dans un autre endroit des Transactions Philosophiques de l'année derniére, N.^{o} 422, M. Gray fait voir que l'eau peut devenir électrique. Voici de quelle maniére se fait cette expérience. On remplit d'eau une petite écuelle de bois ou une soucoupe de procelaine, on la pose sur un de ces petits guéridons, ou sur un verre à boire bien sec, & un peu chauffé; pour lors ayant frotté ce tube, on l'approche de la soucoupe, le passant par dessus & par les côtés deux ou trois fois, sans néantmoins y toucher, cela suffit pour communiquer une vertu électrique trés-sensible à l'écuelle, ou la soucoupe, & à l'eau qui y est contenuë, ce que l'on reconnoît en approchant un cheveu, ou un fil délié dans une situation horisontale de la surface de l'eau, on voit alors ce fil s'en approcher jusqu'à ce qu'il s'y soit plongé. Cette expérience m'a réussi de la maniére que je viens de la décrire, & avec autant de facilité, de la maniére suivante. J'avois ajusté au bout de mon tuyau un bouchon de liége auquel étoit attaché un bout de corde, le tuyau étant rendu électrique par le frottement, j'ai plongé l'extrémité de la corde dans la soucoupe remplie d'eau, & posée sur un verre chauffé, ce qui a communiqué la vertu à la surface de l'eau, de même que par l'opération précédente, & is est vraisemblable qu'il en seroit de même de toutes les liqueurs, mais is est à observer que cette vertu est moins considérable dans l'eau que dans les corps solides.

[25] See [Grab].

> to the water, as it had happened with the earlier procedure, and it is likely that the same [electrification] will take place for all liquids, but it should be observed that this [electric] virtue is smaller in water than in solid bodies.

Figure 12.16 illustrates Du Fay's procedure to electrify water. His electrified glass tube worked as an insulator I. The water bowl was supported on another insulator I. The water, the bowl and the string connected to the tube behaved as conductors C in this experiment.

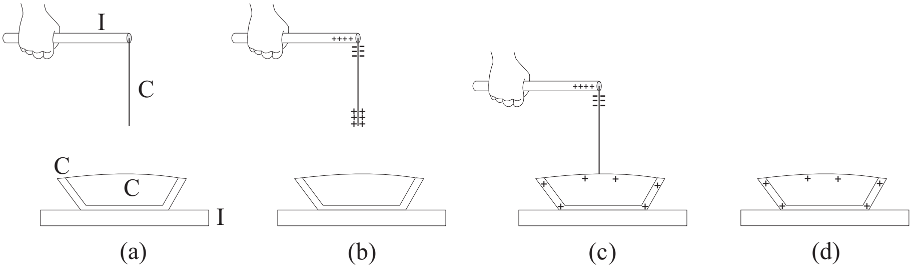


Figure 12.16: (a) Insulating glass tube I with a conducting string C attached to its end. Bowl filled with conducting water C and supported on an insulating material I. (b) The rubbed glass tube polarizes the string. (c) The free end of the string is immersed into water. The charges which were located on the end of the string spread on the system, electrifying the water. (d) Remove the tube with the string. The water remains electrified.

Suppose now that the water was on a conducting dish supported on another conductor (like a wood or metal plate connected to the ground). In this case it would not be possible to electrify water by Gray's procedure (that is, when an electrified glass tube is moved under and over the dish), nor by Du Fay's procedure (that is, touching the water with the free end of a conducting thread connected to the electrified glass tube), as illustrated in Figure 12.17.

The rubbed glass tube polarizes the conducting thread connected to it, Figure 12.17 (b). When the free end of this polarized thread touches the grounded water, the lower charges of the thread are neutralized by the free charges on the Earth, Figure 12.17 (c). After the tube has been removed with the thread, the water is not electrified, Figure 12.17 (d).

12.5 The First Capacitors or Condensers

This Section describes the invention of the condenser or capacitor. It was discovered by chance in 1745 in Germany and Holland, being usually called Leyden jar (or Leyden phial).[26] At that time no one knew how it worked, not even the

---

[26] [Whi73a, p. 45], [Hei99, Chapter XIII: The invention of the condenser] and [JG17].

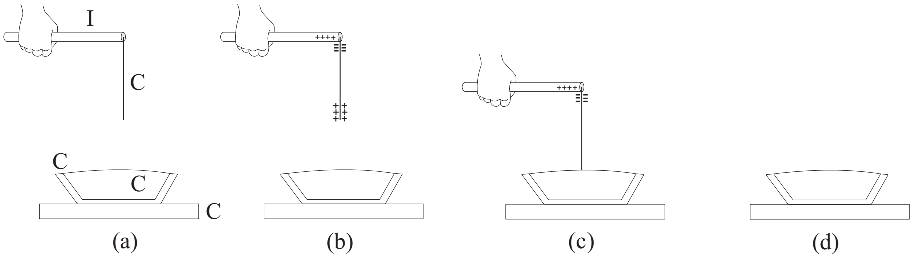


Figure 12.17: (a) Glass tube I with a string C on its end. Water filled dish on a conducting support. Conductors represented by C and insulators by I. (b) Rubbed glass tube with polarized string. (c) String touching the grounded water. The Earth neutralizes the charges on the free end of the string. (d) Remove the tube with its string. The water is not electrified by this procedure.

scientists dealing specifically with electricity. It violated the rule of Du Fay described in Section 12.4. The people who discovered this instrument worked with an electrostatic generator. It was normally a glass globe or cylinder spinning around a fixed axis through a crank. The spinning glass was rubbed against the hand of a person or against another substance (cushion, piece of cotton tissue or leather). Guericke had published in 1672 some experiments, including the down feather floating above a rubbed sulfur globe. Francis Hauksbee built on purpose around 1708 the first electric generators.[27] Georg Matthias Bose (1710-1761) introduced around 1740 an improvement on these generators, the so-called *prime conductor*. It was essentially a conductor insulated from the ground. It might be a sword, iron bar or cannon barrel. One end of the prime conductor was in contact or very close to the spinning glass. This end might also be in contact or very close to the cushion, cotton tissue or leather which was being rubbed against the spinning glass. The prime conductor accumulated the charges generated by the rubbed glass. In this way it was easier to perform several experiments of conduction or discharges through the free end of the prime conductor.[28] It might be insulated from the ground by resting on insulating supports or being suspended by insulating strings.

The first condenser was built in Germany by Ewald Jürgen von Kleist (1700-1748) in 1745. He had an electrostatic machine with a prime conductor connected to it. A nearby water filled receptacle was insulated from the ground. The water was then brought into contact with the prime conductor via a metal wire dipping into the liquid. By running the machine, he was able to produce sparks from his system. He then replaced the water filled receptacle with an insulated wooden spool. By setting a nail on the spool and running the machine, he was able to draw sparks from the nail and from the spool alternately. Although this system was connected to the prime conductor, it was insulated from the ground.

---

[27] Section 4.11 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[28] [Hei66] and [Hei99, pp. 264-265].

Then comes his description of the condenser. A nail was introduced into a small glass bottle insulated from the ground. It was connected to the machine with a conductor. The machine was run and the system electrified. He then held the glass bottle with his hand. That is, he grounded the system. By removing it from the machine, electrical effects were produced with larger power and longer duration than the effects produced with the insulated glass bottle. This casual procedure gave rise to the first capacitor:[29]

> If a nail, a strong wire, etc., is introduced into a narrow-necked little medicine bottle and electrified, especially powerful effects follow. The glass must be very dry and warm. Everything works better if a little mercury or alcohol is placed inside. The flare appears on the little bottle as soon as it is removed from the machine, and I have been able to take over sixty paces around the room by the light of this little burning instrument.

Figure 12.18 (a) illustrates this experiment.

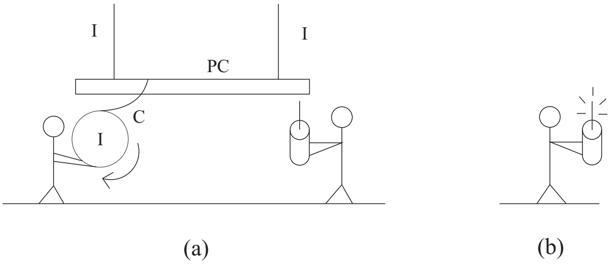


Figure 12.18: (a) Electrification of the glass bottle with a nail. (b) The system shines while the person walks around the room with the bottle in his hands.

The electrostatic generator is represented by an insulating glass globe spinning around its axis. It can be electrified by friction with the hands touching it. The prime conductor PC is connected to the globe by a conducting wire C, being suspended by insulating cables I. The prime conductor is electrified through the conducting wire which touches the rubbed globe. It is also electrified when one end of the conducting wire remains very close to rubbed globe. A person holds a little glass bottle with a nail. When the tip of the nail touches the prime conductor, or stays very close to it, the bottle becomes electrified. When the person removes the bottle and walks around the room, the nail shines by the corona effect (electric discharges in air), Figure 12.18 (b). The glass bottle can also be electrified if the nail touches the spinning globe directly (or when its tip comes very close to it) while the person holds the bottle in his hands.

His description continues as follows:[30]

> If I electrify the nail strongly, so that the light within the glass and the sparks are visible, I can take it into another room and ignite spirit of wine or of terpentine.

---

[29] [Hei99, p. 310].

[30] [Hei99, pp. 310-311].

He himself was curious about the working mechanism of his instrument:[31]

> What really surprises me in all this, is that the powerful effect occurs only in the hand. No spirit can be ignited if it [the instrument] rests on the table. No matter how strongly I electrify the phial, if I set it on the table and approach my finger to it, there is no spark, only a fiery hissing. If I grasp it again, without electrifying it anew, it displays its former strength.

By the rule of Du Fay mentioned in Section 12.4, the system should be discharged when it was grounded by the hands of the person holding it while walking around the room. However, this discharge did not take place. What happened was quite the opposite, namely, the electrical effects were stronger with the grounded glass bottle than with the insulated bottle.

An analogous discovery was made independently in Holland, also in 1745. The professor of experimental physics at the city of Leyden (Leiden), Musschenbroek (1692-1761), wanted to produce sparks from electrified water. He had a water filled receptacle on an insulating support. A conducting wire connected the water with the prime conductor of an electric generator. By running the machine, it electrified the prime conductor and the water connected to it. A finger approaching the prime conductor produced sparks. The lawyer Cunnaeus knew these experiments as he used to visit Musschenbroek's laboratory. When he tried to repeat this experiment at home, he inadvertently held the water receptacle in his hands, instead of placing it on an insulating support. When he tried to produce sparks with a finger approaching the prime conductor, or with his finger coming close to the conducting wire connected to the water, he received a great shock. He reported his discovery to Musschenbroek and his assistant Allamand. By repeating this procedure, they also received an immense shock. The most famous account of this experiment was presented by Musschenbroek in a letter to Réamur (1683-1757) written in January of 1746 which was published in the Proceedings of the Academy of Sciences of Paris:[32]

> As I see that this sheet [containing meteorological observations] is not completely filled, I would like to tell you about a new but terrible experiment, which I advise you never to try yourself, nor would I, who have experienced it and survived by the grace of God, do it again for all the kingdom of France. I was engaged in displaying the powers of electricity. An iron tube *AB* was suspended from blue-silk lines; a globe, rapidly spun and rubbed, was located near *A*, and communicated its electrical power to *AB*. From a point near the other end *B* a brass wire hung; in my right hand I held the globe *D*, partly filled with water, into which the wire dipped; with my left hand *E* I tried to draw the snapping sparks that jump from the iron tube to the finger; thereupon my right hand *F* was struck with such force that my whole body quivered just like someone hit by lightning. Generally the blow does not break the glass, no matter how thin it is, nor does it knock the hand away [from the phial]; but the arm and the entire body are affected so terribly I can't describe it. I thought

---

[31] [Hei99, p. 311].

[32] [Hei99, pp. 313-314].

> I was done for. But here are some peculiarities. When the globe D is made of English glass there is no effect, or almost none; German glass must be used, Dutch doesn't work either; D does not have to be a globe, a drinking glass will do; nor does it matter if it is large or small, thick or thin, tall or short, or of any particular shape; but it must be made of German or Bohemian glass. The globe D that almost killed me was of very thin white glass, five inches in diameter. Most other note-worthy phenomena I here omit. Suffice it that the man should stand directly on the ground; that the same one who holds the globe should draw the spark; the effect is small if two men participate, one grasping the globe and the other pulling the sparks. If the globe D rests on metal lying on a wooden table, and someone touches the metal with one hand and elicits sparks with the other, he also will be struck with an immense force. I've found out so much about electricity that I've reached the point where I understand nothing and can explain nothing. Well, I've filled this sheet up pretty well.

The first picture of this experiment was presented by Nollet in 1750, Figure 12.19.[33]

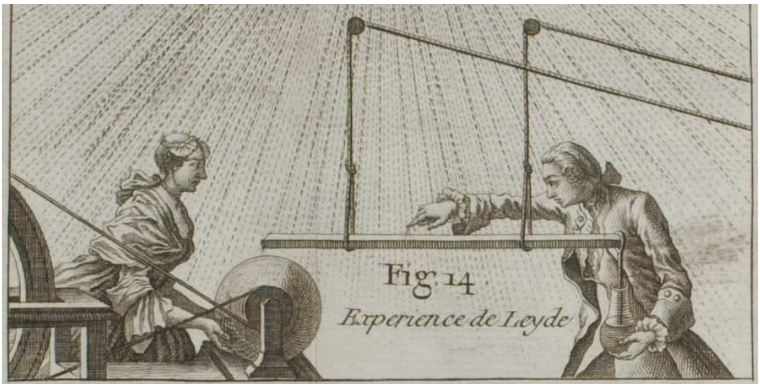


Figure 12.19: First representation of the Leyden jar experiment. The horizontal bar represents the iron tube AB of Musschenbroek's description suspended from insulating silk lines, while the jar in the hand of the experimenter represents his glass globe D.

Musschenbroek was a great scientist specialized in electricity. Despite this fact, he was totally surprised by the outcome of this experiment. He could not explain the working mechanism of this instrument, although he specified very clearly all the main aspects of how to make it operate so powerfully.

Although he said that he would not try again the experiment, his own description indicates that some variations were tried by changing the type, thickness and format of the glass. Probably the German glass which he utilized

---

[33] [Hei99, p. 285].

when receiving the shock behaved as a good insulator, allowing the accumulation of opposite charges on both sides of it (that is, on the internal and external sides of the bottle). The English and Dutch glasses, on the other hand, probably behaved as conductors for electrostatic experiments. If this was the case, they would not allow the accumulation of opposite charges in the internal and external sides of the glass.

Another representation of Cunaeus's experiment appears in Figure 12.20.[34]

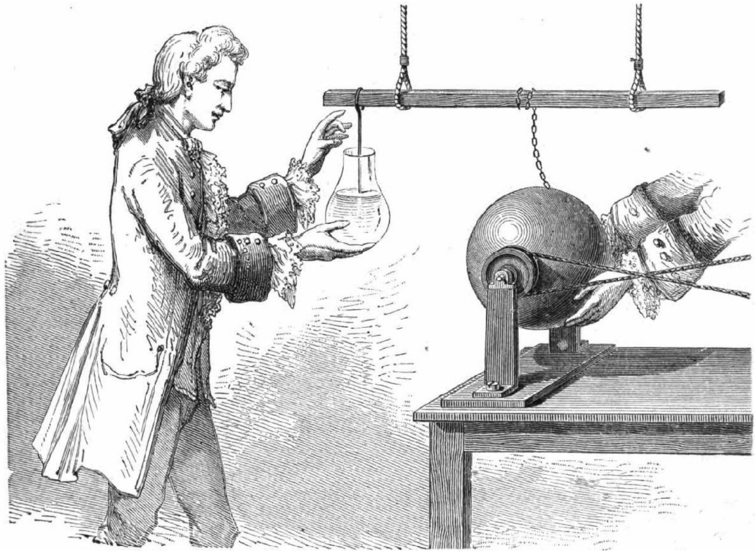


Figure 12.20: Another representation of the Leyden jar experiment.

Figures 12.19 and 12.20 illustrate a glass globe spinning around its axis. It is electrified when rubbed by the hands touching it. A horizontal metal bar is suspended by insulating strings. In Figure 12.19 the bar is electrified through sparks in air as its end is very close to the spinning globe. In Figure 12.20, on the other hand, it is electrified by the metal chain touching it, while the other end of the chain touches the spinning globe. At the extremity of this bar there is a metal wire dipping into the water held inside a glass jar. A person holds the jar in his hand. He tries to produce a spark with his other hand by approaching the bar or metal wire. At this moment, he feels an immense shock.

Benjamin Franklin supplied the working mechanism of the Leyden jar.[35] The main aspect of his explanation is that the glass jar behaved as an insulator. The water inside the jar behaved as a conductor which was in contact with its inner wall. The hand of the person holding the jar behaved as another conductor which was in contact with the external wall of the jar. The person holding the jar behaved as a grounding of its external wall. The water was in contact

---

[34] [Des76, Part 3, p. 570, Figure 382].

[35] [Hei99, pp. 330-334].

with the prime conductor through the metal wire. By running the generator, it electrifies the spinning globe, the prime conductor, the metal wire and the water. All these conductors acquire an electric charge of the same sign as the charge spread on the surface of the rubbed globe. The external surface of the jar is grounded by the hand of the person holding it. By running the generator, the hand of the person holding the jar becomes electrified with a charge of opposite sign to that of the spinning globe. When the jar is removed from the generator, while holding it in the hand, we have an electrified condenser or capacitor, with equal and opposite charges spread on the surfaces of the conductors in contact with the internal and external walls of the glass jar. Franklin said the following in a letter of 1747 to his friend Collinson:[36]

> At the same time that the wire and the top of the bottle, etc., is electrised *positively* or *plus*, the bottom of the bottle is electrised *negatively* or *minus*, in exact proportion; that is, whatever quantity of electrical fire is thrown in at the top, an equal quantity goes out of the bottom.[37]

During the discharge of the jar, there has to be a path for the electrical fire to be transferred between the outer conducting coating and the inner conducting coating. This path was not through the insulating glass. Franklin pointed out that this path was through a conductor touching the top and bottom of the bottle (or its inner and outer coatings):[38]

> 3. The equilibrium cannot be restored in the bottle by *inward* communication or contact of the parts; but it must be done by a communication form'd *without* the bottle between the top and bottom, by some non-electric, [that is, by some conductor,] touching or approaching both at the same time; in which case it is restored with a violence and quickness inexpressible; or, touching each alternately, in which case the equilibrium is restored by degrees.

Suppose the person is holding the electrified jar in his hand. When he touches his other hand in a conductor which is in contact with the water, he will feel an immense shock. The shock will be due to the flow of a sudden electric current through his conducting body. There will be a neutralization of the opposite charges located inside and outside the jar, which were separated by the insulating glass and surrounding air.

You can have an idea of the shock experienced by Cunnaeus or Musschenbroek utilizing the electrophorus and Leyden jar described in Sections 6.1 and 12.1. To this end, utilize a 30 cm diameter pizza pan with an insulating handle at its center, Figure 2.15 (d). The insulating base of this electrophorus can be a square PVC plate with 40 cm sides. It is electrified when briskly rubbed with

---

[36] [Fra69, p. 13], [Fra04, Vol. 2], [Hei99, p. 331] and [Mor04b, Version 1.3, Section III, p. 4].

[37] [Footnote added by Franklin in a later edition of his book:] What is said here, and after, of the *top* and *bottom* of the bottle is true of the *inside* and *outside* surfaces, and should have been so expressed.

[38] [Fra69, pp. 13-14], [Fra04, Vol. 2] and [Mor04b, Version 1.3, Section III, p. 5].

a paper napkin or cotton tissue. The Leyden jar can be a 200 or 300 ml plastic bottle, Figure 12.2. The charging and discharging mechanisms of the Leyden jar were described in Experiment 12.4.

The experiments of Gray and Du Fay described in Section 12.4, together with those on the Leyden jar described in this Section, show that water can store or accumulate electricity. This conducting property of water was utilized in Kelvin's electrostatic generator.[39] Experiments utilizing this fact continue to be performed nowadays.[40]

---

[39] Section 7.12 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[40] [APZ06], [OP09], [San11], [Pol13, Chapter 5] and [GB17, Chapter 6].

Chapter 13

Temporal Preservation of the Electrification of Bodies

This Chapter presents some procedures that increase the amount of time during which a body can remain electrified.

13.1 Discharge through the Air

Experiment 13.1 - *Discharge of an Insulator*

Electrified insulators and conductors normally lose their charge in a few minutes in the open air.[1]

Consider, for instance, a plastic straw electrified when rubbed in hair. It attracts bits of paper close to it, Figure 1.3. However, after a few minutes or a few hours, the rubbed straw no longer attracts small pieces of paper, Figure 13.1.

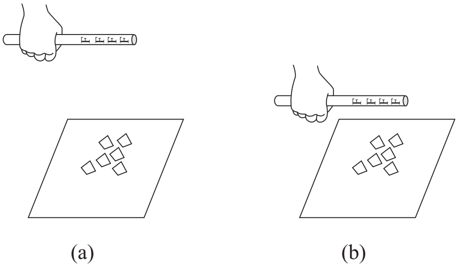


Figure 13.1: (a) A rubbed straw far away from small pieces of paper. (b) A rubbed straw looses its electrification several hours after the initial rubbing. It no longer attracts small pieces of paper when brought close to them.

---

[1] Sections 7.13 and 7.14 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

The time interval required for a rubbed straw to loose its electrification depends on several factors: air conductivity, on how much electricity it acquired when first rubbed, if the plastic material is a good or bad insulator, etc. On very dry weather a well-charged straw can remain electrified for a few hours. On humid days it will discharge after a few minutes.

