Giuseppe Pelosi
Stefano Selleri

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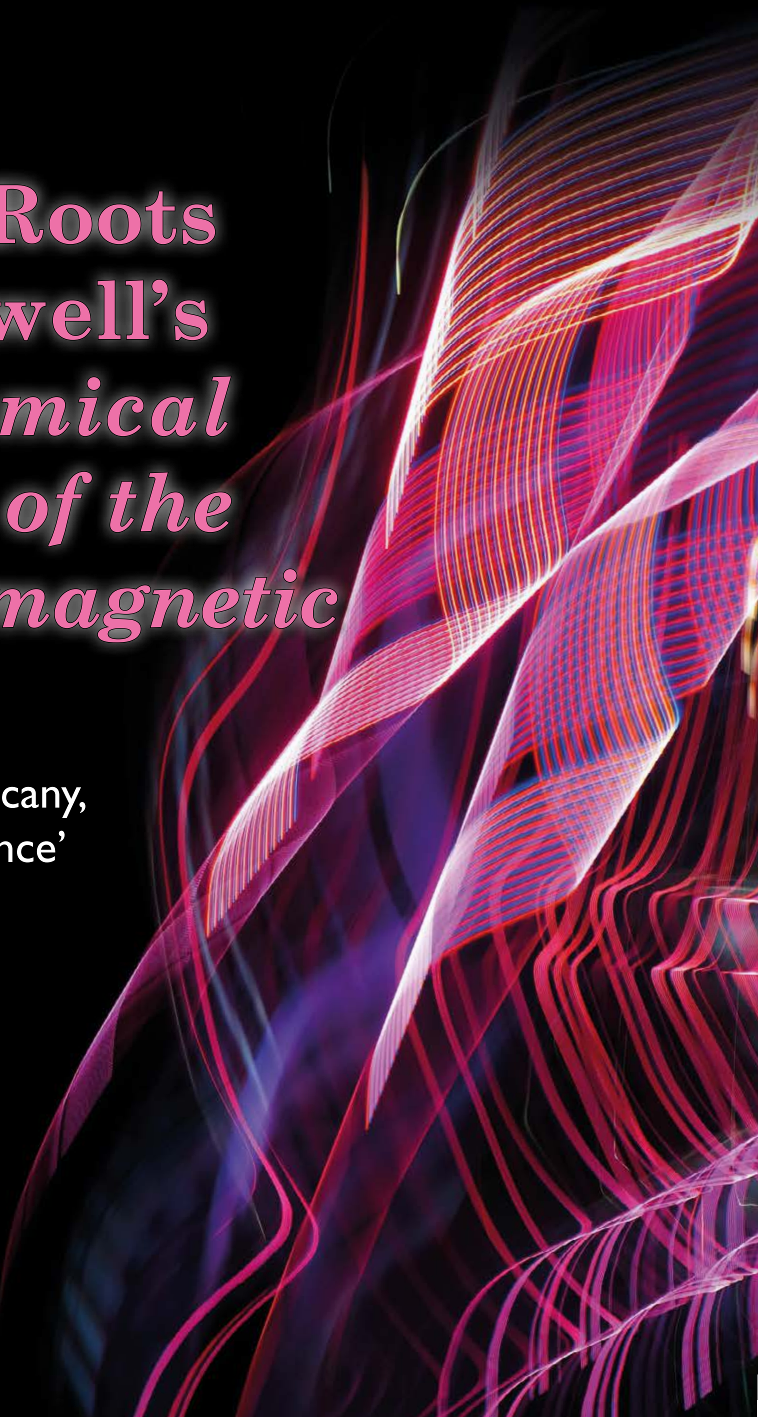
The Roots of Maxwell's *A Dynamical Theory of the Electromagnetic Field*

Scotland and Tuscany, 'twinned by science'



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Presentation

It was in the now distant May 28, 1965, that, thanks to the then Mayor of Florence, Giorgio La Pira, a twinning was signed between our city and the capital of Scotland, Edinburgh. A twinning born of artistic and cultural affinities, and which immediately had the opportunity to show the proximity of the two cities, first, on the occasion of the 'British Week' from 8 to 16 October 1966 in Florence and, immediately after, on the occasion of the flood of November 4, 1966, the city of Edinburgh was able to do its utmost to restore a semi-destroyed Florence.

Many were the events held in collaboration thanks to this twinning, including the celebrations for the 40th anniversary, with a series of events held in Edinburgh in 2004 to which I was personally present. Subsequently, in 2015, when I was President of the Regional Council of Tuscany, on the occasion of the 50th anniversary of the first signing, the agreement was renewed here in Florence by the Mayor Dario Nardella and the Lord Provost, then in office, Donald Wilson.

The link between Scotland and Tuscany is also scientific and not only artistic or literary, and more ancient than a century, as this volume, centred on the birth of James Clerk Maxwell's theory of electromagnetism, tells us. Maxwell was born, lived, and worked for a long time in Edinburgh. His work in electromagnetism, which came to a full theory in 1864, has had an impact on our daily life so pervasive that it now seems impossible to live without it. It paved the way for all the applications of electricity, motors, generators, radio, television, mobile phones, data networks, etc. A revolution that now accompanies us in every moment of our daily life.

This scientific revolution also has Tuscan roots, as this volume shows. To the roots of Maxwell's theory contributed, among others, two distinguished profes-

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sors at the University of Pisa, Ottaviano Mossotti and Riccardo Felici, as well as a great Florentine by adoption, Carlo Matteucci, who was also Minister of Education of the Kingdom of Italy and, at the time of Florence Capital, Director of the Royal Museum of Physics and Natural History of Florence which, at the time, was located at La Specola in via Romana.

It was precisely to meet Carlo Matteucci, as described in the volume, that James Clerk Maxwell undertook in the spring-summer of 1867, with his wife, his only journey outside the United Kingdom. Visiting, as his contemporary biographers and the authors of this book tell us, Florence.

This volume is therefore part of an enhancement, also in a scientific context, of the twinning existing between Edinburgh, Maxwell's hometown, and Florence, where he made his only trip abroad.

I therefore thank the authors of this publication which not only is a means of disseminating scientific culture at an international level but also pays homage to illustrious Tuscans, testifying, once again, how our Region is and has always been a place of science and research.

Eugenio Giani
President of Tuscany
Florence, Italy

Presentazione

Fu nell'ormai lontano 28 maggio 1965 che, grazie all'allora Sindaco di Firenze Giorgio La Pira, venne firmato un gemellaggio fra la nostra città e la capitale della Scozia, Edimburgo. Un gemellaggio nato su affinità artistiche e culturali e che ebbe subito occasione di mostrare la vicinanza delle due città, prima, in occasione della 'Settimana Britannica' dall'8 al 16 ottobre 1966 a Firenze e, subito dopo, in occasione dell'alluvione del 4 novembre 1966, la città di Edimburgo ebbe modo di prodigarsi nel ripristino di una Firenze semidistrutta.

Molte sono state le manifestazioni tenute in collaborazione grazie a questo gemellaggio, fra cui le celebrazioni per i quarant'anni, con una serie di eventi tenutasi a Edimburgo nel 2004 ai quali sono stato personalmente presente. Successivamente, nel 2015, quando ero Presidente del Consiglio Regionale della Toscana, in occasione dei cinquant'anni dalla prima firma, l'accordo è stato rinnovato, qui a Firenze, dal Sindaco Dario Nardella e dal Lord Provost, allora in carica, Donald Wilson.

Il legame tra la Scozia e la Toscana è anche scientifico e non solo artistico o letterario, e più antico di oltre secolo, come questo volume, centrato sulla nascita della teoria di James Clerk Maxwell dell'elettromagnetismo, ci racconta. Maxwell nacque, visse e lavorò per lungo tempo ad Edimburgo. Il suo lavoro in elettromagnetismo, concretizzatosi nel 1864, ha avuto un impatto sulla nostra vita quotidiana così pervasivo da sembrare ormai impossibile vivere senza. Esso ha aperto la strada a tutte le applicazioni dell'elettricità, motori, generatori, radio, televisione, telefonia mobile, reti dati ecc. Una rivoluzione che ormai ci accompagna in ogni attimo della nostra vita quotidiana.

Questa rivoluzione scientifica ha radici anche toscane, come questo volume mostra. Alle radici della teoria di Maxwell contribuirono, fra i molti, due insigni professori dell'Università di Pisa, Ottaviano Mossotti e Riccardo Felici, così come un grande fiorentino d'adozione, Carlo Matteucci, che fu anche Ministro della Pubblica Istruzione del Regno d'Italia e, all'epoca di Firenze Capitale, Direttore del Reale Museo di Fisica e Storia Naturale di Firenze che, allora, si trovava presso La Specola in via Romana.

Fu proprio per incontrare Carlo Matteucci, come descritto nel volume, che James Clerk Maxwell intraprese nella primavera-estate del 1867, con la moglie, il suo unico viaggio fuori dal Regno Unito. Visitando, come ci raccontano i suoi biografi contemporanei e gli autori di questo libro, Firenze.

Questo volume si inquadra quindi in una valorizzazione, in un contesto anche scientifico, del gemellaggio esistente fra Edimburgo, città natale di Maxwell, e Firenze, ove fece il suo unico viaggio all'estero.

Ringrazio quindi gli autori di questa pubblicazione che non solo è mezzo di diffusione a livello internazionale di cultura scientifica ma che rende anche omaggio a illustri toscani testimoniando, ancora una volta, come la nostra Regione sia e sia sempre stata luogo di scienza e di ricerca.

Eugenio Giani
Presidente della Regione Toscana
Firenze, Italia

Preface

It was in 1865 that Maxwell resigned his professorship at King's College and retired to Glenlair. Maxwell did not travel widely although he had wide correspondence with scientists in the UK and all over Europe. As a result, he was aware of current research in electromagnetism, which greatly influenced his thinking. Although we know of one overseas excursion in the spring and early summer of 1867 when he toured Italy with his wife Katherine, most of his energies and time up to 1873 were devoted to writing his book completing the *Dynamical Theory of the Electromagnetic Field*. There is little record remaining of what Maxwell did in Italy and it is not known if Maxwell made any contacts with Italian researchers working on electricity and magnetics. A keen reader of science reports and papers though, he would have been aware of the work of Mossotti, a great physicist and Italian independence fighter. Mossotti held a view that the best way to explain all physical phenomena was by means of forces acting centrally at a distance between various fluids, which Maxwell ultimately rejected. However, Maxwell was very much aware of another Italian physicist Riccardo Felici, for in his third chapter, Maxwell made use of a series of experiments devised by Felici as well as those of Faraday to state the law of electromagnetic induction: «the total electromotive force acting around a circuit at any instant is measured by the rate of decrease of the number of lines of magnetic force which pass through it». In this current exposition by Giuseppe Pelosi and Stefano Selleri, we learn more of the scientists who influenced Maxwell as well as details of Mossotti and Felici, who, by the way, held senior positions at the University of Pisa. Their thoughts and writings were important for extending existing theories of Oested and Faraday and, ultimately, building blocks for James Clerk Max-

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well. I commend this excellent new contribution to the origins and history of the field we know today as electromagnetics.

Trevor S. Bird
IEEE Antennas and Propagation Society, History Committee, President
Eastwood, New South Wales, Australia

Prefazione

Fu nel 1865 che Maxwell si dimise dalla cattedra al King's College e si ritirò a Glenlair. Maxwell non viaggiò molto sebbene avesse un'ampia corrispondenza con scienziati nel Regno Unito e in tutta Europa. Di conseguenza, era a conoscenza delle attuali ricerche sull'elettromagnetismo, che hanno fortemente influenzato il suo pensiero. Sebbene si sappia di un viaggio all'estero nella primavera e all'inizio dell'estate del 1867, quando fece un giro per l'Italia con la moglie Katherine, la maggior parte delle sue energie e del suo tempo fino al 1873 furono dedicate alla scrittura del libro che completava la *Dynamical Theory of the Electromagnetic Field*. Restano poche tracce di ciò che Maxwell ha fatto in Italia e non è noto se Maxwell abbia avuto contatti diretti con ricercatori italiani che si occupano di elettricità e magnetismo. Appassionato lettore di relazioni e articoli scientifici, tuttavia, sarebbe stato a conoscenza del lavoro di Mossotti, un grande fisico e combattente per l'indipendenza italiano. Mossotti riteneva che il modo migliore per spiegare tutti i fenomeni fisici fosse per mezzo di forze che agiscono centralmente a distanza tra vari fluidi, cosa che alla fine Maxwell rifiutò. Tuttavia, Maxwell era ben a conoscenza di un altro fisico italiano: Riccardo Felici, poiché nel suo terzo capitolo Maxwell utilizzò una serie di esperimenti ideati da Felici, insieme a quelli di Faraday, per formulare la legge dell'induzione elettromagnetica: «la forza elettromotrice totale che agisce in un circuito ad ogni istante è proporzionale alla velocità di decremento del numero di linee di forza magnetica che lo attraversano». In questa esposizione di Giuseppe Pelosi e Stefano Selleri, apprendiamo di più sugli scienziati che hanno influenzato Maxwell e dettagli su Mossotti e Felici, che, tra l'altro, hanno ricoperto incarichi di alto livello presso l'Università di Pisa. I loro pensieri e scritti sono stati importanti per estendere le teorie esistenti di Oested e Faraday e, in definitiva, per costruire le basi di James Clerk Maxwell. Lodo questo nuovo eccellente contributo alle origini e alla storia del campo che oggi conosciamo come elettromagnetismo.

Trevor S. Bird
IEEE Antennas and Propagation Society, History Committee, President
Eastwood, New South Wales, Australia

Introduction

There are several reasons why we decided to write this book: *The Roots of Maxwell's* A Dynamical Theory of the Electromagnetic Field*: Scotland and Tuscany, 'twinned by science'.*

The first motivation for this volume arose when the celebrations for the 150 years since the presentation of the theory to the Royal Society (the British scientific association founded in 1660 in London) took place. This anniversary was celebrated by countless technical-scientific journals. In 1864 the Scottish physicist James Clerk Maxwell (1831-1879) presented his *memoir*, later published in 1865, in which he introduced the equations, which since then have borne his name. The formulation of Maxwell's equations completely defined the connection between the electric field and the magnetic field, definitively unifying electricity and magnetism and at the same time providing a theoretical synthesis of all the experimental phenomena connected to these areas. In his memoir Maxwell cites a handful of scientists, as the first contribution of this book will show. Three of these scientists were Italian: hence we can affirm what the title says, Maxwell's Dynamical Theory also had its roots in Italy.

Maxwell's theory, which gave us full comprehension of electrical and magnetic phenomena, has allowed many technological feats to be achieved, ranging from efficient electric motors and generators, the telephone, radio, television, and in general nearly every piece of modern technological equipment we commonly use in our daily life.

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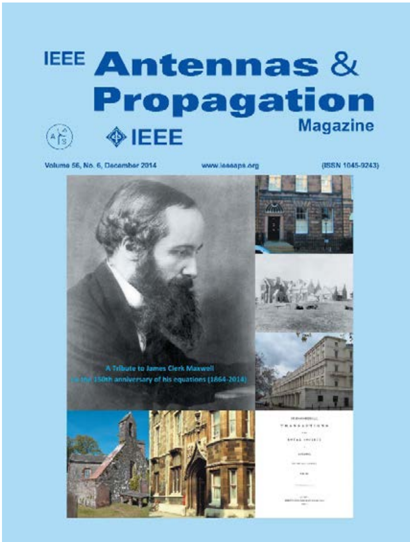

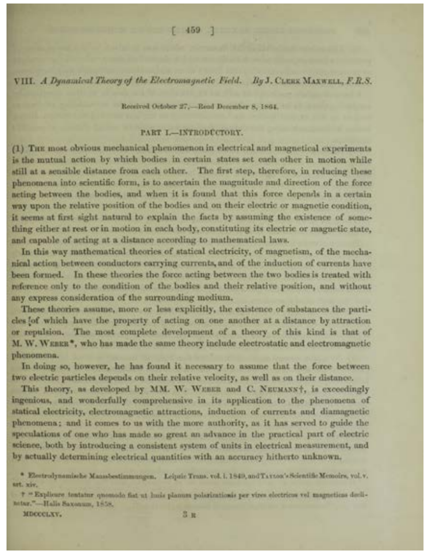

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VIII. *A Dynamical Theory of the Electromagnetic Field.* *By* J. CLERK MAXWELL, *F.R.S.*

Received October 27,—Read December 8, 1864.

PART I.—INTRODUCTORY.

(1) THE most obvious mechanical phenomenon in electrical and magnetical experiments is the mutual action by which bodies in certain states set each other in motion while still at a sensible distance from each other. The first step, therefore, in reducing these phenomena into scientific form, is to ascertain the magnitude and direction of the force acting between the bodies, and when it is found that this force depends in a certain way upon the relative position of the bodies and on their electric or magnetic condition, it seems at first sight natural to explain the facts by assuming the existence of something either at rest or in motion in each body, constituting its electric or magnetic state, and capable of acting at a distance according to mathematical laws.

In this way mathematical theories of statical electricity, of magnetism, of the mechanical action between conductors carrying currents, and of the induction of currents have been formed. In these theories the force acting between the two bodies is treated with reference only to the condition of the bodies and their relative position, and without any express consideration of the surrounding medium.

These theories assume, more or less explicitly, the existence of substances the particles of which have the property of acting on one another at a distance by attraction or repulsion. The most complete development of a theory of this kind is that of M. W. WEBER*, who has made the same theory include electrostatic and electromagnetic phenomena.

In doing so, however, he has found it necessary to assume that the force between two electric particles depends on their relative velocity, as well as on their distance.

This theory, as developed by MM. W. WEBER and C. NEUMANN†, is exceedingly ingenious, and wonderfully comprehensive in its application to the phenomena of statical electricity, electromagnetic attractions, induction of currents and diamagnetic phenomena; and it comes to us with the more authority, as it has served to guide the speculations of one who has made so great an advance in the practical part of electric science, both by introducing a consistent system of units in electrical measurement, and by actually determining electrical quantities with an accuracy hitherto unknown.

* Electrodynamische Maassbestimmungen. Leipzic Trans. vol. i. 1849, and TAYLOR's Scientific Memoirs, vol. v. art. xiv.

† "Explicare tentatur quomodo fiat ut lucis planum polarizationis per vires electricas vel magneticas declinetur."—Halis Saxonum, 1858.

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Fig. 1 – Left, the cover of the Special Issue of the *IEEE Antennas and Propagation Magazine* (vol. 56, no. 6, December 2014, pp. 295-316) entitled "A Tribute to James Clerk Maxwell on the 150th Anniversary of His Equations (1864-2014)", edited by G. Pelosi; right, the first page of Maxwell's *A Dynamical Theory of the Electromagnetic Field*.

The second motivation was an Historical conference in Glasgow, 2019, where we had the occasion to visit several 'Maxwellian' places: James. C. Maxwell's birthplace and his home in Edinburgh, his beloved cottage in Glenlair and his tomb in the cemetery nearby.

Lastly, though no less significant, there is the twinning, between Maxwell's hometown of Edinburgh and our city of Florence. A twinning more than half a century long, promoted by Mayor Giorgio la Pira in 1964, and signed by the successive Mayor Lelio Lagorio and the Lord Provost of Edinburgh Duncan W. Weatherstone on 28 May 1965. The twinning was then renewed by Mayor Dario Nardella and Lord Provost of Edinburgh Donald Wilson in 2015. We further extend our gratitude to the president of the Tuscany Region, Eugenio Giani, who actively contributed to keeping these ties between the two cities alive by participating in the events in Edinburgh in 2004 and in his role as president of the Regional Council of Tuscany at the time of the renewal, for the introduction that opens this book.

Indeed, while our humble pilgrimage to Maxwell's places was one of many trips we have made, J.C. Maxwell took only one voyage outside Great Britain in his whole life, when he came to Florence, to meet a scientist, Carlo Matteucci, who indirectly influenced his theories.

This book is aimed to present, to the general public, where the roots of such a revolutionary theory began to germinate. To present the subject in a clear framework, the book is divided into two parts:

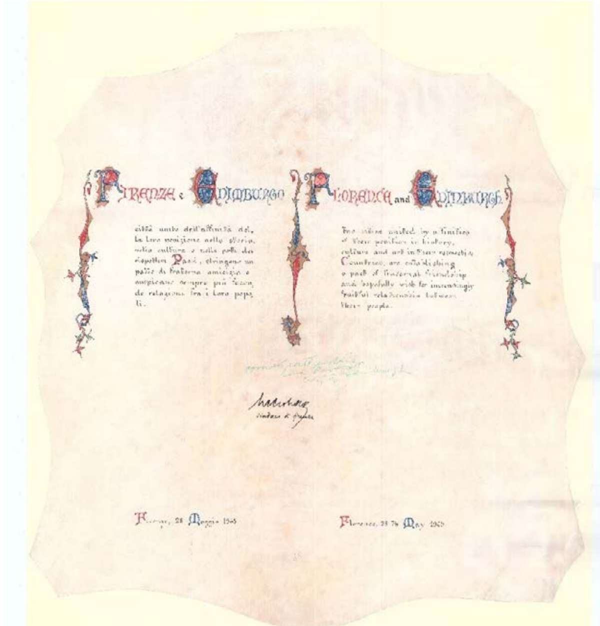


Fig. 2 – Original parchment of the twinning signed by the Mayor of Florence Lelio Lagorio and by the Lord Provost of Edinburgh Duncan W. Weatherstone on 28 May 1965

Fig. 3 – The Mayor of Florence Dario Nardella and the Lord Provost of Edinburgh Donald Wilson at the renewal of the twinning between the two cities on 23 June 2015.

1. The first part, *Roots all over Europe* has two chapters, with the first being a general overview of the Electromagnetic developments, from Volta's 'pile' up to Marconi's radio. The second chapter is devoted to a systematic analysis of the papers cited by Maxwell in his *A Dynamical Theory of the Electromagnetic Field* and of the papers cited in those papers, aiming at reconstructing the tree of knowledge which was at the basis of Maxwell's revolutionary theory.
2. The second part, *Roots in Italy*, has been divided into three sections, each containing some chapters, where the Italians outlined in the first part are discussed in greater detail. The first two sections*: On Ottaviano Fabrizio Mossotti* and *On Riccardo Felici* presents the two main Italian contributors to Maxwell's theory; Joseph-Louis Lagrange who, despite his French-sounding name was Italian, is cited for mechanical – not electromagnetic – reasons therefore, there is no dedicated section. Then the third section *Maxwell and Italy, after the presentation of* A Dynamical Theory of the Electromagnetic Field highlights some even less-known links between Maxwell and Italy: his 1867 voyage to Florence and his 1878 Laurea Onoris Causa awarded in Pavia, where, he was not able to go due to poor health, since the ceremony was just one year before his death.

These parts contain both original contributions and the republication of significant papers that have appeared in: *URSI Radio Science Bullettin*, and *Il Colle di Galileo* journal.

Fig. 4 – Left, the statue of Maxwell in Edinburgh, on the avenue near his home, where his faithful dog Toby is also featured. Right, the entrance to Maxwell's house in Edinburgh, now the site of the James Clerk Maxwell Foundation.

Concerning Italy's influence on the development of Electromagnetism, it should be recalled that the English scientist Michael Faraday had many, well-known, documented, links with Italian scientists; in particular, he befriended Carlo Matteucci who was a renowned physicist at the time. Indeed, Carlo Matteucci is cited twice in Part I because of his works which were cited by scientists who were then cited by Maxwell. Hence, Matteucci also had an indirect influence on Maxwell's *A Dynamical Theory of the Electromagnetic Field*. In addition, Matteucci, who was friend of Arago, Becquerel and many others, was awarded the Copley Medal from the Royal Society in 1844, only the third Italian to receive that honour. Today, Carlo Matteucci is not very well known outside of Italy. Nevertheless, it is stated in the most authoritative biography of Maxwell that among other reasons for his 1867 voyage to Italy was the opportunity to meet with Matteucci. This meeting unfortunately, was not very well documented and investigations are still ongoing, as the contributions in part two will show.

Fig. 5 – Some of the medals awarded to Maxwell, on display at the Maxwell Foundation. Note, at the bottom left there is the Volta Medal awarded by the University of Pavia in 1878.

Even if the focus of this book shifts to Italy in the second part, the reconstruction of the international network of scientists provided in part I encompasses all Europe and indeed, the United States, with Morse, as well. Each of the parts is initiated by a brief foreword, followed by the various contributions.

Giuseppe Pelosi, Stefano Selleri
University of Florence (Italy)
December 2022

Introduzione

Sono diversi i motivi per cui abbiamo deciso di scrivere questo libro: *The Roots of Maxwell's* A Dynamical Theory of the Electromagnetic Field*: Scotland and Tuscany, 'twinned by science'*.

La prima motivazione nasce in occasione delle celebrazioni per i 150 anni dalla presentazione alla Royal Society (associazione scientifica britannica e tra le più prestigiose al mondo, fondata nel 1660 a Londra) della teoria di James Clerk Maxwell (1831-1879) dell'elettromagnetismo. Questo anniversario è stato celebrato pochi anni fa da innumerevoli riviste tecnico-scientifiche. Nel 1864 il fisico scozzese James Clerk Maxwell presentò una memoria, poi pubblicata nel 1865, in cui introduceva le equazioni che da allora portavano il suo nome. La formulazione delle equazioni di Maxwell definiva completamente la connessione tra campo elettrico e campo magnetico, unificando definitivamente elettricità e magnetismo e fornendo al tempo stesso una sintesi teorica di tutti i fenomeni sperimentali connessi a queste aree. Nella sua memoria Maxwell cita una manciata di scienziati, come vedremo nella prima parte di questo libro. Tre di tali scienziati sono italiani, possiamo quindi affermare quanto dice il titolo: la teoria di Maxwell ha radici anche in Italia.

La teoria di Maxwell ha consentito, negli anni, risultati tecnologici che vanno da motori e generatori elettrici efficienti, telefono, radio, televisione, cellulari, internet e in generale ogni oggetto che funzioni con l'elettricità della nostra vita quotidiana.

La seconda motivazione è stata una conferenza di storia della scienza tenutasi a Glasgow nel 2019, dove abbiamo avuto l'occasione di visitare diversi luoghi 'maxwelliani': la casa natale di Maxwell, e dimora per gran parte della sua vita, a Edimburgo, e ora sede di una Fondazione a lui dedicata, il suo amato cottage a Glenlair e la tomba nel cimitero vicino a quest'ultimo.