Experiment 13.2 - *Discharge of a Conductor*

A conductor also looses its electrification in the open air. Rub a plastic straw in hair and then scratch it on the thin cardboard, charging the electroscope, Figure 13.2 (a). Leave it on a table on a dry day. It discharges slowly, as can be observed by its strip. After a few minutes or an hour it is totally discharged, Figure 13.2 (b).

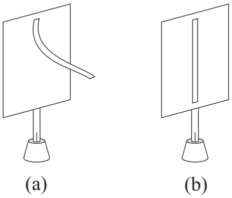


Figure 13.2: (a) A charged electroscope. (b) The electroscope is totally discharged after an hour in the open air.

The discharge time depends again on several factors: Atmospheric conditions, on the amount of electricity it received by scratching the rubbed straw on the cardboard, on the shape and size of the electroscope, on the conductivity of the straw supporting the cardboard, etc. The dryer the weather, the longer will it remain electrified.

How can we increase the amount of time during which insulators and conductors remain electrified?

13.2 Preserving the Electrification of Insulators

The simplest way of increasing the electrification time of a charged insulator is to prevent its contact with open air.[2]

Experiment 13.3 - *Wrapping a charged insulator with a conductor*

Electrify equally 10 or 20 plastic straws by rubbing each one of them briskly in hair or in a piece of paper. Place them side by side on a piece of cotton cloth or paper sheet (like a paper napkin), Figure 13.3 (a). Cover the straws, Figure 13.3 (b). The wrapped set of straws can be stored inside a shoe box.

At a fixed time interval (once a day or once a week) remove one of the straws and test its electrification. Utilize sensible tests in order to detect small

---

[2] [Grad], [Bos11, Chapter 8] and [BAC12, Chapter 9].

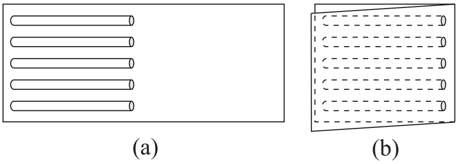


Figure 13.3: (a) Rubbed straws on a piece of cotton or paper. (b) Wrapped straws.

amounts of electricity. Observe if it attracts the tissue paper strip of a discharged electroscope, if it attracts the paper disk of a discharged electric pendulum, or if it orientates a metal versorium. When the wrapped straws are initially well charged, observe that they remain electrified for days, weeks or even a few months.

The time interval in which the straw remains electrified depends again on several factors like the weather conditions, on the degree of charge it received by friction, if the plastic material of the straw is a good or bad insulator, etc.

Experiment 13.4 - *Wrapping a charged insulator with another insulator*

In Experiment 13.3 the straws were wrapped in conductors like a piece of cotton or paper. Repeat this procedure, this time wrapping the rubbed straws in an insulating plastic bag. The straws also remain electrified in this situation for days, weeks or a few months.

Experiment 13.5 - *Wraping a charged straw with a sheet of paper and a plastic bag*

You can also see how long rubbed straws wrapped in conductors (like a sheet of paper) remain electrified, in comparison with rubbed straws wrapped in insulators (like a plastic bag). On the same day wrap some of them in conductors and others in insulators, assuming the straws to be equally electrified before covering them. From time to time remove one straw wrapped in a conductor and another straw wrapped in an insulator. Verify the electrification of each one of them.

By performing this experiment sometimes we notice that, on the same day, the straws wrapped in an insulator maintain their electrification with a higher intensity than those wrapped in a conductor. We also observe that the straws wrapped in an insulator remain electrified for a longer time than those straws wrapped in a conductor.

Table 13.1 compares the time intervals in which charged straws remain electrified when maintained in the open air, wrapped in a paper or in a plastic bag.

Experiment 13.6 - *Electrified plate discharging through the air*

Utilize in this experiment some boards or plates made of PVC and Styrofoam. They can have any shape. They can be, for instance, a square with a

Condition	Duration
In the open air	A few minutes
Wrapped in a conductor	Days, weeks or a few months
Wrapped in an insulator	Days, weeks or a few months

Table 13.1: Approximate time intervals to discharge an electrified straw.

side 20 or 30 cm long, a circle with a diameter of 20 or 30 cm, etc. Rub one of their faces briskly with a piece of paper, napkin or tissue. Then set these plates in the open air with their rubbed sides facing up. Every 10 minutes test their electrification. Test, for instance, if the rubbed face attracts the tissue paper strip of a discharged electroscope, if it attracts the paper disk of a discharged electric pendulum, or if it orientates a metal versorium. Measure how long each face remains electrified.

Depending on weather conditions, on the insulating property of the plate, and on the degree of initial charge acquired by friction, the plates can remain electrified for 10 minutes up to one hour, approximately.

Experiment 13.7 - *Superimposed electrified plates*

Repeat Experiment 13.6. Electrify pairs of plates of the same material, of the same shape and equal size. Superimpose the plates of the same material with the rubbed sides facing each other. Tie them together with rubber bands. The pairs are then stored in a shoe box. From time to time open one of these pairs and test the electrification of the internal faces. If the pair remains electrified, superimpose again the rubbed faces and store them in the shoe box.

Verify with this procedure that the rubbed faces can remain electrified for days, weeks or a few months, Table 13.2. As always, the discharge time depends on the amount of initial charge acquired by friction, on the insulating property of the plate, on weather conditions, etc.

A plate in the open air	A few minutes up to 1 hour
Superimposed plates	Days, weeks or a few months

Table 13.2: Approximate time intervals to discharge an electrified insulating plate.

13.2.1 Some Comments on These Experiments

The experiments of this Section show that the time interval in which an insulator remains electrified can be increased significantly by protecting it from the surrounding open air. Obviously the rubbed straws remain in contact with air when wrapped on a piece of paper, tissue or plastic. The same happens when two rubbed plates are superimposed and stored in a shoe box. In any event, the air molecules around these wrapped bodies are approximately the same with the passage of time. On the other hand, when an electrified body is kept in the open air, there will be different air molecules and charged ions around it. This aspect may be one of the main reasons that increases the discharge time of wrapped bodies in comparison with the low discharge time of bodies kept in the open air.

An electrified straw may be discharged in the open air by the ACR mechanism. Water vapor, other particles, molecules and ions present in the air may be attracted by the straw, touch it, acquire some of the charge on the straw, being then repelled by it. A wrapped straw decreases the possibility of this mechanism.

Another aspect may also be relevant. When an electrified plastic straw is covered with a conducting or insulating material, a redistribution of charges takes place in these cover materials. Consequently, the *total or resultant force* acting on external particles of air has now a smaller intensity. These external particles of air contain molecules, ions, impurities etc. The total force exerted on them by the wrapped body is now due not only to the electrified straw, but also to the charges redistributed on the conducting or insulating material around the straw. The total force acting on any external particle is now smaller than the force due only to the straw. These external particles have then a smaller tendency to interact with the electrified straw.

13.3 Preserving the Electrification of Conductors

Experiment 13.8 - *Leyden jars*

Experiment 13.2 shows that a charged conductor in the open air looses its electrification in a few minutes. We present now a procedure that increases significantly the preservation of this electrification.

Utilize here the Leyden jar made with a glass bottle of 200 or 300 ml.[3] Ideally you should have 5 or 10 bottles of equal size and shape, made of the same materials. One of these bottles appears in Figure 12.2. It will be electrified with a Volta electrophorus made with a 30 cm diameter pizza pan with a handle made of PVC, acrylic or hard plastic. The insulating base of this electrophorus can be a square PVC plate with sides of 40 cm. This insulating base is electrified by rubbing it briskly against a paper napkin or a cotton tissue, Figure 6.1 (a). The pizza pan is electrified by following the procedure of Figures 6.2 up to 6.4. The pizza pan is discharged when it is brought very close to the metal ball of a grounded Leyden jar, Figure 12.6. The Leyden jar can be well electrified by repeating this procedure 20 or so times. After being charged, the bottles should be kept in a shelf, closet or cabinet, taking notice of the date in which they were electrified.

---

[3] Section 12.1 and [MF].

At equal time intervals (1 hour, 1 day or 1 week) test the electrification of one of these jars. To this end, just touch one finger to the external conducting strip of the bottle and bring another finger of the same hand very close to the metal ball of the jar. Suppose there is a spark like that of Figure 12.7. It means that the bottle remained electrified from the initial moment until this discharge. The discharged bottle should no longer be utilized in this experiment. At another equal time interval test the charge of another bottle kept in the shelf. Follow the same procedure until all bottles have been discharged.

By performing this experiment, conclude that a charged bottle can remain electrified for a few days (like a week, for instance). The exact time interval depends on the initial amount of electrification, on the insulating properties of the bottle, on its size and shape, etc.

This experiment can also be performed with a single bottle. Follow the procedure of this experiment to charge it. After 1 hour, 1 day or 1 week, test its electrification. After the bottle has been discharged, charge the bottle again approximately up the same initial amount by following the procedure of this experiment. Then, after 2 hours, 2 days or 2 weeks, test its electrification. After it is discharged, charge it once more by the procedure of this experiment. Then, after 3 hours, 3 days or 3 weeks, test its electrification. Continue this procedure until the bottle is no longer electrified after a certain amount of time (which can be 10 hours, 10 days or 10 weeks, for instance). Discover how long it remains electrified while stored in a safe place and nothing happens to it.

We can then compare Experiment 13.2 with the experiments of this Section. These last experiments show that the charges located on the internal and external conductors of a capacitor like a Leiden jar are stored for a longer time than the charges spread on the conducting cardboard of an electroscope maintained in the open air.

13.4 Electrets

13.4.1 Definitions

An *electret* is a piece of insulating or dielectric material exhibiting a permanent electric charge or a permanent electric polarization. In reality the amount of electrification of any body decays with time. However, when the time constant characteristic for the decay of the charge is much longer than the time periods over which studies are performed with this material, the electrified body can be considered an electret. For instance, when the experiment lasts for a few seconds, a body with an electrification lasting for a few minutes can be considered an electret. In this sense the straws or plastic rulers electrified by friction can be considered electrets as regards most experiments described in this book. There are some instruments in which internal bodies must remain electrified for weeks or months. In these cases a body which remains electrified for a year can be considered a good electret. We can now clarify the definition:

Definition 13.1 - *Electret*

Electrets are pieces of insulating materials exhibiting a quasi-permanent electrification or dipole polarization, with a time constant characteristic for the decay of the charge much longer than the time period over which studies are performed with the body.

Usually the word "electret" is utilized only when the electrification or polarization lasts for some months, years or decades. This word was coined in 1885 by Oliver Heaviside (1850-1925):[4]

> A word is evidently wanted to describe a body which is naturally permanently electrized by internal causes. Noticing that "magnet" is got from "magnetism" by curtailment at the third joint from the end, it is suggested that we may get what we want by performing the same operation upon electricity. An "electric," which is what results, would be a very good name for an intrinsically electrized body, but for two reasons. First, it was once used to signify what we should now call a dielectric or an insulator; and secondly, electric is now used as an adjective, or, equivalently, electrical. The former of these objections is of hardly any weight, that use of the word as a substantive being wholly obsolete. The latter is heavier, but still of no great importance. Another word that suggests itself is electret, against which there is nothing to be said except that it sounds strange. That is, however, a mere question of habit.

There are several kinds of electrets and various production methods. There are also many classification of electrets which vary from author to author. Here we present a simple classification.

Electrets which have a total, resultant or net charge different from zero are called monopolar electrets, excess charge electrets, real charge electrets or electrets with net charge. Figure 13.4 (a) illustrates an electret with surface charge, while Figure 13.4 (b) shows a material with real charge spread inside the dielectric, sometimes called a space charge electret.

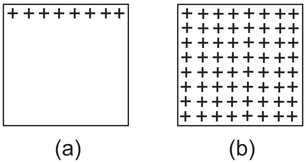


Figure 13.4: (a) Electret with real surface charge. (b) A space charge electret with real excess charge within the dielectric's volume.

Bodies with zero total charge and permanent electric polarization are called bipolar, dipolar or polarized electrets. Figure 13.5 (a) represents a polarized

---

[4] [Hea87, Article 30: Electromagnetic induction and its propagation, Section 12: Electrisation and Electrification. Natural Electrets, p. 488], [JW80] and [Sil10b, pág. 30].

electret with real and opposite surface charges. Figure 13.5 (b) shows a polarized electret with opposite real charges spread within the dielectric's volume. Figure 13.5 (c) illustrates an electret containing oriented (aligned) molecular dipoles.

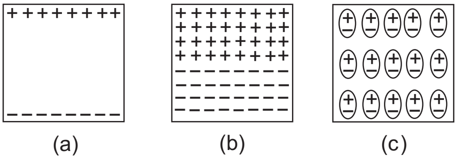


Figure 13.5: Polarized electrets. (a) With real and opposite surface charges. (b) With opposite real charges spread within the dielectric's volume. (c) Containing oriented molecular dipoles.

The electret of Figure 13.5 (c) is the electrostatic equivalent of a permanent magnet.

A general electret can have quasi-permanent charges of all these kinds, Figure 13.6.

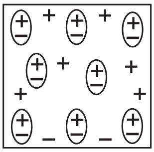


Figure 13.6: A generic electret.

In practical applications there are electrets with one or two faces covered with a conducting layer. These cases will not be discussed here.

13.5 Electret Production

13.5.1 Materials

We show here how to produce electrets which remain electrified or polarized for days, weeks or months. These experiments were performed by Silva Junior and Boss.[5]

People should be careful when performing these experiments as we deal with fire, gases and smoke from different substances. Some security procedures can be found in the appropriate literature.[6]

The materials utilized in these experiments are paraffin, beeswax, carnauba wax and shellac. Paraffin wax is usually derivable from petroleum and used to make candles. The paraffin utilized in these experiments can be obtained from candles or acquired in rigid bars or tablets. Carnauba wax is obtained from the

---

[5] [Sil10a], [Bos11, Section 8.2, pp. 234-248] and [BAC12, Chapter 19].

[6] [Bos11, Section 8.2] and [BAC12, Section 19.3].

leaves of a palm native to northeastern Brazil. It usually comes in the form of hard yellow or brown flakes, sometimes as a rigid bar or tablet. Shellac or lac is a resinous substance secreted by species of scale insects on trees of India and Thailand. It is normally sold as dry flakes and used as a colorant or wood finish. These materials can be found in paint or building material stores, wood shops and in some supermarkets.

The melting point of these substances ranges from 60 to 80 degrees Celsius. They can be melted in the flame of a kitchen stove utilizing metal pie pan, aluminum or iron ladles, glass cups, etc.

Experiment 13.9 - *Insulating behavior before melting*

Before melting these substances, test their insulating or conducting behavior utilizing the procedures of Section 3.1. For liquid substances or those coming in the form of flakes, a border of the charged electroscope should touch them, as in Figure 3.6.

Observe that the tissue paper strip of a charged electroscope remains raised when all substances of this Subsection touch the cardboard, showing that they are insulators.

Experiment 13.10 - *Charge neutrality before melting*

Verify also if any of these substances are electrified before melting them. This test can be performed when one of these substances is brought close to a metal versorium, to the paper disk of a discharged electric pendulum, to the tissue paper strip of a discharged electroscope, or close to a thin stream of water running smoothly from a tap. When these bodies are not attracted by this substance, conclude that it is neutral or discharged. This is the most common situation found when performing this test.

Sometimes carnauba wax presents a small degree of electrification on some of its sides before being melted. The other substances normally do not attract these conducting bodies.

13.5.2 Making Electrets

In order to produce electrets, melt these substances in the listed containers (recipients), wait until they cool down and solidify, and finally reheat the containers briefly to release the materials. The whole procedure takes some 4 hours including the preparation of the material, production of the electrets and cleaning the working environment. We suggest making a trial run over a whole day in order to master the entire process, to discover what is necessary in each phase, to know the required materials and procedures, etc. Then, with all this acquired knowledge, on another day produce the electrets which will be utilized in the following experiments.

People usually prepare electrets by combining different amounts of these substances, like a mixture of wax and resin. However, in the experiments described here, we will utilize a single substance in each container.

The waxes and paraffins were broken into pieces before placing them into the containers. Place the containers directly into fire or heat them in bain-marie (water bath) which heats the substances gently and gradually. After melting, the container is removed from the heat source until the substance cools down and solidify. This process lasts 1 to 3 hours. Water should not go inside the containers at any moment during this whole procedure. The substance will be removed from the container after cooling to ambient temperature. An insulating handle is helpful to remove the substance and to manipulate it in the experiments. To this end, the handle should be inserted in the substance before it solidifies. The handle can be, for instance, a plastic tube or an acrylic ruler, Figure 13.7 (a). When the substance cools down and becomes rigid, the container should be briefly reheated in order to remove the electret, Figure 13.7 (b).

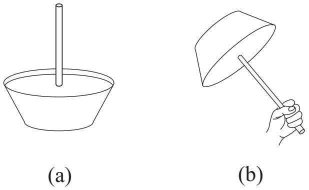

(a) (b)

Figure 13.7: (a) Melted substance with insulating handle inside the heating container. (b) Solid electret.

However, sometimes it is not easy to remove the reheated electret from the container even with a handle. It may be necessary to deform the metal pie pan or to break the glass cup to remove it. Shellac, for instance, may become powdery or frail, making it difficult to remove the material as a single piece. Paraffin shrinks a little when it solidifies. Sometimes it is possible to remove it from the container without it being necessary to reheat.

Experiment 13.11 - *Insulating behavior after melting*

After preparing the electrets, test their insulating or conducting behavior as in Experiment 13.9.

Hold the electret by hand and touch it on the upper edge of a charged electroscope. The tissue paper strip does not drop. Conclude that all these substances behave as insulators after being melted.

Experiment 13.12 will show that these substances are electrified after being melted and solidified. However, as they still behave as insulators after they are removed from the containers, you can touch them with the hand without discharging the substances.

Experiment 13.12 - *Electrification of the substances after melting*

Hold each piece by the handle, or directly in the hand, and test its electrification by the procedures of Experiment 13.10.

Now we normally find that paraffin, shellac, carnauba wax and beeswax are electrified. That is, they attract the legs of a metal versorium, the paper disk of a discharged electric pendulum, the tissue paper strip of a discharge electroscope and the thin stream of water running out of a tap. This electrification takes place regardless of the container in which they were melted (aluminum, iron or glass). The electrification of beeswax is sometimes very weak and difficult to detect.

Experiment 13.13 - *Sign of the charge of the electrets after melting*

Electrify two electroscopes by induction, one positively and the other negatively.[7] Place them on a table separated from one another. Slowly bring the electret close to the raised strip of each electroscope. Normally the substance repels the strip of the negative electroscope and attracts the strip of the positive electroscope, showing that the electret is negatively electrified.

Do not bring the electret too close to the raised strip when there is a repulsion between them. After all, the repulsion can turn into an attraction when this distance becomes very small.[8]

Experiment 13.14 - *Time interval in which the substances remained electrified in the open air*

After preparing the pieces, place them in the open air. From time to time test their electrification as in Experiment 13.12.

The paraffin pieces remained electrified from a few hours up to a few days. The pieces of carnauba wax remained electrified from a few days up to a few months.

Experiment 13.15 - *Time interval in which the substances remained electrified when kept inside the containers in which they had been melted*

After being melted and removed from the containers, some pieces were returned to these containers after cooling down. From time to time we removed one of these pieces. We tested its electrification as in Experiment 13.12. We then returned the piece to the container. This procedure was repeated until the piece showed no more signs of being electrified.

The pieces of paraffin remained electrified from some 5 to 20 days. The pieces of carnauba wax remained electrified for some months.

Experiment 13.16 - *Time interval in which the substances remained electrified when kept in the containers in which they had been melted, with a plastic bag placed between the container and the substance*

After preparing some pieces of paraffin, they were removed from the containers. These recipients were then wrapped with a plastic bag and the substances

---

[7] Section 7.5 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[8] Section 7.10 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

were returned to the containers. From time to time the substances were removed. We tested their electrification and placed them again in the wrapped containers. This procedure was repeated until they showed no more signs of electrification, some 7 or 8 days after being melted.

Experiment 13.17 - *Time interval in which the substances remained electrified when wrapped in conductors and kept inside the containers in which they had been melted*

Some of the paraffin pieces after being melted and solidified were wrapped with a conductor (cotton flannel or paper napkin) and again placed in the containers in which they had been melted. From time to time they were unwrapped. We tested their electrification, wrapped the pieces and placed them again in the containers. This procedure was repeated until they showed no more signs of electrification. They remained electrified from 7 to 12 days.

Experiment 13.18 - *Time interval in which the substances remained electrified when wrapped in conductors*

We removed the handles of some pieces and wrapped them in conductors (cotton flannel, napkin or a piece of paper). We placed the wrapped pieces inside a shoe box. From time to time we removed one of the pieces. We then tested its electrification as in Experiment 13.12. After each test the piece was wrapped again, remaining inside the box until the next test.

The pieces of bees wax remained electrified for some 5 months. Some pieces of paraffin remained electrified for 7 months, others for at least 10 months, when we stopped the tests, although they remained electrified. The pieces of shellac and carnauba wax remained electrified for at least 10 months (when we stopped the tests, although all of them remained electrified).

It should be remarked that the degree of electrification of these pieces decreased with the passage of time. That is, the attractions they exerted on nearby bodies decreased in intensity over the days or months of the experiments. Sometimes it was necessary to bring the pieces very close to conductors which were initially neutral in order to detect an attraction of these conductors.

Experiments 13.14 to 13.18 indicate that these pieces can be really considered electrets, as they remained electrified for days or months after being melted.