Ultima motivazione, ma non meno importante, il gemellaggio tra la città natale di Maxwell, Edimburgo, e la nostra città di Firenze. Un gemellaggio che dura da più di mezzo secolo: promosso dal sindaco Giorgio La Pira nel 1964, siglato dal successivo sindaco di Firenze Lelio Lagorio e dal Lord Provost di Edimburgo Duncan W. Weatherstone il 28 maggio 1965. Tale gemellaggio è stato poi rinnovato dal sindaco Dario Nardella nel 2015. Siamo grati al presidente della Regione Toscana, Eugenio Giani, che ha contribuito attivamente a mantenere vivo questi legami tra le due città partecipando alle manifestazioni a Edimburgo del 2004 e da presidente del Consiglio Regionale della Toscana all'atto del rinnovo, per l'introduzione che apre questo libro.

Sempre nell'ottica dei collegamenti fra Firenze ed Edimburgo, ricordiamo che, mentre il nostro umile pellegrinaggio ai luoghi di Maxwell è stato uno dei tanti nostri tanti viaggi di ricercatori moderni, J.C. Maxwell in tutta la sua vita fece un solo viaggio fuori dalla Gran Bretagna, e proprio a Firenze, per incontrare uno scienziato, Carlo Matteucci.

Questo libro ha quindi lo scopo di presentare, al grande pubblico internazionale, e quindi in lingua inglese, da dove una teoria così rivoluzionaria abbia tratto origine e dove affondi le sue radici. Per chiarezza di esposizione, il libro è diviso in due parti:

1. La prima, *Roots all over Europe*, presenta due capitoli, il primo è una panoramica generale degli sviluppi in elettromagnetismo, dalla 'pila' di Volta fino alla radio di Marconi, e quindi la nascita delle telecomunicazioni. Il secondo è dedicato ad un'analisi sistematica degli articoli citati da Maxwell nella sua *A Dynamical Theory of the Electromagnetic Field* e degli articoli citati in detti articoli, mirante a ricostruire l''albero della conoscenza' che sta alla base della teoria rivoluzionaria di Maxwell.
2. La seconda parte, *Roots in Italy*, ulteriormente suddivisa in tre sezioni, ciascuna contenente alcuni capitoli, approfondisce gli italiani delineati nella prima parte. Le prime due sezioni: *On Ottaviano Fabrizio Mossotti* e *On Riccardo Felici* presentano i due principali scienziati italiani che hanno contribuito alla teoria di Maxwell; il terzo, Joseph-Louis Lagrange che, nonostante il nome francesizzante era italiano, viene citato per i suoi lavori di meccanica, non di elettricità o magnetismo e non viene quindi approfondito. Infine, una terza sezione *Maxwell and Italy, after the* A Dynamical Theory of the Electromagnetic Field mette in luce alcuni legami poco noti tra Maxwell e l'Italia: il suo già citato viaggio del 1867 a Firenze e la sua Laurea *Onoris Causa* a Pavia del 1878, dove non poté recarsi per motivi di salute, Maxwell morirà infatti nel 1879.

Queste parti contengono sia contributi originali sia la ripubblicazione di articoli pertinenti apparsi sulle riviste scientifiche: *URSI Radio Science Bullettin* e *Il Colle di Galileo*.

Per quanto riguarda l'influenza dell'Italia nello sviluppo dell'elettromagnetismo, dobbiamo poi ricordare che Michael Faraday aveva molti, ben noti e documentati, legami con l'Italia e, in particolare, fece amicizia con Carlo Matteucci celebre fisico dell'epoca. Carlo Matteucci è infatti ricordato due volte nella Parte I di questo volume, per dei suoi lavori citati dagli scienziati menzionati da Maxwell. Matteucci ha quindi avuto un'influenza indiretta anche su Maxwell e la sua *A Dynamical Theory of the Electromagnetic Field*. Matteucci ricevette la Medaglia Copley dalla Royal Society nel 1844, prestigioso riconoscimento internazionale, terzo italiano a riceverla, e fu amico di Arago, Becquerel e molti altri. Carlo Matteucci è ormai poco conosciuto fuori d'Italia, ma la biografia più autorevole di Maxwell afferma che il suo viaggio in Italia del 1867 aveva lo scopo preminente di incontrare Matteucci. Questo incontro, purtroppo, è scarsamente documentato e le indagini sono ancora in corso, come dimostreranno i contributi della seconda parte.

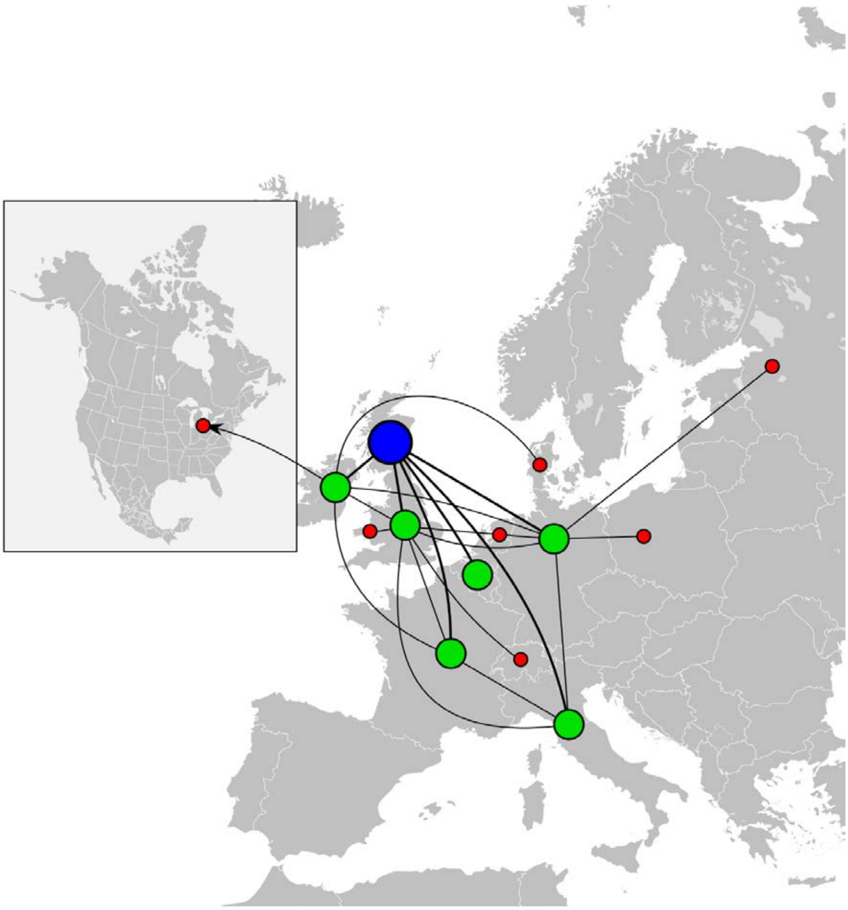
Anche se questo libro, nella seconda parte è concentrato sull'Italia e Firenze, i legami con Edimburgo e la ricostruzione della rete internazionale di scienziati fornita nella Parte I abbraccia tutta l'Europa e anche gli Stati Uniti, con Morse, rendendo l'argomento di interesse internazionale, da cui la decisione di pubblicarlo, salvo le introduzioni e presentazioni, in lingua inglese.

Ciascuna delle suddette parti o sezioni è poi iniziata da una breve prefazione, seguita dai vari contributi.

Giuseppe Pelosi, Stefano Selleri
Università di Firenze
Dicembre 2022

PART I

Roots All Over Europe



Maxwell's network of scientists in 1864. Maxwell: the large dot; First level (scientists cited by Maxwell): the medium-size dots; second level (Scientists cited in the papers cited by Maxwell): the smallest dots.

Introduction

This first part, *Roots all over Europe*, contains two chapters, with the first being a brief general overview of the developments in electromagnetism in the century spanning from Alessandro Volta's invention of the «pile», the first generator able to provide continuous current over a nonnegligible timespan, up to Marconi's trans-Atlantic leap. Without Volta's battery the subsequent findings in electromagnetism which eventually led to Maxwell's unification and his hypothesis of the existence of electromagnetic waves would not have been possible. After Hertz's first experiments which proved this latter hypothesis, Marconi, developed a radio communications technology based on electromagnetic waves, which has since provided benefits for all humanity.

The second chapter then focuses on Maxwell's unification and is devoted to a systematic analysis of the papers cited by Maxwell in *A Dynamical Theory of the Electromagnetic Field*. The citation path then goes onto a second stage, where the papers cited in those papers are analysed with the aim of reconstructing the tree of scientists and knowledge which formed the basis of Maxwell's revolutionary theory.

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From the 'pila' to radiotelegraphy through Maxwell's *A Dynamical Theory of the Electromagnetic Field*

Maxwell's equations constitute a system of coupled linear partial differential equations, consisting of two vector equations and two scalar equations. In the context of classical physics, together with the Lorentz force, Maxwell's equations govern every possible electromagnetic phenomenon, describing the temporal evolution and the constraints to which the electromagnetic field is subject, starting from the charge and electric current distributions from which it is generated.

James Clerk Maxwell synthesized his equations by grouping and harmonizing laws known up to the mid-nineteenth century, discovered among others by Gauss, Faraday, Neumann, Lenz and Ampère. In particular, Maxwell's fundamental contribution was the introduction of the displacement current to the original Ampère law, hence deriving what is now Ampère-Maxwell's law. This elaboration made the equations that describe, in the classical manner, the electric field and the magnetic field as symmetrical; showing even more effectively how these are two forms of a single entity: the electromagnetic field. These equations in fact account for the fact that dynamic electric fields are capable of generating magnetic fields and vice versa, thus unifying, at a theoretical level and in a perfectly symmetrical way, electricity with magnetism (Fig. 1).

This symmetry is the prerequisite for a wave-like solution to Maxwell's system of equations, which is, for the theoretical prediction of electromagnetic waves, the discovery that allowed the nature of light to be explained. Electromagnetic waves, whose existence had been predicted as a mathematical entity, therefore acquired their own physical reality.

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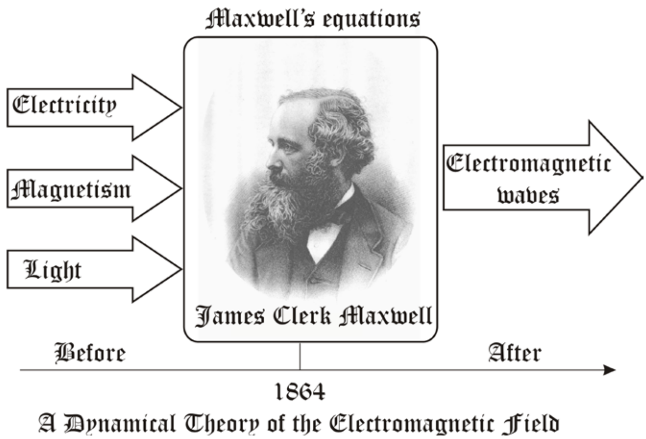

Fig. 1 – The unification of physical phenomena operated by J.C. Maxwell with the 1864 memoir, which completes his theory first proposed in 1861.

The history of electromagnetism has its roots in the remote past, when the ancient Greeks were already aware of electrical and magnetic phenomena, although they had no real scientific understanding of them.

We must wait for the modern era, after Galileo, to have the first truly scientific observations of static electric and magnetic fields, mainly by Charles Augustin de Coulomb (1736-1806), who drew a parallel between gravitational attraction and the electrostatic attraction of two point charges.

But it is only with the advent of the 'pila', or battery (Fig. 2), created in 1799 by the Italian Alessandro Volta (1745-1827), that, by allowing the generation of a direct current, there was a truly fruitful explosion of research into electricity and magnetism. In just 65 years the interpretation of electromagnetism was completed by James Clerk Maxwell (1831-1879) in his famous memoir of 1864.

Fig. 2 – Some original Volta batteries in the Tempio Voltiano in Como, Italy.

And then, after about twenty years Heinrich Hertz (1857-1894) managed to produce electromagnetic waves. In just another eight years, radio telegraphy was born thanks to Guglielmo Marconi (1874-1937), and, with it, telecommunications as we know them today. Again, only a few years were needed for a radio signal to cross the Atlantic Ocean (Fig. 3). From 1799 to 1901: in just one century modern telecommunications were born.

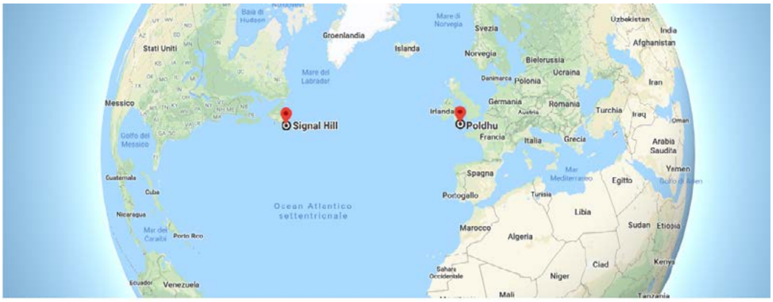

Fig. 3 – Location of the transmitting station (Poldhu, UK) and receiving station (Signal Hill, NL, Canada) of the first transatlantic radio link, 1901.

Table I below shows a short timeline, which is necessarily incomplete and personal, of the century that separated the invention of the battery to the rise of radiotelegraphy. The third column indicates the presence of an *IEEE Milestone*. As part of the *IEEE Global History Network program*, Milestones commemorate outstanding scientific or technological achievements.

Table 1 – A selection of key events in electromagnetism and the dedicated IEEE Milestones.

1799	Alessandro Volta (Italian, 1745-1827) develops the first battery, which is the first source of continuous currents	IEEE MILESTONE PROGRAM ITALY
1820	Hans Christian Ørsted (Danish, 1777-1851) proves the link between electricity and magnetism: a wire carrying a current forces a magnetic needle to turn so as to be perpendicular to the wire.	
1820	Andre-Marie Ampère (French, 1775-1836) discovers that parallel wires carrying currents mutually attract or repel.	
1820	Jean-Baptiste Biot (French, 1774-1862) and Félix Savart (French 1791-1841) formulate the law bearing their name, linking the intensity of the magnetic field generated by a wire carrying a current to the intensity of the current.	
1825	Leopoldo Nobili (Italian, 1784-1835) builds the first precision galvanometer (astatic galvanometer) which will allow exact measurements and repeatable experiments.	
1826	Andre-Marie Ampère (French, 1775-1836) completes the mathematical formulation of the interaction of currents. Theoretical electrodynamics is born.	

1827 Georg Simon Ohm (German, 1971-1841) formulates the law bearing his name which expresses the relationship between current, voltage and resistance.

1831 Michael Faraday (English, 1791-1867) discovers how a variation of magnetic flux can generate an electromotive force.

1832 Joseph Henry (American, 1797 – 1878) discovers self-induction.

1834 Heinrich Lenz (Russian, 1804-1865) on the basis of energy shows that the current induced by a variation in magnetic flux is such that it will generate a magnetic field in opposition to such a variation.

1835 Carl Friedrich Gauss (German, 1777-1855) formulates the law bearing his name linking the flux of the electric field through a closed surface to the electric charge in the volume enclosed by the surface itself.

1845 Franz Ernst Neumann (German, 1798-1895) gives the definitive mathematical formulation to the law of induction: the Faraday-Neumann-Lenz law.

1864 James Clerk Maxwell (Scottish, 1831-1879) presents *A Dynamical Theory of the Electromagnetic Field* where the displacement current is introduced, hence formulating the Ampère-Maxwell law. He unifies all preceding discoveries and demonstrates the possibility of electromagnetic waves, suggesting that light is an electromagnetic wave.

IEEE MILESTONE PROGRAM
SCOTLAND

1873 James Clerk Maxwell (Scottish, 1831-1879) publishes his *Treatise on electricity and magnetism* summarizing all his theory with a new quaternions-based notation.

1888 Heinrich Hertz (German, 1857-1894) builds laboratory equipment able to generate and detect electromagnetic waves.

IEEE MILESTONE PROGRAM
GERMANY

1893 Oliver Heaviside (English, 1850-1925) publishes the first of the three volumes of his *Electromagnetic Theory*, ending in 1912. Here Heaviside discards the quaternion notation and introduces the vector notation still in use.

1895 Guglielmo Marconi (Italian, 1874-1937) manages to build a radio link outdoors, at a nonnegligible distance and with physical obstacles in between. [1]

IEEE MILESTONE PROGRAM
ITALY

1901 Guglielmo Marconi (Italian, 1874-1937) manages to build a radio link across the Atlantic ocean, from a transmitter in Poldhu, (Cornwall, England), to a receiver on Signal Hill (Nova Scotia, Canada). Telecommunication is born.

IEEE MILESTONE PROGRAM
CANADA/ENGLAND

[1] It is interesting to note that this milestone was somewhat 'challenged' by the Swiss, who insisted that Marconi performed his first experiments in Salvan in 1894. The Swiss Milestone was finally revoked, Pelosi 2019. On the other hand, at about the same time Jagadish Chandra Bose (1858-1937), Aleksander Popov (1859-1906) and Nikola Tesla (1856-1943) were carrying out radio link experiments.

Fig. 4 – The Royal Society, which is the British Academy of Sciences, is preeminent in the world. Founded on November 28, 1660, it is among the oldest academies still active (http://royalsociety.org/).

However, in this timeline, it is worth focusing on the year 1864, when, on December 8, at a meeting of the Royal Society of London, Maxwell presented his memoir *A Dynamical Theory of the Electromagnetic Field*. The Royal Society, which, is still active and preeminent in the world, is a British scientific association founded in 1660 in London. Maxwell's dissertation was then submitted to the Proceedings of the Royal Society and published in January of the next year, Maxwell (1865). In the published dissertation Maxwell mentions only twenty-three scholars who preceded him and on whose ideas the unification that Maxwell accomplished was based.

It is evident that the analysis of these citations allows us to reconstruct which previous scientific results inspired Maxwell and led him to the synthesis contained in his famous equations, whilst at the same time providing us a glimpse, probably partial though very interesting, of the nations that contributed the most to scientific research in that era. Of course, this is a reflection of Maxwell's personal views, at least of those he chose to mention in his writing. There may have been other influences, which he may have acknowledged, but which he chose not to mention, or which he did not consciously recognise.

In particular, Maxwell quotes or mentions 23 scientists, all European, in order of their numbers: 7 Germans, 6 Frenchmen, 5 Englishmen, 3 Italians, 1 Belgian, and 1 Irishman. Many of these 23 scientists were known to Maxwell only through having read their works, whilst some had direct personal knowledge or maintained correspondence with him (Faraday, Hockin, and Jenkin). These latter had a particular importance in the development of Maxwell's point of view of electromagnetic phenomena.

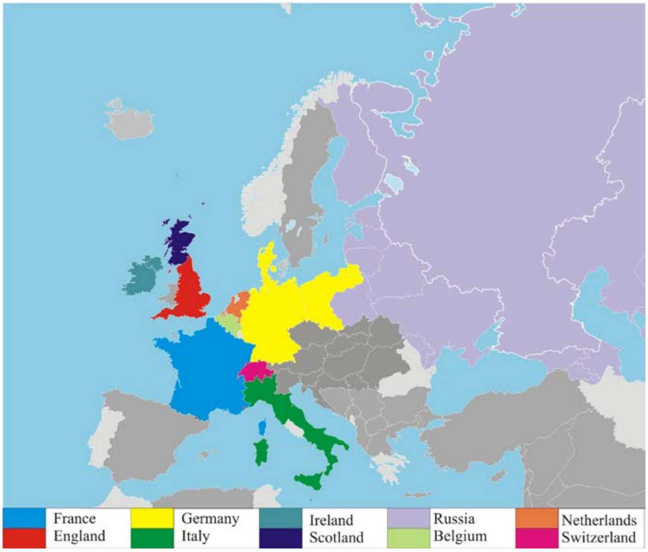

Fig. 5 – Map of Europe (Agastra 2014) showing the nations whose scientists were cited by Maxwell, at the first and second levels as quantified in the Table in the following chapter.

In the next chapter, we will analyse the bibliography of the works of these 23 scholars cited by Maxwell, to reconstruct a genealogical tree of Maxwell's equations. Fig. 5 gives a first glance of the results.

Among these scientists, Maxwell explicitly quotes the Italians Ottaviano Fabrizio Mossotti, Riccardo Felici and Giuseppe Luigi Lagrangia (better known, internationally, with the French version of his name: Joseph-Louis Lagrange). In particular Maxwell quotes Mossotti in paragraph no. 11 where he introduces the concept of «displacement» of the electricity of the molecules. Displacement whose variation is, indeed the «displacement current» he will introduce, and which leads to the second of his equations, also known as the Ampère-Maxwell law:

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \boldsymbol{D}}{\partial t} \tag{1}$$

with **H** being the magnetic field, **D** the electric induction and **J** the current density.

It is important to note that Maxwell never wrote his equations in the form we are now accustomed to. His 1864 presentation was in cartesian coordinates, while his subsequent *Treatise* exploited quaternions, introduced a few years before by W.R. Hamilton. Quaternion notation was awkward in any case, and it was only when O. Heaviside recast them in J.W. Gibb's vector notation that Maxwell's equations assumed the form we still use today, Arthur (2013), Nahin (1988).

He then quotes Felici, together with Faraday, in paragraph no. 25 among those who had carried out experiments on electromagnetic induction. Induction is then summarized in the first of Maxwell's equations, also known as the Faraday-Neumann-Lenz law:

$$\nabla \times \mathbf{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{2}$$

With **E** being the electric field and **B** the magnetic induction.

Finally, Joseph-Louis Lagrange is cited in paragraph no. 24. However, because this is related to the mechanical equations of dynamics and not at all to electromagnetism, Lagrange was excluded from this book.

On the other hand, Carlo Matteucci is cited twice at the second level, making his influence quite significant, as an Italian, in this analysis, which is why there will be a contribution devoted to him in the last part.

It is also important to note that Maxwell's equations can indeed be found in essentially the same form in which they appeared in his 1864 dissertation, in Maxwell's previous paper *On physical lines of force*, published in four parts, Maxwell (1861a, 1861b, 1862a, 1862b). It was a matter of concern for the authors, in preparing the analysis in part I of this volume, whether to consider the 1861-62 paper as fundamental, or at least equal to the 1865 *A Dynamical Theory of the Electromagnetic Field*.

Finally, the choice was made to adhere to the 1865 paper for several reasons. First of all, even starting from its title, as the many celebrations held in 2015 for the 150 year anniversary of Maxwell's equations testify, his 1865 paper contains the true complete unification of his Electromagnetic Field theory and is universally considered as the landmark paper that gave birth to classical electrodynamics. Second, even if displacement current was introduced initially in the 1861-62 paper, it was only in his 1865 paper that this new term proved its fundamental importance, when Maxwell finally derived, theoretically, the possibility of electromagnetic waves and the proposition that their theoretic speed equals the speed of light.

In his 1861-62 paper Maxwell resorted to a purely mechanical view, using the concept of «molecular vortices,» to provide a mechanical analogy for the behaviour of electromagnetic media and hence an aid to understanding how electromagnetic forces behave. In his 1865 paper the mechanical analogy was abandoned in favour of a more abstract concept, that describes an «electromagnetic field» that pervades all space, including materials.

Maxwell's vision presented in his 1865 paper is fully mature. Hence, we elected to focus on this 1865 paper as a key one, whilst, of course, also giving full attention to the 1861-62 paper, which is the first analysed among those cited by Maxwell.

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A systematic analysis of Maxwell's citations in *A Dynamical Theory of the Electromagnetic Field*

Here an accurate reconstruction of the tree of citations stemming from Maxwell's *A Dynamical Theory of the Electromagnetic Field* is set out. While a paper of some years ago (Agastra, 2014) included the aggregated data, here the full citations in Maxwell's (1865) paper (level I) as well as the full citations of all papers cited in the papers cited by Maxwell (level II) are given.

It is worth noting that, with respect to what was published by Agastra (2014) some papers that were not available to the authors at that time have been retrieved in the meantime, hence allowing for a more accurate and updated reconstruction of the aggregate data in Table I. First row, Level I citations (bold – which means a specific work by an author is addressed) or mentions (italics – which mean there is just a reference to the scientist, but not to any one of that scientist's works). Self-citations are in parentheses and were added to the other citations. In each column, Level II citations, aggregated from the citations of each level I nationality, are divided by country. The last column shows totals of all the citations and mentions on both levels, comprising the self-citations.

It is apparent how, at the time, England, France and Germany were the key countries for scientific development – at least for this topic – whilst Ireland, Italy and Scotland followed at a certain distance. Furthermore, it seems that French scientists tended to cite other Frenchmen, while the English had a wider range of citations, with Englishmen still preeminent, and Germans having a more even distribution.

Details are given below. For Level I scientists, the data is organized in records as follows:

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Name FamilyName [Birthplace, Country (modern), date - Deathplace, country (modern), date]

Short bio, mostly focused on his achievements in electromagnetics, and possibly some items of interest.

Nationality: cited #of times, mentioned #of times

Maxwell paragraph where the citation occurs

DT: p. page#, par. (par#) **citation to** "title." *Journal*, volume, year, pages.

[1] Author, Name. Year. *Book title*, pages. City (country): publisher (eventual notes).

A. Author [Birthplace, County, date - Deathplace, Country, date] very short bio the first time the scientist is cited.

[2] Author, Name. Year. "Article title." *Journal* volume: pages (eventual notes).

Only Mentioned: C. Author

C. Author [Birthplace, County, date - Deathplace, Country, date] very short bio the first time the scientist is cited.

Another paragraph, with a simple mention

DT: p. page#, par. (par#) no explicit citation given.

Included, there will be a portrait, when available, the person's full name, place and date of birth and death, followed by a short biography with highlighted links to Maxwell and any items of interest. Then their nationality and the number of citations/mentions in *A Dynamical Theory of the Electromagnetic Field* (hereinafter abbreviated to **DT** in bold) is given. For each of these the relative paragraph is cited with a specification of where it can be found in the Maxwell paper.

Authors are not repeated in first level unless other authors besides those cited are present. If Maxwell does not explicitly cite any work by the scientist, this is considered a 'mention' rather than a 'citation'.

A list of papers cited in the paper under analysis, which represents the second level of citations then follows. Simple second level mentions are also given later on.

For all these 'second level' scientists a brief biographical profile is given the first time they are encountered.

If Maxwell cites the same author more than once each citation is treated separately.

People are cited in alphabetical order for level I, and, within the level I record, level II citations and biographies are given in the order they appear in the cited papers. With the notable exception of Maxwell's self-citation, which is given first hereafter.