13.6 Electrophorus with a Base Made of Electret

In Chapter 6 we described an electrophorus made of two parts, namely, (a) an electrified insulating base, and (b) a charge collector composed of a conducting disk with an insulating handle. We performed some experiments utilizing a base made of Styrofoam or PVC which was electrified by rubbing it with a napkin. All these experiments can be reproduced replacing the electrified base with an electret (like a paraffin disk or a plate of carnauba wax).

Advantages of utilizing an electrified Styrofoam or PVC plate as a base of the electrophorus: It is very easy to obtain these plates and it is simple to electrify them by friction. Disadvantages: These plates discharge in a few minutes. It is then necessary to rub the plate from time to time in order to continue with the experiments.

Advantage of utilizing an electret base: It remains electrified for a few days or months, loosing very slowly its electrification. The disadvantage is the production of the electrets which is not so easy.

13.7 Stephen Gray, the Electrets and the Temporal Preservation of the Electrification of Bodies

The production and some of the main properties of electrets were first described by Stephen Gray, who presented his discoveries in an important paper of 1732.[9] In the same work he described for the first time a procedure to preserve the electrification of bodies for a very long time.

Du Fay described these discoveries of Gray with the following words:[10,11]

> Mr. Gray found two new properties in electricity, the first that it is permanent, namely, that it can persist in the bodies for a very long time after being excited, & the other that it can be found in some cases without rubbing the bodies.

Here we present some of the main portions of this extremely important work of Gray, with our words in square brackets and in the footnotes:

> **A Letter from Mr. Stephen Gray to Dr. Mortimer, Secr. R. S. Containing a Farther Account of His Experiments concerning Electricity**
>
> *Charter-House*, June 7th, 1732.
>
> Sir,
>
> Since my last [paper in the *Philosophical Transactions*] (N° 422)[12] wherein I gave an account of my experiments, shewing water will be attracted by electrick bodies [that is, by electrified insulators], and that it may have an electrick vertue communicated to it, so as to attract solid ones, I have been upon another enquiry; Whether there might not be a way found to make

---

[9] [Grad], [Bos11, Chapter 8] and [BAC12, Chapter 9].

[10] [DF34, p. 341].

[11] M. Gray a trouvé dans l'électricité deux propriétés nouvelles, l'une qu'elle est permanente, c'est-à-dire, qu'elle peut subsister dans les corps très-long-temps après qu'elle y a été excitée, & l'autre qu'elle s'y trouve dans certains cas sans que les corps ayent été frottés.

[12] [Grab], [Bos11, Chapter 7] and [BAC12, Chapter 8].

this property of electrical attraction more permanent in bodies? How far I have succeeded in this attempt, will appear by the experiments I have made on the several bodies mentioned in the following Catalogue;[13] and as they were all of them prepared after the same manner, excepting numb. 18 and 19, which shall be described afterwards, a general description of the method of preparing and preserving them in a state of attraction, may suffice.

The bodies on which the experiments were made were rosin both black and white, stone-pitch, shell or gum-lac, bees-wax, and sulphur. I procured three iron ladles of several sizes, in which I melted these substances, making use of that which I thought most convenient for the quantity I designed to melt. When any of these bodies were melted they were taken off the fire, and set by in the ladle to cool and harden; then it was returned to the fire, where it remained 'till it was melted about the bottom and sides of the ladle, so as to be moveable; so that by inverting the ladle it might be taken out; having the form of nearly the section of a sphere, the convex surface, as also the plain one, being naturally (if I may so say) polished excepting the sulphur, which cools without retaining its polish, except when cast in glass vessels, as shall be shewed hereafter. I shall now proceed to the experiments and observations made on these electric bodies [that is, made on these insulators].

When any of them were taken out of the ladle, and their convex surface hardened, they would not at first attract, 'till the heat was abated, or 'till they came to a certain degree of warmth, and then there was a small attraction; which warmth I estimated to be nearly that of a hen's egg when just laid: The attraction encreasing so, as when cold, to attract at least ten times farther than at first.

---

[13] This Catalogue appears on page 255 of this book.

Table 13.3: *A CATALOGUE of the several* Electrick Bodies [that is, insulators] *mentioned in the foregoing Discourse.*

N°	Names of the several bodies.	Weight.		Month.	Days.
		Ounces	Drachms		
1	Fine black rosin	2	0	*Jan.*	31
2	Stone pitch and black rosin	2	2	*Jan.*	31
3	Fine rosin and bees-wax	2	1	*Feb.*	1
4	Stone pitch	1	7	*Feb.*	1
5	Stone sulphur	3	6	*Feb.*	4
6	Shell-lac	10	0	*Feb.*	10
7	Fine black rosin	10	4	*Feb.*	11
8	Bess-wax and rosin	9	0	*Feb.*	12
9	Rosin 4 [*parts*], and gum-lac 1 *part*	10	0	*Feb.*	12
10	Sulphur	18	0	*Feb.*	15
11	Stone pitch	10	12	*Feb.*	16
12	Black rosin	23	0	*Feb.*	23
13	White rosin	7	12	*Feb.*	25
14	Gum-lac	11	14	*Feb.*	26
15	Gum-lac and black rosin *ana*	9	12	*Feb.*	26
16	Gum-lac 4 *parts*, rosin 1 *pt.*	17	8	*Feb.*	28
17	Shell-lac, fine black rosin *ana*	28	4	*Mar.*	2
18	A cylinder of stone sulphur	19	4	*Mar.*	20
19	A large cone of stone sulphur	30	0	*Mar.*	29
20	A cake of sulphur	11	4	*Apr.*	29

Gray did not present his reasons for choosing these specific materials. Nor did he specify why he expected them to become electrified with this procedure. In any event, he was an acute observer. Since 1708 he had been making electrical experiments. In 1729 he discovered conductors and insulators by realizing that, after rubbing a glass tube, the cork at the end of the tube began to attract light bodies close to it. This detail called his attention. If he had rubbed the cork while holding it with his bare hand, the cork would not attract light bodies close to it.[14] By following these experiments, he discovered that he could communicate the electric virtue (or the property of attracting light bodies) to some substances which were not rubbed but which were in contact with the electrified glass tube. These substances are nowadays called conductors. Other substances did not allow the flow and dissipation of the electric virtue to the ground, being called insulators nowadays. He described in his published

---

[14] Appendix B of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

papers the following insulators: silk thread, horse-hair fishing-lines, cake of resin, warmed glass, cakes of beeswax, sulfur and shell-lack. Maybe he observed by chance that some of these resins and waxes were electrified, *without being rubbed previously*, as they attracted light bodies placed close to them. He may have suspected that some of these materials became electrified as they were melted. This paper of 1732 might be a systematic study of this casual observation. The materials described by Gray in the present paper remained electrified for a very long time, without being rubbed previously. They are called electrets nowadays. They can be electrified by his procedure or by other modern means of electrification. He was the first person who presented a procedure for the production of electrets and a list of materials which could become electrets.

In the sequence of this paper Gray presented another very important discovery, namely, a procedure to increase the time interval in which a body can remain electrified:[15]

> The manner of preserving them in a state of attraction, was by wrapping them up in any thing that would keep them from the external air; as at first for the smaller bodies I used white paper, but for the larger ones white flannel; but afterwards found that black worsted stockings would do as well. Being thus clothed, they were put into a large fir box, there to remain 'till I had occasion to make use of them.
>
> The cylinder of sulphur, numb. 18, was made by melting the sulphur, and pouring into a cylindrick glass vessel, which had first been heated, to prevent its cracking. When the sulphur was hardened, it was somewhat less than the glass; so that by inverting the glass, it came out easily, and had a polished surface almost as smooth as the glass in which it was cast. The large cone of sulphur, numb. 19, was made after the same manner; *viz.* by being cast in a large drinking-glass.
>
> I am now to give an account of the observations made on the several bodies mentioned in the Catalogue, but must first give a description of the Catalogue. The first column contains the number, which in a small piece of paper is fixed on each of the several bodies; the name of which is given in the second column, whether they are single or compound substances. The third column shews of what weight they were of when melted, in Ounces and Drachms of *Averdupois* Weight.[16] In the fourth column you have the days of the month when the body was melted and received its form, and consequently when it first began to attract.
>
> I did for thirty days continue to observe every one of these bodies, and found that at the end of the said time they attracted as vigorously as at the first or second day, as they do now at the writing hereof. By the times mentioned in the Catalogue, being subtracted from any time after, will be shewn how long any of the bodies have continued their attractive vertue; by which it will appear, that some of them have not lost their

---

[15] [Grad], [Bos11, Chapter 8] and [BAC12, Chapter 9].

[16] 1 *ounce* = (1/16) *pound* ≈ 28.35 *g*, while 1 *drachm* = (1/16) *ounce* = (1/256) *pound* ≈ 1.772 *g*.

attraction for more than four months:[17] So that we have some reason to believe, that we have now discovered that there is *a perpetual attractive power* in all electrick bodies [that is, in all electrified insulators], without exciting by either rubbing, beating, &c. or any other attrition. But this will further appear by the account I am now to give of the two last bodies mentioned in the Catalogue. The cone of sulphur, numb. 19, that was cast in a large drinking-glass, in about two hours after it was taken out of the glass, attracted, and the glass attracted too, but at a small distance. Next day the sulphur was taken out of the glass, and then it attracted strongly, but there was now no perceivable attraction of the glass. Then the cone of sulphur was set with its base upon the lid of the fir box, wherein the other electrick bodies lay, and the glass whelmed over it. I examined it every day after, and still found it to attract; but finding the place not so convenient having occasion to look into the box often, I removed it to the table that stands between the two windows of my chamber, where it has continued to this time, and whenever the glass is taken off, attracts at near as great a distance as the sulphur that is clothed and shut up in the box abovementioned. And though at first there was no attraction, when the glass was taken off, yet I now find, that in fair weather the glass also attracts, but not at so great a distance as the sulphur, which never fails to attract, let the wind or weather be never so variable, as do all the other bodies mentioned in the Catalogue; only in wet weather the attractions are not made at so great a distance as in fair weather.

Number 20 is a cake of sulphur that was melted; and as the other bodies have taken the form of a convex section of a sphere, this, when cold, was laid with its flat side downwards, on the same table with the cone of sulphur: They were both placed so near the wall, as to prevent the sun

---

[17] This letter was dated June 7, 1732. Based on this paragraph, it seems that the Catalogue on page 255 of this book refers to 1732, as Gray said that some of the substances have not lost their attractive power for more than four months (that is, from January 31, 1732, the date when the body was melted, to June 07, 1732, at the writing of the paper). Du Fay, on the other hand, when discussing this work, believed that these bodies maintained their attractive power for one and a half year, [DF34, p. 342]:

> Mr. Gray wrapped these different bodies on paper, flannel or any other similar material, and in this way they preserved their electricity for several months, up to the time of writing, which took place approximately one and a half year after his first experiments.

Original text:

> M. Gray enveloppoit alors ces différents corps dans du papier, dans de la flanelle, ou dans toute autre matiére semblable, & ils y ont conservé leur électricité pendant plusieurs mois, & même jusqu'au temps qu'il écrit, qui étoit environ un an & demi après ses premiéres expériences.

It seems to us that Du Fay interpreted the Catalogue as referring to 1731. Probably this interpretation was due to the fact that Volume 37 of the *Philosophical Transactions* was related to 1731-1732.

In any event, regardless of which interpretation is the correct one, we can be sure that Gray succeeded in maintaining his bodies electrified for a very long time of at least 4 months.

> shining on them. This was, as the Catalogue shews, on the 18th of *April*;[18] and though it had no manner of clothing or covering, has attracted ever since. And in this, as in the other bodies, the attraction will be according to the weather; but when it attracts the strongest, it is not more than the tenth part of what the cone of sulphur, that is covered, attracts.
>
> The manner of observing these attractions is best performed by holding the attracting body in one hand, and a fine white thread[19] tied to the end of a stick, in the other; by this means far less degrees of attraction will be perceived, than by making use of leaf-brass. When the thread is held at the utmost distance, it may be attracted; the motion of it is at first very slow, but still accelerating as it approaches nearer to the attracting body.
>
> I am now on the subject of permanent attraction in glass, then in the other bodies, but have not yet compleated those experiments, meeting with more interruption by the weather.
>
> [...]

From this description we conclude that Gray succeeded in increasing the amount of time during which the body remained electrified in two ways. The first one was to wrap the electrified body in paper, flannel or other similar materials. The second procedure was to cover them in the container where they were melted or hardened.

When the container was made of glass, Gray perceived that not only the resin attracted light bodies placed near them, but the glass itself was electrified. It is easy to detect the electrification of the container in which the dielectric body was melted or hardened when this recipient is made of an insulating material like glass. In this case the container can be grounded or manipulated with the hands without loosing its acquired electricity. On the other hand, when this container is made of a conducting material like metal, it is more difficult to know if it was electrified during the production of the electret inside it. In order to detect its electrification, the container should be insulated from the ground before and after the preparation of the electret. You can then test its charge after the electret has been removed.

In Section 13.2 we showed some experiments in which electrified straws remained charged for some months. The only requirement was to wrap them in a paper napkin, cotton flannel or plastic bag in order to prevent their contact with the external air. Although these are extremely simple experiments, we have not seen procedures like this one described in the textbooks dealing with electricity. In any event, this is a remarkable achievement. In the open air a rubbed straw looses its electrification in a few minutes or in one hour. On the other hand, when wrapped in a paper napkin or in a plastic bag, it can remain electrified for some 3 months or even more.

Just to give an order of magnitude, suppose a charged straw remains electrified for 10 minutes when kept in the open air. Moreover, suppose it remains

---

[18] The Catalogue mentions April *29*.

[19] Probably it was a cotton or linen thread. These materials behave as conductors in the usual experiments of electrostatics. Gray is utilizing here his pendulous thread, see Section 2.5.

electrified for 3 months when wrapped in a plastic bag. The time interval in which it remains electrified increased almost 13,000 times by simply wrapping it! It is amazing how such a simple procedure can have a huge impact.

Our inspiration in order to try this procedure came directly from this fundamental paper of Gray published in 1732 in which he utilized this technique with his electrets.

13.8 Development and Applications of Electrets

The electrets developed by Gray were also studied by Du Fay and some other scientists. However, this subject remained a simple scientific curiosity for a long time. Heaviside presented in 1885 a theoretical recipe for the production of electrets inside a high voltage capacitor.[20] However, it was only in the 1920's that Momotaro Eguchi made some electrets essentially in accordance with this procedure utilizing a mixture of carnauba wax and resin.[21]

Fukada described Eguchi's experiments and the duration of the electrification of his electrets as follows:[22]

> The original electrets, permanently charged dielectrics, were prepared by Eguchi in 1924 using a mixture of carnauba wax and resin [1].[23] An electric field of about 1.5 MV/m was applied on a molten mixture at about 130° C. A disk of electret made of carnauba wax and resin, 20 cm in diameter and 1 cm thick, is preserved at the Science Museum in Tokyo. Its surface charges remain 45 years after preparation and were observed to be approximately one-seventh the original charges [2].[24]

Since then electrets have been produced by many different methods and procedures. They are normally classified according to the production technique.

We quote here some applications of the electrets:

- As the electrified base of an electrophorus.
- Microphones.
- Headphones and loudspeakers.
- Radiation detectors.
- Dosimeters.

---

[20] [Hea87, Article 30: Electromagnetic induction and its propagation, Section 12: Electrisation and Electrification. Natural Electrets, pp. 491-2], [JW80] and [Sil10b, pp. 20-22].

[21] [Egu25], [Mas87] and [Sil10b].

[22] [Fuk00].

[23] [1] Eiichi FukadaEiichi Fukada and M. Eguchi, "On the permanent electret," Phil. Mag., vol. 49, pp. 178-192, 1925. [Although reference [1] of Fukada's paper presents the authors as written here, this work was written only by Eguchi, [Egu25].]

[24] [2] T. Takamatsu and I. Sumoto, "Life time of carnauba wax electrets," Riken Hokoku, vol. 45, pp. 141-148, 1969 (in Japanese).

- Photocopy machines or electrophotography.
- Memory storage units or electrostatic recording.
- Humidity detectors.
- Electrostatic batteries.
- Air filters.
- Vibration detectors.
- Pressure detectors.
- Electrostatic motors.
- Current generators.
- Tension generators.
- Lichtenberg figures.
- Etc.

Electrets remain an active area of research. There are several references dealing with this topic.[25]

---

[25] [Net94], [Gro54], [Jef59], [Jef73, Chapter 9: Electret motors], [JW80], [Ses87], [Fer00], [MWW07], [MW08], [Sil10b] and [GB17, Chapter 7: Excess charge in solids: electrets].

Chapter 14

The Mysterious Non-Electrostatic Forces

14.1 Electrostatic Force or Coulomb's Force

Charles Augustin de Coulomb obtained in 1785 the law of force between two electrified bodies. He presented his results in two papers of 1785, published in 1788.[1] He called these electrified bodies by different names, namely, "electrical masses," "electric molecules," "electrified molecules," or "densities of electric fluids."[2]

In the case of bodies electrified with charges of the same sign, Coulomb expressed himself as follows:[3]

> *Fundamental Law of Electricity*
>
> *The repulsive force between two small spheres charged with the same sort of electricity is in the inverse ratio of the squares of the distances between the centers of the two spheres.*

For bodies electrified with charges of opposite signs, Coulomb concluded that:[4]

> We have thus come, by a method absolutely different from the first, to a similar result; we may therefore conclude that the mutual attraction of the electric fluid which is called positive on the electric fluid which is ordinarily called negative is in the inverse ratio of the square of the distances; just as we have found in our first memoir, that the mutual action of the electric fluid of the same sort is in the inverse ratio of the square of the distances.

---

[1] [Cou85a], [Cou85b], [Pot84] and [Cou35].

[2] [Gil71b] and [Gil71a, pp. 190-192].

[3] [Cou85a, p. 572], [Pot84, p. 110] and [Cou35].

[4] [Cou85b, p. 572], [Pot84, p. 123] and [Cou35].

Up to now Coulomb mentioned only how the electric force varied with the distance between the electrified bodies. It was only in the final section of his second memoir, when he recapitulated the major propositions that resulted from his researches, that he mentioned that this force was proportional to the product between the densities of the electric fluid of the two electrified bodies (or proportional to the product of the two charges, as usually expressed):[5]

> Recapitulation of the subjects contained in this Memoir
>
> From the foregoing researches, it follows that:
>
> 1. The electric action, whether repulsive or attractive, of the two electrified spheres, and therefore of two electrified molecules, is in the ratio compounded of the densities of the electric fluid of the two electrified molecules and inversely as the square of the distances; [...]

Gillmor pointed out correctly that Coulomb did not experimentally prove that the electric force law was proportional to the product of the charges.[6] He only implied or assumed this proportionality, although he did not consider it important to demonstrate this result experimentally. Since then there have been different points of view in the literature over this subject.[7] Some authors argue that the intensity of electric force is *by definition* proportional to the product between the two charges (that is, the amount of charge in a body would be defined by the amount of force it produced). Other authors argue that we can define and measure charge independently from the definition and measurement of force. If this is the case, the proportionality between the electric force and the product of the two charges might be obtained *experimentally*.

This electrostatic force is very similar to the gravitational force which Newton presented in his book *Mathematical Principles of Natural Philosophy*, usually known by its first Latin name, *Principia*.[8] This book was originally published in 1687. These two forces point along the straight line connecting the interacting bodies, they follow the principle of action and reaction, varying as the inverse square of the distance between the particles. Moreover, while the electric force depends on the product of the magnitude of the two charges, the gravitational force is proportional to the product between the interacting masses. It seems that Coulomb arrived at his force law more by analogy with Newton's law of gravitation than by his doubtful few measurements with the torsion balance.[9]

---

[5] [Cou85b, p. 611], [Pot84, p. 146] and [Gil71a, pp. 190-191].

[6] [Gil71b] and [Gil71a, pp. 190-192].

[7] [BW13].

[8] [New34], [New52], [New90], [New99], [New08] and [New10].

[9] [Hee92].

Definition 14.1

The fundamental interaction characterizing electric phenomena of charges at rest is called *electrostatic force*, *coulombic force*, *Coulomb's force* or *Coulomb's law*. Particles electrified with charges of the same sign repel one another, while particles electrified with opposite charges attract one another. This force is proportional to the product of the magnitude of the charges in the two bodies, varying as the inverse square of their distance (supposing bodies with small sizes compared with the distance between them). This force follows the principle of action and reaction, pointing along the straight line connecting the interacting particles.
The so-called *non-electrostatic forces* or *non-coulombic forces* are the forces acting on electrified particles which do not follow Coulomb's law.

In 1822 André-Marie Ampère (1775-1836) coined the expressions *electrostatic* and *electrodynamic*.[10]

Non-electrostatic forces are required in order to maintain a set of electrified bodies at rest relative to one another, in stable equilibrium. Non-electrostatic forces are also necessary in order to separate oppositely electrified particles, as in the amber effect. They are also necessary in resistive circuits carrying steady currents,[11] and in several other situations. This Chapter presents some phenomena which require the existence of these forces of non-electrostatic origin.

14.2 Non-Electrostatic Forces in Configurations of Stable Equilibrium

Samuel Earnshaw (1805-1888) proved in 1842 that it is impossible for a system of bodies to remain at rest relative to one another, in stable equilibrium, when the only forces acting between them are central and varying as the inverse square of their distances.[12] In nature, on the other hand, there are several systems in which the interacting electrified bodies remain at rest relative to one another, in stable equilibrium. Therefore, in all these situations, forces of non-electrostatic origin are necessary to balance the electrostatic forces and to give stability to the system.[13]

Suppose a spherical conductor C negatively electrified and insulated from the ground. It may have been charged, for instance, scraping a rubbed plastic ruler on its surface. Or by the ACR method, by touching a rubbed straw.

---

[10] [Amp22a, p. 60], [Amp22c, note on p. 200], [Amp22b, note on p. 237], [Amp85b, note on p. 239], [Amp85a, note on p. 192], [Blo82, p. 78], [Cha09, Section 1.3], [AC11, Section 1.4] and [AC15, Section 1.4].

[11] [AH07], [AH09] and [AH13].

[12] [Ear42], [Max54a, article 116, pp. 174-176] and [Sco59].

[13] See [VF80], [CS02, Section 18.7], [AH07, Section 5.3 and Appendix A], [AH09, Section 5.3 and Appendix A], [AH13, Section 5.3 and Appendix A], [AC11, Section 2.4], [AC15, Section 2.4], together with Sections 7.8 and 7.9 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

The charges on the conductor repel one another. In equilibrium they remain uniformly distributed on its surface, Figure 14.1.

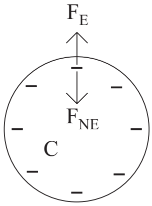


Figure 14.1: A spherical conductor C uniformly electrified. We show the net repulsive electrostatic force F_E acting on the upper negative charge, due to all other negative charges, and the force of non-electrostatic origin, F_{NE}, responsible for holding this upper charge at rest on the surface of the sphere.

Consider the negatively electrified particle located at the top of the sphere. It is repelled by all other negatively charged particles. Therefore, it is acted upon by a vertical electrostatic force F_E pointing away from the center of the sphere. A force of non-electrostatic origin pointing downward, F_{NE}, having the same intensity as the upward F_E, is needed to keep this negative particle at rest on the surface of the sphere. In this specific situation, this non-electrostatic force is sometimes called a contact force. But its origin is not clearly understood. We also don't know how it is produced, etc.

Heilbron mentioned the vexed question of the agency that prevents the escape of the electric fluids from the surface of conductors.[14]

The same situation happens when the conducting sphere is positively charged, Figure 14.2 (a). The same reasoning is also valid for an insulating sphere that is uniformly electrified, either negatively or positively, Figure 14.2 (b) and (c).

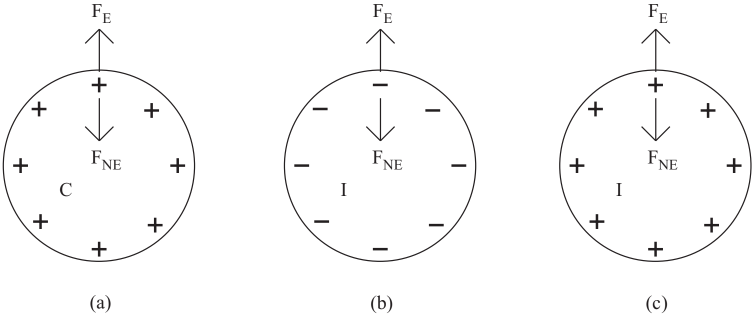


Figure 14.2: (a) Conducting sphere C positively electrified. (b) Insulating sphere I negatively electrified. (c) Insulating sphere I positively electrified.

In this figure F_E represents the net electrostatic force acting on the upper electrified particle and being due to the electrostatic repulsion exerted by

---

[14] [Hei99, pp. 499-500].

other electrified particles on the surface of the sphere where it is located. We represented by F_{NE} the force of non-electrostatic origin acting on the upper electrified particle and keeping it at rest on the surface of the sphere. When the electrified sphere is in equilibrium, F_{NE} has the same magnitude as F_E, but points in the opposite direction.

Another configuration of stable equilibrium takes place when a conductor, insulated from the ground, is polarized due to the presence of a nearby electrified body. Assume that a straw becomes negatively electrified after being rubbed in hair. Bring it close to an insulated conductor. The conductor becomes polarized by the electrified straw, Figure 14.3.

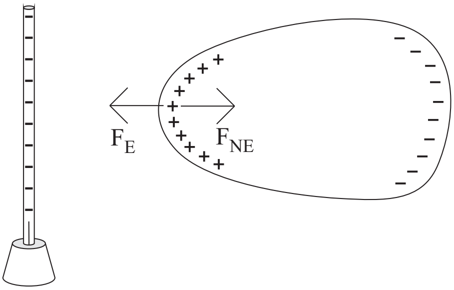


Figure 14.3: Conductor polarized by a nearby negatively charged straw.

In Figure 14.3 we represented by F_E the net electrostatic force acting on the positively electrified particle located at the left extremity of the conductor. It is due to the attraction exerted by the negative charges of the straw, and also to the electrostatic forces exerted on this particle by all other electrified particles on the surface of this conductor. In equilibrium this particle remains at rest. This equilibrium can only take place with the presence of another force acting on this positive particle, namely, a force of non-electrostatic origin represented here by F_{NE}. In equilibrium these two forces have the same magnitude, but point in opposite directions.

Consider now an insulator located close to a negatively charged straw. Each molecule of the insulator becomes polarized, positive in the region close to the straw and negative in the region far away from the straw, Figure 14.4 (a).

In Figure 14.4 (b) we considered a single molecule of this polarized insulator, that molecule located at its left end, closest to the straw. We represented by F_E and F_{NE} the net electrostatic and non-electrostatic forces, respectively, acting on the positive end of this polarized molecule. The electrostatic force is exerted by the negative charges of the straw, by the negative end of this molecule, and also by all other polarized molecules of this insulator. The net electrostatic force F_E points towards the negative straw. In equilibrium, the positive end of this molecule remains at rest. Therefore, in order to balance F_E, we need a force of non-electrostatic origin, F_{NE}. In equilibrium, both forces have the same magnitude, but point in opposite directions.

That is, in order to prevent the motion of electrified particles in bodies

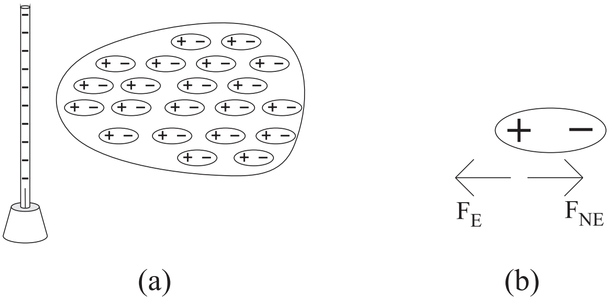


Figure 14.4: (a) Insulator polarized by a nearby negative straw. (b) Electrostatic and non-electrostatic forces, F_E and F_{NE}, acting on the positive end of a specific polarized molecule of the insulator.

like those of Figures 14.1 and 14.2, we need non-electrostatic forces opposing Coulomb's force. We also need non-electrostatic forces for conductors or insulators which are polarized due to nearby electrified bodies, as in Figures 14.3 and 14.4. Without the presence of these non-electrostatic forces, it would be impossible to keep bodies electrified and/or polarized in configurations of stable equilibrium.

There are a few situations in which there are zero net electrostatic forces acting on all particles of a system of charges. We illustrate an example in Figure 14.5.

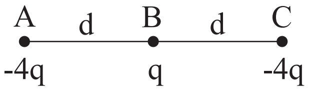


Figure 14.5: Particles A, B and C separated by a distance d along the straight line connecting them. Particles A and C are electrified with charge $-4q$, while particle B is electrified with charge q.

Suppose three point particles A, B and C separated by a distance d along a straight line. Particles A and C are equally electrified with charge $-4q$, while particle B is electrified with charge q. The electrostatic forces acting on these particles are represented in Figure 14.6.

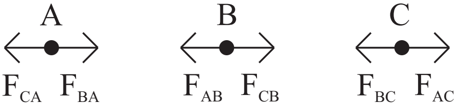


Figure 14.6: Electrostatic forces acting on the particles.

The left side of Figure 14.6 shows the repulsive force F_{CA} exerted by C on A and the attractive force F_{BA} exerted by B on A. According to Coulomb's law, these two forces cancel one another. The center of Figure 14.6 presents the attractive force F_{AB} exerted by A on B and the attractive force F_{CB} exerted by C on B. According to Coulomb's law, these two forces cancel one another. The right of Figure 14.6 illustrates the attractive force F_{BC} exerted by B on C and the repulsive force F_{AC} exerted by A on C. Once more, according to Coulomb's law, these two forces cancel one another.

In principle, these three particles might remain at rest in an inertial frame of reference, as there is no net force acting on each one of them, Figure 14.6. It might seem, therefore, that non-electrostatic forces are not required in this case. However, the equilibrium of this system is unstable. This fact can be illustrated by Figure 14.7 in which particle B has been moved slightly to the right, closer to C than to A.

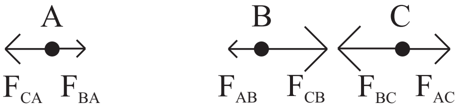


Figure 14.7: Electrostatic forces acting on the particles when B gets closer to C.

When particle B gets closer to C by any reason, the attractive force between them increases its magnitude. Likewise, the attractive force between A and B decreases its magnitude, due to the larger distance between these particles. Therefore, the net force acting on B points now towards C. By the same reason, the net force acting on C points towards B. The net force acting on A points now to the left, that is, away from the pair BC. Suppose that these particles are free to move under the action of these electric forces acting on them, beginning with the configuration of Figure 14.6. If any external perturbation makes B move slightly towards C, these two particles will begin to move towards one another. Particle A, on the other hand, will move away from the pair BC. This system of particles will then move away from the initial configuration of equilibrium.

That is, although the configuration of Figure 14.5 represents equilibrium, it is unstable. Any perturbation in this system will break it apart. This example illustrates Earnshaw's theorem. Therefore, in order to maintain this system of three particles in stable equilibrium, we need again forces of non-electrostatic origin.

Sodium chloride or kitchen salt is a typical ionic compound in stable equilibrium. It has a cubic crystalline structure composed of sodium and chloride ions, Na^+ and Cl^-. Non-electrostatic forces are required to balance the coulombic forces acting on the ions.

14.3 Non-Electrostatic Forces in the Amber Effect

Forces of non-electrostatic origin are also required in order to separate oppositely electrified particles, as in the amber effect. Before considering this effect, we remember the action of Coulomb's force on bodies oppositely electrified.

Suppose a conductor $C1$ positively electrified with a charge $+Q$, insulated from the ground, and another conductor $C2$ negatively electrified with a charge $-Q$, also insulated. When they touch one another, both conductors are neutralized. They remain neutral after separation, Figure 14.8.

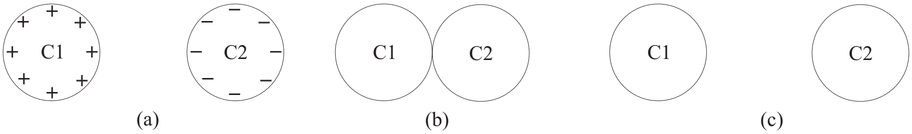


Figure 14.8: (a) Conducting spheres $C1$ and $C2$ separated from one another and oppositely electrified. (b) Neutralization of both spheres when they touch one another. (c) The spheres remain neutral after separation.

An experiment of this kind was performed in Volume 1 of this book.[15] It utilized two electroscopes oppositely electrified, Figure 14.9.

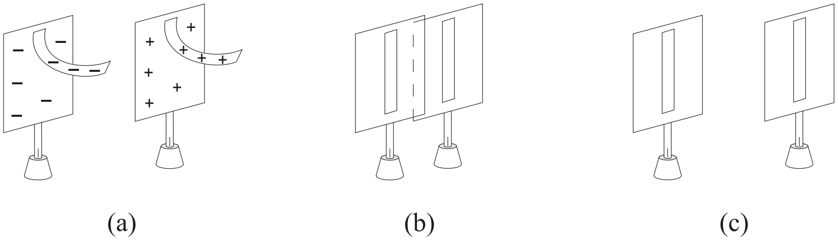


Figure 14.9: (a) A positive electroscope and a negative electroscope. (b) After contact, the strips drop. (c) After separation, the strips remain vertical, indicating that the electroscopes are now discharged.

Suppose now an insulator I electrified on its surface, like a straw negatively electrified after being rubbed in hair or in a paper napkin. Volume 1 of this book showed that one of the procedures to neutralize this insulator is to dip it into fresh water placed in a grounded metal bowl. After removing it from the water, the insulator has been neutralized. That is, it no longer attracts bits of paper close to it.[16] Figure 14.10 illustrates this procedure.

Water behaves as a conductor in electrostatic experiments. It contains free electrified particles (charged ions, H_3O^-, OH^- and many other electrified im-

---

[15] Section 6.9 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

[16] Section 7.14 of [Ass10b], [Ass10a], [Ass11], [Ass15b] and [Ass17].

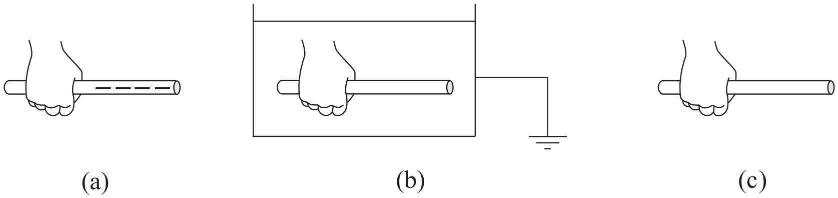


Figure 14.10: (a) Plastic straw negatively charged. (b) It is dipped into fresh water placed in a grounded metal bowl. (c) It is neutral when removed from the water.

purities) which can move through the water. When all portions of the electrified straw come into contact with the surrounding water, the straw becomes neutralized. The charges which were spread on its surface are now distributed through the liquid. As the water in this experiment is grounded, these net charges are then spread over the whole Earth. When the straw comes out of the water, observe that it is neutral. It is no longer able to attract small pieces of paper brought close to it.

This procedure shows that in order to neutralize an insulator which is electrified along its surface, you can submerge it in a conductor like water, grounding all points along the surface of the insulator.

Suppose now two insulating bodies A and B electrified with opposite charges $+Q$ and $-Q$ spread over their surfaces. These charges are not free to move along these bodies, as they are insulators. Therefore, in order to neutralize them, it would be necessary to bring into contact all their points oppositely charged. What will be described now is a supposition of what might happen in this ideal situation. Figure 14.11 illustrates qualitatively this hypothetical neutralization process of two oppositely electrified insulators with charges spread along their surfaces. We did not perform real experiments in which we succeeded in obtaining the neutralization of these two bodies by the process described in Figure 14.11.

Figure 14.11 (a) shows insulator A with three positive charges located at points $A1$, $A2$ and $A3$ of its surface, while insulator B has three negative charges located at points $B1$, $B2$ and $B3$ of its surface. In (b) points $A1$ and $B3$ touch one another, neutralizing these points. In (c) points $A2$ and $B2$ touch one another, neutralizing these points. In (d) points $A3$ and $B1$ touch one another, neutralizing these points. We finish with two neutral insulators when they are separated from one another, Figure 14.11 (e). Figure 14.11 (f) presents the electrostatic force F_E attracting oppositely charged particles when they are close to one another.

We will now consider the amber effect. The separation of charges taking place in this effect occurs against the action of Coulomb's force.

In the amber effect what takes place is exactly the opposite of the process represented in Figure 14.11. Suppose two insulators A and B made of different materials and initially neutral. Briskly rub one against the other with a relative velocity V. After separation, one of them becomes positively electrified with

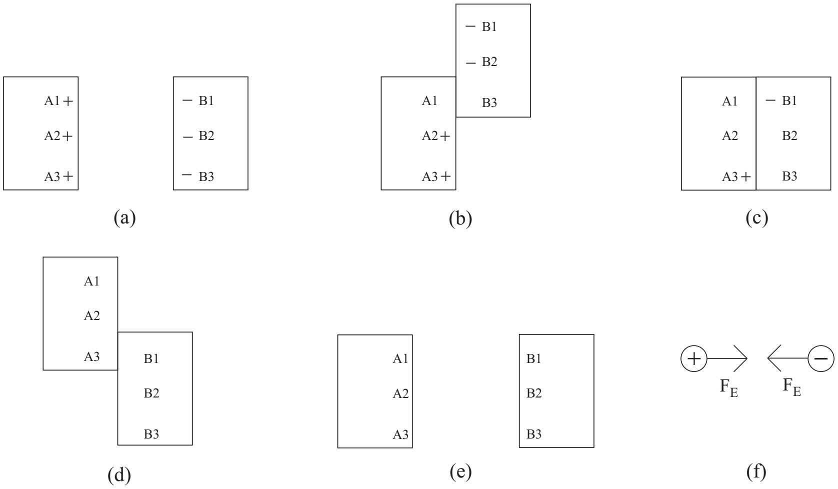


Figure 14.11: (a) Hypothetical neutralization of two insulators A and B oppositely electrified. (b) Neutralization of points $A1$ and $B3$ during their contact. (c) Neutralization of points $A2$ and $B2$ during their contact. (d) Neutralization of points $A3$ and $B1$ during their contact. (e) The insulators remain neutral after separation. (f) Electrostatic forces of attraction, F_E, acting between oppositely electrified particles.

a charge $+Q$, while the other insulator becomes negatively electrified with a charge $-Q$. Figure 14.12 illustrates the amber effect.

There are no electrostatic forces between two neutral particles, while two particles oppositely electrified attract one another with a force of electrostatic origin, F_E. In the amber effect we begin with two neutral insulators and finish with two bodies oppositely charged. Therefore, this separation of opposite charges could take place only through the action of a force of non-electrostatic origin, F_{NE}, acting between the oppositely charged particles while they were being separated from one another. This force F_{NE} tries to separate oppositely charged particles, while the electrostatic force F_E tries to unite them. These two types of force are represented in Figure 14.12 (f). Moreover, the magnitude of F_{NE} must be bigger than that of F_E while these oppositely charged particles were being separated during friction in the amber effect.

In conclusion, electrostatic forces could explain the hypothetical neutralization of the oppositely electrified insulators represented in Figure 14.11. However, these electrostatic forces acting alone could not explain the amber effect. After all, we begin with two neutral insulators and finish with them oppositely charged, Figure 14.12.

Therefore, the amber effect requires the existence of forces of non-electrostatic origin, F_{NE}. The oldest and simplest phenomenon of electricity requires the existence of these forces, otherwise it could not take place.

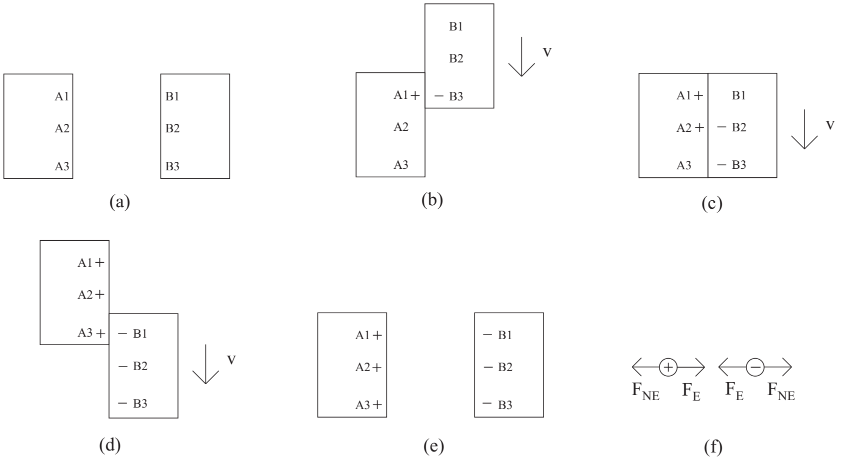


Figure 14.12: Qualitative representation of the amber effect. (a) Two insulators A and B initially neutral. From (b) to (d): Due to the friction between the interacting surfaces, these two bodies become electrified with opposite charges. (e) Final situation with the two oppositely electrified insulators. (f) Electrostatic forces of attraction, F_E, acting between oppositely charged particles, together with the forces of non-electrostatic origin, F_{NE}, acting between them. These forces of non-electrostatic origin are responsible for the separation of charges in situations (b) to (d).

14.3.1 Other Mysteries in the Amber Effect

Although the amber effect is the oldest phenomenon studied in electricity, there are still several mysteries associated with it. We don't know exactly the origin of the non-electrostatic force causing the separation of charges when two different substances are rubbed against each other. We also don't know the origin of the non-electrostatic force which maintains the charges at rest on the surface of electrified or polarized bodies. There are also other aspects of this effect which are still clouded in mysteries.

Most textbooks claim that there is a transfer of electrons between the two bodies of different nature which are being rubbed in the amber effect, one of them receiving electrons and the other losing these fundamental particles. However, even if the electrification is due to a transfer of electrons, the mechanism responsible for this exchange of particles taking place against Coulomb's force is not at all clear.

Moreover, is the amber effect (or triboelectrification in general) really due to a transfer of electrons? This claim appears in the textbooks as a general statement, no supporting experiments are quoted.

However, when we read the specialized literature written by scientists who are really performing experiments on this topic, we realize that there are still many doubts and uncertainties related to the fundamental electrification process taking place in the amber effect. W. R. Harper in his 1965 book *Contact and Frictional Electrification*, for instance, said the following:[17]

> A crucial question for the explanation of the production of static charge is whether the charging of insulators comes from a transfer of electrons, of ions, or of both. Montgomery would say that the carriers of charge are *always* electrons and Loeb that they are *generally* electrons: Henry feels that the question is still an open one. I am of the opinion that a definite answer can now be given which is that the carriers are *never* electrons—when the material being charged is strictly an insulator.

I don't know the answer to this question. I just quote here a few references discussing this topic experimentally.[18]

14.4 Non-Electrostatic Forces Acting Inside a Battery

In 1800 Volta published his invention of the electric pile or battery.[19] He arranged sequences of disks in the following order, from bottom to top: silver, zinc, disk of moistened pasteboard; silver, zinc, disk of moistened pasteboard; silver, zinc, disk of moistened pasteboard; etc. By connecting the lower silver with the upper zinc through a metal wire, he observed that a constant current flowed through the wire.