To provide the reader with an index to browse the tree of scientists cited by Maxwell, the following table lists them in alphabetical order. Their relevant field of interest, relevant in the sense that it is the field for which they are cited by Maxwell, is given using the following letter codes:

A – Astronomy
C – Chemistry
D – Divulgator
E – Electricity
F – Fluid dynamics
Ed – Editor of scientific journal
Ma – Magnetism
Me – Mechanics
Mt – Math
O – Optics
T – Thermodynamics

The same letters, in parenthesis, indicate that the main research area of the scientist was indeed not the one for which Maxwell cites them. It is important to understand that Maxwell also worked on Thermodynamics, developing the gas-kinetic model and that, in his mind, Electromagnetic phenomena were – at least at the beginning – mechanical in nature and bound to molecular vortices. Hence, both theoretical papers on Thermodynamics and Mechanics were cited and sometimes relevant to his development of electrodynamics.

A third column shows the level of citation or mentions (I – directly by Maxwell, II – Cited by scientists cited by Maxwell). A letter 'C' or 'M' also specifies whether it is a citation or just a mention.

The fourth and fifth column indicates the relevance of the work by that scientist in Maxwell's development of his theory. The two columns concern, respectively, theoretical and experimental findings and their relevance to Maxwell's Theory, given as a star rating from 0 (negligible) to ★★★ (fundamental). These ratings are of course the results of the author's personal interpretation.

Finally, the last column points to the page where a short biographical profile of the scientist can be found.

It is also worth mentioning two other scientists, who do not appear in the research limited to a depth of two levels but who were in any event highly influential – at times more influential than those cited – to the development of electrodynamics. These two are in italics in the table below and their biographic profiles can be found at the end of this part.

Name	Field	Level	Teory	Exp.	Page
Ampère, André-Marie	E,Ma	IM	★★★		44
Anderson, Charles	E (Faraday Assistant)	IIM			47
Andrews, Thomas	T	IIC			71
Arago, Dominique François Jean	E	IIM	★★		52
Babbage, Charles	Ma(Mt,Me)	IIC		★	51
Becquerel, Alexandre-Edmond	T,E	IIC			66
Beek, Albertus van	C	IIC		★	51
Berthelot, Marcellin Pierre Eugène	C	IIM			57
Berthollet, Claude Louis	T (Ch)	IIC			63
Bertin, Pierre Auguste	O	IIC			89
Blackburn, Bailie Hugh	Mt	IIM			85
Böhm, Josef Georg	A	IIM			88
Carnot, Nicolas Léonard Sadi	T	IIM			66
Challis, James	Ma (A)	IIC	★		41
Christie, Samuel Hunter	E	IIC		★	47
Clapeyron, Benoît Paul Émile	T	IIC	★		63
Clausius, Rudolf Julius Emanuel	T	IIM			87
Coulomb, Charles-Augustin de	E	IIC	★★		48
Daniell, John Frederic	E (C)	IM			45
Davy, Humphry	C	IIC			50
Faraday, Michael	E,C	IM	★★★		46
Favre, Pierre Antoine	C	IIC			71
Felici, Riccardo	ELE	IC	★★		53
Fizeau, Armand Hippolyte Louis	A	IC		★★	54
Foucault, Jean Bernard Léon	E,Ma	IC		★★	55
Franklin, Benjamin	*E*				93
Fresnel, Augustin-Jean	O	IIM	★		43
Galilei, Galileo	A	IIM			76
Gaugain, Jean-Mothée	E	IC			56
Gauss, Johann Carl Friedrich	M	IIM	★		91
Gay-Lussac, Joseph Louis	T,Ch	IIM			67
Geißler, Johann Heinrich Wilhelm	Glassmaker	IM			59
Goodeve, Thomas Minchin	Me	IIC			40
Grassmann, Hermann Günther	Mt,E	IIC	★		66

Name	Field	Level	Teory	Exp.	Page
Green, George	Mt	IC	★★		60
Hachette, Jean Nicolas Pierre	Mt (Ed)	IIM			52
Harris, William Snow	E	IIC	★1/2		48
Helmholtz, Hermann Ludwig Ferdinand von	Mt, E	IC	★★		62
Henry, Joseph	*Mt*				93
Henry, William	T (C)	IIC			63
Herschel, John Frederick William	Ma(A)	IIC		★	51
Hess, Germain Henry	T (C)	IIC			63
Hind, John Russell	A	IIM			88
Hockin, Charles	E	IC			68
Holtzmann, Carl Alexander	T	IIC			64
Jenkin, Henry Charles Fleeming	E,Me	IC		★	69
Joule, James Prescott	T,Me	IIC	★		62
Kepler, Johannes	A	IIM			90
Knoblauch, Karl Hermann	O	IC		★	73
Knochenhauer, Karl Wilhelm	E	IIC			64
Kohlrausch, Friedrich Wilhelm Georg	E	IC		★★	74
La Rive, Auguste Arthur de	E (T)	IIC			57
Lagrange, Joseph-Louis	Mt	IC	★		76
Laplace, Pierre-Simon de	Mt	IIC			60
Laugier, Paul-Auguste-Ernest	A	IIM			88
Lenz, Heinrich Friedrich Emil	E,T	IIC	★		65
MacCullagh, James	M	IIM	★		43
Marianini, Stefano	E	IIC		★	51
Mariotte, Edme	T	IIM			67
Matteucci, Carlo	E	IIC		★	57
Matthiessen, Augustus	E	IIC			70
Miller, William Hallowes	E	IIC			70
Morse, Samuel Finley Breese	E	IIM			86
Mossotti, Ottaviano Fabrizio	ELE	IC	★★★		77
Neumann, Carl Gottfried	Mt	IC	★★		79
Neumann, Franz Ernst	T	IIM			43
Newton, Isaac	Ma,Mt	IIC	★★		84

Name	Field	Level	Teory	Exp.	Page
Nichol, John Pringle	D	IIC			42
Nicholson, William	E (C,D)	IIC			48
Ohm, Georg Simon	E	IIC		★	65
Peltier, Jean Charles Athanase	E	IIM			67
Petersen, Adolph Cornelius	A	IIM			88
Plateau, Joseph Antoine Ferdinand	E (C,O)	IM			81
Plücker, Julius	O	IM			82
Poggendorff, Johann Christian	E (Ed)	IIC			65
Poisson, Siméon-Denis	E (Mt)	IIC	★		49
Pouillet, Claude Servais Mathias	A	IC			83
Rankine, William John Macquorn	Me (T)	IIC	★		40
Regnault, Henri-Victor	C,T	IIM			58
Riess, Peter Theophil	E	IIC		★	64
Ritchie, William	Me	IIC			48
Sainte-Claire Deville, Henri Étienne	C	IIM			57
Saweljev, A.	E	IIC			66
Schroeder van der Kolk, Hendrik Willem	E	IIC			70
Scoresby, William	E (T)	IIC	★		86
Siemens, Ernst Werner von	E	IIC		★	85
Stokes, George Gabriel	Mt,F	IIC	★★		40
Thomson, William (Lord Kelvin)	T,Me,E	IC	★★★		84
Tyndall, John	Ma,O	IIC			73
Verdet, Marcel-Émile	Ma,O	IC		★	89
Vogt, August Christoph Carl	E	IIC			70
Vorsselman de Heer, Pieter Otto Coenraad	E,T	IIC			64
Wartmann, Elie François	E,O	IIC			47
Waterston, John James	T	IIM			88
Weber, Wilhelm Eduard	ELE	IC	★★		90
Wheatstone, Charles	E	IIC			69
Wiedemann, Gustav Heinrich	O,Ma (Ed)	IIC			79
Wollaston, William Hyde	C	IIC			50

James Clerk Maxwell [Edinburgh, Scotland, June 13, 1831 - Cambridge, England, November 5, 1879]

Scottish 'natural Philosopher' working in mathematical physics. His most notable achievement, which indeed we celebrate in this book, is the formulation of the classical theory of electromagnetic radiation, bringing together for the first time electricity, magnetism, and light as different manifestations of the same phenomenon.

This is often referred to as the *second great unification in physics*, the first having been realized by Isaac Newton.

He also developed the Maxwell-Boltzmann distribution, a statistical means of describing aspects of the kinetic theory of gases and he created the first durable colour photograph in 1861.

Maxwell's work can be considered at the roots of modern physics by laying the foundation for the eventual rise of special relativity and quantum mechanics. Many physicists regard Maxwell as the 19th-century scientist who had the greatest influence on 20th-century physics. [Campbell 1882, James Clerk Maxwell Foundation, Domb 2022, O'Connor 2022]

One self-citation:

> I have on a former occasion* attempted to describe a particular kind of motion and a particular kind of strain, so arranged as to account for the phenomena. In the present paper I avoid any hypothesis of this kind; and in using such words as electric momentum and electric elasticity in reference to the known phenomena of the induction of currents and the polarization of dielectrics, I wish merely to direct the mind of the reader to mechanical phenomena which will assist him in understanding the electrical ones. All such phrases in the present paper are to be considered as illustrative, not as explanatory.

DT: p. 487 par. (73) **citation to** "On physical lines of force" in four parts, analysed singularly:

Part I, 1861. "The theory of molecular vortices applied to magnetic phenomena." *Philosophical Magazine* 4, 21: 161-75.

[1] Faraday, Michael. 1855. *Experimental Researches in Electricity*, volume III. London (UK): R. & J.E. Taylor, exp. 3122.
[2] Maxwell, James Clerk. 1858. "On Faraday's lines of force." *Transactions of Cambridge Philosophical Society* 10, part. I: 27-83.
[3] Thomson, William. 1847. "On a mechanical representation of electric, magnetic, and galvanic forces." *Cambridge and Dublin Mathematical Journal* 2: 61-4.
[4] Faraday, Michael. 1855. *Experimental Researches in Electricity*, volume III. London (UK): R. & J.E. Taylor, exp. 3152.

[5] Rankine, William. 1858. *A Manual of Applied Mechanics*. Glasgow (UK): R. Griffin & Co., par. 106.

[6] Rankine, William. 1858. *A Manual of Applied Mechanics*. Glasgow (UK): R. Griffin & Co., par. 116.

> **William John Macquorn Rankine** [Edinburgh, Scotland July 5, 1820 - Glasgow, Scotland, December 24, 1872] physicist and engineer. Rudolf Clausius, William Thomson and Rankine were the father of thermodynamics. His science specifically focused on the first of the three thermodynamic laws. He developed the Rankine scale for temperature and published several hundred papers. His interests were extremely varied, including, in his youth, botany, music theory and number theory, and, in his mature years, most major branches of science, mathematics and engineering. As a professor, Rankine worked closely with Glasgow shipbuilders on radical improvements to the design of vessels and their engines. He introduced the famous 'sandwich courses' that required students to work with local engineering firms during their vacations, and he campaigned vigorously for the recognition of Engineering as a degree subject. [University of Glasgow "Macquorn Rankine"]

Part II, 1861. "The theory of molecular vortices applied to electric currents." *Philosophical Magazine* 4, 21: 281-91 and 338-48.

[7] Goodeve, Thomas Minchin. 1860. *The Elements of Mechanism*. London (UK): Longman Green, (Maxwell cites only p. 118).

> **Thomas Minchin Goodeve** [Greatham Hampshire, England, November 26, 1820 - Hitchin, England, February 10, 1902] professor of Natural Philosophy at King's College, London, who worked on mechanics and steam engines. [King's College London "Goodeve, Thomas Minchin"]

[8] Stokes, George Gabriel. 1851. "On the Dynamical Theory of Diffraction." *Transactions of Cambridge Philosophical* Society 9, part. I: 1-62 (Maxwell cites explicitly only Part I Sect. 6 of the paper, but part I has only 3 sections).

> **George Gabriel Stokes** [Skreen, Ireland, August 13, 1819 - Cambridge, England, February 1st, 1903) spent his entire career at the University of Cambridge, where he was the 13th Lucasian Professor of Mathematics from 1849 until his death in 1903. Stokes made seminal contributions to fluid mechanics, including the Navier–Stokes equations and to physical optics, with notable works on polarization and fluorescence. He worked on fluorescence (term which he introduced) and used it in the study of ultraviolet light. He demonstrated that quartz, unlike ordinary glass, is transparent to ultraviolet light.
> As a mathematician, we should recall Stokes' theorem of vector calculus and his contributions to the theory of asymptotic expansions. Stokes, along with Felix Hoppe-Seyler, first demonstrated the oxygen transport function of haemoglobin and showed colour changes produced by the aeration of haemoglobin solutions. [Encyclopaedia Britannica "Sir George Gabriel Stokes", O'Connor 2003]

[9] Maxwell, James Clerk. 1858. "On Faraday's lines of force." *Transactions of Cambridge Philosophical Society* 10, part. I: 27-83.

[10] Helmholtz, Hermann. 1858. "Über integrale der hydrodynamischen gleichungen, welche den wirbelbewegungen entsprechen [On the integrals of the hydrodynamic equations, which correspond to the vortex movements]." *Journal für die Reine und Angewandte Mathematik* LV: 25-55 (Maxwell erroneously cite 1859 as the year of publication).

Part III, 1862. "The theory of molecular vortices applied to statical electricity." *Philosophical Magazine*, 4, 23: 12-24.

[11] Maxwell, James Clerk. 1861. "On physical lines of force, part I." *Philosophical Magazine* 4, 21: 161-75 (cited several times).
[12] Maxwell, James Clerk. 1861. "On physical lines of force, part II." *Philosophical Magazine* 4, 21: 281-91 and 338-48.
[13] Faraday, Michael. 1839. *Experimental Researches in Electricity*, volume I. London (UK): R. & J.E. Taylor, Series XI.
[14] Mossotti, Ottaviano Fabrizio. 1850. "Discussione analitica sull'influenza che l'azione di un mezzo dielettrico ha sulla distribuzione dell'elettricità alla superficie di più corpi elettrici disseminati in esso [Analytical discussion on the influence that the action of a dielectric medium has on the surface distribution of electricity of several electric bodies scattered in it]." *Memorie di Matematica e di Fisica della Società Italiana delle Scienze di Modena* 24, part. II: 49-75.
[15] Rankine, William. 1851. "On the laws of elasticity of solid bodies." *Cambridge and Dublin Mathematical Journal* 4: 47-80, 178-81 and 185-6.
[16] Green, George. 1828. *An Essay on the Application of Mathematical Analysis to the Theories of Electricity and Magnetism*. Nottingham (UK): T. Wheelhouse.
[17] Kohlrausch, Rudolf, and Wilhelm Weber. 1857. "Elektrodynamische maasbestimmungen insbesondere zurückführung der stromintensitäts-messungen auf mechanisches maass [Electrodynamic measurements, in particular tracing back current intensity measurements to mechanical measurements]." *Abhandlungen der Mathematisch-Physischen Classe der König. Sächsischen* 3: 219-93 (Maxwell cites only p. 260).
[18] Fizeau, Hippolyte Louis. 1849. "Sur une expérience relative à la vitesse de propagation de la lumière [On an experiment relating to the speed of propagation of light]." *Comptes Rendus* 29: 90-2 and errata at 132 (Maxwell cites only p. 90).

Part IV, 1862. "The theory of molecular vortices applied to the action of magnetism on polarized light." *Philosophical Magazine* 4, 23: 85-95.

[19] Maxwell, James Clerk. 1861. "On physical lines of force, part I." *Philosophical Magazine* 4, 21: 161-75 (cited several times).
[20] Thomson, William. 1847. "On a mechanical representation of electric, magnetic, and galvanic forces." *Cambridge and Dublin Mathematical Journal* 2: 61-4.
[21] Challis, James. 1860. "A theory of galvanic force." *Philosophical Magazine* 4, 20: 431-41.
[22] Challis, James. 1861. "A theory of magnetic force." *Philosophical Magazine* 4, 21: 92-107.

James Challis [Braintree, England, December 12, 1802 - Cambridge, England, December 3, 1882] clergyman, physicist and astronomer. Plumian Professor of Astronomy and Experimental Philosophy and the director of the Cambridge Observatory. He investigat-

ed a wide range of physical phenomena but his contributions outside astronomy had a limited impact.
John Couch Adams in Cambridge had predicted the location of an eighth planet as early as 1844, based on irregularities in the orbit of Uranus, but failed to promote his prediction until George Airy's intervention. Challis reluctantly began to search for the planet in July 1846. In the meantime, Urbain Le Verrier had independently made an identical prediction and Johann Gottfried Galle with Heinrich Louis d'Arrest confirmed Le Verrier's prediction on 23 September 1846. The planet was named 'Neptune'. It soon became apparent from Challis's notebooks that he had observed Neptune twice, a month earlier, failing to make the identification through lack of diligence and a current star chart. [Encyclopaedia Britannica "James Challis", Minds of Science "James Challis"]

[23] Helmholtz, Hermann. 1858. "Über integrale der hydrodynamischen gleichungen, welche den wirbelbewegungen entsprechen [On the integrals of the hydrodynamic equations, which correspond to the vortex movements]." *Journal für die Reine und Angewandte Mathematik* LV: 25-55 (This time Maxwell correctly cites the year of publication).
[24] Faraday, Michael. 1855. *Experimental Researches in Electricity*, volume III. London (UK): R. & J.E. Taylor, exp. 2216-2220.
[25] Faraday, Michael. 1855. *Experimental Researches in Electricity*, volume III. London (UK): R. & J.E. Taylor, Series XIX.
[26] Verdet, Marcel-Émile 1856. "Note sur les propriétés optiques des corps transparent soumis à l'action du magnétisme [Note on the optical properties of transparent bodies subjected to the action of magnetism]." *Comptes Rendus* 43: 529-32.
[27] Verdet, Marcel-Émile 1856. "Note sur les propriétés optiques des corps magnétiques [Note on the optical properties of magnetic bodies]." *Comptes Rendus* 44: 1209-13.
[28] Thomson, William. 1860. "Magnetism, dynamical relations of." In J.P. Nichol, *Cyclopaedia of the Physical Sciences*, 544-8, 2nd ed. London (UK): R. Griffin & Co.

John Pringle Nichol [Huntly Hill, Scotland, January 13, 1804 - Rothesay, Scotland, September 19, 1859] educator, phrenologist, astronomer and economist, but, overall, populariser of astronomy and science in general in a manner that appealed to nineteenth century tastes.
Nichol, a leading figure at the Astronomical Institution of Glasgow, was responsible for raising the funds for the erection of a new observatory at Horeslethill in the West End in 1841. He was appointed Observer, and moved with his family to a house attached to the Observatory. [University of Glasgow "John Pringle Nichol"]

[29] Thomson, William. 1856. "On the theory of the electric telegraph." *Proceedings of the Royal Society* 7: 382-99.
[30] Thomson, William. 1861. "On the measurement of electric resistance." *Proceedings of the Royal Society* 11: 313-28.
[31] Verdet, Marcel-Émile 1854. "Recherches sur les propriétés optiques développées dans les corps transparents par l'action du magnétisme [Research on the optical properties developed in transparent bodies by the action of magnetism]." *Annales de Chimie et de Physique* 3, 41: 370-412 (cited twice).
[32] Verdet, Marcel-Émile 1855. "Recherches sur les propriétés optiques développées dans les corps transparents par l'action du magnétisme [Research on the optical properties developed in transparent bodies by the action of magnetism]." *Annales de Chimie et de Physique* 3, 43: 37-43.

[33] Weber, Wilhelm. 1852. "On the excitation and action of diamagnetic according to the laws of induced currents." *Selected Memoirs selected from the Transactions of Foreign Academies of Sciences* 5: 477-84.

Only mentioned: *A.-M. Ampère (See below), A.-J. Fresnel, J. McCullagh, F.E. Neumann*

Augustin-Jean Fresnel [Broglie, France, May 10, 1788 - Ville-d'Avray, France, July 14, 1827] civil engineer and physicist whose research in optics played a key role in the acceptance of the wave theory of light, against Newton's old corpuscular theory. In this framework, Fresnel presented his work on diffraction as an entry to a competition on the subject at the French Academy of Sciences in 1819. The committee of judges comprised several of Newton's advocates, among whom there was Siméon-Denis Poisson, who pointed out that Fresnel's model predicted a seemingly absurd result: a parallel beam of light falling on a small spherical obstacle would produce a bright spot at the centre of the circular shadow. French physicist François Arago performed the experiment and observed the spot, which was then named Poisson's spot. Fresnel, eventually won the competition. He invented the catadioptric Fresnel lens and the 'stepped' lenses of lighthouses, saving countless lives at sea. [Encyclopaedia Britannica "Augustine jean Fresnel", O'Connor 2022]

James MacCullagh [Landahaussy, Northen Ireland,1809 - Dublin, Ireland, October 24, 1847] Irish mathematician, fellow of Trinity College, Dublin and a contemporary there of William Rowan Hamilton, who introduced quaternions.
MacCullagh found that a conventional potential function proportional to the squared norm of the displacement field was incompatible with known properties of light waves. Transverse waves need a potential function to be proportional to the squared norm of the curl of the displacement. MacCullagh's ideas were largely abandoned and forgotten until 1880, when George Francis FitzGerald re-discovered and re-interpreted his findings in the light of Maxwell's work. William Thomson, then succeeded in developing a physical model of MacCullagh's rotationally elastic but translationally insensitive aether. [Leaney 2009]

Franz Ernst Neumann [Joachimsthal, Germany, September 11, 1798 - Königsberg, Russia, May 23, 1895] was a mineralogist, physicist and mathematician. Volunteer who fought against Napoleon, he was wounded in the Battle of Ligny. His 1831 study on the specific heats of compounds included what is now known as Neumann's Law: the molecular heat of a compound is equal to the sum of the atomic heats of its constituents. He also studied optics and refraction. His son, Carl Gottfried Neumann studied electromagnetism and is cited by Maxwell in **DT** (see below). In "On physical lines of force." Maxwell does not specify *which* Neumann he mentions, but due to the optical context it should be Franz. [Encicloedia.com "Neumann, Franz Ernst"]

André-Marie Ampère [Poleymieux-au-Mont-d'Or, France, January 22, 1775 - Marseille, France, June 10, 1836]

One of the main contributors to the development of classical Electromagnetism, or «electrodynamics» as he called it. In 1820 he learned from François Arago of the discovery by the Danish physicist Hans Christian Ørsted that a magnetic needle is deflected by an adjacent electric current. Ampère hence began experimenting himself and, having conceived the idea that, if a current wire generates a magnetic action, then it might also be subject to an external magnetic action, he showed that two parallel wires carrying electric currents attract or repel each other, depending on whether the currents flow in the same or in opposite directions.

More accurate experiments, with wires of different lengths and orientation, allowed him to develop a mathematical and physical theory to understand the relationship between electricity and magnetism. This laid the foundation of electrodynamics and led to Ampère's law, which states that the mutual action of two lengths of current-carrying wire is proportional to their lengths, to the intensities of their currents and to the cosine of the angle between the directions of the wires, while being inversely proportional to the distance.

Ampère also provided a physical understanding of the electromagnetic relationship, theorizing the existence of an *electrodynamic molecule* (which is an embryo of the concept, which will later evolve into the *electron*), which was source of *both* electricity and magnetism. Using his explanation based on the motion of the *electrodynamic molecule*, Ampère developed an interpretation of electromagnetic phenomena that was both suited to empirical and predictive proofs from a mathematical point of view.

Ampère published his main work in 1827, "Mémoire sur la Théorie Mathématique des Phénomènes Électrodynamiques Uniquement Déduite de l'Experience [Dissertation on the Mathematical Theory of Electrodynamic Phenomena Uniquely Deduced from Experience]" where, as already said, he coined the term «electrodynamics».

The SI (*Système International d'Unités*) unit of measurement of electric current, the ampère (symbol: A), is named after him. [Enciclopédie Larousse "André Marie Ampère", Shank 2022]

French, mentioned once

> If, therefore, the phenomena described by FARADAY in the Ninth Series of his Experimental Researches were the only known facts about electric currents, the laws of AMPERE relating to the attraction of conductors carrying currents, as well as those of FARADAY about the mutual induction of currents, might be deduced by mechanical reasoning

DT: p. 471 par. (34) – no explicit reference to any Ampère paper is given.

John Frederic Daniell [London, England, March 12, 1790 - London, England, March 13, 1845]

Chemist and Physicist. Was the first professor of chemistry at the newly founded King's College London (1831), and at the East India Company's Military Seminary at Addiscombe, Surrey (1835). He is best known for his invention of the Daniell cell, in 1836, which was a great improvement over the Voltaic cells in electric battery manufacturing. He also invented the dew-point hygrometer now known by his name and a register pyrometer. In 1830 he erected in the hall of the Royal Society a water-barometer, with which he carried out a large number of observations.

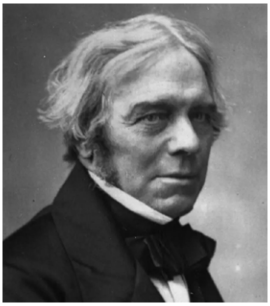
Most renowned for his meteorological and botanical writings, in 1840 he was nevertheless invited to hold a *Christmas Lecture* at the Royal Society on "The First Principles of Franklinic Electricity".

English, mentioned twice (in the same paragraph)

This gives the maximum value of *P* in direct sunlight at the Earth's distance from the Sun, *P*=60,000,000, or about 600 DANIELL'S cells per metre[1]. At the Sun's surface the value of *P* would be about 13,000 DANIELL'S cells per metre. At the Earth the maximum magnetic force would be 0.193. At the Sun it would be 4.13.

DT: p. 505 par. (108) – no explicit reference to any Daniell paper is given.

[1] In par. (108) Maxwell has already introduced his electromagnetic theory of light (part VI) and he then discusses sunlight. At the time the potential was not measured in volts but rather with a practical unit: the potential difference of a Daniell cell in an open circuit. The Daniell cell was an improvement on Volta's battery. Although it still relied on zinc and copper and sulphuric acid, it did not generate gaseous hydrogen and hence was rechargeable. A Daniell cell generated 1.1 modern volts. Indeed, as the volt was originally defined, at the 1881 International Conference of Electricians, it rated the electromotive force of the Daniell cell at about 1.0 volts. More refined definitions of the volt followed, so that in modern units a Daniell cell would indeed produce 1.1 volts.



Michael Faraday [Newington Butts, England, September 22, 1791 - Hampton Court, Middlesex, England, August 25, 1867]

The biographies of Faraday and the books showing his influence on Maxwell are countless (Forbes 2014, Tricker 2013, Thomas 1991). He was maybe the greatest experimenter of all times. He contributed to the fields of electromagnetism and electrochemistry. His main discoveries include those of electromagnetic induction, diamagnetism and electrolysis. Although Faraday received little formal education, he was one of the most influential scientists in history.