Figure 14.13 illustrates schematically the chemical pile or battery.

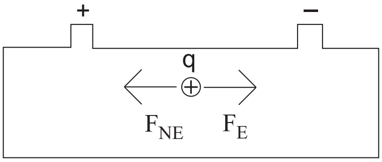


Figure 14.13: Charged battery with a positive and mobile ion q inside it.

The battery has a positive terminal $+$ and a negative terminal $-$. We also drew a particle electrified with a charge q inside the battery. It represents an ion which can move inside the battery, that is, a mobile electrified particle. Assume that q is positive. There is then an electrostatic force F_E acting on it and pointing from the positive to the negative terminal. This electrostatic force tends to discharge the battery. That is, if it were acting alone, the positive particle q would move towards the negative terminal of the battery, neutralizing it. However, it is possible to keep a battery charged for many days when its terminals are not connected through a metal wire. Therefore, in this situation of equilibrium in which the battery remains electrified, despite the existence

---

[17] As quoted in [Bai01] and [Gal14].

[18] [Bai01], [Sch07], [MWW07], [MW08], [LB08], [LB09], [Wil12], [Gal14] and [GB17].

[19] [Vol00a], [Vol00b], [Vol64], [Mag06] and [MA08].

of mobile ions inside it, a force of non-electrostatic origin, F_{NE}, is necessary. When there is no current flowing through the battery, these two forces acting simultaneously on the ion, F_E and F_{NE}, have the same magnitude but point in opposite directions, Figure 14.13.

There is another situation showing the necessary existence of a force of non-electrostatic origin inside a battery, namely, when it is being charged or electrified. Place diluted sulfuric acid inside an insulating receptacle. This acid is electrically neutral as a whole, although there are many positive and negative mobile ions inside it. Consider two neutral laminae or plates, one of zinc and the other of copper. The zinc plate is partially dipped into the acid at a border of the receptacle, while the copper plate is partially dipped at the other border. This simple process electrifies oppositely these two plates. Zinc becomes negatively electrified, while copper becomes positively electrified. This separation of charges can only take place due to the action of a non-electrostatic force. After all, electrostatic forces tend to neutralize bodies oppositely charged. In this particular example, on the other hand, we begin with two different bodies, zinc and copper, initially neutral. At the end of the process, one of them is positively electrified, while the other is negatively electrified. This charging mechanism does not increase indefinitely. We reach a saturation value in which there is a constant potential difference between the zinc and copper plates. In the time interval during which the potential difference went from zero up to this saturation value, the force of non-electrostatic origin separating the opposite charges had a greater magnitude than the electrostatic force tending to unite them.

Therefore, forces of non-electrostatic origin are also acting in the chemical reactions which take place at the electrodes of an electrical pile or battery.

14.5 Non-Electrostatic Forces in Circuits Carrying Steady Currents

When a resistive metal wire is connected to the two terminals of a battery, a constant electric current flows through the closed circuit, as discussed in Section 3.4. According to Ohm's law, the voltage or potential difference between the extremities of the wire is proportional to its resistance and to the electric current flowing through it. This law can also be expressed microscopically. A metal has free electrons which can move relative to the lattice of the metal. According to the microscopic version of Ohm's law, the electric force acting on a mobile free electron is balanced by a resistive force when there is a constant current flowing in the circuit. This resistive force is proportional to the velocity of the conduction electron relative to the lattice of the metal. The electric and resistive forces act in opposite directions. They have the same magnitude when a steady current is flowing in the circuit.

The electric force is due to Coulomb's law. It acts on any free electron, being exerted by a distribution of charges located on the surface of the resistive wire.

The surface density of these charges varies along the length of the resistive wire, although it is constant in time for steady currents. The electric force propels the free electron, creating the electric current.

The resistive force acting on any free electron, on the other hand, has a non-electrostatic origin. It is proportional to the drifting velocity of the electron relative to the lattice of the metal. The magnitude of this force increases when the velocity of the free electron is increasing. In a very short time after the connection of the wire to the battery, the free electron reaches a constant velocity. In this steady situation the resistive force has the same magnitude as the electric force, with these two forces acting in opposite directions. This resistive force prevents the indefinite acceleration of the free electron exerted by the electric force.

There is also a force of non-electrostatic origin acting on the mobile negative charges located inside the battery. It propels them from the positive terminal of the battery towards the negative terminal. The electrostatic force acting on a negative particle located inside the battery, on the other hand, points from the negative terminal towards the positive terminal.

These topics were discussed in detail in our book *The Electric Force of a Current: Weber and the Surface Charges of Resistive Conductors Carrying Steady Currents*.[20]

14.6 Non-Electrostatic Forces in Other Situations

There are several other mechanisms in which we begin with two neutral bodies A and B, ending with A positively electrified and B negatively electrified. There are also many other procedures in which we begin with a single neutral body insulated from the ground, ending with this body electrically polarized, that is, with one side positive and another side negative. Non-electrostatic forces are required in all these mechanisms. We list a few of these processes below:

- When two dissimilar metals are placed in contact, one of them becomes positively electrified and the other negatively electrified, with a potential difference between them. This effect is determined by work function differences between the metals. This is the so-called Volta effect, Volta potential difference, outer potential difference, or contact potential difference.[21]

- Contact electrification (or contact tension) in general.[22] In Chapter 5, for instance, we discussed the electrification of adhesive tapes.

- Electrification by chemical reactions. There are several different processes studied in electrochemistry.

---

[20] [AH07], [AH09] and [AH13].

[21] [Whi73a, pp. 71-73] and [Whi73b, pp. 90 and 235].

[22] [Jef59].

- The thermoelectric effect, that is, the direct conversion of temperature differences to electric voltage. A thermoelectric device creates a potential difference between two sides when there is a different temperature on each side.

- The pyroelectric effect, which should not be confused with thermoelectricity. Some crystals generate a temporary voltage when they are heated or cooled. When the whole material is changed from one temperature to another, a temporary voltage appears across the crystal.

- The piezoelectric effect, that is, the production of a potential difference between two faces of a material when it is mechanically compressed or deformed.

- Electrification by pressure, which should not be confused with piezoelectricity.[23]

- The photoelectric effect, that is, the emission of electrons by a material when light of a sufficiently high frequency, which depends on the substance, is shone onto the material.

- The production of electrets. They can be monopolar (with a total charge different from zero) or dipolar (with zero total charge, but with a permanent dipole moment). Forces of non-electrostatic origin are required to separate these charges and produce the electrets.[24]

- Non-electrostatic forces are required not only to produce electrets, but also to maintain their electrification after they were produced. These forces are necessary to prevent their discharge or to prevent their neutralization.

- Etc.

In all these cases we need a force of non-electrostatic origin to produce the polarization of an initially neutral body, with one side of this body becoming positive and the other side negative. A force of non-electrostatic origin is also required to produce the separation of charges between two bodies initially neutral, with one of these bodies becoming positive and the other negative. We also need a force of non-electrostatic origin to induce a current along a closed resistive circuit, like a ring.

14.7 Origins of the Non-Electrostatic Forces

We believe that the origin of the non-electrostatic forces mentioned in Sections 14.2 up to 14.6 is not well known. These forces must exist in order to produce these phenomena. On the other hand, in our opinion, many aspects related

---

[23] [Kat06, pp. 15 and 239-246], [BW10] and [WB11].

[24] [Net94], [Sil10b], [Sil10a], [Bos11, Chapter 8, pp. 226-248] and [BAC12, Chapter 19, pp. 373-392].

to these forces have not yet been clarified in many situations: their origins, their mathematical expressions, their properties and the magnitudes on which they depend. This lack of a complete knowledge happens even in the oldest phenomenon of electrostatics, namely, the amber effect. It is not yet completely clear what causes the separation of charges when two bodies are rubbed against one another. Likewise, the mechanism responsible for charge separation when there is no friction, like in contact electrification of two different materials, has not been completely explained. Maybe the mechanism taking place in the electrification (due to contact or due to friction) of two kinds of metal (like copper and zinc) may be different from the mechanism taking place in the mutual electrification of a conductor and an insulator (like copper and plastic), or from the mechanism taking place in the mutual electrification of two kinds of insulator (like plastic and rubber).

There are, however, some cases in which we do have a good knowledge about the origins and properties of these non-electrostatic forces. We quote here some examples:

- When an open conductor, like a metal bar, moves relative to a permanent magnet, the conductor may become polarized (positive in one extremity and negative in the other). The same effect may also happen when the open conductor moves relative to a closed circuit carrying a steady current.

- When a closed conductor, like a ring, moves relative to a permanent magnet, an electric current can be induced in the ring. The same effect can also happen when the ring moves relative to another closed circuit carrying a steady current.

- Suppose now an open conductor, like a metal bar, at rest relative to a nearby closed circuit. When a variable current flows in the circuit, the conductor can become polarized.

- Suppose now a closed conductor, like a ring, at rest relative to a nearby closed circuit. When a variable current flows in the circuit, a current can be induced in the ring.

There are more general situations in which we have mathematical expressions describing non-electrostatic forces, namely:

- The force between two magnets.

- The force between two conductors carrying steady currents.

- The force between a magnet and a conductor carrying a steady current.

- The force between a magnet and an electrified particle which is in motion relative to the magnet.

- The force between a closed circuit carrying a steady current and an electrified particle which is in motion relative to the circuit.

- The force between a closed circuit carrying a current varying in time and an electrified particle which is stationary or in motion relative to the circuit.

- The force between two electrified particles moving relative to one another.

In these specific situations there are two main electromagnetic theories yielding the forces acting between the electrified particles. These forces may, for instance, polarize an initially neutral conductor insulated from the ground. These forces can also induce a current in a resistive metal ring. These two theories describe the forces between electrified particles not only when they are at rest, but also when they move relative to one another. This motion can be a relative velocity or a relative acceleration between these particles.

The next Subsections present briefly these two rival theories.

14.7.1 Faraday and Maxwell's Theory Based on Electromagnetic Fields

The electromagnetic theory appearing in most textbooks was developed by many authors, including Michael Faraday, James Clerk Maxwell and Hendrik Antoon Lorentz (1853-1928).[25] This theory assumes that a moving charged particle, called a source charge, generates an electric field and a magnetic field around it. These fields would be propagated in space, tipically at light velocity. When they reach another moving charged particle, called a test charge, these fields would exert an electric force and a magnetic force on this test charge. One of the great problems with this theory is to understand the meaning of these electromagnetic fields. Usually this topic is not discussed in the textbooks.

Faraday, Maxwell and most textbooks present several definitions for the field concept. Sometimes they say that it is a region of space around the source charge. In other situations they claim that this field propagates in space. Sometimes they define field as a vector quantity that has both magnitude and direction. In some contexts they mention that these fields carry linear momentum and energy. They also present many other different definitions and properties of the field concept.

The problem is that these several definitions contradict one another.[26] For instance, how can a region of space propagate in space? How can a region of space have magnitude and direction? The gravitational field, the electric field and the magnetic field have different dimensions. Therefore these three magnitudes could not have the same name, "field," as they are magnitudes of different nature. Each one of these three magnitudes should be classified in a different category, receiving a different name according to the category where it belongs. There are many other contradictions between these several definitions of the field concept which will not be discussed here.

---

[25] [Far52], [Max54b] and [Lor95].

[26] As discussed in Section 2.9 of [Ass13] and in Sections 3.1 and 3.2 of [Ass14].

The mathematical expression of the force exerted by the electric and magnetic fields acting on a test charge is due essentially to the works of Maxwell and Lorentz. This force expression is also problematic. In the magnetic force, in particular, we have the velocity of the test charge. However, the meaning of this velocity changes according to the scientist presenting this magnetic force. The meaning of this velocity is different, for instance, according to the following scientists: Maxwell, J. J. Thomson (1856-1940) e O. Heaviside (1850-1925), Lorentz, A. Einstein (1879-1955), etc. We are then puzzled or at a loss here. The velocity $\vec{v}$ appearing in the magnetic force is then the velocity of the test charge relative to what? Normally the textbooks do not discuss this question. This lack of discussion is absurd. After all, we can only apply this force when we understand the frame of reference relative to which this velocity should be understood. Moreover, even when these textbooks present this velocity, they disagree with one another as regards its meaning. Some authors mention that it is relative to the magnetic field. Other authors mention that it should be understood relative to an inertial frame of reference. Some authors say that it is relative to the medium where the test charge is moving. In other situations they claim that it is relative to the detector of the magnetic field. Some authors mention that it is relative to the source of the magnetic field (like a magnet or current carrying wire). Etc. We discussed the meanings and origins of the magnetic force acting on a test charge in another book and will not go into details here.[27]

14.7.2 Weber's Electrodynamics Based on the Interaction between Electrified Particles

There is another theory which explains these phenomena without utilizing the concepts of electric and magnetic fields. It is based on the direct interaction between electrified particles. There is no intermediate agent for this interaction.

This theory is based essentially on the ideas developed by Isaac Newton, Figure 7.12. In his book *Principia* of 1687 Newton presented his law of universal gravitation.[28] According to Newton, the force between two particles is proportional to the product of their masses, varies inversely as the inverse square of their distance, acts along the straight line connecting the particles and follows the principle of action and reaction.

Charles Augustin de Coulomb, Figure 2.16, obtained an analogous expression describing the interaction between two electrified particles at rest relative to one another, as discussed in Section 14.1. He also obtained a similar expression describing the force between magnetic poles. That is, a force proportional to the product of the intensities of the magnetic poles, varying as the inverse square of their distance, acting along the straight line connecting them and following the principle of action and reaction.[29]

---

[27] See Section 14.5 of [Ass13] and Section 15.5 of [Ass14].

[28] [New34], [New90], [New08] and [New10].

[29] Section 2.5 of [Ass13] and [Ass14].

Oersted published in 1820 his famous experiment describing the deflection of a magnetized needle due to the action of a nearby straight wire carrying a steady current, as mentioned on Section 3.4. André-Marie Ampère, Figure 14.14, was greatly influenced by Oersted's discovery.

Figure 14.14: André-Marie Ampère (1775-1836).

Between 1820 and 1827 Ampère made many experiments and theoretical researches showing for the first time the existence of forces and torques between current carrying wires. Moreover, in order to explain Oersted's discovery, he assumed the existence of microscopic electric currents inside magnets. He obtained an extremely important expression yielding the force between two current elements. This force acts along the straight line connecting the elements, is proportional to the product of the current intensities, varies as the inverse square of their distance and follows the principle of action and reaction. Maxwell considered Ampère's force between current elements the cardinal formula of electrodynamics, that is, its most important result:[30]

> The experimental investigation by which Ampère established the laws of the mechanical action between electric currents is one of the most brilliant achievements in science. The whole, theory and experiment, seems as if it had leaped, full grown and full armed, from the brain of the 'Newton of electricity.' It is perfect in form, and unassailable in accuracy, and it is summed up in a formula from which all the phenomena may be deduced, and which must always remain the cardinal formula of electro-dynamics.

Unfortunately Ampère's force between current elements does not appear in most modern textbooks dealing with electromagnetism, being unknown by most scientists. These textbooks present only the force between current elements due to H. G. Grassmann (1809-1877). This force is based on the works of J.-B. Biot (1774-1862) and F. Savart (1791-1841). Maxwell knew Grassmann's force. He compared Grassmann's force, Ampère's force and two other expressions created by Maxwell himself. After comparing these four expressions, Maxwell came to the following conclusion:[31]

---

[30] [Max54b, article 528, p. 175].

[31] [Max54b, article 527, p. 174].

> 527.] Of these four different assumptions that of Ampère is undoubtedly the best, since it is the only one which makes the forces on the two elements not only equal and opposite but in the straight line which joins them.

By integrating his force between two current elements around two closed circuits, coupled with the assumption of microscopic electric currents inside magnets and also inside the Earth, Ampère succeeded in explaining quantitatively three kinds of phenomena, namely, (I) magnetism (forces and torques between magnets, together with the torques and forces between a magnet and the Earth), (II) electrodynamics (forces and torques between current carrying wires), and (III) electromagnetism (forces and torques between a magnet and a current carrying wire, together with the forces and torques between the Earth and a current carrying wire). In 1826 he published his main book on this subject, which is available in French, Portuguese and English.[32]

The works of Newton, Coulomb and Ampère were developed by the physicist Wilhelm Eduard Weber (1804-1891), Figure 14.15.

Figure 14.15: Wilhelm Eduard Weber (1804-1891).

Weber's complete works were published in six volumes between 1892 and 1894.[33] He wrote eight major Memoirs between 1846 and 1878 under the general title *Elektrodynamische Maassbestimmungen*.[34] This title can be translated

---

[32] [Amp26], [Amp23], [Cha09], [AC11] and [AC15]. See also [Ass92a], [Ass94], [BA01], [BA15] and [Ass15a].

[33] [Web92b], [Web92a], [Web93], [Web94b], [WW93] and [WW94].

[34] [Web46], [Web52b], [Web52a], [KW57], [Web64], [Web71], [Web78] and [Web94a].

as *Electrodynamic Measurements*, *Determination of Electrodynamic Measures* or *Electrodynamic Measure Determinations*. The eighth Memoir was published only posthumously in his complete works. Three of these eight major Memoirs have already been translated into English, namely, the first, *Determinations of electrodynamic measure: Concerning a universal law of electrical action*;[35] the sixth, *Electrodynamic measurements—Sixth Memoir, relating specially to the principle of the conservation of energy*;[36] and the eighth, *Determinations of electrodynamic measure: Particularly in respect to the connection of the fundamental laws of electricity with the law of gravitation*.[37] An abridged version of the first Memoir was published in 1848,[38] which has also been translated into English, *On the measurement of electro-dynamic forces*.[39] In 2010 we published a list with all his works translated into English.[40] His only work translated into Portuguese was a joint work with his collaborator Rudolf Kohlrausch (1809-1858) describing the first measurement of a fundamental constant appearing in Weber's force.[41] Several authors discussed this extremely important and pioneering measurement of Weber and Kohlrausch.[42]

Weber obtained a force between electrified particles depending only on the distance between these charges, on the relative radial velocity between them, and on the relative radial acceleration between them. It is a central force acting along the straight line connecting these two particles and complying with the principle of action and reaction. It satisfies the three principles of conservation, namely, linear momentum, angular momentum and energy. With Weber's electrodynamics we can deduce Coulomb's force and also the law of C. F. Gauss (1777-1855). With Weber's law we can also deduce Ampère's force between current elements, the magnetic circuital law and Faraday's law of induction.

Weber's electrodynamics is not discussed in modern textbooks. Despite this fact, there is a growing interest in this theory in recent times. This interest has been motivated by new experiments and new theoretical results.

I believe in Weber's electrodynamics and consider it the deepest and most important formulation ever presented describing the interactions between electrified particles. I have been working with this theory ever since I discovered about it.[43]

---

[35] [Web07].

[36] [Web72].

[37] [Web08].

[38] [Web48].

[39] [Web66].

[40] [Ass10c].

[41] [WK56] and [WK08].

[42] [Kir57], [Ros57], [Woo68], [Woo81], [Wis81], [Ros81], [Har82], [JM86, Vol. 1, pp. 144-146 and 296-297] and [Hec96].

[43] See, for instance, [Wie60], [Wie67], [Whi73a, pp. 201-206], [Ass89], [Ass90a], [Ass90b], [Ass91b], [Ass91a], [Ass92a], [Ass92c], [Ass92b], [AC93], [Ass94], [GA94], [Ass95a], [Ass95c], [Ass95b], [AB95], [AB96], [GV99], [BA01], [ARW02], [Fuk03], [AW03], [ARW04], [AH07], [AH09], [AWW11], [AH13], [AWW14], [BA15] and [Ass15a], together with the references quoted in these works.

Bibliography

[AB95] A. K. T. Assis and M. Bueno. Longitudinal forces in Weber's electrodynamics. *International Journal of Modern Physics B*, 9:3689–3696, 1995.

[AB96] A. K. T. Assis and M. A. Bueno. Equivalence between Ampère and Grassmann's forces. *IEEE Transactions on Magnetics*, 32:431–436, 1996.

[AC93] A. K. T. Assis and R. A. Clemente. The influence of temperature on gravitation. *Il Nuovo Cimento B*, 108:713–716, 1993.

[AC11] A. K. T. Assis and J. P. M. d. C. Chaib. *Eletrodinâmica de Ampère: Análise do Significado e da Evolução da Força de Ampère, Juntamente com a Tradução Comentada de Sua Principal Obra sobre Eletrodinâmica.* Editora da Unicamp, Campinas, 2011. ISBN: 9788526809383.

[AC15] A. K. T. Assis and J. P. M. C. Chaib. *Ampère's Electrodynamics — Analysis of the Meaning and Evolution of Ampère's Force between Current Elements, together with a Complete Translation of His Masterpiece: Theory of Electrodynamic Phenomena, Uniquely Deduced from Experience.* Apeiron, Montreal, 2015. ISBN: 978-1-987980-03-5. Available at `www.ifi.unicamp.br/~assis`.

[Ach96] M. Achilles. *Historische Versuche der Physik nachgebaut und kommentiert.* Wötzel, Frankfurt, 2nd edition, 1996.

[AH07] A. K. T. Assis and J. A. Hernandes. *The Electric Force of a Current: Weber and the Surface Charges of Resistive Conductors Carrying Steady Currents.* Apeiron, Montreal, 2007. ISBN: 9780973291155. Available at `www.ifi.unicamp.br/~assis`.