In Chemistry he set out the laws of electrolysis, developed a first prototype of what would later become the Bunsen burner, and he studied colloidal compounds of gold, showing that its nanoparticles had different properties than the bulk metal.

In Electromagnetism, after Ørsted's discovery (1820) of the magnetic effects of a direct current, he wrapped two insulated coils of wire around an iron ring, and found that upon passing a current through one coil a momentary current was induced in the other coil, a phenomenon now known as mutual induction. In subsequent experiments, he found that if he moved a magnet through a loop of wire an electric current flowed in that wire. The current also flowed if the loop was moved over a stationary magnet. His demonstrations established that a changing magnetic field produces an electric field; this relation was later modelled mathematically by James Clerk Maxwell as Faraday's law, which subsequently became one of the four Maxwell equations.

The SI unit of measurement of capacitance, the farad (symbol: F), is named after him. [Williams 2021b, O'Connor 2001b]

English, cited six times and mentioned three times

> Now we know that the luminiferous medium is in certain cases acted on by magnetism; for FARADAY* discovered that when a plane polarized ray traverses a transparent diamagnetic medium in the direction of the lines of magnetic force produced by magnets or currents in the neighbourhood, the plane of polarization is caused to rotate.

DT: p. 461 par. (8) **citation to** 1855. *Experimental Researches in Electricity*, volume III. London (UK): R. & J.E. Taylor, Series XIX, exp. 2146-2242.

[1] Faraday, Michael. 1844. *Experimental Researches in Electricity*, volume I. London (UK): R. & J.E. Taylor, exp. 57, 366, 877, 951-5, 961; volume 2, exp. 2071 (also published in 1834 on the *Philosophical Transactions of the Royal Society* 124).

[2] Wartman, Elie François. 1842. "Sur les relations qui lient la lumière a l'électricité, lorsque l'un des deux fluids produit une action chimique [On the relations between light and electricity, when one of the two fluids produces a chemical action]." *Archives de l'Electricite* 2: 596-600.

Elie François Wartmann [Geneva, Switzerland, November 7, 1811 - Versoix, Switzerland, September 11, 1886 – full professor of Physics at Geneva University. [Cetta 2015]

[3] Faraday, Michael. 1830. "The Bakerian Lecture: on the manufacture of glass for optical purposes." *Philosophical Transactions of the Royal Society* 120: 1-57.
In a note to this Lecture Faraday writes "I cannot resist the occasion which is thus offered to me of mentioning the name of Mr. Anderson, who came to me as an assistant in the glass experiments, and has remained ever since in the Laboratory of the Royal Institution.

Charles Anderson [1790-1866], army officer and Faraday assistant. [Royal Society (The), Science Lives Here, "Charles Anderson"]

[4] Christie, Samuel Hunter. 1826. "On magnetic influence in the solar rays." *Philosophical Transactions of the Royal Society* 116: 219-39. And a second paper, by the same author and with the same title, 1828. *Philosophical Transactions of the Royal Society* 118: 379-96.

Samuel Hunter Christie [London, England, March 22, 1784 - Twickenham, England, January 24, 1865] was a British scientist, physicist and mathematician, Fellow of the Royal Society since 1826. [Royal Society (The), Science in the Making, "Samuel Hunter Christie"]

[5] Faraday, Michael. 1844. *Experimental Researches in Electricity*, volume II, 284. London (UK): R. & J.E. Taylor (also published on the *Philosophical Magazine* 24: 136).

But when electromotive force acts on a dielectric it produces a state of polarization of its parts similar in distribution to the polarity of the parts of a mass of iron under the influence of a magnet, and like the magnetic polarization, capable of being described as a state in which every particle has its opposite poles in opposite conditions.

DT: p. 462 par. (11) **citation to** *Experimental Researches in Electricity*, vol. I, London (UK): R. & J.E. Taylor. 1839, Series XI, exp. 1161-1319.

[6] Coulomb, Charles-Augustin. 1786. "Quatrième mémoire sur l'électricité, où l'on démontre deux principales propriétés du fluide électrique [Fourth dissertation on electricity, where we demonstrate two main properties of electric fluid]." *Histoire de l'Académie Royale des Sciences avec les Memoires de Mathématique et de Physique*, 67-77 (but Faraday explicitly cites only pp. 67, 69 and 72).
[7] Coulomb, Charles-Augustin. 1787. "Cinquième mémoire sur l'électricité et le magnétisme [Fifth dissertation on electricity and magnetism]." *Histoire de l'Académie Royale des Sciences avec les Memoires de Mathématique et de Physique*, 421-467 (but Faraday explicitly cites only pp. 452 and 453).
[8] Coulomb, Charles-Augustin. 1785. "Premier mémoire sur l'électricité et le magnétisme [First dissertation on electricity and magnetism]." *Histoire de l'Académie Royale des Sciences avec les Memoires de Mathématique et de Physique*, 569-577 (but Faraday explicitly cites only p. 570).

Charles-Augustin de Coulomb [Angoulême, France, June 14, 1736 - Paris, France, August 23, 1806] is regarded as the founder of a mathematical theory of electricity, due to his law describing the force between charges. Even if his importance is unquestionable, Maxwell never cites him directly in his **DT**. Upon the outbreak of the French Revolution, he retired to a small estate at Blois and devoted himself to scientific research, even if his health was no longer good. He was called back to Paris to join the committee for the determination of metric weights and measures, which had been decreed by the Revolutionary government. [Encyclopaedia Britannica "Charles-Augustin de Coulomb"]

[9] Ritchie, William. 1830. "On the elasticity of threads of glass, with some of the most useful applications of this property to torsion balances." *Philosophical Transactions of the Royal Society* 120: 215-22.

William Ritchie [1790?-1837] Scottish physicist and ingenious experimentalist. After unsuccessfully applying in 1820 for the rectorship of Dundee Academy, Ritchie became rector of Tain Royal Academy in the following year. Professor of natural philosophy and Fellow of the Royal Society, Ritchie had access to one of the best-equipped laboratories in the country. Hence, he did research on the newest field of physics, and in particular pursued the consequences of the discovery of electromagnetic induction made by his colleague, Michael Faraday. In later years he dedicated himself to glass manufacturing. [James 2004]

[10] 1797. "Electricity." in Encyclopaedia Britannica (3rd ed.) 4: 418-545 (Faraday refers to the experiment by William Nicholson at pp. 503-4).

William Nicholson [London, England, December 13, 1753 - Bloomsbury, England, May 21, 1837] was a renowned English chemist, inventor and publisher, as well as a scientist, and writer. In May 1800, with Anthony Carlisle, he discovered electrolysis and how water decomposed into hydrogen and oxygen by voltaic current. The name *electrolysis* on the other hand will be coined later on by Faraday. Nicholson and Carlisle were appointed to the committee for chemical investigation at the new Royal Institution, though Nicholson never had the honour of a fellowship at the Royal Society, while Carlisle did. [Golinsky 2015]

[11] Harris, William Snow. 1834. "On some elementary laws of electricity." *Philosophical Transactions of the Royal Society* 124: 213-45. (but Faraday explicitly cites only pp. 213, 223, 224, 237 and 244).

William Snow Harris [Plymouth, England, April 1, 1791 - Plymouth, England, January 22, 1867] was a British physician and electrical researcher, noted for his invention of a successful system of lightning conductors for ships, with the metal permanently fixed to the masts and extending throughout the hull. One of the successful test vessels was the HMS Beagle, which survived lightning strikes unharmed on her famous voyage with Charles Darwin. In 1835 he received the Copley gold medal from the Royal Society for his papers on the laws of electricity of high tension, and in 1839 he was chosen to deliver the Bakerian lecture. [NNDB "William Snow Harris"]

[12] Poisson, Siméon-Denis. 1811. "Memoire sur la distribution de l'électricité à la surface des corps conducteurs [Dissertation on the distribution of electricity on the surface of conductive bodies]." *Memoires de la Classe de Sciences Mathématiques et Physiques de l'Istitut Impérial* 12: 1-92.

[13] Poisson, Siméon-Denis. 1811. "Seconde Memoire sur la distribution de l'électricité à la surface des corps conducteurs [Second dissertation on the distribution of electricity on the surface of conductive bodies]." *Memoires de la Classe de Sciences Mathématiques et Physiques de l'Istitut Impérial* 12: 163-274.

Siméon-Denis Poisson [Loiret, France, June 21, 1781 - Sceaux, France, April 25, 1840] French mathematician, engineer, and physicist. In this context his contribution to electrical theory, with the solution of the charge distribution over a conductor and the formulation of the generalization of Laplace's equation now known as Poisson's equation was significant. [O'Connor 2002b, Encyclopaedia Britannica "Siméon-Denis Poisson"]

> The practical investigation of the inductive capacity of dielectrics is rendered difficult on account of two disturbing phenomena. The first is the conductivity of the dielectric, which, though in many cases exceedingly small, is not altogether insensible. The second is the phenomenon called electric absorption, in virtue of which, when the dielectric is exposed to electromotive force, the electric displacement gradually increases, and when the electromotive force is removed, the dielectric does not instantly return to its primitive state, but only discharges a portion of its electrification, and when left to itself gradually acquires electrification on its surface, as the interior gradually becomes depolarized.

DT: p. 463 par. (13) **citation to** 1839. *Experimental Researches in Electricity*, volume I. London (UK): R. & J.E. Taylor, Series XI, exp. 1233-1250.
This Maxwell's citation is indeed a subset of the former, so Farady's citation there are a subset of those given before.

> The conception of the propagation of transverse magnetic disturbances to the exclusion of normal ones is distinctly set forth by Professor FARADAY in his "Thoughts on Ray Vibrations." The electromagnetic theory of light, as proposed by him, is the same in substance as that which I have begun to develop in this paper, except that in 1846 there were no data to calculate the velocity of propagation.

DT: p. 466 par. (20) **citation to** May 1846. *Philosophical Magazine*, or 1839. *Experimental Researches*, volume I. London (UK): R. & J.E. Taylor, Series III. p. 447.
No second-level citations here.

> This dynamical illustration is to be considered merely as assisting the reader to understand what is meant in mechanics by Reduced Momentum. The facts of the induction of currents as depending on the variations of the quantity called Electromagnetic Momentum, or Electrotonic State, rest on the experiments of FARADAY, FELICI, &c.

DT: p. 468 par. (25) **citation to** 1839. *Experimental Researches*, volume I. London (UK): R. & J.E. Taylor, Series IX.

[14] Faraday, Michael. 1834. "On the magneto-electric spark and shock, and on a peculiar condition of electric and magneto-electric induction." *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 5, article 47: 349-54.
[15] Faraday, Michael. 1832. "Experimental researches in electricity." *Philosophical Transactions of the Royal Society* 122: 125-62. (but Faraday explicitly cites only p. 126).
[16] Faraday, Michael. 1830. "Electricity, magnetism &c." *Quarterly Journal of Science, Literature and the Arts* 12, p. 414-21 (but Faraday explicitly cites only p. 420).
[17] Ampére, André-Marie. 1822. *Recueil d'observations* électro-dynamiques*: contenant divers mémoires, notices, extraits de lettres ou d'ouvrages périodiques sur les sciences relatifs à l'action mutuelle de deux courants* électriques*, à celle qui existe entre un courant* électrique *et un aimant ou le globe terrestre, et à celle de deux aimants l'un sur l'autre* [*Collection of electro-dynamic observations: containing various memories, notices, extracts from letters or periodical works on the sciences relating to the mutual action of two electric currents, to that which exists between an electric current and a magnet or the globe terrestrial, and that of two magnets on top of each other*]. Paris: Crochard (Faraday explicitly cites only p. 285).
[18] Davy, Humphry. 1823. "On a new phenomenon of electro-magnetism." *Philosophical Transactions of the Royal Society* 113: 153-9 (but Faraday explicitly cites only p. 155).

Humphry Davy [Penzance, England, December 17, 1778 - Geneva, Switzerland, May 29, 1829] was a chemist and inventor, who, using electricity, isolated a series of elements for the first time: potassium and sodium in 1807 and calcium, strontium, barium, magnesium and boron the following year, as well as discovering the elemental nature of chlorine and iodine. Davy also studied the forces involved in these separations, inventing the new field of electrochemistry.
But his main contribution, in our context, is having been young Faraday's mentor. [Gibbs 2022, Science History Institute "Humphry Davy"]

What I have called electromagnetic momentum is the same quantity which is called by FARADAY the electrotonic state of the circuit, every change of which involves the action of an electromotive force, just as change of momentum involves the action of mechanical force.
If, therefore, the phenomena described by FARADAY in the Ninth Series of his Experimental Researches were the only known facts about electric currents, the laws of AMPERE relating to the attraction of conductors carrying currents, as well as those of FARADAY about the mutual induction of currents, might be deduced by mechanical reasoning.

DT: p. 471, par. (34) **citation to** *Experimental Researches*, volume I. London (UK): R. & J.E. Taylor. Series I. 60, &c.

[19] Wollaston, William Hyde. 1801. "Experiments on the chemical production and agency of electricity." *Philosophical Transactions of the Royal Society* 91: 427-34 (but Faraday – erroneously – explicitly cites only p. 247 in place of 427).

William Hyde Wollaston [Dereham, England, August 6, 1766 - Chislehurst, England, December 22, 1828). Chemist, Fellow of the Royal Society famous for discovering palladium and rhodium. He also developed a way to process platinum ore into ingots. [Usselman 2021]

[20] Marianini, Stefano. 1828. "Sur les piles secondaires de Ritter [On Ritter's secondary piles]." *Annales de Chimie et de Physique* 38: 5-40.

> **Stefano Marianini** [Zeme, Italy, January 5, 1790 - Modena, Italy, June 9, 1866] was Volta's adjunct professor in Pavia and later professor in Modena. His studies on electromotors, conducted between 1823 and 1840, are the largest part of his scientific work. Still alive, he was named 'hero of voltaic electricity' for his strenuous defence of the explanation of the function of the cell according to the Volta theory of contact electricity between heterogeneous conductors. [Fregonese 2008]

[21] van Beek, Albertus. 1828. "Sur un phénomène extraordinaire concernant l'influence continue qu'exerce le contact de métaux hétérogènes sur leurs propriétés chimiques, long-temps après que ce contact a cessé [On an extraordinary phenomenon concerning the continuous influence which the contact of heterogeneous metals exerts on their chemical properties, long after this contact has ceased]." *Annales de Chimie et de Physique* 38: 49-53.

> **Albertus van Beek** [Utrecht, Netherlands, December 2, 1787 - Utrecht, Netherlands, January 7, 1856], businessman and amateur physicist, held lectures on the new electromagnetic phenomena before the Natuurkcundig Gezelschap (Physical Society) in Utrecht, also writing a few papers. [Biography portaal van Nederland "Albertus van Beek", Snelders 1974]

[22] Babbage, Charles, and John Frederick William Herschel. 1825. "Account of the repetition of M. Arago's experiments on the magnetism manifested by various substances during the act of rotation." *Philosophical Transactions of the Royal Society* 115: 467-96.

> **Charles Babbage** [London, England, December 26, 1791 - London, England, October 18, 1871] mathematician, philosopher, inventor and mechanical engineer, Babbage conceived, and tried to build, the first mechanical computers, the differential engine and the analytical engine, which were too costly to produce in his times but which were built after his death proving their functionality and which originated the concept of a digital programmable computer. [Encyclopaedia Britannica "Charles Babbage"]

> **John Frederick William Herschel**, [Slough, England, March 7, 1792 - Collingwood, England, May 11, 1871] was a polymath, mathematician, astronomer, chemist, inventor. Son of William Hershel, the astronomer who discovered Uranus, he catalogued and named seven moons of Saturn and four of the new planets discovered by his father. He was also an experimental photographer and invented the blueprint. [Encyclopaedia Britannica "Sir John Herschel, 1st Baronet", O'Connor 1999a]

[23] Christie, Samuel Hunter. 1827. "On the mutual action of the particles of magnetic bodies, and on the law of variation of the magnetic forces generated at different distances during rotation." *Philosophical Transactions of the Royal Society* 117: 71-121 (but Faraday explicitly cites only p. 82).

Citations already reported earlier in this section: Faraday *Quarterly Journal of Science vol. XII*

Only mentioned: *A.M. Ampére (see above), D.F.J. Arago, A. Fresnel (see above), J. Hachette and W.S. Harris (see above):*

Dominique François Jean Arago [Estagel, France, February 26, 1786 - Paris, France, October 2, 1853] mathematician, physicist, astronomer. With Foucault he discovered eddy currents and was a stimulus to Fresnel for many of his discoveries in optics. He was also active in politics and twice minister. [Encyclopaedia Britannica "François Arago", O'Connor 2006a]

Jean Nicolas Pierre Hachette [Mézières, France, May 6, 1769 - Paris, France, January 16, 1834] mathematician, he taught Poisson, Arago and Fresnel. Full Professor at the École Polytechnique, he was editor of the academic Journal. Then, in 1804, he founded a new publication for the School setting up the *Correspondance sur l'École Polytechnique*. Hachette edited this publication until he was forced out of the School in 1816. [O'Connor 2000a]

Let *s* be the length of the circuit, then if we integrate

$$\int\left(F\frac{dx}{ds}+G\frac{dy}{ds}+H\frac{dz}{ds}\right)ds$$

round the circuit, we shall get the total electromagnetic momentum of the circuit, or the number of lines of magnetic force which pass through it, the variations of which measure the total electromotive force in the circuit. This electromagnetic momentum is the same thing to which Professor FARADAY has applied the name of the Electrotonic State.

DT: p. 481, par. (58) no explicit reference to any Faraday paper is given.

When the dielectric of which the condenser is formed is not a perfect insulator, the phenomena of conduction are combined with those of electric displacement. The condenser, when left charged, gradually loses its charge, and in some cases, after being discharged completely, it gradually acquires a new charge of the same sign as the original charge, and this finally disappears. These phenomena have been described by Professor FARADAY (Experimental Researches, Series XI.) and by Mr. F. JENKIN (Report of Committee of Board of Trade on Submarine Cables), and may be classed under the name of "Electric Absorption."

DT: p. 494, par. (58) **citation to** 1839. *Experimental Researches in Electricity*, volume I. London (UK): R. & J.E. Taylor, Series XI, exp. 1161-1319. Already analyzed above.

We know, from the magnetic experiments of FARADAY, PLUCKER, &c., that in many crystals λ, μ, ν are unequal.

DT: p. 504, par. (104) no explicit reference to any Faraday paper is given.

Riccardo Felici [Parma or Pisa[2], Italy, June 11, 1819 - Sant'Alessio, Lucca, Italy, July 20, 1902]

Italian mathematician and Physicist. In 1851 he began studying electromagnetic induction and optics.

He enunciated the law now bearing his name, which allows the total charge flowing in a circuit with induced current to be evaluated as the difference between the final and initial magnetic flux across the circuit divided by the circuit's resistance.

In the second part of this book, there is an entire section dedicated to Felici, with full bibliographic references.

Italian, cited once (this paragraph was already reported above since Faraday is cited too)

> This dynamical illustration is to be considered merely as assisting the reader to understand what is meant in mechanics by Reduced Momentum. The facts of the induction of currents as depending on the variations of the quantity called Electromagnetic Momentum, or Electrotonic State, rest on the experiments of FARADAY, FELICI &c.

DT: p. 468 par. (25) **citation to** 1852. "Memoire sur l'induction electrodynamique [Dissertation on electrodynamic induction]." *Annales de Chimie et Physique* 3, 34: 64-77.

No second-level citations here.

[2] Commonly Felici's birthplace has been reported to be Parma. However, he possessed a baptism certificate (with some errors) issued in Pisa. See the contribution by Paolo Rossi in this book for details.

Armand Hippolyte Louis Fizeau [Paris, France, September 23, 1819 - Venteuil, France, 18 September 1896]

French physicist, student of Arago, he worked with Foucault. Interested in photography, he was one of the first to photograph the sun, opening a new branch of astronomy.

In 1849, he calculated a value for the speed of light, which was more precise than the previous value determined by Ole Rømer in 1676. He used a beam of light reflected from a mirror eight kilometres away. The beam passed through the gaps between the teeth of a rapidly rotating wheel. The speed of the wheel was increased until the returning light passed through the next gap and could be seen. Fizeau calculated the speed of light to be 314,858 kilometres per second, which was within about five percent of the correct value (299,792.458 kilometres per second).

Indeed, it was for his accurate estimation of the speed of light that Maxwell cites him. [Encyclopaedia Britannica "Armand-Hippolyte-Louis Fizeau", O'Connor 2008a]

French, cited once:

The velocity of light in air, by M. FIZEAU'S experiments, is

V =314,858,000: [3]

DT: p. 499 par. (96) **citation to** 1849. "Sur une expérience relative à la vitesse de propagation de la lumière [On an experiment relating to the speed of propagation of light]." *Comptes Rendus* 29: 90-2 and errata at 132 (Maxwell cites only p. 90).

No second-level citations here.

[3] Maxwell, who intended metres per second, obtained this value by converting Fizeau's value, which was given in terms of 70948 leagues per second.

Jean Bernard Léon Foucault [Paris, France, September 18, 1819 - Paris, France, February 11, 1868]

French Physicist best known for his demonstration of the Earth's rotation with Foucault's pendulum. He also made an early measurement of the speed of light in 1850, using the Fizeau–Foucault apparatus, and showed that light travels more slowly through water than through air.

In 1855 he discovered that the force required for the rotation of a copper disc becomes greater when it is made to rotate with its rim between the poles of a magnet, the disc at the same time becoming heated by the eddy current or 'Foucault currents' induced in the metal. This was a deeper investigation of the phenomenon already discovered by Arago.

Foucault devised another technique, different from Fizeau's, and using a rotating mirror, to measure the speed of light. Maxwell also refers to his value in his paper. [Tobin 2003, O'Connor 2006b]

French, cited twice, mentioned once

according to the more accurate experiments of M. FOUCAULT,
V =298,000,000.

DT: p. 499 par. (96) **citation to** 1862. "Détermination expérimentale de la vitesse de la lumière; parallaxe du Soleil [Experimental determination of the speed of light; parallax of the sun]." *Comptes Rendus* 55: 501-3 (Maxwell cites only p. 501).

No second-level citations here.

and to 1862. "Détermination expérimentale de la vitesse de la lumière; description des appareils [Experimental determination of the speed of light; device description]." *Comptes Rendus* 55: 792-6 (Maxwell cites only p. 792).

No second-level citations here.

The only use made of light in the experiment was to see the instruments. The value of *V* found by M. FOUCAULT was obtained by determining the angle through which a revolving mirror turned, while the light reflected from it went and returned along a measured course. No use whatever was made of electricity or magnetism.

DT: p. 499 par. (97), no explicit reference to any Foucault paper is given.

Jean-Mothée Gaugain[4] [Sully, France, 1810 - Saint-Martin-des-Entrées, France, 1880]

French Engineer, in 1854 developed an ameliorated amperometer, by placing the magnetic needle at an offset with respect to the induction coil, so that the response of the needle is linear with respect to the current intensity.

In 1855 he studied the rectifying action between two metal balls in an evacuated chamber, effectively producing the first electric valve. [T. 1880, Treccani "Gaugain, Jean-Mothee"]

French, cited once

$$q = \frac{\Psi}{akrR}\left\{a_1k_1a_2k_2\left(\frac{r_1}{a_1k_1}-\frac{r_2}{a_2k_2}\right)^2 + a_2k_2a_3k_3\left(\frac{r_2}{a_2k_2}-\frac{r_3}{a_3k_3}\right)^2 + \&c.\right\}$$

a quantity essentially positive; so that, when the primary electrification is in one direction, the secondary discharge is always in the same direction as the primary discharge*.

* Since this paper was communicated to the Royal Society, I have seen a paper by M. GAUGAIN in the Annales de Chimie for 1864, in which he has deduced the phenomena of electric absorption and secondary discharge from the theory of compound condensers.

DT: p. 497 par. (39) **citation to** 1864. "Mémoire sur la conductibilité *électrique* et la capacité inductive des corps isolants [Dissertation on electrical conductivity and inductive capacity of insulating bodies]." *Annales de Chimie et Physique* 4, 2: 264-316.

[1] Gaugain, Jean-Mothée. 1860. "Mémoire sur les lois de la propagation de l'électricité dans les conducteurs médiocres [Dissertation on the laws of the propagation of electricity in poor conductors]." *Annales de Chimie et Physique* 3, 59: 5-63.
[2] Gaugain, Jean-Mothée. 1860. "Deuxième Mémoire sur les lois de la propagation de l'électricité dans les conducteurs médiocres [Second dissertation on the laws of the propagation of electricity in poor conductors]." *Annales de Chimie et Physique* 3, 60: 326-85.
[3] Gaugain, Jean-Mothée. 1861. "Troisième Mémoire sur les lois de la propagation de l'électricité dans les conducteurs médiocres [Third dissertation on the laws of the propagation of electricity in poor conductors]." *Annales de Chimie et Physique* 3, 63: 201-57.
[4] Gaugain, Jean-Mothée. 1862. "Quatrième Mémoire sur les lois de la propagation de l'électricité dans les conducteurs médiocres [Fourth dissertation on the laws of the propagation of electricity in poor conductors]." *Annales de Chimie et Physique* 3, 64: 174-229.
[5] Faraday, Michael. 1839. *Experimental Researches in Electricity,* volume I. London (UK): R. & J.E. Taylor, exp. 387-391.

[4] No portrait of Jean-Mothée Gaugain is known to the authors.

[6] Matteucci, Carlo. 1849. "Mémoire sur la propagation de l'électricité dans les corps solides isolants [Dissertation on the propagation of electricity in insulating solid bodies]." *Annales de Chimie et Physique* 3, 27: 122-72 (Gaugain cites only p. 162).

Carlo Matteucci will be discussed in a contribution in the second part of this book.

[7] de la Rive, Auguste Arthur. 1856. *Traité d'*Électricité *Théorique et Appliquée. Tome 2* [*Treatise on Theoretical and Applied Electricity. Volume 2*]. Paris: Bailliere, p. 5.

Auguste Arthur de La Rive [Geneva, Switzerland, October 9, - Marseille, France, November 27, 1873] started his career studying the specific heat of gases. Electrical studies, however, engaged most of his attention, especially voltaic cells and the electric discharge in rarefied gases, leading him to form a new theory of the aurora borealis. The principal work of De la Rive was his Treatise on Electricity in Theory and Practice in three volumes published simultaneously in French and English in the years 1854–58.
De la Rive's birth and fortune gave him considerable social and political influence. He was known for his hospitality to literary and scientific men, and for his interest in the welfare and independence of his native country. [Encyclopaedia Britannica "Auguste-Arthur de La Rive"]

[8] Faraday, Michael. 1839. *Experimental Researches in Electricity*, volume I. London (UK): R. & J.E. Taylor, exp. 1283-1294.
[9] Coulomb, Charles-Augustin. 1785. "Troisième mémoire sur l'électricité et le magnetisme. De la quantité d'électricité qu'un corps isolé perd dans un temps donné, soit par contact avec l'air plus ou moins humide, soit le long des soutiens plus ou moins idio-électriques [Third dissertation on electricity and magnetism. Of the quantity of electricity that an isolated body loses in a given time, either by contact with more or less humid air, or along more or less idio-electric supports]." *Histoire de l'Académie Royale des Sciences avec les Memoires de Mathématique et de Physique*, 612-38 (but Gugain explicitely cites only p. 633).

Only mentioned: *M. Berthelot, H.E. Deville, W.S. Harris (see above), S.D. Poisson (see above), H.V. Regnault:*

Marcellin Pierre Eugène Berthelot [Paris, October 25, 1827 - Paris, France, March 18, 1907] was considered one of the most famous chemists in the world in his times and was the Minister of Foreign Affairs for the French government in 1895. His investigations concentrated on the synthesis of organic compounds and were published in numerous papers and books. In this area some of his more notable achievements included the synthesis of formic acid, methane and acetylene. His synthesis of benzene in 1851 by heating acetylene in a glass tube opened the way to the production of aromatic compounds. [Bensaude-Vincent 2022]

Henri Étienne Sainte-Claire Deville [St. Thomas, Virgin islands, March 11, 1818 - Boulogne-sur-Seine, France, July 1, 1881] son of the French consul in what were at the time the Danish West Indies. He investigated the oil of turpentine and tolu balsam, in the course of which he discovered toluene. In 1849 he discovered anhydrous nitric acid (nitrogen pentoxide). In 1854, he succeeded in obtaining metallic aluminium, and ultimately, he devised a method by which the metal could be prepared on a large scale. [Encyclopaedia Britannica "Henri-Étienne Sainte-Claire Deville"]

Henri-Victor Regnault [Aix-la-Chapelle, France, July 21, 1810 - Paris, France, January 19, 1878] chemist and physicist best known for his careful measurements of the thermal properties of gases. He was an early thermodynamicist and was mentor to William Thomson in the late 1840s.
Regnault was also an amateur photographer. He introduced the use of pyrogallic acid as a developing agent, and was one of the first photographers to use paper negatives. In 1854, he became the founding president of the *Société française de photographie*. [Encyclopaedia Britannica "Henri-Victor Regnault"]

Johann Heinrich Wilhelm Geißler [Igelshieb, Germany, May 26, 1814 - Jena, Germany, January 24, 1879]

Skilled glassblower and Physicist, famous for his invention of the Geißler tube, made of glass and used as a low pressure gas-discharge tube.

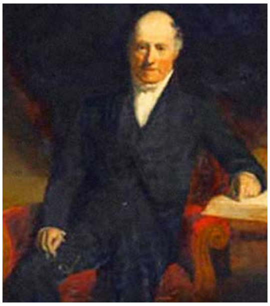
The Physicist Julius Plücker [see below] owed his success in the electric discharge experiments in large measure to the instrument made by Geißler. Ernst Lecher used Geißler tubes across a parallel wire transmission line to measure the wavelength of a standing wave and hence proving that the speed of the electrical signal on such a line was equal to the speed of light.

The Geißler tube was used for entertainment throughout the 1800s and evolved around 1910 into commercial neon lighting. Advances in Plücker's and Geißler's discharge tube technology developed into the Crookes tube, with which the electron was discovered in 1897, and in 1906 into the amplifying vacuum tube, the basis of electronics and long distance communication technologies like radio and television. [Encyclopaedia Britannica "Heinrich Geissler", Deutsche Biographie, "Geißler, Johann Heinrich Wilhelm"]

German, mentioned once

The electromagnetic field is that part of space which contains and surrounds bodies in electric or magnetic conditions.
It may be filled with any kind of matter, or we may endeavour to render it empty of all gross matter, as in the case of GEISSLER'S tubes and other so-called vacua. There is always, however, enough of matter left to receive and transmit the undulations of light and heat, and it is because the transmission of these radiations is not greatly altered when transparent bodies of measurable density are substituted for the so-called vacuum, that we are obliged to admit that the undulations are those of an aethereal substance, and not of the gross matter, the presence of which merely modifies in some way the motion of the aether.

DT: p. 460 par. (4), no explicit reference to any Geißler paper is given.



George Green [Sneiton, England, July 14, 1793 - Nottingham, England, May 31, 1841]

British Mathematical Physicist, he wrote *An Essay on the Application of Mathematical Analysis to the Theories of Electricity and Magnetism* (1828) in which he introduced several important concepts, among them was a theorem similar to the modern Green's theorem, the idea of potential functions as currently used in physics, and the concept of what are now called Green's functions.

Green was the first person to create a mathematical theory of electricity and magnetism and his theory formed the foundation for the work of other scientists such as James Clerk Maxwell, William Thomson, and others. His work on potential theory ran parallel to that of Carl Friedrich Gauss.

Green's life story is remarkable in that he was almost entirely self-taught. He received only about one year of formal schooling as a child, between the ages of 8 and 9.

A single portrait of George Green is known to the authors, the one reproduced here, whose authenticity is uncertain. Indeed a recent, accurate, biography of Green does not reproduce any portrait. [Cannell 2001]

English, cited once

Since the distribution φ_1 is determined by m_1 and φ_2 by m_2 the quantities $\varphi_1 m_1$ and $\varphi_2 m_2$ will remain constant.
It can be shown also, as GREEN has proved (Essay, p. 10), that

$$\varphi_1 m_1 = \varphi_2 m_1$$

DT: p. 490 par. (77), **citation to** *An Essay on the Application of mathematical Analysis to the Theories of Electricity and Magnetism,* Wheelhouse, Nottingam, UK, 1828, par. 10. (Following analysis is limited to cited paragraph):

[1] Poisson, Siméon-Denis. 1811. "Memoire sur la distribution de l'électricité à la surface descorps conducteurs [Dissertation on the distribution of electricity on the surface of conductive bodies]." *Memoires de la Classe de Sciences Mathématiques et Physiques de l'Istitut Impérial* 12: 1-92.
[2] Poisson, Siméon-Denis. 1811. "Seconde Memoire sur la distribution de l'électricité à la surface descorps conducteurs [Second dissertation on the distribution of electricity on the surface of conductive bodies]." *Memoires de la Classe de Sciences Mathématiques et Physiques de l'Istitut Impérial* 12: 163-274.
[3] de Laplace, Pierre Simon. 1798. *Traité de Mécanique Celeste* [*Treatise of Celestial Mechanics*]. Book III, Ch. 2. Paris: Crapelet.

Pierre-Simon de Laplace [Beaumont-en-Auge, France, March 23, 1749 - Paris, France, March 5, 1827] scholar and polymath who contributed greatly to the development of engineering, mathematics, statistics, physics, astronomy, and philosophy.

He summarized and extended the work of his predecessors in his five-volume Mécanique Céleste (1799-1825) leaving the classical geometrical description of mechanics in favour of calculus, opening up a broader range of problems.
He formulated what we now call Laplace's equation and the Laplace operator, and he conceived the Laplace transform, which now appears in many branches of mathematical physics, a field that he took a leading role in forming.
Laplace is remembered as one of the greatest scientists of all time. The French consider him "their Newton". [Whitrow 2022, O'Connor 1999b]

Only mentioned: *J.-L. Lagrange* *(see later on)*

Hermann Ludwig Ferdinand von Helmholtz [Potsdam, Germany, August 31, 1821 - Charlottenburg, Germany, September 8, 1894]
Physician and physicist who made significant contributions to several widely varied areas of modern science.

Indeed, he started as a professor of anatomy and his first contributions were in in physiology and psychology. In the vision area he is known for his mathematics of the eye, his theories of vision, and on the visual perception of space and colour. In addition he studied the sensation of tone, the perception of sound, and the physiology of perception. In physics, he is known for his theories on the conservation of energy, work in electrodynamics, chemical thermodynamics, and on a mechanical foundation of thermodynamics.

He became interested in electromagnetism and studied the phenomena of electrical oscillations from 1869 to 1871. In 1871, Helmholtz moved from Heidelberg to Berlin to become a professor in physics and the Helmholtz equation is named after him. Although he did not make major contributions to this field personally, his student Heinrich Rudolf Hertz became famous as the first to demonstrate electromagnetic radiation. [Cahan 2018, Williams 2021a, O'Connor 2001a]

German, cited once

The second result, which is deduced from this, is the mechanical action between conductors carrying currents. The phenomenon of the induction of currents has been deduced from their mechanical action by HELMHOLTZ and THOMSON. I have followed the reverse order, and deduced the mechanical action from the laws of induction. I have then described experimental methods of determining the quantities *L, M, N*, on which these phenomena depend.

DT: p. 464 par. (17), **citation to** 1853. "Conservation of forces" here Maxwell uses the English title and cites both the original work, in German: *Die erhaltung der kraft, eine physikalishe abhandlung*, G. Reimer, Berlin, Germany, and the translation in English, "On the Conservation of Forces." *Selected Memoirs Selected from the Transactions of Foreign Academies of Sciences*, 114-162.

[1] Joule, James Prescott. 1845. "On the existence of an equivalent relation between heat and the ordinary forms of mechanical power." *Philosophical Magazine* 3, 27: 205-7.

James Prescott Joule [Salford, England, December 24, 1818 - Sale, England, October 11, 1889] physicist and mathematician and brewer he studied the nature of heat, and discovered its relationship to mechanical work. This led to the law of conservation of energy, which in turn led to the development of the first law of thermodynamics. He worked with Lord Kelvin to develop an absolute thermodynamic temperature scale, which came to be called the Kelvin scale.
The SI derived unit of energy, the joule, is named after him. [Encyclopaedia Britannica "James Prescott Joule", Science + Industry Museum "James Joule: from establishment irritant to honoured scientist"]

[2] Henry, William. 1802. "On certain experiments supposed to disprove the materiality of heat." *Memories of the Literary and Philosophical Society of Manchester* 5: 603-21.

William Henry [Manchester, England, December 12, 1774 - Pendlebury, England, September 2, 1836] was an English chemist, still remembered for Henry's law: a gas law that states that the amount of dissolved gas in a liquid is proportional to its partial pressure above the liquid. Henry earned his doctor of medicine degree at Edinburgh University in 1807, but ill health forced him to retire from medical practice, so he turned to chemistry. He was awarded the Copley Medal in 1808 and the following year became a fellow of the Royal Society. [Encyclopaedia Britannica "William Henry"]

[3] Berthollet, Claude Louis. 1803. *Essay de Statique chimique*, volume I. Paris: Firmin Didot, p. 217.

Claude Louis Berthollet [Talloires, France, December 9, 1748 - Arcueil, France, November 6, 1822] chemist, and vice president of the French Senate in 1804. He contributed to the theory of chemical equilibria and to modern chemical nomenclature. Berthollet was the first to demonstrate the bleaching action of chlorine gas, and was first to develop a solution of sodium hypochlorite as a modern bleaching agent. He discovered the chemical composition of ammonia.
Berthollet was one of several scientists who went with Napoleon to Egypt. [Hahn 2022]

[4] Davy, Humphry. 1799. "An essay on heat, light, and the combinations of light." In T. Beddoes (ed.), *Contributions to Physical and Medical Knowledge, Principally from the West of England*, 5-147. London (UK): Longman.
[5] Joule, James Prescott. 1844. "On specific heat." *Philosophical Magazine* 25: 334-7.
[6] Hess, Germain Henry. 1840. "Thermochemische untersuchungen [Thermochemical studies]." *Poggendorff's Annalen* 50: 385-404, and 56: 593-604.

Germain Henry Hess [Geneva, Switzerland, August 7, 1802 - St. Petersburg, Russia, December 13, 1850] though born in Switzerland, he moved to Russia while a child. Adjunct professor of Chemistry at the St. Petersburg Academy of Sciences, he formulated Hess's law: in a series of chemical reactions, the total energy gained or lost depends only on the initial and final states, regardless of the number or path of the steps. This is also known as the law of constant heat summation and is a progenitor for the first law of thermodynamics. [Encyclopaedia Britannica "Germain Henri Hess"]

[7] Joule, James Prescott. 1845. "On the changes of temperature produced by the rarefaction and condensation of air." *Philosophical Magazine* 3, 24: 369-83.
[8] Clapeyron, Benoît Paul Émile. 1843. "Ueber die bewegende kraft der wärme [On the moving power of heat]." *Poggendorff's Annalen* 59: 445-51, and 566-87.

Benoît Paul Émile Clapeyron [Paris, France, January 26, 1799 - Paris, France, January 28, 1864] engineer and physicist, one of the founders of thermodynamics. Clapeyron, reprised Carnot's work making it more accessible with an analytic and graphical form, introducing the chart of pressure against volume (now named Clapeyron's graph). Clapeyron further developed the idea of a reversible process, already suggested by Carnot and made the definitive statement of what is now known as the second law of thermodynamics. He developed the formula, now known as the Clausius–Clapeyron relation, which characterizes the phase transition between two phases of matter. He also performed calculations of the statics of continuous beams, developing what is now Clapeyron's theorem. [O'Connor 1998a]

[9] Holtzmann, Carl Alexander. 1845. *Ueber die Wärme und Elasticität der Gase und Dämpfe* [*About the Warmth and Elasticity of Gases and Vapors*]. Mannheim: T. Loeffer.

Carl Alexander Holtzmann [Karlsruhe, Germany, October 23, 1811 - Stuttgart, Germany, April 25, 1865] studied mining and metallurgy. He taught mathematics and physics at the Karlsruhe Polytechnic and the Mannheim Lyceum, then he was granted a professorship for physics and mechanics at the Stuttgart Polytechnic. He made significant contributions in the field of thermodynamics and mechanics. [Deutsche Biographie, "Holtzmann, Karl"]

[10] Riess, Peter Theophil. 1838. "Ueber die erwärmung im schliessungsbogen der elektrischen batterie [About the heating in the closing arc of the electric battery]." *Poggendorff's Annalen* 43: 47-88.

Peter Theophil Riess [Berlin, Germany, June 27, 1804 - Berlin, Germany, October 22, 1883] physicist, known mostly for his work in electricity, particularly friction electricity and in the field of electromagnetic induction, but his interests spanned history, literature, art and music. We must remember that he developed two devices: the spark micrometer (or Riess micrometer) and the Riess spiral coils, both of which were used by Heinrich Hertz in his experiments to prove the propagation of electromagnetic waves. [Deutsche Biographie, "Rieß, Peter Theophil"]

[11] Vorsselman de Heer, Pieter Otto Coenraad. 1839. "Bemerkungen uber die thermische wirkung elektrischer entladungen. ans einem schreiben an den herausgober [Remarks on the thermal effect of electrical discharges. On a letter to the editor]." *Poggendorff's Annalen* 48: 292-300.

Pieter Otto Coenraad Vorsselman de Heer [Valburg, Netherlands, September 20, 1809 - Utrecht, Netherlands, December 26, 1841] [Biography portaal van Nederland "Pieter Otto Coenraad Vorsselman de Heer"]

[12] Riess, Peter Theophil 1839. "Ueber Hrn. Vorsselman de Heer's bearbeitung meiner warmenntersnchnngen an der elektrischen batterie [About Mr. Vorsselman de Heer's processing of my heating hints on the electric battery." *Poggendorff's Annalen* 48: 320-26.
[13] Knochenhauer, Karl Wilhelm. 1844. "Ueber die schwachung des hauptstroms bei gethèiltem schlie- fsungsdraht der batterie [About the weakening of the main current when the connecting wire of the battery is closed]." *Poggendorff's Annalen* 62: 353-66.
[14] Knochenhauer, Karl Wilhelm. 1845. "Neue versuche über den elektrischen nebenstrom [New experiments on the electrical shortening]." *Poggendorff's Annalen* 64: 64-81.

Karl Wilhelm Knochenhauer [Postdam, Germany, April 10, 1805 - Meiningen, Germany, March 13, 1875] teacher, in the spring of 1837 he received an appointment to the position of director of the Meiningen Realschule, which was to be newly founded. On May 1, 1838 he opened this secondary school. In the following years he expanded the school to University level. In addition to this full-time job, he worked as a physicist, wrote a guide for differential, integral calculus, theory of undulation and electricity. [Wikipedia "Karl Wilhelm Knochenhauer"]

[15] Faraday, Michael. 1844. *Experimental Researches in Electricity*, volume II. London (UK): R. & J.E. Taylor, Series XVII.
[16] Lenz, Heinrich Friedrich Emil. 1843. "Ueber die gesetze der wärme-entwicklung durch den galvanischen strom [About the laws of heat development through the galvanic current]." *Poggendorff's Annalen* 59: 203-40, and 407-20.

Heinrich Friedrich Emil Lenz [Dorpat, Estonia, February 12, 1804 - Rome, Italy, February 10, 1865] studied chemistry and physics at the University of Dorpat. He then travelled with the navigator Otto von Kotzebue on his third expedition around the world from 1823 to 1826, studying climatic conditions and the physical properties of seawater. Later he began working at the University of St. Petersburg, Russia, where he later served as the Dean of Mathematics and Physics from 1840 to 1863 and was Rector from 1863 until his death in 1865.
Lenz had begun studying electromagnetism in 1831. Besides the law named in his honour, Lenz also independently discovered Joule's law in 1842. [The Great Soviet Encyclopedia, 1970-1979]

[17] Faraday, Michael. 1844. *Experimental Researches in Electricity*, volume II. London (UK): R. & J.E. Taylor, Series XVII.
[18] Ohm, Georg Simon. 1844. "Galvanische einzelheiten [Galvanic details]." *Poggendorff's Annalen* 63: 389-406.

Georg Simon Ohm [Erlang, Germany, March 16, 1789 - Munich, Germany, July 6, 1854] physicist, mathematician and school teacher. Ohm began his research with the new electrochemical cell, invented by Italian scientist Alessandro Volta using equipment of his own creation. Ohm found a proportionality between the potential difference (voltage) applied across a conductor and the resultant electric current. This relationship is now known as Ohm's law. In 1841 he was awarded the Copley Medal of the Royal Society of London and was made a foreign member a year later.
The SI unit of electric resistance, the ohm (symbol: Ω) is named after him. [Encyclopaedia Britannica "Georg Ohm"]

[19] Poggendorff, Johann Christian. 1844. "Ueber ein bei der galvanischen polarisation vorkommendes gesetz [On a law that occurs in galvanic polarization]." *Poggendorff's Annalen* 63: 528-34.

Johann Christian Poggendorff [Hamburg, Germany, December 29, 1796 - Berlin, Germany, January 24, 1877], physicist born in Hamburg whose principal work was related to electricity and magnetism. Poggendorff devised an electrostatic motor analogous to Wilhelm Holtz's electrostatic machine.
He had an extraordinary memory, well stocked with scientific knowledge, both modern and historical, a cool and impartial judgment, and a strong preference for facts as opposed to theory of the speculative kind. These qualities soon made *Poggendorff's Annalen,* in his 52 years of editorship, the foremost scientific journal in Europe, as you can notice by the sheer number of citations in this part. [N. 1877]

[20] Lenz, Heinrich Friedrich Emil, and A. Saweljev. 1846. "Ueber die galvanische polarisation und elektromotorische kraft in hydroketten [About galvanic polarization and electromotive force in hydrochains]." *Annalen der Physik* 143: 497-527.

> **A. Saweljev** - no data found, not even a given name. In this paper, the only available citation where Saweljev appears, he and Lenz are affiliated with the St. Petersburg Science Academy.

[21] Joule, James Prescott. 1841. "On the heat evolved by metallic conductors of electricity, and in the cells of a battery during electrolysis." *Philosophical Magazine* 19: 260-77.
[22] Joule, James Prescott. 1843. "On the electrical origin of chemical heat." *Philosophical Magazine* 22: 204-8.
[23] Becquerel, Alexandre-Edmond. 1843. "Des lois du dégagement de la chaleur pendant le passage des courants électriques à travers les corps solides et liquids [On the laws of the release of heat during the passage of electric currents through solid and liquid bodies]." *Comptes Rendues*. vol. 16: 724-8.

> **Alexandre-Edmond Becquerel** [Paris, France, March 24, 1820 - Paris, France, May 11, 1891] French physicist who studied the solar spectrum, magnetism, electricity and optics. He is credited with the discovery of the photovoltaic effect, at the basis of modern solar cells. He was the son of Antoine César Becquerel, who received the Copley Medal for his various memoirs on electricity, and the father of Henri Becquerel, one of the discoverers of radioactivity. [Badash 2021]

[24] Neumann, Franz Ernst. 1846. "Allgemeine gesetze der inducirten elektrischen ströme [General laws of induced electric currents]." *Poggendorff's Annalen* 67: 31-44.
[25] Grassman, Hermann Günther. 1845. "Neue theorie der elektrodynamik [New theory of electrodynamics]." *Poggendorff's Annalen* 64: 1-18.

> **Hermann Günther Grassmann** [Stettin, Poland, April 15, 1809 - Stettin, Poland, September 26, 1877] renowned in his days as a linguist and now more as a mathematician. He was also a physicist, general scholar, and publisher. Grassmann wrote a variety of work applying his mathematical theory of extension, including his 1845 *Neue Theorie der Elektrodynamik*. [Encyclopaedia Britannica "Hermann Günther Grassmann", O'Connor 2005a]

[26] Weber, Wilhelm. 1852. "On the Measurement of Electro-dynamic Forces." *Selected Memoirs selected from the Transactions of Foreign Academies of Sciences* 5: 489-539.
[27] Matteucci, Carlo. 1847. "De la relation qui existe entre la quantité de l'action chimique et la quantité de chaleur, d'électricité et de lumière qu'elle produit [On the relationship between the amount of chemical action and the amount of heat, electricity and light it produces]." *Bibliothèque Universelle de Gèneve*, Supplement 4: 375-80.

Only mentioned: *A.M. Ampére (see above), N.L.S. Carnot, J.L. Gay-Lussac, E. Mariotte, J.C.A. Peltier.*

> **Nicolas Léonard Sadi Carnot** [Paris, France, June 1st, 1796 - Paris, France, August 24, 1832] mechanical engineer, military scientist and physicist, considered the «father of thermodynamics». Indeed, he wrote only one book, like Copernicus before him, *the Réflexions sur la puissance motrice du feu* [*Reflections on the Motive Power of Fire*] which he published in 1824, at the age of only 27 years, where he devised the first successful theory of the maximum efficiency of heat engines and laid the foundations of an entirely new discipline: thermodynamics.

Carnot's work was overlooked in his times, but later Clapeyron modernized Carnot's work and Rudolf Clausius and Lord Kelvin started from this to formalize the second law of thermodynamics and define the concept of entropy. [Mendoza 2022, O'Connor 1998b]

Joseph Louis Gay-Lussac [Saint-Léonard-de-Noblat, France, December 6, 1778 - Paris, France - May 9, 1850] chemist and physicist. He discovered the proportions (2 to 1) in hydrogen and oxygen in water. He also formulated two laws related to gases (First: the pressure of a given mass of gas varies directly with the absolute temperature of the gas, when the volume is kept constant. Second: when gases react together they do so in volume which bears simple whole number ratio provided that the temperature and pressure of the reacting gases and their products remain constant). Gay-Lussac worked also on alcohol-water mixtures, which led to the «degrees Gay-Lussac» or «alcohol by volume» used on the labels of alcoholic beverages in many countries.
He and Jean-Baptiste Biot made a hot-air balloon ascent to a height of 7,016 meters (23,018 ft) in an early investigation of the Earth's atmosphere. [Science History Institute "Joseph Louis Gay-Lussac"]

Edme Mariotte [Dijon, France, c. 1620 - Paris, France, 12 May 1684] physicist and abbot, he was one of the first members of the French Academy of Sciences founded at Paris in 1666. The law about the inverse relationship of volume and pressures in gases was discovered independently and about at the same time by him and by Robert Boyle and is usually named after both.
Mariotte discovered the retina blind spot. He used this discovery to amaze the French royal court with the seemingly magical disappearance of a small coin from the vision of spectators while he had their gaze following another object. He also invented what is now called the «Newton cradle» which demonstrates Newton's first law through the collision of suspended bodies of equal mass, with the motion of the moving body being transferred to the one at rest. [Encyclopaedia Britannica "Edme Mariotte"]

Jean Charles Athanase Peltier [Ham, France, February 22, 1785 - Paris, France, October 27, 1845] originally a watch dealer, at 30 years old took up experiments and observations in physics. He authored numerous papers in different branches of physics, but his name is specially associated with the thermal effects at junctions in a voltaic circuit, the Peltier effect. Peltier also introduced the concept of electrostatic induction, which is the modification of the distribution of an electric charge in a material under the influence of a second object in proximity and bearing an electrical charge. [Encyclopaedia Britannica "Jean-Charles-Athanase Peltier"]

Charles Hockin[5] [1840-1882]

Very little is known about him to the authors, and all data comes from his obituary. He graduated from Cambridge in 1863 and joined Fleeming Jenkin as an assistant and participated in a Committee with J.C. Maxwell and W. Thomson. He joined the Clark, Ford and Taylor Co. in 1872 and was in Australia, China, India and the United States following the laying of submarine telegraph cables for that company, also devising a method for locating a double fault in them. [Obituary 1882]

British, mentioned once

Gold, silver, and platinum are good conductors, and yet when reduced to sufficiently thin plates they allow light to pass through them. If the resistance of gold is the same for electromotive forces of short period as for those with which we make experiments, the amount of light which passes through a piece of gold-leaf, of which the resistance was determined by Mr. C. HOCKIN, would be only 10^{-50} of the incident light, a totally imperceptible quantity. I find that between $\frac{1}{500}$ and $\frac{1}{1000}$ of green light gets through such gold-leaf.

DT: p. 504 par. (107), no explicit reference to any Hockin paper is given.

There is also a letter to him, by Maxwell:

Glenlair, Dalbeattie, September 7th 1864.