[AH09] A. K. T. Assis and J. A. Hernandes. *A Força Elétrica de uma Corrente: Weber e as Cargas Superficiais de Condutores Resistivos com Correntes Constantes*, volume 73 of *Coleção Acadêmica.* Edusp and Edufal, São Paulo and Maceió, 2009. ISBNs: 9788531411236 and 9788571774315.

[AH13] A. K. T. Assis and J. A. Hernandes. *Elektrischer Strom und Oberflächenladungen: was Wilhelm Weber schon vor mehr als 150 Jahre wußte.* Apeiron, Montreal, 2013. German translation by H. Härtel. ISBN: 9780992045609. Available at www.ifi.unicamp.br/~assis.

[Amp22a] A.-M. Ampère. Expériences relatives à de nouveaux phénomènes électro-dynamiques. *Annales de Chimie et de Physique*, 20:60–74, 1822.

[Amp22b] A.-M. Ampère. Expériences relatives aux nouveaux phénomènes électro-dynamiques que j'ai obtenus au mois de décembre 1821. In A.-M. Ampère, editor, *Recueil d'Observations Électro-dynamiques*, pages 237–250. Crochard, Paris, 1822. Despite this date, the volume of the Recueil was only published in 1823.

[Amp22c] A.-M. Ampère. Exposé sommaire des nouvelles Expériences électromagnétiques faites par différens Physiciens, depuis le mois de mars 1821, lu dans la séance publique de l'Académie royale des Sciences, le 8 avril 1822. In A.-M. Ampère, editor, *Recueil d'Observations Électro-dynamiques*, pages 199–206. Crochard, Paris, 1822. Despite this date, the volume of the Recueil was only published in 1823.

[Amp23] A.-M. Ampère. Mémoire sur la théorie mathématique des phénomènes électro-dynamiques uniquement déduite de l'expérience, dans lequel se trouvent réunis les Mémoires que M. Ampère a communiqués à l'Académie royale des Sciences, dans les séances des 4 et 26 décembre 1820, 10 juin 1822, 22 décembre 1823, 12 septembre et 21 novembre 1825. *Mémoires de l'Académie Royale des Sciences de l'Institut de France*, 6:175–387, 1823. Despite this date, the work was only published in 1827.

[Amp26] A.-M. Ampère. *Théorie des Phénomènes Électro-dynamiques, Uniquement Déduite de l'Expérience.* Méquignon-Marvis, Paris, 1826.

[Amp85a] A.-M. Ampère. Expériences relatives aux nouveaux phénomènes électro-dynamiques obtenus au mois de décembre 1821. In J. Joubert, editor, *Collection de Mémoires relatifs a la Physique,* Vol. II: *Mémoires sur l'Électrodynamique*, pages 192–204. Gauthier-Villars, Paris, 1885.

[Amp85b] A.-M. Ampère. Exposé sommaire des nouvelles expériences électromagnétiques faites par différens physiciens, depuis le mois de mars 1821, lu dans la séance publique de l'Académie royale des Sciences, le 8 avril 1822. In J. Joubert, editor, *Collection de Mémoires relatifs a la Physique,* Vol. II: *Mémoires sur l'Électrodynamique*, pages 238–244. Gauthier-Villars, Paris, 1885.

[APZ06] M. S. Amin, T. F. Peterson Jr., and M. Zahn. Advanced Faraday cage measurements of charge and open-circuit voltage using water dielectrics. *Journal of Electrostatics*, 64:424–340, 2006.

[ARW02] A. K. T. Assis, K. Reich, and K. H. Wiederkehr. Gauss and Weber's creation of the absolute system of units in physics. *21st Century Science & Technology*, Vol. 15, No. 3:40–48, 2002.

[ARW04] A. K. T. Assis, K. Reich, and K. H. Wiederkehr. On the electromagnetic and electrostatic units of current and the meaning of the absolute system of units — For the 200th anniversary of Wilhelm Weber's birth. *Sudhoffs Archiv*, 88:10–31, 2004.

[Ass89] A. K. T. Assis. On Mach's principle. *Foundations of Physics Letters*, 2:301–318, 1989.

[Ass90a] A. K. T. Assis. Deriving Ampère's law from Weber's law. *Hadronic Journal*, 13:441–451, 1990.

[Ass90b] A. K. T. Assis. Modern experiments related to Weber's electrodynamics. In U. Bartocci and J. P. Wesley, editors, *Proceedings of the Conference on Foundations of Mathematics and Physics*, pages 8–22, Blumberg, Germany, 1990. Benjamin Wesley Publisher.

[Ass91a] A. K. T. Assis. Can a steady current generate an electric field? *Physics Essays*, 4:109–114, 1991.

[Ass91b] A. K. T. Assis. Wilhelm Eduard Weber (1804-1891) — Sua vida e sua obra. *Revista da Sociedade Brasileira de História da Ciência*, 5:53–59, 1991.

[Ass92a] A. K. T. Assis. *Curso de Eletrodinâmica de Weber*. Setor de Publicações do Instituto de Física da Universidade Estadual de Campinas — UNICAMP, Campinas, 1992. Notas de Física IFGW Número 5. Available at `www.ifi.unicamp.br/~assis` and `www.bibliotecadigital.unicamp.br/document/?down=60362`.

[Ass92b] A. K. T. Assis. On forces that depend on the acceleration of the test body. *Physics Essays*, 5:328–330, 1992.

[Ass92c] A. K. T. Assis. On the mechanism of railguns. *Galilean Electrodynamics*, 3:93–95, 1992.

[Ass94] A. K. T. Assis. *Weber's Electrodynamics*. Kluwer Academic Publishers, Dordrecht, 1994. ISBN: 0792331370.

[Ass95a] A. K. T. Assis. Acceleration dependent forces: reply to Smulsky. *Apeiron*, 2:25, 1995.

[Ass95b] A. K. T. Assis. A eletrodinâmica de Weber e seus desenvolvimentos recentes. *Ciência e Natura*, 17:7–16, 1995.

[Ass95c] A. K. T. Assis. Weber's force versus Lorentz's force. *Physics Essays*, 8:335–341, 1995.

[Ass10a] A. K. T. Assis. *The Experimental and Historical Foundations of Electricity*. Apeiron, Montreal, 2010. ISBN: 9780986492631. Available at `www.ifi.unicamp.br/~assis`.

[Ass10b] A. K. T. Assis. *Os Fundamentos Experimentais e Históricos da Eletricidade*. Apeiron, Montreal, 2010. ISBN: 9780986492617. Available at `www.ifi.unicamp.br/~assis`.

[Ass10c] A. K. T. Assis. Wilhelm Weber's works translated into English. *21st Century Science & Technology*, Vol. 22, No. 4:67–69, 2010.

[Ass11] A. K. T. Assis. *Os Fundamentos Experimentais e Históricos da Eletricidade*. Editora Livraria da Física, São Paulo, 2011. ISBN: 9788578610975.

[Ass13] A. K. T. Assis. *Mecânica Relacional e Implementação do Princípio de Mach com a Força de Weber Gravitacional*. Apeiron, Montreal, 2013. ISBN: 9780986492693. Available at `www.ifi.unicamp.br/~assis`.

[Ass14] A. K. T. Assis. *Relational Mechanics and Implementation of Mach's Principle with Weber's Gravitational Force*. Apeiron, Montreal, 2014. ISBN: 978-0-9920456-3-0. Available at `www.ifi.unicamp.br/~assis`.

[Ass15a] A. K. T. Assis. *Eletrodinâmica de Weber: Teoria, Aplicações e Exercícios*. Editora da Unicamp, Campinas, 2nd edition, 2015. e-ISBN: 978-85-268-1240-6.

[Ass15b] A. K. T. Assis. *The Experimental and Historical Foundations of Electricity*. Apeiron, Montreal, 2015. Book in Russian translated from the English version by A. Baraov. ISBN: 978-0-9920456-9-2. Available at `www.ifi.unicamp.br/~assis`.

[Ass17] A. K. T. Assis. *I Fondamenti Sperimentali e Storici dell'Elettricità*. Associazione per l'Insegnamento della Fisica, Parma, 2017. La Fisica nella Scuola, Anno L, n. 2 Supplemento, Quaderno 26. Translated by P. Cerreta, A. Cerreta and R. Cerreta. Edited by P. Cerreta, R. Serafini and R. Urigu. Available at `www.ifi.unicamp.br/~assis`.

[AW03] A. K. T. Assis and K. H. Wiederkehr. Weber quoting Maxwell. *Mitteilungen der Gauss-Gesellschaft*, 40:53–74, 2003.

[AWW11] A. K. T. Assis, K. H. Wiederkehr, and G. Wolfschmidt. *Weber's Planetary Model of the Atom*, volume 19 of *Nuncius Hamburgensis — Beiträge zur Geschichte der Naturwissenschaften*. Tredition Science, Hamburg, 2011. Edited by G. Wolfschmidt. ISBN: 9783842402416.

[AWW14] A. K. T. Assis, K. H. Wiederkehr, and G. Wolfschmidt. *O Modelo Planetário de Weber para o Átomo*. Apeiron, Montreal, 2014. ISBN: 9780992045654. Available at www.ifi.unicamp.br/~assis.

[BA01] M. d. A. Bueno and A. K. T. Assis. *Inductance and Force Calculations in Electrical Circuits*. Nova Science Publishers, Huntington, New York, 2001. ISBN: 1560729171.

[BA15] M. Bueno and A. K. T. Assis. *Cálculo de Indutância e de Força em Circuitos Elétricos*. Apeiron, Montreal, 2nd edition, 2015. ISBN: 978-1-987980-01-1. Available at www.ifi.unicamp.br/~assis.

[BAC12] S. L. B. Boss, A. K. T. Assis, and J. J. Caluzi. *Stephen Gray e a Descoberta dos Condutores e Isolantes: Tradução Comentada de Seus Artigos sobre Eletricidade e Reprodução de Seus Principais Experimentos*. Editora Cultura Acadêmica da Unesp, São Paulo, 2012. Available at: www.culturaacademica.com.br/catalogo-detalhe.asp?ctl_id=354.

[Bai01] A. G. Bailey. The charging of insulator surfaces. *Journal of Electrostatics*, 51-52:82–90, 2001.

[BC07] S. L. B. Boss and J. J. Caluzi. Os conceitos de eletricidade vítrea e eletricidade resinosa segundo Du Fay. *Revista Brasileira de Ensino de Física*, 29:635–644, 2007.

[Bea96] W. Beaty. Sticky electrostatics. Available at www.amasci.com/emotor/sticky.html, 1996.

[Beu92] G. Beuermann. "Sie schwänzen aber jetzt schon, bis es blitzt und donnert" - Physik - Lichtenbergs Leidenschaft. *Physikalische Blätter*, 48:440–444, 1992.

[BGP16] T. A. L. Burgo, F. Galembeck, and G. H. Pollack. Where is water in the triboelectric series? *Journal of Electrostatics*, 80:30–33, 2016. Doi: 10.1016/j.elstat.2016.01.002.

[BJ92] P. Brix and U. Joost. Mit weningen Worten viel sagen - Georg Christoph Lichtenberg zum 250. Geburtstag. *Physikalische Blätter*, 48:437–439, 1992.

[Blo82] C. Blondel. *A.-M. Ampère et la Création de l'Électrodynamique (1820-1827)*. Bibliothèque Nationale, Paris, 1982.

[Bos] T. H. S. Bossa *et al.* Estudo da condutividade elétrica de vidros isoladores de linhas de transmissão HVDC dopados. In: Congresso da Academia Trinacional de Ciências, II, 2007, Foz do Iguaçu, PR, Brazil. Electronic Proceedings available at: www.foz.unioeste.br/~lamat/publicvidros/condutivc3n2007.pdf.

[Bos11] S. L. B. Boss. *Tradução comentada de artigos de Stephen Gray (1666-1736) e reprodução de experimentos históricos com materiais acessíveis - subsídios para o ensino do eletricidade.* PhD in Science Education, Faculdade de Ciências, Universidade Estadual Paulista - UNESP, Bauru, SP, Brazil, 2011. Supervisors: J. J. Caluzi and A. K. T. Assis. Available at `www.ifi.unicamp.br/~assis`.

[BW10] C. Blondel and B. Wolff. L'électricité de pression de Haüy et l'électricité de frottement font cause commune. Available at `www.ampere.cnrs.fr/labo/`, 2010.

[BW12a] C. Blondel and B. Wolff. La loi d'Ohm: la délicate genèse d'une loi "simple". Available at: `www.ampere.cnrs.fr/parcourspedagogique`, 2012.

[BW12b] C. Blondel and B. Wolff. Que dit l'article ELECTRICITE de l'Encyclopédie? Available at `www.ampere.cnrs.fr/parcourspedagogique`, 2012.

[BW12c] C. Blondel and B. Wolff. Teinturiers et tubes de verre: Gray et Dufay. Available at `www.ampere.cnrs.fr/parcourspedagogique`, 2012.

[BW12d] C. Blondel and B. Wolff. Un phénomène plus complexe qu'il n'y paraît: l'attraction des corps légers ou d'un filet d'eau. Available at: `www.ampere.cnrs.fr/labo/`, 2012.

[BW13] C. Blondel and B. Wolff. La proportionnalité de la force électrique aux charges: définition ou loi expérimentale? Available at `www.ampere.cnrs.fr/parcourspedagogique`, 2013.

[CA08] J. Camillo and A. K. T. Assis. Construção de um gerador eletrostático gotejante: chuva elétrica de Kelvin. *A Física na Escola*, 9:29–32, 2008. Video showing the spark produced in this device available at `www.ifi.unicamp.br/~assis` and `www.youtube.com/watch?v=X7WPSQMtiU0`.

[Cam06] J. Camillo. Geradores eletrostáticos: esfera de enxofre de Otto von Guericke e chuva elétrica de Kelvin. Undergraduate work developed at the Institute of Physics of the University of Campinas — UNICAMP, Brazil. Supervisor: A. K. T. Assis. Available at `www.ifi.unicamp.br/~assis` and `www.ifi.unicamp.br/~lunazzi/F530_F590_F690_F809_F895/F809/F809_sem2_2006/JulianoC-Assis_F809_RFcompleto.pdf`, 2006.

[Cer14a] P. Cerreta, 2014. Esperimenti di elettrostatica. Available at: `www.scienzaviva.it/Esperimenti_elettrostatica_2014.php`.

[Cer14b] P. Cerreta. *Il pendolino, il versorium e l'elettroscopio*, pages 53–56. Associazione per l'Insegnamento della Fisica, Perugia, 2014. Supplemento al n. 3/2015 LFnS, Atti del LIII Congresso Nazionale AIF.

[Cer17] P. Cerreta, 2017. Rubbing. Electroscopes and Conductors. Video dall'edizione 2017 di *Science on Stage*, Debrecen, Hungary. Available at: `www.scienzaviva.it/video_15.php`.

[Cha09] J. P. M. d. C. Chaib. *Análise do Significado e da Evolução do Conceito de Força de Ampère, juntamente com a Tradução Comentada de sua Principal Obra sobre Eletrodinâmica*. PhD thesis, University of Campinas — UNICAMP, Campinas, Brazil, 2009. Supervisor: A. K. T. Assis. Available at `webbif.ifi.unicamp.br/teses` and at `www.ifi.unicamp.br/~assis`.

[Chi54] R. A. Chipman. An unpublished letter of Stephen Gray on electrical experiments, 1707-1708. *Isis*, 45:33–40, 1954.

[Coh66] I. B. Cohen. *Franklin and Newton: An Inquiry into Speculative Newtonian Experimental Science and Franklin's Work in Electricity as an Example Thereof*. Harvard University Press, Cambridge, 1966.

[Coh96] I. B. Cohen. *Benjamin Franklin's Science*. Harvard Univ. Press, Cambridge, 1996.

[Cou85a] C. A. Coulomb. Premier mémoire sur l'électricité et le magnétisme: Construction et usage d'une balance électrique, fondée sur la propriété qu'ont les fils de métal, d'avoir une force de réaction de torsion proportionelle à l'angle de torsion. Détermination expérimentale de la loi suivant laquelle les élémens des corps électrisés du même genre d'électricité, se repoussent mutuellement. *Mémoires de l'Académie royale des Sciences de l'Institut de France*, 88:569–577, 1785. Published in 1788.

[Cou85b] C. A. Coulomb. Second mémoire sur l'électricité et le magnétisme, où l'on détermine, suivant quelles loix de fluide magnétique, ainsi que le fluide électrique, agissent, soit par répulsion, soit par attraction. *Mémoires de l'Académie royale des Sciences de l'Institut de France*, 88:578–611, 1785. Published in 1788.

[Cou35] A. Coulomb. First memoir on electricity and magnetism. In W. F. Magie, editor, *A Source Book in Physics*, pages 408–413, New York, 1935. McGraw-Hill. Original publication in French in 1785.

[CS02] R. W. Chabay and B. A. Sherwood. *Matter & Interactions*, volume 2: Electric and Magnetic Interactions. Wiley, New York, 2002.

[Des76] A. P. Deschanel. *Elementary Treatise on Natural Philosophy*. D. Appleton and Co., New York, 1876. Translated by J. D. Everett.

[DF] C. F. d. C. Du Fay. A letter from Mons. Du Fay, F. R. S. and of the Royal Academy of Sciences at Paris, to His Grace Charles Duke of Richmond and Lenox, concerning electricity. Translated from the French by T. S. M D. *Philosophical Transactions*, 38:258–266, 1733–4.

[DF33a] C. F. d. C. Du Fay. Premier mémoire sur l'électricité. Histoire de l'électricité. *Mémoires de l'Académie Royale des Sciences*, pages 23–35, 1733.

[DF33b] C. F. d. C. Du Fay. Quatriéme mémoire sur l'électricité. De l'attraction et répulsion des corps électriques. *Mémoires de l'Académie Royale des Sciences*, pages 457–476, 1733.

[DF33c] C. F. d. C. Du Fay. Second mémoire sur l'électricité. Quels sont les corps qui sont susceptibles d'électricité. *Mémoires de l'Académie Royale des Sciences*, pages 73–84, 1733.

[DF34] C. F. d. C. Du Fay. Cinquiéme mémoire sur l'électricité. Oú l'on rend compte des nouvelles découvertes sur cette matiére, faites depuis peu par M. Gray; et où l'on examine quelles sont les circonstances qui peuvent apporter quelque changement à l'électricité pour l'augmentation ou la diminution de la force, comme la tempèrature de l'air, le vuide, l'air comprimé, etc. *Mémoires de l'Académie Royale des Sciences*, pages 341–361, 1734.

[Ear42] S. Earnshaw. On the nature of the molecular forces which regulate the constitution of the luminiferous ether. *Transactions of the Cambridge Philosophical Society*, 7:97–114, 1842.

[Egu25] M. Eguchi. On the permanent electret. *Philosophical Magazine*, 49:178–192, 1925.

[Far38] M. Faraday. On induction. *Philosophical Transactions*, 128:1–40, 1838. Reprinted in *Great Books of the Western World*, R. M. Hutchins (editor), (Encyclopaedia Britannica, Chicago, 1952), Vol. 45: Lavoisier, Fourier, Faraday. Pp. 440-467.

[Far43a] M. Faraday. On static electrical inductive action. *Philosophical Magazine*, 22:200–204, 1843. Reprinted in *Great Books of the Western World*, R. M. Hutchins (editor), (Encyclopaedia Britannica, Chicago, 1952), Vol. 45: Lavoisier, Fourier, Faraday. Pp. 848-850.

[Far43b] M. Faraday. On the electricity evolved by the friction of water and steam against other bodies. *Philosophical Transactions*, 133:17–32, 1843. Reprinted in *Great Books of the Western World*, R. M. Hutchins (editor), (Encyclopaedia Britannica, Chicago, 1952), Vol. 45: Lavoisier, Fourier, Faraday. Pp. 584-594.

[Far52] M. Faraday. *Experimental Researches in Electricity*, volume 45, pp. 253-898 of *Great Books of the Western World.* Encyclopaedia Britannica, Chicago, 1952.

[Fera] N. Ferreira. *Mecânica.* Instituto de Física, USP, São Paulo, Brazil. Projeto RIPE — Rede de Instrumentação para o Ensino. Available at `www.cienciamao.usp.br/tudo/indice.php?midia=rip`.

[Ferb] N. Ferreira. *Eletrostática*, Vol. 1. Instituto de Física, USP, São Paulo, Brazil. Projeto RIPE — Rede de Instrumentação para o Ensino. Available at `www.cienciamao.usp.br/tudo/indice.php?midia=rip`.

[Ferc] N. Ferreira. *Eletrostática*, Vol. 2. Instituto de Física, USP, São Paulo, Brazil. Projeto RIPE — Rede de Instrumentação para o Ensino. Available at `www.cienciamao.usp.br/tudo/indice.php?midia=rip`.

[Ferd] N. C. Ferreira. Construa sua própria bússola! Available at: `chc.cienciahoje.uol.com.br/construa-sua-propria-bussola`.

[Fer78] N. C. Ferreira. Proposta de Laboratório para a Escola Brasileira—Um Ensaio sobre a Instrumentalização no Ensino Médio de Física. Master's thesis, Universidade de São Paulo, São Paulo, Brazil, 1978.

[Fer00] G. F. L. Ferreira. Há 50 anos: o efeito Costa Ribeiro. *Revista Brasileira de Ensino de Física*, 22:434–443, 2000.

[Fer01a] N. C. Ferreira. Acende aqui, apaga ali. *Ciência Hoje na Escola*, 12:65–67, 2001.

[Fer01b] N. C. Ferreira. Faça como Gilbert: construa uma bússola de declinação. *Ciência Hoje na Escola*, 12:21–22, 2001.

[Fer01c] N. C. Ferreira. Magnetismo e eletricidade. *Ciência Hoje na Escola*, 12:14–17, 2001.