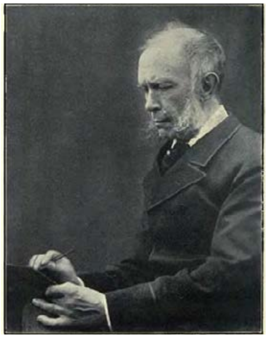
... I have been doing several electrical problems. I have got a theory of "electric absorption." i.e. residual charge, etc., and I very much want determinations of the specific induction, electric resistance, and absorption of good dielectrics, such as glass, shell-lac, gutta-percha, ebonite, sulphur, etc.

I have also cleared the electromagnetic theory of light from all unwarrantable assumption, so that we may safely determine the velocity of light by measuring the attraction between bodies kept at a given difference of potential, the value of which is known in electromagnetic measure.

I hope there will be resistance coils at the British Association.

J.C. Maxwell to C. Hockins
[Campbell 1882]

[5] No portrait of Charles Hockin is known to the authors.



Henry Charles Fleeming Jenkin [Dungeness, England, March 25, 1833 - Edinburgh, Scotland, June 12, 1885]

Young Jenkin was Maxwell's school fellow, but then travelled much with his parents, ending up studying at the University of Genoa (Italy), the first protestant student there. In Genoa he also worked in a locomotive shop.

After he returned to Great Britain, he become Regius Professor of Engineering at the University of Edinburgh, remarkable for his versatility. Known to the world as the inventor of the cable car or telpherage, he was an electrician and cable engineer, economist, lecturer, linguist, critic, actor, dramatist and artist.

Jenkin joined a partnership in cable work with Varley and Thomson, whom he always admired. He participated in many cable-lying naval expeditions in Europe. In 1873 Thomson and Jenkin were engineers for the Western and Brazilian cable. His treatise on *Electricity and Magnetism*, published in 1873, was notable at the time, including the latest developments in the subject. [Obituary of Professor Fleeming Jenkin, LL.D., FRS, 1885, Encyclopaedia Britannica "Fleeming Jenkin"]

British, cited twice

> In determining t by experiment, it is best to make the alteration of resistance in one of the arms by means of the arrangement described by Mr. JENKIN in the Report of the British Association for 1863, by which any value of ρ from 1 to 1.01 can be accurately measured.

DT: p. 477 par. (45), "Report on Standards of Electrical Resistance. By a Committee, consisting of Professor Weatstone, Professor Williamson, Mr. C.F. Varley, Professor Thomson, Mr. Balfour Stewart, Mr. C.W. Siemens, Dr. A. Matthiessen, Professor Maxwell, Professor Miller, Dr. Joule, Mr. Fleeming Jenkin, Dr. Esselbach, Sir C. Bright." *Report of the British Association for the Advancement of Science*, J. Murray, London, UK, 1863: 111-176. (This report has many co-authors but Maxwell explicitly cite Jenkin's contribution, so, while analysing its citation in full no details on co-authors are given unless explicitly mentioned later.)

[1] Thomson, William. 1851. "Applications of the principle of mechanical effect to the measurement of electro-motive forces, and of galvanic resistances, in absolute units." *Philosophical Magazine*, 4, 2: 551-562.

[2] Wheatstone, Charles, Thomson William, Miller William Hallowes, Matthiensen Augustus, and Fleeming Jenkin. 1862. "Report on standard electric resistance" *Report of the British Association for the Advancement of* Science, 125-64. London (UK): J. Murray (cited several times).

Charles Wheatstone [Gloucester, England, February 6, 1802 - Paris, France, October 19, 1875] British physicist and inventor. He invented the stereoscope, to show three dimensional images and an encryption technique, the first cipher to encrypt pairs of letters in cryptologic history, to guarantee secrecy in telegraph messages. He is most known for his contributions to the development of the Wheatstone bridge, (indeed an invention of Samuel Hunter Christie), which is still used to measure an unknown electrical resistance. [The Institution of Engineering and Technology "Sir Charles Wheatstone 1802-1875"]

William Hallowes Miller [Llandovery, Wales, April 6, 1801 - Cambridge, England, May 20, 1880] mineralogist who laid the foundations of modern crystallography, but also a member of the committee as well as of the Royal Commission which oversaw the new measurement standards. [Dictionary of Welsh Biography 1959]

Augustus Matthiessen [London, England, January 2, 1831 - London, England, October 6, 1870] chemist and physicist, he studied in Germany and then worked with Robert Bunsen at the University of Heidelberg where he isolated calcium and strontium in their pure states.
In the 1860s, Matthiessen was in contrast with Werner Siemens on the Ohm specimen: Siemens' standard was defined as a column of mercury of uniform cross-section area of 1 square mm and a length of 1 m at 0°C; Matthiessen felt the best material for the standard was an alloy of equal volumes of gold and silver. Finally the British Association for the Advancement of Science rejected both approaches and favoured a silver-platinum alloy. [Engineering and Technology History 2016]

[3] Schröder van der Kolk, Hendrik Willem. 1860. "Ueber die bestimmung des galvanischen leitungswiderstandes [On the determination of the galvanic line resistance]." *Poggendorff's Annalen* 110: 452-76.

Hendrik Willem Schroeder van der Kolk [Utrecht, The Netherlands, February 6, 1836 - Deventer, The Netherlands, July 15, 1867] studied Mathematics and Physics in Utrecht with Richard van Rees. His thesis published in 1860 is the one cited here. He taught in Maastricht and Deventer. [Hartsen 1996]

[4] Matthiessen, Augustus, and August Christoph Carl Vogt. 1863. "On the influence of temperature on the electric conducting power of thallium and iron." *Proceedings of the Royal Society* 12: 472-5 (cited several times).

August Christoph Carl Vogt [Gießen, Germany, July 5, 1817 - Geneva, Switzerland, May 5, 1895] scientist, philosopher and politician. Vogt published a number of notable works on zoology, geology and physiology. All his life he was engaged in politics, in the German Frankfurt Parliament and in Swiss Geneva *Grand Conseil*. [Scholl 2015]

[5] de Laplace, Pierre-Simon. 1798. *Traité de Mécanique Celeste* [*Treatise of Celestial Mechanics*], Book III. Paris: Crapelet.
[6] Faraday, Michael. 1855. *Experimental Researches in Electricity,* volume III. London (UK): R. & J.E. Taylor, exp. 3122 etc.
[7] Maxwell, James Clerk. 1856. "On Faraday's lines of force." *Transactions of the Cambridge Phylosophical Society* 10, 1: 27-84.

[8] Thomson, William. 1851. "Applications of the principle of mechanical effect to the measurement of electro-motive forces, and of galvanic resistances, in absolute units." *Philosophical Magazine* 4, 2: 551-444.
[9] Faraday, Michael. 1855. *Experimental Researches in Electricity,* volume III. London (UK): R. & J.E. Taylor, exp. 3082 etc.
[10] Helmholtz, Hermann. 1853. "On the conservation of forces." *Selected Memoirs selected from the Transactions of Foreign Academies of Sciences,* 114-62.
[11] Thomson, William. 1851. "On the mechanical theory of electrolysis" *Philosophical Magazine* 2: 429-562 (cited several times).
[12] Faraday, Michael. 1839. *Experimental Researches in Electricity,* volume I. London (UK): R. & J.E. Taylor, exp. 361 etc.
[13] Weber, Wilhelm, and Friedrich Kohlrausch. 1856. "Ueber die elektricitätsmenge, welche bei galvanischen strömen durch den querschnitt der kette fliesst [About the amount of electricity that flows through the cross section of the wire in the case of galvanic currents]." *Poggendorff's Annalen* 99: 10-25 (cited several times).
[14] Thomson, William. 1860. "Measurement of the electrostatic force produced by a Daniell's battery." *Proceedings of the Royal Society* 10: 319-26 (cited several times).
[15] Jenkin, Fleeming. 1859. "On gutta percha as an insulator at various temperatures." in *Report of the British Association for the Advancement of Science,* 248. London (UK): J. Murray.
[16] Thomson, William. 1853. "On the mutual attraction or repulsion between two electrified spherical conductors." *Philosophical magazine* 5: 287-97.
[17] Thomson, William. 1860. "Measurement of the electromotive force required to produce a spark in air between parallel metal plates at different distances." *Proceedings of the Royal Society* 10: 326-38.
[18] Faraday, Michael. 1839. *Experimental Researches in Electricity,* volume I. London (UK): R. & J.E. Taylor, Series XI.
[19] Faraday, Michael. 1839. *Experimental Researches in Electricity* volume I. London (UK): R. & J.E. Taylor, Series VII.
[20] Andrews, Thomas. 1849. "Report on the heat of combination." in *Report of the British Association for the Advancement of Science,* 63-78. London (UK): J. Murray.

Thomas Andrews [Belfast, Ireland, December 19, 1813 - Belfast, Ireland, November 26, 1885] chemist and physicist, he carried out important work on phase transitions between gases and liquids. Andrews first became known as a scientific investigator with his work on the heat developed in chemical reactions, for which the Royal Society awarded him a Royal medal in 1844. He was professor of chemistry at Queen's University of Belfast. [Encyclopaedia Britannica "Thomas Andrews"]

[21] Favre, Pierre Antoine. 1853. "Notes sur les effets calorifiques développés dans le circuit voltaique, dans leurs rapports avec l'action chimique qui donne naissance [Notes on the calorific effects developed in the voltaic circuit, in their relation to the chemical action which gives rise to it]." *Comptes Rendus* 36: 324-44. (Citation is to Andrews, Favre and Silberman, *Comptes Rendus* 36 and 38, but only this paper by Favre is present in the two volumes, while the only paper by Silbermann is clearly unrelated to heat.)

Pierre Antoine Favre [Lyons, France, February 20, 1813 - Marseilles, France, February 17, 1880] began as a chemist helping Eugene Peligot in his classic work on uranium compounds. In 1851 he became head of the analytical chemistry laboratory of the Central School of Arts and Manufactures and was later called to the newly created Faculty of Science at Marseilles in 1856. [Obituary 1880]

[22] Rankine, William. 1853. "On the general law of the transformation of energy." *Philosophical magazine* 4, 5: 106-17.
[23] Weber, Wilhelm. 1851. "Messungen galvanischer leitungswiderstände nach einem absoluten Maasse [Measurements of galvanic line resistances according to an absolute measure]." *Poggendorff's Annalen* 82: 337-69.

> These phenomena have been described by Professor FARADAY (Experimental Researches, Series XI.) and by Mr. F. JENKIN (Report of Committee of Board of Trade on Submarine Cables), and may be classed under the name of "Electric Absorption."

DT: p. 494 par. (85), C. Wheatstone, W. Fairbairn, G.P. Bidder, E. Clark, C.F. Varley, L. Clark, G. Saward. 1860. *Report of the joint committee appointed by the Lords of the Committee of Privy Council for Trade and the Atlantic Telegraph Company to inquire into the construction of submarine telegraph cables together with the minutes of evidence and appendix*. 67, paper 2744.

Not available to the authors

Karl Hermann Knoblauch [Berlin, Germany, April 11, 1820 - Baden Baden, Germany, June 30, 1895]

Physicist. He was most notable for his studies of radiant heat, performing valuable experiments that established some of the optical properties of radiant heat (infrared radiation).

He produced valuable experimental demonstrations on the nature of diamagnetism. He also gave his time to various administrative functions in German science including being president for 17 years of the German Academy of Sciences. [Knott 1906]

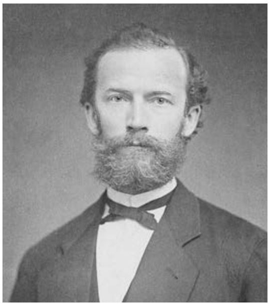
German, cited once

The experiments of KNOBLAUCH* on electric induction through crystals seem to show that *a*, *b* and *c*, may be different.

DT: p. 503 par. (105), Maxwell here cites simply «*Phi. Mag.* 1852» without pages. Yet no paper by Knoblauch can be found in 1852 volume of the *Philosophical Magazine*, there is an the other hand a paper in 1851 volume which seems the one cited by Maxwell since it deals with polarization changes in anisotropic materials: 1851. "On the deportment of crystalline bodies between electric poles." *Philosophical Magazine* 4, 2: 33-6.

[1] Tyndall, John, and Hermann Knoblauch. 1850. "Second memoir on the magneto-optic properties of crystals, and the relation of magnetism and diamagnetism to molecular arrangement." *Philosophical magazine* 37: 1-33.

John Tyndall [Leighlinbridge, Ireland, August 2, 1820 - Haslemere, England, December 4, 1893] was a prominent 19th-century Irish physicist. In the 1850s he began studying diamagnetism. Later he studied alpine glaciers, and especially glacier motion; made discoveries in the realms of infrared radiation and the physical properties of air, proving the connection between atmospheric CO_2 and what is now known as the greenhouse effect in 1859.
Tyndall also published more than a dozen science books which brought state-of-the-art 19th century experimental physics to a wide audience.
Tyndall was appointed the successor to the positions held by Michael Faraday at the Royal Institution on Faraday's retirement. [Barton 2021]



Friedrich Wilhelm Georg Kohlrausch [Rinteln, Germany, October 14, 1840 - Marburg, Germany, January 17, 1910]

Physicist who investigated the conductive properties of electrolytes and contributed to knowledge of their behaviour. He established that, to a high accuracy in dilute solutions, molar conductivity could be decomposed into contributions of the individual ions. This is known as the Kohlrausch's law of independent ionic migration. He also investigated elasticity, thermoelasticity, and thermal conduction as well as magnetic and electrical precision measurements.

Nowadays, Friedrich Kohlrausch is classed as one of the most important experimental physicists. His early work helped to extend the absolute system of Carl Friedrich Gauss and Wilhelm Weber to include electrical and magnetic measuring units. He succeeded Hermann von Helmholtz as President of the Physikalisch-Technische Reichsanstalt (PTR – Imperial Physical Technical Institute) where he created numerous standards and calibration standards which were also used internationally outside Germany. [Wien 1910, Encyclopaedia Britannica "Friedrich Wilhelm Georg Kohlrausch"]

German, cited once, mentioned twice

> The last result, namely, the mechanical force acting on an electrified body, gives rise to an independent method of electrical measurement founded on its electrostatic effects. The relation between the units employed in the two methods is shown to depend on what I have called the 'electric elasticity' of the medium, and to be a velocity, which has been experimentally determined by MM. WEBER and KOHLRAUSCH.

DT: p. 465 par. (19), no explicit reference to any Kohlrausch paper is given.

> The quantity v may be determined by experiment in several ways. According to the experiments of MM. WEBER and KOHLRAUSCH,
>
> v=310,740,000 metres per second.

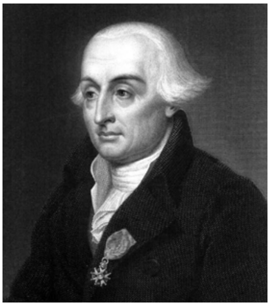
DT: p. 492 par. (80), no explicit reference to any Kohlrausch paper is given.

> By the electromagnetic experiments of MM. WEBER and KOHLRAUSCH *,
>
> v=310,740,000 met.res per second

DT: p. 499 par. (96), indeed, even if citation is given only here, all three mentions of Kohlraush clearly refers to the same paper: W. Weber and R. Kohlraush, "Ueber die elektricitätsmenge, welche bei galvanischen strömen durch den querschnitt der kette fliesst [About the amount of electricity that flows

through the cross section of the wire in the case of galvanic currents]." *Poggendorff's Annalen* 99, 1856: 10-25.

[1] Weber, Wilhelm. 1846. *Elektrodynamische Maassbestimmungen* [*Electrodynamic measurements*]. Leipzig: Weididmannsche Buchhandlung.



Joseph-Louis Lagrange, French, worldwide accepted version of his original Italian name **Giuseppe Lodovico Lagrangia** [Turin, Italy, January 25, 1736 - Paris, France, April 10, 1813]

Italian mathematician and astronomer who also worked for a long time in Germany and France. He made significant contributions to the fields of analysis, number theory, and both classical and celestial mechanics. In particular he studied the movements of the moon and of Jupiter's satellites, studying the three-body problem mathematically.

In 1766, on the recommendation of Euler and d'Alembert, Lagrange succeeded Euler as the director of mathematics at the Prussian Academy of Sciences in Berlin, Prussia, where he stayed for over twenty years, producing volumes of works and winning several prizes from the French Academy of Sciences. Lagrange's treatise on analytical mechanics, offered the most comprehensive treatment of classical mechanics since Newton and formed a basis for the development of mathematical physics in the nineteenth century.

In 1787, he moved from Berlin to Paris and became a member of the French Academy. He became the first professor of analysis at the École Polytechnique upon its opening in 1794, founding member of the Bureau des Longitudes and Senator in 1799, remaining in France until the end of his life. [Borgato 1990, Ball 1908]

Italian, cited once

> As a dynamical illustration, let us suppose a body C so connected with two independent driving-points A and B that its velocity is p times that of A together with q times that of B. Let u be the velocity of A, v that of B, and w that of C, and let δx, δy, δz be their simultaneous displacements, then by the general equation of dynamics.

DT: p. 467 par. (24), *Méchanique Analitique [Analytical Mechanics],* Desaint, Paris, France, 1788. Maxwell cites explicitly Part. II, Sec. 2 par. 5, In said paragraph no scientist is cited, in Section 2, containing paragraph 5, it is mentioned Galileo Galilei:

Galileo di Vincenzo Bonaiuti de' Galilei – commonly referred as **Galileo Galilei** [Pisa, Italy, February 15, 1564 - Arcetri, Italy, January 8, 1642] astronomer, physicist and engineer. Galileo has been called the «father of observational astronomy» for perfecting the telescope, the «father of modern physics» for his studies of motion, the «father of the scientific method» and the «father of modern science» for his approach to the study of all these phenomena. Galileo investigated speed and velocity, gravity and free fall, the principle of relativity, inertia, projectile motion and also worked in applied science and technology. He invented the thermoscope and used the telescope for scientific observations of celestial objects, confirming the phases of Venus, discovering the four largest satellites of Jupiter, Saturn's rings (which he could not resolve clearly, so he believed Saturn to be a triple planet), and analysing sunspots. Galileo's sustained heliocentrism was condemned by the Roman Inquisition in 1615. [O'Connor 2002a]

Ottaviano Fabrizio Mossotti [Novara, Italy, April 17, 1791 - Pisa, Italy, March 20, 1863]

Physicist, exiled from Italy for his liberal ideas. His name is associated with a type of multiple-element lens correcting spherical aberration and coma, but not chromatic aberration and to the Clausius-Mossotti formula for the relationship between the dielectric constants of two different media.

Mossotti was Chair of Experimental Physics in Buenos Aires (1827-1835) and taught numerous Argentinian physicians his views on dielectrics, thereby becoming influential on the Argentine-German neurobiological tradition as regards electricity inside brain tissue.

He returned to Italy, participated in military actions when in his sixties, and was later appointed Senator of Italy. Mossotti also influenced Hendrik Lorentz's views on fundamental forces.

A section of the second part of this book is dedicated to him with full bibliographic references.

Italian, cited once

> But when electromotive force acts on a dielectric it produces a state of polarization of its parts similar in distribution to the polarity of the parts of a mass of iron under the influence of a magnet, and like the magnetic polarization, capable of being described as a state in which every particle has its opposite poles in opposite conditions.

DT: p. 463 par. (11), this is one of the paragraphs also concerning Farady. Maxwell cites 1850. "Discussione analitica sull'influenza che l'azione di un mezzo dielettrico ha sulla distribuzione dell'elettricità alla superficie di più corpi elettrici disseminati in esso [Analytical discussion on the influence that the action of a dielectric medium has on the surface distribution of electricity of several electric bodies scattered in it]." *Memorie di Matematica e di Fisica della Società Italiana delle Scienze di Modena* 24, part. II: 49-75.

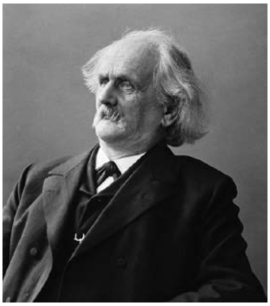
[1] Faraday, Michael. 1838. "Experimental Researches in Electricity, XI Series." *Philosophical Transactions of the Royal Society* 128: 1-40.

[2] Faraday, Michael. 1838. "Experimental Researches in Electricity, XII Series." *Philosophical Transactions of the Royal Society* 128: 83-123.

[3] Mossotti, Ottaviano Fabrizio. 1836. "On the forces which regulate the internal constitution of bodies." *Selected Memoirs selected from the Transactions of Foreign Academies of Sciences* 1: 448-70.

[4] Mossotti, Ottaviano Fabrizio. 1846. "Considerazioni sulle forze di capillarità e coesione dei liquidi relative alle recenti esperienze dei Sigg. Henry, Donny ed Hager [Considerations on capillarity and coesion forces in liquids, related to the recent

experiences of Mr. Henry, Donny ed Hager].” *Il Cimento, Giornale di Fisica, Chimica e Storia Naturale* 4: 439-56.
[5] Mossotti, Ottaviano Fabrizio. 1841. “Sul principio che la riflessione e rifrazione su di una superficie unirifrangente polarizzano nelle due porzioni in cui vien diviso il raggio incidente due quantità di luce uguali, rispettivamente in due piani ortogonali fra loro [On the principle that reflection and refraction on a non-refractive surface polarize two equal quantities of light in the two portions into which the incident ray is divided, respectively in two planes orthogonal to each other].” *Giornale Toscano di Scienze Mediche, Fisiche e Naturali* 1: 330-7.
[6] Mossotti, Ottaviano Fabrizio. 1841. “Sulla causa della dispersione della luce nel sistema delle ondulazioni [On the cause of the scattering of light in its system of undulation].” *Giornale Toscano di Scienze Mediche, Fisiche e Naturali* I: 337-41.
[7] Poisson, Siméon-Denis. 1824. “Sur la theorie du magnetisme en mouvement [On the theory of magnetism in motion].” *Mémoires de l’Academie des Sciences* 4: 441-550.
[8] Poisson, Siméon-Denis. 1824. *Mémoire sur la théorie du magnétisme* [*Dissertation on the theory of magnetism*]. Paris: Impr. royale.
[9] Poisson, Siméon-Denis. 1831. “Mémoire sur les équations générales de l’équilibre et du mouvement des corps solides élastiques et des fluides [Dissertation on general equations of balance and motion of elastic solid bodies and fluids].” *Journal de l’Ecole Polytechnique* 13: 14-174.



Carl Gottfried Neumann [Königsberg, Russia, May 7, 1832 - Leipzig, Germany, March 27, 1925]

German mathematician, son of the mineralogist, physicist and mathematician Franz Ernst Neumann (1798-1895), who was professor of mineralogy and physics at Königsberg University. Carl Neumann studied in Königsberg and Halle and was a professor at the universities of Halle, Basel, Tübingen, and Leipzig. Neumann worked with Weber on electrodynamics.

Neumann, chiefly remembered as a mathematician, worked on the Dirichlet principle, and can be considered one of the initiators of the theory of integral equations. The Neumann boundary condition for certain types of ordinary and partial differential equations is named after him. [O'Connor 2017]

German, cited once

> This theory, as developed by MM. W. WEBER and C. NEUMANN, is exceedingly ingenious, and wonderfully comprehensive in its application to the phenomena of statical electricity, electromagnetic attractions, induction of currents and diamagnetic phenomena; and it comes to us with the more authority, as it has served to guide the speculations of one who has made so great an advance in the practical part of electric science, both by introducing a consistent system of units in electrical measurement, and by actually determining electrical quantities with an accuracy hitherto unknown.

DT: p. 459 par. (1), *Explicare tentatur quomodo fiat ut lucis planum polarizationis per vires electricas vel magneticas declinetur [How to explain the plane of polarization of light, how it happens that it is tempted to change direction by means of magnetic or electrical forces], Halis Saxonum,* 1858.

[1] Wiedmann, Gustav Heinrich. 1851. "Ueber die drehung der polarisationsebene des lichts durch den galvanischen strom [On the rotation of the polarization plane of the light by the galvanic current]." *Poggendorff's Annalen* 82: 215-32 (Neumann cites only p. 224).

> **Gustav Heinrich Wiedemann** [Berlin, Germany, October 2, 1826 - Leipzig, Germany, March 24, 1899] graduated with a thesis on organic chemistry, because he held the opinion that the study of chemistry is an indispensable preliminary to the study of physics, which was his ultimate aim. In Berlin he met Hermann von Helmholtz and was one of the founders of the Berlin Physical Society. With Rudolph Franz, Wiedemann he developed the Wiedemann–Franz law relating thermal and electrical conductivity in 1853.
> His name is probably most widely known for his editorial work. In 1877 he undertook the editorship of the *Annalen der Physik und Chemie* succeeding Johann Christian Poggendorff [indeed they were called *Poggendorff's Annalen*, and we followed that way of citing them in this book], thus starting the series of that scientific periodical which is familiarly cited as *Wiedemann Annalen.* [Deutsche Biographie, "Wiedemann, Gustav Heinrich"]

[2] Verdet, Marcel-Émile. 1855. "On the optical properties developed in transparent bodies by the action of magnetism" *Philosophical Magazine* 4, 9: 481-509 (Neumann cites only p. 508).

Only mentioned: *M. Faraday*

Joseph Antoine Ferdinand Plateau [Brussels, Belgium, October 14, 1801 - Gand, Belgium, September 15, 1883]

Physicist. He was one of the very first to demonstrate the illusion of a moving image. To this aim he used counter rotating disks with repeating drawn images in small increments of motion on one and regularly spaced slits in the other. He called this device «phenakistoscope» (1832).

Plateau also studied the phenomena of capillary action and surface tension, and the mathematical problem of existence of a minimal surface with a given boundary is named after him. He conducted extensive studies of soap films and formulated Plateau's laws which describe the structures formed by such films in foams. [Van der Mensbrugghe 1885]

Belgian, mentioned once

These surfaces, therefore, are connected with the electric current as soap-bubbles are connected with a ring in M. PLATEAU'S experiments. Every current γ has $4\pi\gamma$ surfaces attached to it. These surfaces have the current for their common edge and meet it at equal angles. The form of the surfaces in other parts depends on the presence of other currents and magnets, as well as on the shape of the circuit to which they belong.

DT: p. 480 par. (52), no explicit reference to any Plateau paper is given.

Julius Plücker [Elberfeld, Germany, June 16, 1801 - Bonn, Germany, May 22, 1868]

Mathematician and Physicist, professor at Bonn University. He worked with Heinrich Geißler and published research papers, which become classical, on the action of a magnet on the electric discharge in rarefied gases. This led him to important discoveries in the cathode ray area and the spectroscopy of gasses.

He also made fundamental contributions to the field of analytical geometry inventing what was known as 'line geometry' in the nineteenth century and 'line coordinates' now. He also vastly extended the study of Lamé curves. [Karsten, C. 1888, Encyclopaedia Britannica "Julius Plücker"]

German, mentioned once

We know, from the magnetic experiments of FARADAY, PLUCKER, &c., that in many crystals λ, μ, ν are unequal.

DT: p. 504, par. (104) no explicit reference to any Plücker paper is given.

Claude Servais Mathias Pouillet [Cusance, France, February 16, 1790 - Paris, France, June 14, 1868]

Physicist and professor of Physics at the Sorbonne and member of the French Academy of Science.

He developed a pyrheliometer, the instrument used to measure solar radiance, and made, between 1837 and 1838, the first quantitative measurements of the solar constant, estimating it to be 1228 W/m^2, which, for being the first measurement ever, is remarkably close to the current estimate of 1367 W/m^2.

As a meteorologist, he developed the first real mathematical treatment of the greenhouse effect and speculated that, in the distant past, water vapor and carbon dioxide might trap infrared radiation in the atmosphere, warming the earth enough to support plant and animal life. [Trimble 2007]

French, mentioned once

According to POUILLET'S data, as calculated by Professor W. THOMSON, the mechanical value of direct sunlight at the Earth is

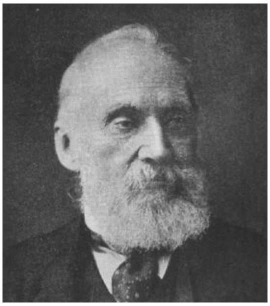
83.4 foot-pounds per second per square foot[6].

This gives the maximum value of P in direct sunlight at the Earth's distance from the Sun,

$$P=60,000,000,$$

DT: p. 505, par. (108) no explicit reference to any Pouillet paper is given.

[6] 1 foot-pound per second is 1.3558 watts, a square foot is 0.092903 square meters, in metric units this estimate equals to 1.228kWm^{-2}.



William Thomson, 1st Baron Kelvin [Belfast, Ireland, June 26, 1824 - Largs, Scotland, December 17, 1907]

Northern-Irish and British mathematical physicist and engineer. At the University of Glasgow, he did important work in the mathematical analysis of electricity and in the formulation of the first and second laws of thermodynamics, and much to unify the emerging discipline of physics in its modern form. He also had a career as an electric telegraph engineer and inventor, which propelled him into the public eye and ensured his wealth, fame and honour.

Thomson did more than any other electrician up to his time to introduce accurate methods and apparatus for measuring electricity. Acknowledging his contribution to electrical standardization, the International Electrotechnical Commission elected Thomson as its first President at its preliminary meeting, held in London on 26–27 June 1906.

The SI unit of measurement of temperature, the kelvin is named after him. [Gray 1908, Sharlin 2022]

Irish, cited five times

Now the energy communicated to the body in heating it must have formerly existed in the moving medium, for the undulations had left the source of heat some time before they reached the body, and during that time the energy must have been half in the form of motion of the medium and half in the form of elastic resilience. From these considerations Professor W. THOMSON has argued, that the medium must have a density capable of comparison with that of gross matter, and has even assigned an inferior limit to that density.

DT: p. 460, par. (5) **citation to** 1854. "On the possible density of the luminiferous medium, and on the mechanical value of a cubic mile of sunlight." *Transactions of the Royal Society of Edinburgh* XXI: 57-63.

[1] Newton, Isaac. 1687. *Philosophiæ Naturalis Principia Mathematica*[7], Book III: 512. London (UK): J. Streater.

Isaac Newton [Woolsthorpe-by-Colsterworth, England, December 25, 1642 - Kensington, England, March 20, 1726] mathematician, physicist, astronomer, theologian, or, as it was used in that time *natural philosopher.* Like Galileo, one of the most influential scientists of all time and as a key figure in the scientific revolution. His *Philosophiæ Naturalis Principia Mathematica* (1687) established classical mechanics.
Newton built the first practical reflecting telescope and developed a sophisticated theory

[7] This book is so fundamental and widely known that a translation of the Latin title would be pointless.

of colour based on the observation that a prism separates white light into the colours of the visible spectrum. All his research on light is collected in his book *Opticks* (1704). His contributions to mathematics were also very influential, sharing with Leibnitz the invention of infinitesimal calculus, studying power series, and generalizing the binomial theorem to non-integer exponents
Newton was a fellow of Trinity College and the second Lucasian Professor of Mathematics at the University of Cambridge. Beyond his work on the mathematical sciences, Newton dedicated much of his time to the study of alchemy and biblical chronology. [Westfall 2022]

Only mentioned: *G.G. Stokes (see above):*

Now Professor W. Thomson has pointed out that no distribution of forces acting between the parts of a medium whose only motion is that of the luminous vibrations, is sufficient to account for the phenomena, but that we must admit the existence of a motion in the medium depending on the magnetization, in addition to the vibratory motion which constitutes light.

DT: p. 461, par. (8) **citation to** 1856. "Dynamical illustrations of the magnetic and the helicoidal rotatory effects of transparent bodies on polarized light." *Proceedings of the Royal Society* 8: 150-8.

Only mentioned: *M. Faraday (see above), W. Rankine (see above), H. Blackburn*

Bailie Hugh Blackburn [Craigflower, Scotland, July 2, 1823 - Roshven, Scotland, October 9, 1909] mathematician, lifelong friend of William Thomson and the husband of illustrator Jemima Blackburn. Professor of mathematics at the University of Glasgow from 1849 to 1879. He succeeded Thomson's father James in the Chair of Mathematics. [O'Connor 2005b]

and to 1861. "On the measurement of electric resistance." *Proceedings of the Royal Society* 9: 313-29.

[2] Siemens, Ernst Werner. 1861. "Proposal for a new reproducible standard measure of resistance to galvanic currents." *Philosophical Magazine* 21: 25-39.

Ernst Werner von Siemens [Lenthe, Germany, December 13, 1816 - Berlin, Germany, December 6, 1892] electrical engineer, inventor and industrialist. In the Prussian army he earned various medals and invented a sea mine. He then invented a telegraph and opened a company soon to become international, with foreign offices chaired by his brothers. The Siemens company diversified and is still running. He built the world's first electric elevator in 1880. His company produced the tubes with which Wilhelm Conrad Röntgen investigated X-rays.
Siemens's name has been adopted as the SI unit of electrical conductance, the siemens. [Encyclopaedia Britannica "Werner von Siemens"]

[3] Matthiessen, Augustus. 1861. "On an alloy which may be used as a standard of electrical resistance." *Philosophical Magazine* 21: 107-15.

[4] Thomson, William. 1851. "On the mechanical theory of electrolysis." *Philosophical Magazine* 2: 429-44.
[5] Thomson, William. 1860. "Analytical and synthetical attempts to ascertain the cause of the differences of electric conductivity discovered in wires of nearly pure copper." *Proceedings of the Royal Society* 10: 309-11.
[6] Thomson, William. 1853. "On transient electric currents." *Philosophical Magazine* 5: 393-405.
[7] Thomson, William. 1860. "Magnetism, dynamical relations of." In J.P. Nicho, *Cyclopaedia of the Physical Sciences*, 2nd ed., 544-8. London (UK): R. Griffin & Co.
[8] Thomson, William. 1856. "On the theory of the electric telegraph." *Proceedings of the Royal Society* 7: 382-99.
[9] Thomson, William. 1856. "Dynamical theory of heat, Part VI., thermo-electric currents." *Philosophical Magazine* 11: 379-88.

Only mentioned: *C. Wheatstone (see above), Weber (see below), S. Morse*

Samuel Finley Breese Morse [Charleston, MA, USA, April 27, 1791 - New York, NY, USA, April 2, 1872] was an American painter with a good reputation as a portrait painter. In his middle age Morse switched to telecommunications and contributed to the invention of a single-wire telegraph system. He developed the Morse code and contributed to the development of commercial telegraphy. [Mabee 2002]

The second result, which is deduced from this, is the mechanical action between conductors carrying currents. The phenomenon of the induction of currents has been deduced from their mechanical action by HELMHOLTZ and THOMSON. I have followed the reverse order and deduced the mechanical action from the laws of induction. I have then described experimental methods of determining the quantities *L, M, N*, on which these phenomena depend.

DT: p. 464 par. (17), **citation to** 1851. "On the mechanical theory of Electrolysis." *Philosophical Magazine* 4, II: 429-44.

[10] Faraday, Michael. 1839. *Experimental Researches in Electricity*, volume I. London (UK): R. & J.E. Taylor, Series I, exp. 124 (also Bakerian Lecture 1832).
[11] Joule, James Prescott. 1843."On the heat evolved during the electrolysis of water." *Manchester Literary and Philosophical Society* 2, 7, Part 3: 87-114.
[12] Thomson, William. 1851. "On the dynamical theory of heat, with numerical results deduced from Mr. Joule's equivalent of a thermal unit, and Mr. Regnault's observation on steam." *Transactions of the Royal Society of Edinburgh* 20: 261-89 (Thomson cites only part 2).
[13] Scoresby, William and James Prescott Joule. 1846. "On the powers of electromagnetism, steam, and horses,'" *Philosophical Magazine* 28: 448-55.

William Scoresby [Cropton, England, October 5, 1789 - Torquay, Devon, March 21, 1857], was an English Arctic explorer, scientist, and clergyman. In 1820, he published "An Account of the Arctic Regions and Northern Whale Fishery." in which he gathers up the results of his own observations, as well as those of previous navigators. In 1820 and 1821 he commanded the ship *Fame* on whale hunting voyages to the Greenland whale

fishery. In his voyage of 1822 to Greenland, Scoresby surveyed and charted with remarkable accuracy 400 miles of the east coast, between 69° 30' and 72° 30'.
Scoresby was an active member and official of the British Association for the Advancement of Science, and he contributed especially to the knowledge of terrestrial magnetism. His observations also extended to optics and, with James Joule, to the comparison of electromagnetic (chemical), thermal (coal/steam), and organic (horse) power sources. [Encyclopaedia Britannica "William Scoresby"]

Only mentioned: *J.P. Joule (See above), N.L.S. Carnot (see above) R. Clausius*

Rudolf Julius Emanuel Clausius [Köslin, Poland, January 2, 1822 - Bonn, Germany, August 24, 1888] to be considered German, since Köslin was then in the German Empire. He was a physicist and mathematician who was considered one of the founders of the science of thermodynamics. By his restatement of Sadi Carnot's principle, he provided a sounder basis for the theory of heat. His most important paper, "Ueber die bewegende Kraft der Wärme und die Gesetze, welche sich daraus für die Wärmelehre selbst ableiten lassen." *Poggendorff's Annalen* 79, 1850: 368–397 and 500–524, first stated the basic ideas of the second law of thermodynamics. In 1865 he introduced the concept of entropy. [O'Connor 2000b]

According to POUILLET'S data, as calculated by Professor W. THOMSON, the mechanical value of direct sunlight at the Earth is

83.4 foot-pounds per second per square foot.

This gives the maximum value of P in direct sunlight at the Earth's distance from the Sun,

$$P=60{,}000{,}000,$$

DT: p. 505, par. (108) **citation to** 1854. "Mechanical energies of the solar system." *Transactions of the Royal Society of Edinburgh* 21: 63-80.

[14] Herschel, William. 1833. *A Treatise on Astronomy*. Philadelphia (PA): Carey, Lea e Blanchard.
[15] Joule, James Prescott. 1841. "On the heat evolved by metallic conductors of electricity, and in the cells of a battery during electrolysis." *Philosophical Magazine* 19: 260-77 (Thomson cites a slightly different title, that of the original oral communication).
[16] Joule, James Prescott. 1843. "On the heat evolved during the electrolysis of water." *Manchester Literary and Philosophical Society* 2, 7, Part 3: 87-114.
[17] Joule, James Prescott. 1843. "On the calorific effects of magneto-electricity, and the mechanical value of heat." *Philosophical Magazine* 23: 263-76.
[18] Joule, James Prescott. 1845. "On the changes of temperature produced by the rarefaction and condensation of air." *Philosophical Magazine* 24: 369-83.
[19] Scoresby, William, and James Prescott Joule. 1846. "On the powers of electromagnetism, steam, and horses," *Philosophical Magazine* 28: 448-55.
[20] Joule, James Prescott.1848. "On shooting stars." *Philosophical Magazine* 32: 349-51.
[21] Pouillet, Claude Servais Mathias. 1838. *Mémoire sur la chaleur solaire: sur les pouvoirs rayonnants et absorbants de l'air atmosphérique et sur la température de l'espace*

[*Dissertation on solar heat: on the radiant and absorbent powers of atmospheric air and on the temperature of space*]. Paris: Bachelier.

Only mentioned: *W. Rankine (see above), J.J. Waterston, J.R. Hind, J.G. Böhm, P. Laugier, A.C. Petersen*

John James Waterston [Edinburgh, Scotland, 1811 - Edinburgh, Scotland, June 18, 1883] was a physicist and a forgotten pioneer of the kinetic theory of gases. He published, at his own expense, a book (1843) where he correctly derived all the consequences of the premise that gas pressure is a function of the number of molecules per unit volume. A manuscript sent to the Royal Society in 1845 was rejected and he did not keep a copy. The theory gained acceptance only when it was proposed by Rudolf Clausius and James Clerk Maxwell in the 1850s by which time Waterston's contribution had been forgotten. [O'Connor 2008b]

John Russell Hind [Nottingham, England, May 12, 1823 - Twickenham, England, December 23, 1895] went to London at age 17 to serve an apprenticeship as a civil engineer, but through the help of Charles Wheatstone he left engineering to accept a position at the Royal Observatory, Greenwich under G.B. Airy, to become director of George Bishop's Observatory 4 years later.
Hind is notable for being one of the early discoverers of asteroids. He also discovered and observed several variable stars and the first nova of modern times (1848). [Royal Observatory Greenwich (The), People: "John Russell Hind"]

Josef Georg Böhm [Rožďalovice, Czech Republic, March 28, 1807 - Prague, Czech Republic, January 26, 1868] bohemian astronomer and mathematician, he studied sunspots and the rotation of the sun. Böhm developed the *uranoscope*, a device for the simple identification of stars. When the instrument is pointed at a star, a pointer on the connected celestial globe points to the star being observed. This is an improved version of the *Astrodeiktikon* by Erhard Weigel. [Mucha 1995]

Paul-Auguste-Ernest Laugier [Paris, France, December 22, 1812 - Paris, France, April 5, 1872] studied astronomy under F. Arago, and, when at the observatory at Paris, made important discoveries in regard to magnetism, comets, eclipses, meteors, and sunspots. Laugier determined the exact latitude of the Paris observatory (1853), correcting previous errors and published a catalogue of fifty-three nebulae, and another of the declination of 140 stars. [Obituary 1873]

Adolph Cornelius Petersen [Bylderup, Denmark July 28, 1804 - Altona, Germany, February 4, 1854] employed in 1827 as an assistant and observer at the Altona observatory. Petersen worked mainly on the determination of the orbit of comets, on solar observations and on geographical position determination. Petersen made a name for himself in 1848 and 1850 by discovering three comets.
After Urbain Le Verrier's discovery of Neptune in 1846, he proved that Lalande had already observed the planet in 1795, but thought it was a fixed star. [Obituary, 1854]

Marcel-Émile Verdet [Nîmes, France, March 13, 1824 - Avignon, France, June 3, 1866]

Physicist, who worked in magnetism and optics, editing the works of Augustin-Jean Fresnel.

Verdet was editor of the *Annales de Chimie et de Physique* after Joseph Louis Gay-Lussac and held the position for a certain period together Charles-Adolphe Wurtz, up to 1865. In this role, he strongly promoted the early theory of the conservation of energy in France. [Encyclopedia.com "Verdet, Marcel Émile"]

French, cited twice

This rotation is always in the direction in which positive electricity must be carried round the diamagnetic body in order to produce the actual magnetization of the field.
M. VERDET has since discovered that if a paramagnetic body, such as solution of perchloride of iron in ether, be substituted for the diamagnetic body, the rotation is in the opposite direction.

DT: p. 461, par. (8) **citation to** 1856. "Note sur les propriétés optiques des corps transparent soumis à l'action du magnétisme [Note on the optical properties of transparent bodies subjected to the action of magnetism]." *Comptes Rendus* 43: 529-32.

[1] Bertin, Pierre Auguste. 1848. "La polarization circulaire magnétique [Magnetic circular polarization]." *Annales de Chimie et de Physique* 3, 23: 5-32.

Pierre Auguste Bertin [Besançon, France, February 13, 1818 - Pargots bei Marteau, France, August 20 1884] Professor of physics in Strasbourg until 1866 and then deputy director of the École Normale in Paris. He did research in optics, in particular on polarized light and magnetic rotational polarization. [Federation des Societes d'Histoire & d'Archeologie d'Alsace "Bertin Pierre Auguste", Correspondance de Henry Poincaré (La) "Personne: Pierre Augustin Bertin-Mourot"]

Mentioned only: *A. de la Rive (see above), E. Becquerel (see above)*

and to 1857. "Note sur les propriétés des corps magnétiques." *Comptes Rendus* 44: 1209-13.

[2] Faraday, Michael. 1855. *Experimental Researches in Electricity*, volume III. London (UK): R. & J.E. Taylor, Series XXI.

Mentioned only: *H.E. Deville (see above)*

Wilhelm Eduard Weber [Wittenberg, Germany, October 24, 1804 - Göttingen, Germany, June 23, 1891]

Physicist, nominated professor at Göttingen at the age of only 27, he was soon dismissed due to his liberal ideas in 1837. This allowed him to travel Europe, and in particular England. Professor of physics in Leipzig from 1843 to 1849, when he was reinstated at Göttingen.

He studied magnetism with Gauss, and the two, in 1833, built the first electromagnetic telegraph. Among his works we can remember *Electrodynamic Proportional Measures* (1864) containing a system of absolute measurements for electric currents, which forms the basis of those in use.

The SI unit of measurement of magnetic flux, the weber (symbol: Wb) is named after him. [New International Encyclopaedia 1916, Encyclopaedia Britannica "Wilhelm Eduard Weber"]

German, cited twice, mentioned five times

These theories assume, more or less explicitly, the existence of substances the particles of which have the property of acting on one another at a distance by attraction or repulsion. The most complete development of a theory of this kind is that of M. W. WEBER, who has made the same theory include electrostatic and electromagnetic phenomena.
In doing so, however, he has found it necessary to assume that the force between two electric particles depends on their relative velocity, as well as on their distance. This theory, as developed by MM. W. WEBER and C. NEUMANN, is exceedingly ingenious, and wonderfully comprehensive in its, application to the phenomena of statical electricity, electromagnetic attractions, induction of currents and diamagnetic phenomena; and it comes to us with the more authority, as it has served to guide the speculations of one who has made so great an advance in the practical part of electric science, both by introducing a consistent system of units in electrical measurement, and by actually determining electrical quantities with an accuracy hitherto unknown.

DT: p. 459 par. (1), **citation to** 1848. "Elektrodynamische maassbestimmungen [Electrodynamic measurements]." *Poggendorff's Annalen* 73: 193-241.

Only mentioned: *M. Faraday (see above), A.M. Ampere (see above), I. Newton (see above) J. Kepler, C. Gauss.*

Johannes Kepler [Weil der Stadt, Germany, December 27, 1571 - Regensburg, Germany, November 15, 1630] astronomer, mathematician, and astrologer. He is a key figure in the 17th-century scientific revolution, for his laws of planetary motion, and his books *Astronomia nova, Harmonices Mundi*, and *Epitome Astronomiae Copernicanae*. These works are among the foundations for Newton's theory of universal gravitation.

He improved a version of the refracting telescope and was mentioned by his contemporary Galileo Galilei. He was a corresponding member of the *Accademia dei Lincei* in Rome. [Westman 2001]

Johann Carl Friedrich Gauss [Brunswick, Germany, April 30, 1777 - Göttingen, Germany, February 23, 1855] great mathematician and physicist, so great as to be referred to as the *Princeps mathematicorum* (the foremost of mathematicians). Gauss had an exceptional influence in many fields of mathematics and science.
In particular, for what concerns this book, in 1831, he developed a fruitful collaboration with Weber, leading to new knowledge in magnetism and the formulation his namesake's law. [Gray 2022, O'Connor 1996]

The general equations are next applied to the case of a magnetic disturbance propagated through a non-conducting field, and it is shown that the only disturbances which can be so propagated are those which are transverse to the direction of propagation, and that the velocity of propagation is the velocity v, found from experiments such as those of WEBER, which expresses the number of electrostatic units of electricity which are contained in one electromagnetic unit.

DT: pp. 466-7 par. (20), no explicit reference to any Weber paper is given.

All questions relating to the total quantity of transient currents, as measured by the impulse given to the magnet of the galvanometer, may be solved in this way without the necessity of a complete solution of the equations. The heating effect of the current, and the impulse it gives to the suspended coil of WEBER'S dynamometer, depend on the square of the current at every instant during the short time it lasts. Hence, we must obtain the solution of the equations, and from the solution we may find the effects both on the galvanometer and dynamometer; and we may then make use of the method of WEBER for estimating the intensity and duration of a current uniform while it lasts which would produce the same effects.

DT: pp. 473-4 par. (38), no explicit reference to any Weber paper is given.

The quantity v may be determined by experiment in several ways. According to the experiments of MM. WEBER and KOHLRAUSCH,

v=310,740,000 metres per second.

DT: p. 492 par. (80) no explicit reference to any Weber paper is given.

By the electromagnetic experiments of MM. WEBER and KOHLRAUSCH *,

v=310,740,000 met.res per second

DT: p. 499 par. (96) Weber, Wilhelm, and Friedrich Kohlraush. 1856. "Ueber die elektricitätsmenge, welche bei galvanischen strömen durch den querschnitt der kette fliesst [About the amount of electricity that flows through the cross

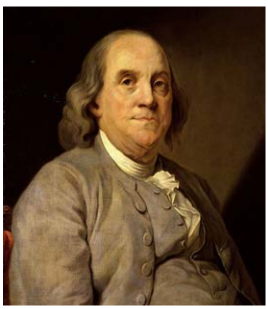
section of the wire in the case of galvanic currents].” *Poggendorff’s Annalen* 99: 10-25 (as already stated this citation also applies to previous mention).

[1] Weber, Wilhelm. 1846. *Elektrodynamische Maassbestimmungen* [*Electrodynamic measurements*]. Leipzig: Weididmannsche Buchhandlung.

Uncited Relevant Scientists

As stated earlier, the scientists in the previous list were not all those who had worked on Electricity and Magnetism, but just those whose work inspired Maxwell most and hence who were deserving of a citation, or, at least, a mention.

There were several other scientists and, among these, we would like to remember just two, whose impact on electromagnetism was indeed at least as important as that of those cited. The first, Franklin, the eldest among those of whom we provide a biography, and to whom the currently used terms of positive and negative charges are due, and Henry, who made important advances in magnetism and might very well have discovered induction at the same time, and independently from Faraday.



Benjamin Franklin [Boston, Massachussets, January 17, 1706 - Philadelphia, Pennsylvania, April 17, 1790]

Polymath, his work spanned from politics to journalism to all kinds of sciences. He is among the Founding Fathers of the United States, drafter and signer of its Declaration of Independence.

In the field of Electricity, although belonging to the school of thought that believed electrical phenomena were due to just one kind of 'electric fluid', he used the terms positive and negative (Franklin 1747) for the volumes in which the pressure of this fluid was higher or lower, respectively, explaining attraction and repulsion of charged bodies in terms of pressure variations. The terms positive and negative were then generally adopted and are still in use in the currently accepted theory of two types of charges. The principle of conservation of charges is to be credited to him (1747) and to William Watson (1746) (Purrington 1997). He also proved the electrical nature of lightning and developed the lightning rod. [Franklin 1909]

Joseph Henry [Albany, New York, December 17, 1797 - Washington, D.C:, May 13, 1878]

Excellent student, in 1826 he was appointed Professor of Mathematics and Natural Philosophy at The Albany Academy. He was Secretary of The National Institution for the Promotion of Science (Washington, D.C.) and later on he became part of the Smithsonian Institution (Washington D.C.) where he also served as a its first Secretary.

He improved (1832) William Sturgeon's electromagnet which exploited loosely coiled uninsulated wire by coiling insulated wire tightly around an iron core, hence building the strongest electromagnet at the time and making the telegraph feasible as something more than a lab experiment. He invented the relais (1835), converting electricity to mechanical movement. Some historians credit Henry with discoveries pre-dating Faraday and Hertz; however, he never published his work. [Carmichael 1967]

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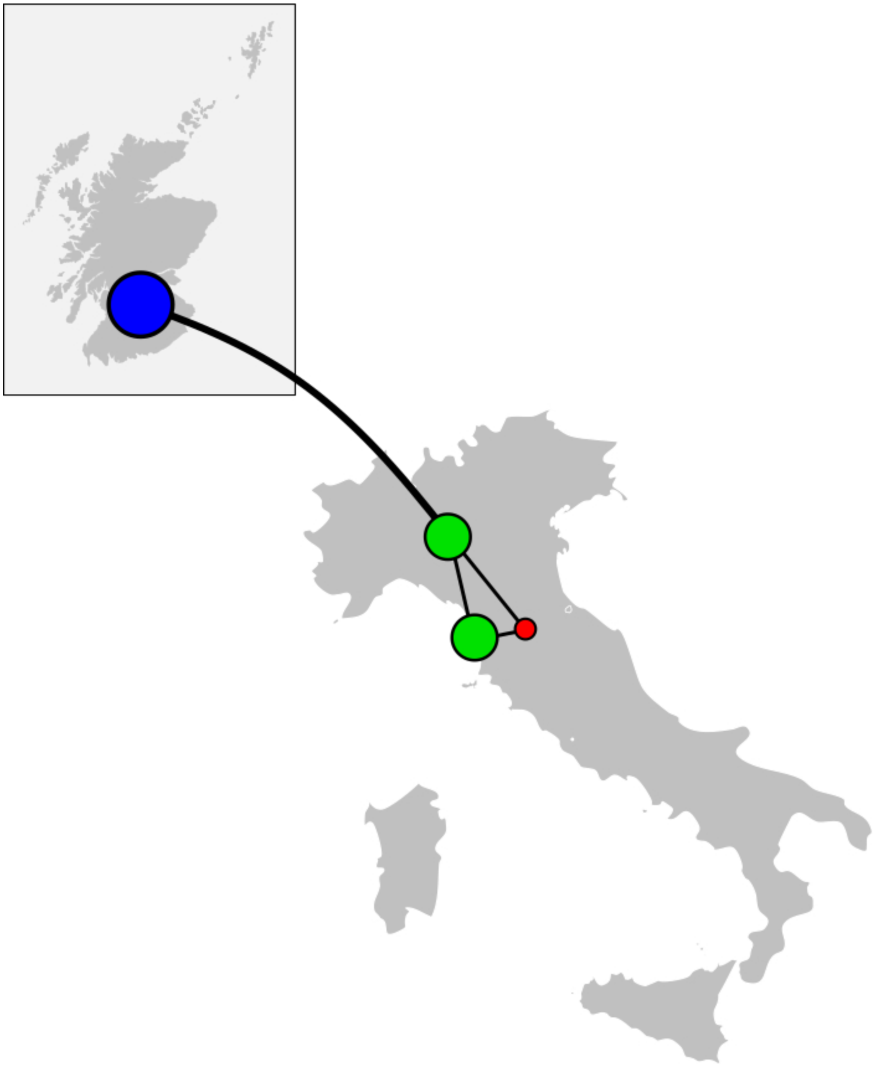
PART II

Roots in Italy



Links from Scotland (large dot) to Italy (Pavia, Pisa and Florence).