[Fer01d] N. C. Ferreira. O versorium. *Ciência Hoje na Escola*, 12:18–20, 2001.

[Fer06] N. Ferreira. *Equilíbrio.* Projeto RIPE — Rede de Instrumentação para o Ensino, Instituto de Física, USP, São Paulo, Brazil, 2006. Available at: `www.cienciamao.usp.br/tudo/indice.php?midia=rip`.

[FLS64] R. P. Feynman, R. B. Leighton, and M. Sands. *The Feynman Lectures on Physics.* Addison-Wesley, Reading, 1964. Volume 2: Mainly Electromagnetism and Matter.

[FM91] N. Ferreira and J.-P. Maury. *Plus et Moins, les Charges Électriques. Qu'est-ce que c'est?* Ophrys, Paris, 1991.

[FR08] N. C. Ferreira and E. M. d. F. Ramos. *Cadernos de Instrumentação para o Ensino de Física: Eletrostática.* Unesp, Rio Claro, 2008. Coleção Ludoteca, Volume 1.

[Fra69] B. Franklin. *Experiments and Observations on Electricity, Made at Philadelphia in America.* David Henry, London, 1769.

[Fra04] B. Franklin. *The Works of Benjamin Franklin.* G. P. Putnam's Sons, 1904. 12 Volumes.

[Fra41] B. Franklin. *Benjamin Franklin's Experiments* — A new edition of Franklin's *Experiments and Observations on Electricity,* I. B. Cohen (ed.). Harvard University Press, Cambridge, 1941.

[Fra81] O. I. Franksen. *H. C. Ørsted — A Man of the Two Cultures.* Strandbergs Forlag, Birkerød, 1981.

[Fre] D. Frerichs and S. Pfeiler, Historische Einführung in die Elektrostatik. Available at: `https://www.physikalische-schulexperimente.de/physo/Historische_Einf%C3%BChrung_in_die_Elektrostatik#cite_ref-1`.

[Fuk00] E. Fukada. History and recent progress in piezoelectric polymers. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 47:1277–1290, 2000.

[Fuk03] J. Fukai. *A Promenade Along Electrodynamics.* Vales Lake Publishing, Pueblo West, 2003.

[GA94] P. Graneau and A. K. T. Assis. Kirchhoff on the motion of electricity in conductors. *Apeiron*, 19:19–25, 1994.

[Gal14] F. Galembeck *et al.* Friction, tribochemistry and triboelectricity: recent progress and perspectives. *RSC Advances*, 4:64280–64298, 2014. Doi: 10.1039/c4ra09604e.

[Gas91] A. Gaspar. Motor de ímã móvel. *Caderno Catarinense de Ensino de Física*, 8:188–193, 1991.

[Gas96] A. Gaspar. *História da Eletricidade.* Ática, São Paulo, 1996.

[Gas00] A. Gaspar. *Eletromagnetismo - Física Moderna.* Ática, São Paulo, 2000.

[Gas03] A. Gaspar. *Experiências de Ciências para o Ensino Fundamental.* Ática, São Paulo, 2003.

[Gas13] A. Gaspar. *Compreendendo a Física*, volume 3: Eletromagnetismo e Física Moderna. Ática, São Paulo, 2013. 2^a edição. Manual do Professor.

[GB17] F. Galembeck and A. L. Burgo. *Chemical Electrostatics.* Springer, Berlin, 2017.

[Gil00] W. Gilbert. *On the Magnet, Magnetick Bodies also, and on the Great Magnet the Earth; a New Physiology, Demonstrated by Many Arguments & Experiments.* Chiswick Press, London, 1900. Translated by S. P. Thompson.

[Gil71a] C. S. Gillmor. *Coulomb and the Evolution of Physics and Engineering in Eighteenth-Century France.* Princeton University Press, Princeton, 1971.

[Gil71b] C. S. Gillmor. Coulomb, Charles Augustin. In C. C. Gillispie, editor, *Dictionary of Scientific Biography,* Vol. 3, pages 439–447. Charles Scribner's Sons, New York, 1971.

[Gil78] W. Gilbert. *On the Loadstone and Magnetic Bodies and on the Great Magnet the Earth*, volume 28, pp. 1-121 of *Great Books of the Western World.* Encyclopaedia Britannica, Chicago, 1978. Translated by P. F. Mottelay.

[Graa] S. Gray. An account of some new electrical experiments. *Philosophical Transactions*, 31:104–107, 1720–1.

[Grab] S. Gray. The electricity of water. *Philosophical Transactions*, 37:227–230 (addenda in page 260), 1731–2.

[Grac] S. Gray. Experiments and observations upon the light that is produced by communicating electrical attraction to animate or inanimate bodies, together with some of its most surprising effects. *Philosophical Transactions*, 39:16–24, 1735–6.

[Grad] S. Gray. Farther account of his experiments concerning electricity. *Philosophical Transactions*, 37:285–291, 1731–2.

[Grae] S. Gray. Farther accounts of his experiments concerning electricity. *Philosophical Transactions*, 37:397–407, 1731–2.

[Graf] S. Gray. Several experiments concerning electricity. *Philosophical Transactions*, 37:18–44, 1731–2.

[Grag] S. Gray. Some experiments relating to electricity. *Philosophical Transactions*, 39:166–170, 1735–6.

[Gre94] T. B. Greenslade Jr. The hydro-electrical machine. *The Physics Teacher*, 32:210–211, 1994.

[Gro54] B. Gross. Theory of thermodielectric effect. *Physical Review*, 94:1545–1551, 1954.

[Gui12] J. Guisasola. Book review: Andre Koch Torres Assis (2010) The Experimental and Historical Foundations of Electricity. *Science & Education*, 21:283–285, 2012. Doi: 10.1007/s11191-010-9318-z.

[GV99] J. Guala-Valverde. *Inercia y Gravitacion.* Fundacion Julio Palacios, Neuquen, Argentina, 1999. In collaboration with J. Tramaglia and R. Rapacioli. Available at: www.educ.ar/sitios/educar/recursos/ver?id=90380.

[Hae12] H. Haertel. Die Natur macht keine Sprünge — auch nicht beim Ohm'schen Gesetz. *Praxis der Naturwissenschaften - Physik in der Schule*, 5:31–35, 2012.

[Har67] W. S. Harris. *A Treatise on Frictional Electricity, in Theory and Practice.* Virtue and Co., London, 1867. Edited by C. Tomlinson.

[Har82] P. M. Harman. *Energy, Force, and Matter — The Conceptual Development of Nineteenth-Century Physics.* Cambridge University Press, Cambridge, 1982.

[Hau] F. Hauksbee. An account of the repetition of an experiment touching motion given bodies included in a glass, by the approach of a finger near its outside: With other experiments on the effluvia of glass. *Philosophical Transactions*, 26:82–86, 1708–1709.

[Hea87] O. Heaviside. Electromagnetic induction and its propagation. *The Electrician*, 1885-87. Reprinted in O. Heaviside, Electrical Papers (Macmillan, London, 1892), Vol. 1, Art. 30, pp. 429-560 and O. Heaviside, Electrical Papers (Macmillan, London, 1894), Vol. 2, Art. 35, pp. 39-155.

[Hec96] L. Hecht. The significance of the 1845 Gauss-Weber correspondence. *21st Century Science & Technology*, 9(3):22–34, 1996.

[Hee92] P. Heering. On Coulomb's inverse square law. *American Journal of Physics*, 60:988–994, 1992.

[Hei66] J. L. Heilbron. G. M. Bose: the prime mover in the invention of the Leyden jar? *Isis*, 57:264–267, 1966.

[Hei99] J. L. Heilbron. *Electricity in the 17th and 18th Centuries — A Study in Early Modern Physics.* Dover, New York, 1999.

[Hom81] R. W. Home. *The Effluvial Theory of Electricity.* Arno Press, New York, 1981.

[Jea27] J. Jeans. *The Mathematical Theory of Electricity and Magnetism.* Cambridge University Press, Cambridge, 1927.

[Jec12] B. Jech. Sur l'expérience de Desaguliers de la déviation d'un filet d'eau par une tige électrisée. *Bulletin de l'Union des Physiciens*, 946:737–760, 2012.

[Jef59] O. Jefimenko. Lecture demonstrations on electrification by contact. *American Journal of Physics*, 27:604–605, 1959. DOI: 10.1119/1.1934925.

[Jef71a] O. Jefimenko. Franklin's electric motors. *American Journal of Physics*, 39:1139–1140, 1971.

[Jef71b] O. Jefimenko. Operation of electric motors from the atmospheric electric field. *American Journal of Physics*, 39:776–778, 1971.

[Jef73] O. D. Jefimenko. *Electrostatic Motors: Their History, Types, and Principles of Operation.* Electret Scientific, Star City, 1973.

[JG17] W. T. Jardim and A. Guerra. República das letras, academias e sociedades científicas no século XVIII: a garrafa de Leiden e a ciência no ensino. *Caderno Brasileiro de Ensino de Física*, 34:774–797, 2017. Doi: 10.5007/2175-7941.2017v34n3p774.

[JM86] C. Jungnickel and R. McCormmach. *Intellectual Mastery of Nature — Theoretical Physics from Ohm to Einstein*, volume 1-2. University of Chicago Press, Chicago, 1986.

[JW71] O. Jefimenko and D. K. Walker. Electrostatic motors. *The Physics Teacher*, 9:121–129, 1971.

[JW80] O. D. Jefimenko and D. Walker. Electrets. *The Physics Teacher*, 18:651–659, 1980.

[Kat06] S. Katzir. *The Beginnings of Piezoelectricity - A Study in Mundane Physics*, volume 246 of *Boston Studies in Philosophy of Science.* Springer, Dordrecht, 2006.

[Kip09] N. Kipnis. A law of physics in the classroom: the case of Ohm's law. *Science & Education*, 18:349–382, 2009. Doi: 10.1007/s11191-008-9142-x.

[Kir49] G. Kirchhoff. Ueber eine Ableitung der Ohm'schen Gesetze, welche sich an die Theorie der Elektrostatik anschliesst. *Annalen der Physik*, 78:506–513, 1849. Reprinted in G. Kirchhoff's *Gesammelte Abhandlungen* (Barth, Leipzig, 1882), pp. 49-55.

[Kir50] G. Kirchhoff. On a deduction of Ohm's law in connexion with the theory of electrostatics. *Philosophical Magazine*, 37:463–468, 1850.

[Kir57] F. Kirchner. Determination of the velocity of light from electromagnetic measurements according to W. Weber and R. Kohlrausch. *American Journal of Physics*, 25:623–629, 1957.

[KW57] R. Kohlrausch and W. Weber. Elektrodynamische Maassbestimmungen insbesondere Zurückführung der Stromintensitäts-Messungen auf mechanisches Maass. *Abhandlungen der Königl. Sächs. Gesellschaft der Wissenschaften, mathematisch-physische Klasse*, 3:221–290, 1857. Reprinted in Wilhelm Weber's *Werke*, Vol. 3, H. Weber (ed.), (Springer, Berlin, 1893), pp. 609-676.

[LB08] C.-Y. Liu and A. J. Bard. Electrostatic electrochemistry at insulators. *Nature Materials*, 7:505–509, 2008. Doi: 10.1038/nmat2160.

[LB09] C.-Y. Liu and A. J. Bard. Electrons on dielectrics and contact electrification. *Chemical Physics Letters*, 480:145–156, 2009. Doi: 10.1016/j.cplett.2009.08.045.

[Lic56] G. C. Lichtenberg. *Über eine neue Methode, die Natur und die Bewegung der elektrischen Materie zu erforschen*, volume 246 of *Ostwald's Klassiker der exakten Wissenschaften*. Akademische Verlagsgesellschaft, Leipzig, 1956. Herausgegeben in neuer deutscher Übersetzung von H. Pupke.

[Llo80] J. T. Lloyd. Lord Kelvin demonstrated. *The Physics Teacher*, 18:16–24, 1980.

[Lom17] M. V. Lomonosov, 2017. Discourse on atmospheric phenomena originating from electrical force. English translation and commentary by V. Shiltsev. arXiv:1709.08847 [physics.hist-ph].

[Lor95] H. A. Lorentz. *Versuch einer Theorie der Electrischen und Optischen Erscheinungen in Bewegten Körpern*. E. J. Brill, Leiden, 1895. Abschmitt I (Die Grundgleichungen für ein System in den Aether eingelagerter Ionen), §12 (Der zweite Theil der auf die ponderable Materie wirkenden Kraft), pp. 21-22.

[LSB08] C. E. Laburú, O. H. M. d. Silva, and M. A. Barros. Laboratório caseiro - pára-raios: um experimento simples e de baixo custo para a eletrostática. *Caderno Brasileiro de Ensino de Física*, 25:168–182, 2008.

[MA08] C. P. Magnaghi and A. K. T. Assis. Sobre a eletricidade excitada pelo simples contato entre substâncias condutoras de tipos diferentes — Uma tradução comentada do artigo de Volta de 1800 descrevendo sua invenção da pilha elétrica. *Caderno Brasileiro de Ensino de Física*, 25:118–140, 2008.

[Mag06] C. P. Magnaghi. Origem da corrente elétrica — a invenção da pilha. Undergraduate work developed at the Institute of Physics of the University of Campinas — UNICAMP, Brazil. Supervisor: A. K. T. Assis. Available at `www.ifi.unicamp.br/~assis` and `www.ifi.unicamp.br/~lunazzi/F530_F590_F690_F809_F895/F809/F809_sem2_2006/CenoP-Assis_RF1.pdf`, 2006.

[Mas87] S. Mascarenhas. Bioelectrets: electrets in biomaterials and biopolymers. In G. M. Sessler, editor, *Electrets*, pages 321–346. Springer, Berlin, 2nd edition, 1987.

[Max54a] J. C. Maxwell. *A Treatise on Electricity and Magnetism*, volume I. Dover, New York, 1954.

[Max54b] J. C. Maxwell. *A Treatise on Electricity and Magnetism.* Dover, New York, 1954.

[MB17] B. A. Moura and T. Bonfim. Benjamin Franklin e a formação de temporais com raios e trovões: tradução comentada de uma carta a John Mitchel. *Caderno Brasileiro de Ensino de Física*, 34:460–478, 2017. Doi: 10.5007/2175-7941.2017v34n2p460.

[MF] G. d. C. Marques and C. Furukawa. Eletromagnetismo - Tema 2 - O potencial elétrico - Experimento 3: Máquina de indução: eletróforo de Volta. Digital classes of the Universidade de São Paulo - USP, São Paulo, Brazil. Available at `http://eaulas.usp.br/portal/home/video.action?idItem=5874`.

[Mil17] R. A. Millikan. *The Electron: Its Isolation and Measurements and the Determination of Some of Its Properties.* The University of Chicago Press, Chicago, 1917. Edited with an introduction by J. W. M. DuMond.

[Mor04a] B. Morse. Pointy tab blunt tab. Electrostatic Video Series. Wright Center for Innovative Science Education. Available at: `https://www.youtube.com/watch?v=6pnXOHjYjOO`, 2004.

[Mor04b] R. A. Morse, 2004. Benjamin Franklin and Electrostatics. Homepage created and collected by R. A. Morse. Available at: `www.compadre.org/psrc/Franklin/`.

[MW08] L. S. McCarty and G. M. Whitesides. Electrostatic charging due to separation of ions at interfaces: contact electrification of ionic electrets. *Angewandte Chemie (International Edition)*, 47:2188–2207, 2008. Doi: 10.1002/anie.200701812.

[MWW07] L. S. McCarty, A. Winkleman, and G. M. Whitesides. Ionic electrets: electrostatic charging of surfaces by transferring mobile ions upon contact. *Journal of the American Chemical Society*, 129:4075–4088, 2007. Doi: 10.1021/ja067301e.

[Net] L. F. Netto. Feira de ciências. Available at: `www.feiradeciencias.com.br`.

[Net94] L. F. Netto. Eletreto (o ímã da eletrostática). Available at: `www.feiradeciencias.com.br/sala11/11_T02.asp`, 1994.

[New34] I. Newton. *Mathematical Principles of Natural Philosophy.* University of California Press, Berkeley, 1934. Cajori edition.

[New52] I. Newton. *Mathematical Principles of Natural Philosophy*, volume 34, pp. 1-372 of *Great Books of the Western World.* Encyclopaedia Britannica, Chicago, 1952. Translated by A. Motte and revised by F. Cajori.

[New90] I. Newton. *Principia — Princípios Matemáticos de Filosofia Natural.* Nova Stella/Edusp, São Paulo, 1990. Livro I: O Movimento dos Corpos. Portuguese translation by T. Ricci, L. G. Brunet, S. T. Gehring and M. H. C. Célia.

[New99] I. Newton. *The Principia: Mathematical Principles of Natural Philosophy.* University of California Press, Berkeley, 1999. A new translation by I. B. Cohen and A. Whitman, assisted by J. Budenz.

[New08] I. Newton. *Principia — Princípios Matemáticos de Filosofia Natural.* Edusp, São Paulo, 2008. Livro II: O Movimento dos Corpos (em Meios com Resistência). Livro III: O Sistema do Mundo (Tratado Matematicamente). Portuguese translation by A. K. T. Assis. ISBN: 9788531410895.

[New10] I. Newton. *Principia — Princípios Matemáticos de Filosofia Natural.* Folha de São Paulo, São Paulo, 2010. Livro III: O Sistema do Mundo (Tratado Matematicamente). ISBN: 9788563270306. Coleção Folha de São Paulo: Livros que Mudaram o Mundo, Volume 9. Portuguese translation by A. K. T. Assis.

[Oer20a] H. C. Oersted. Expériences sur l'effet du conflict électrique sur l'aiguille aimantée. *Annales de Chimie et de Physique*, 14:417–425, 1820.

[Oer20b] H. C. Oersted. Experiments on the effect of a current of electricity on the magnetic needle. *Annals of Philosophy*, 16:273–277, 1820. Translated from a printed account drawn up in Latin by the author and transmitted by him to the Editor of the *Annals of Philosophy.*

[Oer65] H. C. Oersted. Experiments on the effect of a current of electricity on the magnetic needle. In R. A. R. Tricker*, Early Electrodynamics — The First Law of Circulation*, pages 113–117, New York, 1965. Pergamon. Translation from Thomson's *Annals of Philosophy*, October 1820. Translated from a printed account drawn up in Latin by the author and transmitted by him to the Editor of the *Annals of Philosophy.*

[OF38] G. S. Ohm and G. T. Fechner. *Das Grundgesetz des elektrischen Stromes*, volume 244 of *Ostwald's Klassiker der exakten Wissenschaften.* Akad. Verlagsgesellsch., Leipzig, 1938. Drei Abhandlungen von Georg Simon Ohm (1825 und 1826) und Gustav Theodor Fechner (1829). Herausgegeben von C. Piel.

[Ohm25] G. S. Ohm. Vorläufige Anzeige des Gesetzes, nach welchem Metalle die Kontakt-Elektrizität leiten. *Journal für Chemie und Physik*, 44:10–118, 1825. Reprinted in *Ostwald's Klassiker der exakten Wissenschaften*, Nr. 244, C. Piel (ed.), (Akademische Verlagsgesellschaft, Leipzig, 1938), pp. 1-7.

[Ohm26] G. S. Ohm. Bestimmung des Gesetzes, nach welchem Metalle die Kontakt-Elektrizität leiten, nebst einem Entwurfe zu einer Theorie des Voltaschen Apparates und des Schweiggerschen Multiplikators. *Journal für Chemie und Physik*, 46:137–166, 1826. Reprinted in *Ostwald's Klassiker der exakten Wissenschaften*, Nr. 244, C. Piel (ed.), (Akademische Verlagsgesellschaft, Leipzig, 1938), pp. 8-29.

[Ohm66] G. S. Ohm. The galvanic circuit investigated mathematically. In R. Taylor, editor, *Scientific Memoirs,* Vol. 2, pages 401–506, New York, 1966. Johnson Reprint Corporation. English translation by W. Francis.

[OP09] K. Ovchinnikova and G. H. Pollack. Can water store charge? *Langmuir*, 25:542–547, 2009. Doi: 10.1021/la802430k.

[Ørs86] H. C. Ørsted. Experiências sobre o efeito do conflito elétrico sobre a agulha magnética. *Cadernos de História e Filosofia da Ciência*, 10:115–122, 1986. Translated by R. d. A. Martins.

[Per44] E. Perucca. *Física General y Experimental*, volume II: Optica, Electricidad y Magnetismo. Editorial Labor, Barcelona, 1944. Translated from the fourth Italian edition by J. Melis and J. M. V. Llenas.

[Pla52] Plato. *Timaeus.* In *Great Books of the Western World,* R. M. Hutchins, Editor in Chief, Vol. 7, pages 442–477, Chicago, 1952. Encyclopaedia Britannica. Translated by B. Jowett.

[Pla09] Platao. *Timeu e Crítias ou A Atlântida.* Hemus, São Paulo, 2009. Portuguese translation by N. d. P. Lima.

[Pol13] G. H. Pollack. *The Fourth Phase of Water: Beyond Solid, Liquid, and Vapor.* Ebner & Sons, Seattle, 2013.

[Pot84] A. Potier. *Collection de Mémoires relatifs a la Physique*, volume 1: *Mémoires de Coulomb.* Gauthiers-Villars, Paris, 1884.

[Pri75] J. Priestley. *The History and Present State of Electricity, with Original Experiments*, volume II. C. Bathurst and T. Lowndes, London, 3rd edition, 1775.

[Pri66] J. Priestley. *The History and Present State of Electricity*, volume 2. Johnson Reprint Corporation, New York, 1966. The Sources of Science, Number 18. Reprinted from the third edition, London, 1775.

[Rai15] A. C. Raicik. Experimentos exploratórios: os contextos da descoberta e da justificativa nos trabalhos de Gray e Du Fay. Master's thesis, Universidade Federal de Santa Catarina - UFSC, Florianópolis, Brazil, 2015.

[Ram] C. Ramsauer, Das Ohmsche Gesetz (1826), in C. Ramsauer, *Grundversuche der Physik in historischer Darstellung* (Springer, Berlin, 1953), Vol. 1: Von der Fallgesetzen bis zu den elektrischen Wellen.

[Roc89] J. Roche. Applying the history of electricity in the classroom: a reconstruction of the concept of 'potential'. In M. Shortland and A. Warwick, editors, *Teaching the History of Science*, pages 168–184. Basil Blackwell, Oxford, 1989.

[Ros90] F. Rosenberger. *Die Geschichte der Physik*, volume 3. Friedrich Vieweg und Sohn, Braunschweig, 1887-1890.

[Ros57] L. Rosenfeld. The velocity of light and the evolution of electrodynamics. *Il Nuovo Cimento*, Supplement to vol. 4:1630–1669, 1957.

[Ros81] L. Rosenfeld. Kirchhoff, Gustav Robert. In C. C. Gillispie, editor, *Dictionary of Scientific Biography,* Vol. 7, pages 379–383, New York, 1981. Charles Scribner's Sons.

[RP13a] A. C. Raicik and L. O. Q. Peduzzi, 2013. Uma abordagem histórica e experimental à eletricidade em uma disciplina sobre a evolução dos conceitos da física. Anais do XX Simpósio Nacional de Ensino de Física - SNEF, São Paulo, SP. Págs. 1-8.

[RP13b] A. C. Raicik and L. O. Q. Peduzzi, 2013. Uma discussão sobre os contextos da descoberta e da justificativa nos estudos de Du Fay. Anais do IX Encontro Nacional de Pesquisa em Educação em Ciências - IX ENPEC, Águas de Lindóia, SP, 10 a 14 de novembro. Págs. 1-8.

[RP13c] A. C. Raicik and L. O. Q. Peduzzi, 2013. Uma análise da terminologia *descoberta* e sua contextualização nos livros didáticos: os estudos de Gray e Du Fay. Anais do V Encontro Estadual de Ensino de Física, Porto Alegre, RS. Págs. 1-13.

[RP15a] A. C. Raicik and L. O. Q. Peduzzi. Potencialidades e limitações de um módulo de ensino: uma discussão histórico-filosófica dos estudos de Gray e Du Fay. *Investigações em Ensino de Ciências*, 20:138–160, 2015.

[RP15b] A. C. Raicik and L. O. Q. Peduzzi. Um resgate histórico e filosófico dos estudos de Charles Du Fay. *Revista Ensaio*, 17:105–125, 2015. Doi: 10.1590/1983-211720175170105.

[RP16] A. C. Raicik and L. O. Q. Peduzzi. A estrutura conceitual e epistemológica de uma descoberta científica: reflexões para o ensino de ciências. *Alexandria - Revista de Educação em Ciência e Tecnologia*, 9:149–176, 2016. Doi: 10.5007/1982-5153.2016v9n2p149.

[RR57] D. Roller and D. H. D. Roller. The Development of the Concept of Electric Charge. In J. B. Conant, editor, *Harvard Case Studies in Experimental Science*, chapter 8, pages 541–639. Harvard University Press, Cambridge, 1957.

[San11] L. P. Santos *et al.* Water with excess electric charge. *The Journal of Physical Chemistry C*, 115:11226–11232, 2011. Doi: 10.1021/jp202652q.

[Sav] I. V. Savelyev. *Physics: A General Course*, volume II: Electricity and Magnetism, Waves and Optics. Mir, Moscow. Translated from Russian by G. Leib.

[Sch63] M. Schagrin. Resistance to Ohm's law. *American Journal of Physics*, 31:536–547, 1963.

[Sch07] L. B. Schein. Recent progress and continuing puzzles in electrostatics. *Science*, 316:1572–1573, 2007.

[Sco59] W. T. Scott. Who was Earnshaw? *American Journal of Physics*, 27:418–419, 1959.

[Ses87] G. M. Sessler (ed.). *Electrets.* Springer, Berlin, second edition, 1987.

[SGS31] J. B. Seth, B. Gulati, and S. Singh. On an electromotive force between two metals in relative motion. *Philosophical Magazine*, 12:409–429, 1931. DOI: 10.1080/14786443109461818.

[Sil10a] V. A. Silva Júnior. Fabricação e aplicação de eletretos. Undergraduate work developed at the Institute of Physics of the University of Campinas — UNICAMP, Brazil. Supervisor: A. K. T. Assis. Available at `www.ifi.unicamp.br/~assis` and `sites.ifi.unicamp.br/lunazzi/files/2014/03/ValterA-Assis_RF1.pdf`, 2010.

[Sil10b] V. A. Silva Júnior. História e propriedades dos eletretos. Undergraduate work developed at the Institute of Physics of the University of Campinas — UNICAMP, Brazil. Supervisor: A. K. T. Assis. Available at `www.ifi.unicamp.br/~assis`, 2010.

[Sil10c] F. L. d. Silveira. Resenha - Os Fundamentos Experimentais e Históricos da Eletricidade. *Caderno Brasileiro de Ensino de Física*, 27:411–415, 2010.

[Sil11] F. L. d. Silveira. Video in Portuguese on electrostatic experiments. Available at www.if.ufrgs.br/~lang and www.youtube.com/watch?v=GhYKeb99OgA, 2011.

[Sil16] F. L. d. Silveira. Descarga elétrica através do ar NÃO é consequente do arrancamento de elétrons dos eletrodos! Available at www.if.ufrgs.br/cref/?area=questions&id=1652, 2016.

[SP06] C. C. Silva and A. C. Pimentel, 2006. Benjamin Franklin e a história da eletricidade em livros didáticos. Proceedings of the X Encontro de Pesquisa em Ensino de Física, Londrina, PR, Brazil, 15 to 19/08/2006. Available at: www.sbf1.sbfisica.org.br/eventos/epef/x/sys/resumos/T0150-1.pdf.

[SP08] C. C. Silva and A. C. Pimentel. Uma análise da história da eletricidade presente em livros didáticos: o caso de Benjamin Franklin. *Caderno Brasileiro de Ensino de Física*, 25:141–159, 2008.

[Tho] W. Thomson. On a self-acting apparatus for multiplying and maintaining electric charges, with applications to illustrate the voltaic theory. *Proceedings of the Royal Society of London*, 16:67–72, 1867–1868.

[Tho84a] W. Thomson. Atmospheric electricity. In W. Thomson, editor, *Reprint of Papers on Electrostatics and Magnetism*, pages 192–239. Macmillan, London, 2nd edition, 1884. Article XVI. Reprinted from Nichol's *Cyclopaedia*, 2nd edition, 1860.

[Tho84b] W. Thomson. A mathematical theory of magnetism. In W. Thomson, editor, *Reprint of Papers on Electrostatics and Magnetism*, pages 345–430. Macmillan, London, 2nd edition, 1884. Article XXIV. Reprinted from *Philosophical Transactions*, Vol. 141, pp. 243-268 and 269-285 (1851).

[Tho84c] W. Thomson. Measurement of the electromotive force required to produce a spark in air between parallel metal plates at different distances. In W. Thomson, editor, *Reprint of Papers on Electrostatics and Magnetism*, pages 247–259. Macmillan, London, 2nd edition, 1884. Article XIX. Reprinted from *Proceedings of the Royal Society*, Vol. 10, pp. 326-338 (1860).

[Tho84d] W. Thomson. On the mathematical theory of electricity in equilibrium. In W. Thomson, editor, *Reprint of Papers on Electrostatics and Magnetism*, pages 42–68. Macmillan, London, 2nd edition, 1884. Articles IV (pp. 42-51) and V (pp. 52-68). Reprinted from *Cambridge and Dublin Mathematical Journal*, Vol. 3, pp. 131-148 and 266-274 (1848).

[Tho21] J. J. Thomson. *Elements of the Mathematical Theory of Electricity and Magnetism*. Cambridge University Press, Cambridge, 5th edition, 1921.

[TM09] P. A. Tipler and G. Mosca. *Física para Cientistas e Engenheiros*, volume 2: Eletricidade e Magnetismo, Óptica. LTC, Rio de Janeiro, 6th edition, 2009. Portuguese translation by N. M. Balzaretti.

[TP11] J. D. M. Tamayo and M. G. T. Palacio. *El Papel del Experimento en la Construcción del Conocimiento Físico, el Caso de la Construcción del Potencial Eléctrico como una Magnitude Física. Elementos para Propuestas en la Formación Inicial y Continuada de Profesores de Física*. Universidad de Antioquia - Facultad de Educación, Medellín, 2011. Trabajo de Investigación como requisito parcial para optar al título de Magister en Educación, línea de Educación en Ciencias Experimentales. Director: A. E. R. Chacón.

[Vas05] G. M. S. Vasconcelos. Experimentos de eletrostática de baixo custo para o ensino médio. Undergraduate work developed at the Institute of Physics of the University of Campinas — UNICAMP, Brazil. Supervisor: A. K. T. Assis. Available at `www.ifi.unicamp.br/~assis` and `www.ifi.unicamp.br/~lunazzi/F530_F590_F690_F809_F895/F809/F809_sem2_2005/GeraldoM_Assis_RF1.pdf`, 2005.

[VF80] R. N. Varney and L. H. Fisher. Electromotive force: Volta's forgotten concept. *American Journal of Physics*, 48:405–408, 1980.

[Vol00a] A. Volta. On the electricity excited by the mere contact of conducting substances of different kinds. *Philosophical Transactions*, 90:403–431, 1800. Letter in French from A. Volta to J. Banks dated March 20, 1800. It was read before the Royal Society in June 26, 1800.

[Vol00b] A. Volta. On the electricity excited by the mere contact of conducting substances of different kinds. *Philosophical Magazine*, 7:289–311, 1800.

[Vol64] A. Volta. On the electricity excited by the mere contact of conducting substances of different kinds. In B. Dibner, *Alessandro Volta and the Electric Battery*, pages 111–131. Franklin Watts, New York, 1964. Translated from the author's paper published in French in the Philosophical Transactions for 1800, Part 2.

[WB09] B. Wolff and C. Blondel. La balance électrique de Coulomb pouvait-elle constituer sa propre cage de Faraday? Available at: `www.ampere.cnrs.fr/parcourspedagogique`, 2009.

[WB11] B. Wolff and C. Blondel. Quelques questions encore posées aujourd'hui par l'histoire de l'électrostatique. *Union des Professeurs de Physique et de Chimie*, 105:705–717, 2011.

[Web46] W. Weber. Elektrodynamische Maassbestimmungen — Über ein allgemeines Grundgesetz der elektrischen Wirkung. *Abhandlungen bei Begründung der Königl. Sächs. Gesellschaft der Wissenschaften am Tage der zweihundertjährigen Geburtstagfeier Leibnizen's herausgegeben von der Fürstl. Jablonowskischen Gesellschaft (Leipzig)*, pages 211–378, 1846. Reprinted in Wilhelm Weber's *Werke*, Vol. 3, H. Weber (ed.), (Springer, Berlin, 1893), pp. 25-214.

[Web48] W. Weber. Elektrodynamische Maassbestimmungen. *Annalen der Physik und Chemie*, 73:193–240, 1848. Reprinted in Wilhelm Weber's *Werke*, Vol. 3, H. Weber (ed.), (Springer, Berlin, 1893), pp. 215-254.

[Web52a] W. Weber. Elektrodynamische Maassbestimmungen insbesondere über Diamagnetismus. *Abhandlungen der Königl. Sächs. Gesellschaft der Wissenschaften, mathematisch-physische Klasse*, 1:485–577, 1852. Reprinted in Wilhelm Weber's *Werke*, Vol. 3, H. Weber (ed.), (Springer, Berlin, 1893), pp. 473-554.

[Web52b] W. Weber. Elektrodynamische Maassbestimmungen insbesondere Widerstandsmessungen. *Abhandlungen der Königl. Sächs. Gesellschaft der Wissenschaften, mathematisch-physische Klasse*, 1:199–381, 1852. Reprinted in Wilhelm Weber's *Werke*, Vol. 3, H. Weber (ed.), (Springer, Berlin, 1893), pp. 301-471.

[Web64] W. Weber. Elektrodynamische Maassbestimmungen insbesondere über elektrische Schwingungen. *Abhandlungen der Königl. Sächs. Geselschaft der Wissenschaften, mathematisch-physische Klasse*, 6:571–716, 1864. Reprinted in Wilhelm Weber's *Werke*, Vol. 4, H. Weber (ed.), (Springer, Berlin, 1894), pp. 105-241.

[Web71] W. Weber. Elektrodynamische Maassbestimmungen insbesondere über das Princip der Erhaltung der Energie. *Abhandlungen der Königl. Sächs. Gesellschaft der Wissenschaften, mathematisch-physische Klasse (Leipzig)*, 10:1–61, 1871. Reprinted in Wilhelm Weber's *Werke*, Vol. 4, H. Weber (ed.), (Springer, Berlin, 1894), pp. 247-299.

[Web72] W. Weber. Electrodynamic measurements — Sixth memoir, relating specially to the principle of the conservation of energy. *Philosophical Magazine*, 43:1–20 and 119–149, 1872.

[Web78] W. Weber. Elektrodynamische Maassbestimmungen insbesondere über die Energie der Wechselwirkung. *Abhandlungen der Königl. Sächs. Gesellschaft der Wissenschaften, mathematisch-physische Klasse, (Leipzig)*, 11:641–696, 1878. Reprinted in Wilhelm

Weber's *Werke*, Vol. 4, H. Weber (ed.), (Springer, Berlin, 1894), pp. 361-412.

[Web92a] W. Weber. *Wilhelm Weber's Werke,* E. Riecke (ed.), volume 2, *Magnetismus.* Springer, Berlin, 1892.

[Web92b] W. Weber. *Wilhelm Weber's Werke,* W. Voigt, (ed.), volume 1, *Akustik, Mechanik, Optik und Wärmelehre.* Springer, Berlin, 1892.

[Web93] W. Weber. *Wilhelm Weber's Werke,* H. Weber (ed.), volume 3, *Galvanismus und Elektrodynamik*, first part. Springer, Berlin, 1893.

[Web94a] W. Weber. Elektrodynamische Maassbestimmungen insbesondere über den Zusammenhang des elektrischen Grundgesetzes mit dem Gravitationsgesetze. In H. Weber, editor, Wilhelm Weber's *Werke,* Vol. 4, pages 479–525, Berlin, 1894. Springer.

[Web94b] W. Weber. *Wilhelm Weber's Werke,* H. Weber, (ed.), volume 4, *Galvanismus und Elektrodynamik*, second part. Springer, Berlin, 1894.

[Web66] W. Weber. On the measurement of electro-dynamic forces. In R. Taylor, editor, *Scientific Memoirs,* Vol. 5, pages 489–529, New York, 1966. Johnson Reprint Corporation.

[Web07] W. Weber, 2007. Determinations of electrodynamic measure: concerning a universal law of electrical action, 21st Century Science & Technology, posted March 2007, translated by S. P. Johnson, edited by L. Hecht and A. K. T. Assis. Available at: `www.21stcenturysciencetech.com/translation.html`.

[Web08] W. Weber, 2008. Determinations of electrodynamic measure: particularly in respect to the connection of the fundamental laws of electricity with the law of gravitation, 21st Century Science & Technology, posted November 2008, translated by G. Gregory, edited by L. Hecht and A. K. T. Assis. Available at: `www.21stcenturysciencetech.com/translation.html`.

[Whe43] C. Wheatstone. The bakerian lecture - an account of several new instruments and processes for determining the constants of a voltaic circuit. *Philosophical Transactions*, 133:303–327, 1843.

[Whi73a] E. T. Whittaker. *A History of the Theories of Aether and Electricity*, volume 1: *The Classical Theories.* Humanities Press, New York, 1973.

[Whi73b] E. T. Whittaker. *A History of the Theories of Aether and Electricity*, volume 2: *The Modern Theories.* Humanities Press, New York, 1973.

[Wie60] K. H. Wiederkehr. Wilhelm Webers Stellung in der Entwicklung der Elektrizitätslehre. Dissertation, Hamburg, 1960.

[Wie67] K. H. Wiederkehr. *Wilhelm Eduard Weber — Erforscher der Wellenbewegung und der Elektrizität (1804-1891)*, volume 32 of *Grosse Naturforscher,* H. Degen (ed.). Wissenschaftliche Verlagsgesellschaft, Stuttgart, 1967.

[Wil12] M. W. Williams. What creates static electricity? *American Scientist*, 100:316–323, 2012. Doi: 10.1511/2012.97.316.

[Wis81] M. N. Wise. German concepts of force, energy, and the electromagnetic ether: 1845–1880. In G. N. Cantor and M. J. S. Hodge, editors, *Conceptions of Ether — Studies in the History of Ether Theories 1740–1900*, pages 269–307, Cambridge, 1981. Cambridge University Press.

[WK56] W. Weber and R. Kohlrausch. Über die Elektricitätsmenge, welche bei galvanischen Strömen durch den Querschnitt der Kette fliesst. *Annalen der Physik und Chemie,* J. C. Poggendoff (ed.), 99:10–25, 1856. Reprinted in Wilhelm Weber's *Werke*, Vol. 3, H. Weber (ed.), (Springer, Berlin, 1893), pp. 597-608.

[WK08] W. Weber and R. Kohlrausch. Sobre a quantidade de eletricidade que flui através da seção reta do circuito em correntes galvânicas. *Revista Brasileira de História da Ciência*, 1:94–102, 2008. Portuguese translation by A. K. T. Assis.

[Woo68] A. E. Woodruff. The contributions of Hermann von Helmholtz to electrodynamics. *Isis*, 59:300–311, 1968.

[Woo81] A. E. Woodruff. Weber, Wilhelm Eduard. In C. C. Gillispie, editor, *Dictionary of Scientific Biography,* Vol. 14, pages 203–209, New York, 1981. Charles Scribner's Sons.

[WW93] E. H. Weber and W. Weber. *Wilhelm Weber's Werke,* E. Riecke (ed.), volume 5, *Wellenlehre auf Experimente gegründet oder über die Wellen tropfbarer Flüssigkeiten mit Anwendung auf die Schall- und Lichtwellen.* Springer, Berlin, 1893. Originally published in 1825.

[WW94] W. Weber and E. Weber. *Wilhelm Weber's Werke,* F. Merkel and O. Fischer (editors), volume 6, *Mechanik der menschlichen Gehwerkzeuge. Eine anatomisch-physiologische Untersuchung.* Springer, Berlin, 1894. Originally published in 1836.

Volume 2 of The Experimental and Historical Foundations of Electricity deals with the most fundamental aspects of physics. The book describes the main experiments and discoveries in the history of electricity. It deals with attractions and repulsions, positive and negative charges, conductors and insulators, electrification by friction/contact/induction, the triboelectric series, electrification of adhesive tapes, equilibrium and distribution of charges in conductors, electric shielding, the power of points, sparks and electric discharges in air, electrets and the temporal preservation of the electrification of bodies. This work explains how to build several instruments: versorium, electric pendulum, electroscope, charge collector, circuit tester, electrophorus, the Leyden jar and capacitors, etc. All experiments are clearly described and performed with simple, inexpensive materials. These experiments lead to clear concepts, definitions, and laws describing these phenomena. Historical aspects are presented, together with relevant quotations from the main scientists. A large bibliography is included at the end of the work.

The author: Andre Koch Torres Assis was born in Brazil (1962) and studied at the University of Campinas – UNICAMP, BS (1983), PhD (1987). He spent the academic year of 1988 in England with a post-doctoral position at the Culham Laboratory (Oxfordshire, United Kingdom Atomic Energy Authority). He spent one year in 1991-92 as a Visiting Scholar at the Center for Electromagnetics Research of Northeastern University (Boston, USA). From August 2001 to November 2002, and from February to May 2009, he worked at the Institute for the History of Natural Sciences, Hamburg University (Hamburg, Germany) with research fellowships awarded by the Alexander von Humboldt Foundation of Germany. From April to June 2014 he worked at the Technische Universität Dresden (Germany) with a research fellowship also awarded by the Humboldt Foundation. He is the author of many books in English, Portuguese, Italian, German and Russian, including *Weber's Electrodynamics* (1994), *Relational Mechanics* (1999), *Inductance and Force Calculations in Electrical Circuits* (with M. A. Bueno, 2001); *The Electric Force of a Current: Weber and the Surface Charges of Resistive Conductors Carrying Steady Currents* (with J. A. Hernandes, 2007); *Archimedes, the Center of Gravity, and the First Law of Mechanics: The Law of the Lever* (2008 and 2010); *The Experimental and Historical Foundations of Electricity* (Volume 1, 2010); *Weber's Planetary Model of the Atom* (with K. H. Wiederkehr and G. Wolfschmidt, 2011); *Stephen Gray and the Discovery of Conductors and Insulators* (with S. L. B. Boss and J. J. Caluzi, 2012); *The Illustrated Method of Archimedes: Utilizing the Law of the Lever to Calculate Areas, Volumes and Centers of Gravity* (with C. P. Magnaghi, 2012); *Relational Mechanics and Implementation of Mach's Principle with Weber's Gravitational Force* (2014); and *Ampère's Electrodynamics – Analysis of the Meaning and Evolution of Ampère's Force between Current Elements, together with a Complete Translation of His Masterpiece: Theory of Electrodynamic Phenomena, Uniquely Deduced from Experience* (with J. P. M. C. Chaib, 2015). He has been professor of physics at UNICAMP since 1989, working on the foundations of electromagnetism, gravitation, and cosmology.

978-1-987980-10-3