Introduction

This second part, *Roots in Italy*, investigates to a deeper extent the two most relevant Italians whose contribution was acknowledged directly or indirectly by Maxwell, as analysed in Part I. Then, some miscellaneous contributions bring to the reader further information on links between James C. Maxwell and Italy. This part is hence further divided into three sections, each containing some chapters.

The first two sections: *On Ottaviano Fabrizio Mossotti* and *On Riccardo Felici* present the two main Italian contributors to Maxwell's theory. The third Italian presented in part I first level citations, Joseph-Louis Lagrange, was recalled by Maxwell for his works on analytical mechanics and, although one of the greatest scientists of all times, his contribution never touched electromagnetism and is not analysed in depth here.

Finally, a third section, *Maxwell and Italy, after the* A Dynamical Theory of the Electromagnetic Field, highlights some even lesser-known links between Maxwell and Italy: his 1867 voyage to Florence and his 1878 Laurea Onoris Causa in Pavia, where he was unable to go due to poor health, since the ceremony was just one year before his death.

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On Ottaviano Fabrizio Mossotti

Fig. 1 – A word cloud containing the places where Ottaviano Fabrizio Mossotti lived, and was active in education, research or politics. Chronologically:

Novara (Italy) [1791-1808]
Pavia (Italy) [1808-1813]
Milan (Italy) [1813-1823]
Geneva (Switzerland) [1823]
London (England) [1823-1827]
Buenos Aires (Argentina) [1827-1835]
Paris (France) [1835]
Bologna (Italy, called to the University but never allowed to join)
Turin (Italy) [1835-1836]
Corfu (Greece) [1836-1841]
Pisa (Italy) [1841-1863]

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Giuseppe Pelosi, Stefano Selleri, *The Roots of Maxwell's* A Dynamical Theory of the Electromagnetic Field. *Scotland and Tuscany, 'twinned by science'*, © 2023 Author(s), CC BY 4.0, published by Firenze University Press, ISBN 979-12-215-0058-5, DOI 10.36253/979-12-215-0058-5

Mossotti was born in Novara and studied in Pavia. The first contribution of this section will focus on his education and cultural background. Then, since Mossotti's studies on dielectrics inspired Maxwell's displacement current, the second contribution describes Mossotti's academic life and provides his full bibliography.

Yet, Mossotti's results are still finding wide application today in a multitude of fields, as the third contribution outlines.

In particular, the Clausius-Mossotti formula is the foundation of many applications in fields that are very distant from each other. Its usefulness derives from the fact that it relates to a macroscopic quantity, the relative permittivity of a medium, with a microscopic quantity, and the polarizability of materials (Selleri 2019).

Among the applications based on the Clausius-Mossotti formula we can mention the characterization and sintering of artificial structures in modern materials science (Mitić 2018), applications in molecular biology (Markx 1999), up to some aspects of nuclear magnetic resonance (Webb 2011).

In the field of molecular biology it is necessary to at least dwell on the impact that the Clausius-Mossotti formula has had in dielectrophoresis, a technique widely used in molecular biology to separate and classify biological microparticles. (Du 2019).

With the advent of modern *lab on chips* (Miled 2012), molecular characterization based on dielectrophoresis is proving to be even more useful and promising, as it is able to distinguish and separate, among other things, cancer cells from healthy ones.

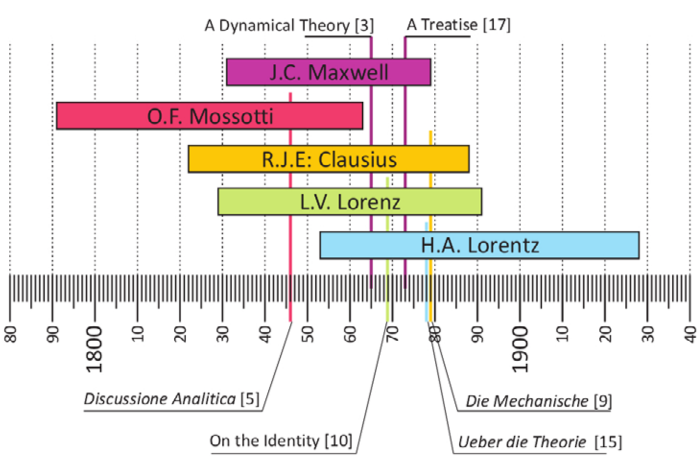

Fig. 2 – A timeline of O.M. Mossotti's and R.J.E. Clausius' lives, as compared to the lives of J.C. Maxwell and L.V. Lorenz and H.A. Lorentz who also studied dielectrics obtaining a very similar relation, also highlighted are their main papers on the subject (from Selleri 2019, see the reference for full bibliographical details of cited papers as well).

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Ottaviano Fabrizio Mossotti's years in Pavia

Antonio Savini[1]

The most complete biography, in Italian, of Ottaviano Fabrizio Mossotti (1791-1863) still appears to be the one edited by L. Liberti and E.L. Ortiz for the Biographical Dictionary of Italians (Liberti 2012). Mossotti's youthful years, in particular, are treated in detail by L. Liberti in 1995 in a publication in English resulting from a thesis. For the years 1808-1815 this publication draws on data from the State Archives of Pavia and the State Archives of Milan. Here we want to add some considerations that characterize the context in which Ottaviano F. Mossotti lived in Pavia as a student and then as a young researcher of that University.

Fig. 1 – Portrait of Ottaviano Fabrizio Mossotti.

Son of Rosa Gola and Giovanni, engineer, Ottaviano Fabrizio Mossotti, after completing his high school studies in his native Novara, perhaps following the instructions of his father, in 1808 moved to Pavia to achieve the title of architect engineer that the University of Pavia granted since 1786. A «stranger» in the then Napoleonic Kingdom of Italy because he came from the Savoy state, in Pavia he found hospitality in the College founded by Giovan Francesco Caccia for students from Novara (Berzolari 1993). Endowed with lively intelligence, at the age of only 17 years on 16 November 1808 he was enrolled to the Physical Mathematical Faculty directly in the second year. For three years he attended courses such as Sublime Calculus, Experimental Physics and Mechanics and Hydrometry, having as teachers A. Lottieri, P. Configliachi and V. Brunacci respectively. Some biographies report that Alessandro Volta was among his teach-

[1] University of Pavia

ers, but it must be remembered that after 1803 the great physicist no longer held regular and complete cycles of lessons.

Endowed with a special talent for mathematics and theoretical subjects in general, because of this attitude Mossotti was particularly appreciated by V. Brunacci. After three years of studies, at the age of only twenty on 6 June 1811 Ottaviano Fabrizio Mossotti acquired his degree from the Royal University of Pavia and was declared an Engineer and Architect with full marks and honours.

After graduation he remained at the University as an auditor, at the invitation of his teachers, in particular of Vincenzo Brunacci, who at the time, among other things, was a member of the Commission to develop the *Naviglio Pavese* project decreed by Napoleon on 20 June, 1805.

The project, which intended to build a canal and so to offer a way to the sea for Milan by connecting the capital of the Kingdom with Pavia and then through the Ticino and the Po rivers with the Adriatic Sea for a length of 33 kilometres and a drop of 56 meters overcome by means of canal sluices. Indeed it concerned a former project that had remained unfinished for centuries. Brunacci offered the project his expertise in dealing with the movement of water. Among which, his treatise on the hydraulic ram, which includes a note by O.F. Mossotti *On a problem of the hydraulic ram theory* (Mossotti 1813). On a hydraulic theme again in that year Mossotti completed a scientific work *On the movement of a fluid that arose from a vase and the pressure it makes on the walls of the same* (Mossotti 1816), obtaining the congratulations of Brunacci, his master, who is reported to have said about the student «Two years ago he was here as a student but now he could be here as a teacher». The work was later published in the *Memoirs of the Italian Society of Sciences or XL Society* based in Modena, of which Mossotti will be member starting from 1822.

Indeed Mossotti wished to remain at the University of Pavia as a teacher of Algebra and Geometry, as proposed by the Faculty and insistently requested by Brunacci himself. The obstacle to career advancement was his "foreigner" status, as indicated by the Royal Commission for Studies in response to his request. Sponsored by Brunacci in 1813 he was hired as a third learner in Milan by the astronomical observatory of Brera, which at that time depended on the University of Pavia. In Milan, at the Observatory, Mossotti remained for about ten years, progressing from third learner (1813) to second (1817) and finally first (1819) and developing new methods of calculating the celestial orbits that also received admiration, among the others, by Karl Gauss in Göttingen.

But this was only the beginning of the scientific and human adventure of Ottaviano Fabrizio Mossotti who developed it in different fields of science and in different locations around the world, in dialogue with great scientists of his time.

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The pavers of Maxwell's pathway to his equations: Ottaviano Fabrizio Mossotti[1]

Giuseppe Pelosi, Stefano Selleri[2]

Life

Ottaviano Fabrizio Mossotti (Fig. 1) [Novara, Italy, 18 April, 1791 – Pisa, Italy, 20 March, 1863] was an Italian physicist, son of an engineer, Giovanni, and of Rosa Gola. Little is known about his early studies, it is likely that his father started teaching him at home. First certain records say he was at the King's College in his hometown in the year 1807-1808, where he was also awarded a prize in Literature, history and mathematics (Nagari 1989, Liberti, 1995).

Fig. 1 – Ottaviano Fabrizio Mossotti, in an undated portrait, when young, from Nagari 1989.

On 1808 Mossotti entered the Faculty of Mathematics at the University of Pavia (Fig. 2), where he graduated as an Architect-Engineer on June 6, 1811. He remained at the University, getting acquainted with the astronomical works of Galileo, Kepler and Newton, and publishing his first scientific paper in 1913.

He then entered the astronomical observatory, or 'specola,' of Brera in Milan, Italy (Fig. 3), an important observatory in Italy, which would then become famous worldwide for the works of Schiaparelli in 1877 (Flamation 1892, Schiaparelli 1893, Selleri 2012). In those post-Napoleonic years Italy, still divided into several small states, was the home of revolts and secret societies promoting unification. Mossotti was involved politically and close to many leaders of unification movements. When several of his friends were imprisoned and he himself was prosecuted he decided to flee in Switzerland in March 1823. He then went to London (May 1823) where he contacted many members of the Royal Society, in particular Thomas Young [Milverton, UK, 13 June 1773 – London, UK, 10 May 1829] (Pelosi 2011) and John Frederick William Herschel [Slough, UK, 7 March 1792 – Hawkhurst, UK, 11 May 1871], of which he eventually became a

[1] From the pages of *URSI Radio Science Bulletin* 355(2015): 78-89.

[2] University of Florence

Fig. 2 – One of the cloisters of the historical building of the University of Pavia.

member in 1826. He then received a teaching appointment at the University of Buenos Aires, so he left London in 1827. In Argentina he could carry out astronomical observations which were not possible in the northern hemisphere, which he published in the Proceedings of the Royal Astronomical Society of London.

He was then able to go back to Italy. Called to the Astronomical Observatory of Bologna 1835, he failed to get the position due to Austrian government opposition, motivated by his political past. He then went to Turin where, in 1836, he published his fundamental work on dielectric induction (Mossotti 1836), which was publicly appreciated by Michael Faraday himself and which was among the basis of J.C. Maxwell's development of displacement current.

He was later offered (1840) the Chair of Mathematics, Physics and Celestial Mechanics at the University of Pisa and was among the founders of the Mathematical School of Pisa. He participated in the 1848 Italian war of independence, and, after Unification, he was nominated Senator of the newborn Kingdom of Italy (1861).

Mossotti (Fig. 4) died in 1863, after a short illness and was buried in the monumental cemetery of Pisa, with Angelo Battelli [Macerata Feltria, Pesaro e Urbino, Italy, 28 March 1862 – Pisa, Italy, 11 December 1916], Physicist, founder of the Italian society of Physics, and pioneer of radioactivity studies; Antonio Pacinotti [Pisa, Italy, 17 June 1841 – Pisa, Italy 25 March 1912], Physicist, who substantially improved the earliest design of the direct-current electrical generator, or dynamo; Ulisse Dini [Pisa, Italy, 14 November 1845 – Pisa, Italy, 28 October 1918], Mathematician.

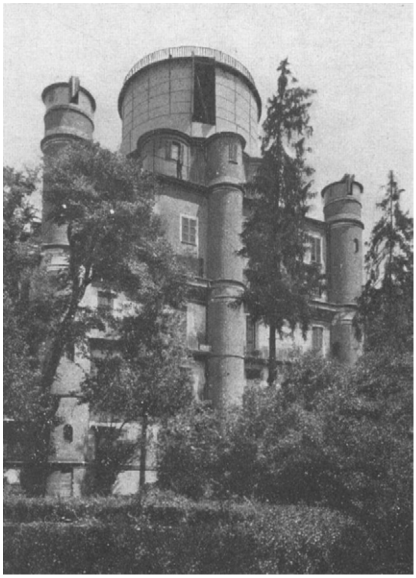


Fig. 3 –The astronomical observatory, or 'specola' of Brera, in Milan.

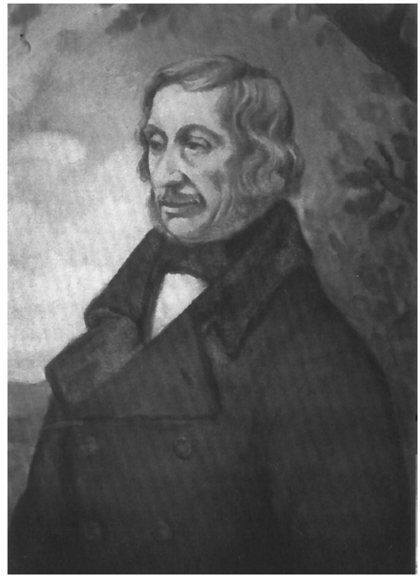
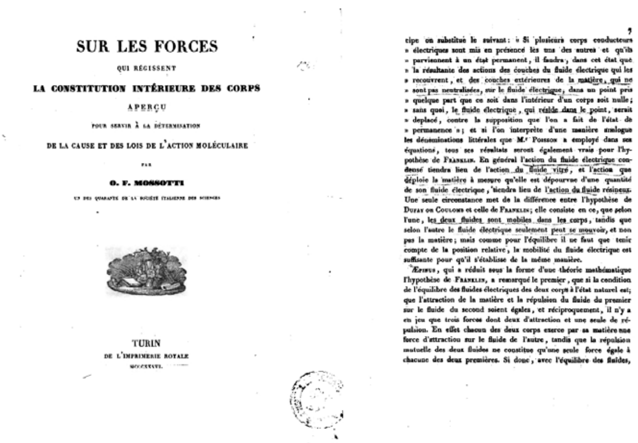


Fig. 4 – Ottaviano Fabrizio Mossotti, in an undated portrait, when old, from Nagari, 1989.

Achievements and connections to Maxwell

Early in the XIX century the concept of a dielectric was still a matter of open research. It was apparent that even if unable to conduct current, dielectrics had electric properties, since, for example, the strength of the attraction between two charges changes if a dielectric is placed in between.

Concerning the nature of electricity, two rival theories were being debated at the time. There was a one-fluid theory, which had Benjamin Franklin [Boston, Massachusetts, 6 January 1705 - Philadelphia, Pennsylvania, 17 April 1790] among its first and most notable supporters. Franklin viewed electric phenomena as caused by a single «electric» fluid, or an aether. The amount of fluid at equilibrium would make a body uncharged. If fluid was added or removed, for example by rubbing, the body would become positively or negatively charged (respectively) from the concentration or rarefaction of the fluid. The motion of the same fluid was the electric current. This was opposed by the two-fluid theory, named «vitreous» and «resinous» developed earlier by Charles François de Cisternay du Fay [Paris, 14 September 1698 - Paris, 16 July 1739]. He explained his observations on electrification by means of «vitreous» and «resinous» kinds of electricity. The first theory was adopted in England, Germany and Italy, while the second was accepted mainly in France (Whittaker 1910). Current was not covered by this theory.



SUR LES FORCES
QUI RÉGISSENT
LA CONSTITUTION INTÉRIEURE DES CORPS
APERÇU
POUR SERVIR À LA DÉTERMINATION
DE LA CAUSE ET DES LOIS DE L'ACTION MOLÉCULAIRE
PAR
O. F. MOSSOTTI
UN DES QUARANTE DE LA SOCIÉTÉ ITALIENNE DES SCIENCES

TURIN
DE L'IMPRIMERIE ROYALE

7

cipe on substitue le suivant: « Si plusieurs corps conducteurs » électriques sont mis en présence les uns des autres et qu'ils » parviennent à un état permanent, il faudra, dans cet état que » la résultante des actions des couches du fluide électrique qui les » recouvrent, et des couches extérieures de la matière, qui ne » sont pas neutralisées, sur le fluide électrique, dans un point pris » quelque part que ce soit dans l'intérieur d'un corps soit nulle; » sans quoi, le fluide électrique, qui réside dans le point, serait » deplacé, contre la supposition que l'on a fait de l'état de » permanence »; et si l'on interprète d'une manière analogue les dénominations littérales que M.r Poisson a employé dans ses équations, tous ses résultats seront également vrais pour l'hypothèse de Franklin. En général l'action du fluide électrique condensé tiendra lieu de l'action du fluide vitré, et l'action que déploie la matière à mesure qu'elle est dépourvue d'une quantité de son fluide électrique, tiendra lieu de l'action du fluide résineux. Une seule circonstance met de la différence entre l'hypothèse de Dufay ou Coulomb et celle de Franklin; elle consiste en ce, que selon l'une, les deux fluides sont mobiles dans les corps, tandis que selon l'autre le fluide électrique seulement peut se mouvoir, et non pas la matière; mais comme pour l'équilibre il ne faut que tenir compte de la position relative, la mobilité du fluide électrique est suffisante pour qu'il s'établisse de la même manière.

Æpinus, qui a réduit sous la forme d'une théorie mathématique l'hypothèse de Franklin, a remarqué le premier, que si la condition de l'équilibre des fluides électriques des deux corps à l'état naturel est; que l'attraction de la matière et la répulsion du fluide du premier sur le fluide du second soient égales, et réciproquement, il n'y a en jeu que trois forces dont deux d'attraction et une seule de répulsion. En effet chacun des deux corps exerce par sa matière une force d'attraction sur le fluide de l'autre, tandis que la répulsion mutuelle des deux fluides ne constitue qu'une seule force égale à chacune des deux premières. Si donc, avec l'équilibre des fluides,

Fig. 5 – Cover of Mossotti's 1936 paper (left) and page 7 (right) where the single fluid displacement theory of dielectrics is discussed.

Hence, Mossotti's 1836 paper (Mossotti 1836) (Fig. 5) was written in the context of the one-fluid theory, and was opposed to a similar work by Poisson on magnetism (Poisson 1824a 1824b). Mossotti recognised how the results by Poisson with the two «vitreous» and «resinous» fluids could be explained by a single «electric» fluid by considering the action of the «vitreous fluid» to be equivalent to a condensation of the «electric» fluid, and the action of the «resinous» fluid to the rarefaction of the «electric» fluid (Mossotti 1836). In this context, it is very important to note, for the following development by Faraday and Maxwell, that Mossotti focused on the *movement* of such a fluid, not on the mere action due to the presence of a fluid.

Hence, in Mossotti's work, equilibrium was reached with the electric forces of the matter (unmovable) and the «electric» fluid (movable). Mossotti then mathematically developed this concept. He considered the molecules of the matter as unmovable, isolated, spherical objects, within an homogeneous «electric» fluid, or aether. Among the molecules there was a repulsion force, which at equilibrium was nullified by the attractive force between the molecules and the aether. In this way Mossotti explained why solids cannot be compressed (the repulsion force between molecules became stronger if molecules got closer) or expanded (the attractive force of the aether opposed the molecular separation).

This paper by Mossotti was appreciated by Michael Faraday [Southwark, UK, 22 September 1791 – Hampton Court, UK, 25 August 1867]. Faraday supposed that an impressed electric field exerts a change in the distribution of molecules and «electric» fluid (Faraday 1839, Whittaker 1910). However, the model by Mossotti was much more detailed than Faraday's 0(Markow 1999). These concepts were very clearly stated later by Mossoti, who gave an analytic solution to the problem, explicitly speaking of «polarization of the molecules» (Mossotti 1850).

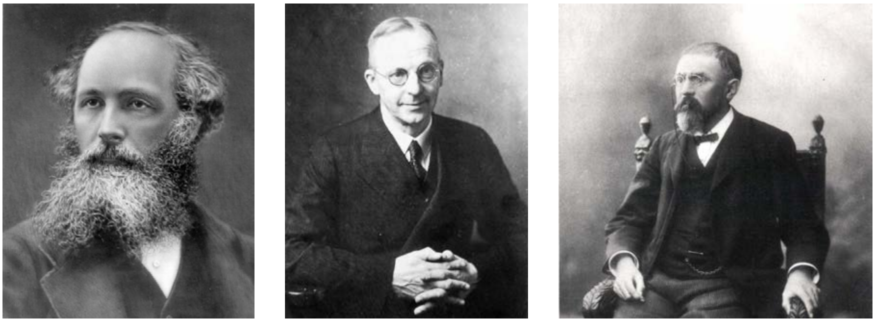


Fig. 6 – From left to right: J.C. Maxwell, E.T. Whittaker and J.H. Poincaré.

Mossotti's contribution was also recognized by James Clerk Maxwell (Agastra 2014, Maxwell 1865 1891) (Fig. 6 and Fig. 7), as well as by early writers of electromagnetic history, for example Edmund Taylor Whittaker [Southport, UK, 24 October 1873 - Edinburgh, UK, 24 March 1956] (Fig. 6), British mathematician and physics historian, who wrote:

> The principle which is peculiar to Maxwell's theory must now be introduced. Currents of conduction are not the only kind of currents; even in the older theory of Faraday, Thomson, and Mossotti, it had been assumed that electric charges are set in motion in the particles of a dielectric when the dielectric is subjected to an electric field; and the predecessors of Maxwell would not have refused to admit that the motion of these charges is in some sense a current. (Whittaker 1910) (Fig. 8)

while Poincaré [Nancy, France, 29 April 1854 – Paris, France, 17 July 1912] (Fig. 6), French mathematician and physicist wrote:

> It is probable that it is the concept of Poisson and Mossotti on the nature of dielectrics which led Maxwell to his theory. He says to have developed it since Faraday's works, and to have done nothing else than to convert to mathematical formulas the words of the renown Physicist, but Faraday did adopt Mossotti's Ideas (see Experimental Researches, Faraday, Ser. XIV, §1679. (Poincaré 1901) (Fig. 9).

Mossotti subsequent, more detailed, 1946 manuscript published in 1850 (Mossotti 1850)(Fig. 10) better presented his ideas on polarization. These ideas were later mathematically formalized by Rudolph Clausius [Koszalin, Poland, 2 January 1822 – Bonn, Germany, 24 August 1888](Clausius 1879). Indeed, as already said, the original papers by Mossotti were based on an ether concept typical of his epoch and are hence difficult to follow for the modern reader. Clausius' later approach revised Mossotti's work in a way much easier to follow for the modern reader (Markow 1999, Landauer 1977). The Clausius-Mossotti formula is:

$$\frac{\varepsilon - \varepsilon_0}{\varepsilon + 2\varepsilon_0} = \frac{4\pi N_A \alpha}{3} \frac{\rho_m}{M} \tag{1}$$

introduced when any difficulty occurs. Thus, Mossotti has deduced the mathematical theory of dielectrics from the ordinary theory of attraction merely by giving an electric instead of a magnetic interpretation to the symbols in the investigation by which Poisson has deduced the theory of magnetic induction from the theory of magnetic fluids. He assumes the existence within the dielectric of small conducting elements, capable of having their opposite surfaces oppositely electrified by induction, but not capable of losing or gaining electricity on the whole, owing to their being insulated from each other by a non-conducting medium. This theory of dielectrics is consistent with the laws of electricity, and may be actually true. If it is true, the specific inductive capacity of a dielectric may be greater, but cannot be less, than that of a vacuum. No instance has yet been found of a dielectric having an inductive capacity less than that of a vacuum, but if such should be discovered, Mossotti's physical theory must be abandoned, although his formulae would all remain exact, and would only require us to alter the sign of a coefficient.

Fig. 7 – Part of page 70 in (Maxwell 1891) where Maxwell not only acknowledge the importance of Mossotti analytic development, but states that, in Mossotti theory, no material can have a permittivity smaller than that of empty space.

286 *Maxwell.*

from which equation it is evident that ψ represents the electrostatic potential.

The principle which is peculiar to Maxwell's theory must now be introduced. Currents of conduction are not the only kind of currents; even in the older theory of Faraday, Thomson, and Mossotti, it had been assumed that electric charges are set in motion in the particles of a dielectric when the dielectric is subjected to an electric field; and the predecessors of Maxwell would not have refused to admit that the motion of these charges is in some sense a current. Suppose, then, that **S** denotes the total current which is capable of generating a magnetic field: since the integral of the magnetic force round any curve is proportional to the electric current which flows through the gap enclosed by the curve, we have in suitable units

Fig. 8 – Top of page 286 in (Whittaker 1910) where Whittaker acknowledges Faraday, Thomson, and Mossotti among the predecessors of Maxwell who studied dielectric polarization.

> Il est probable que c'est la conception de Poisson et Mossotti sur la nature des diélectriques qui a conduit Maxwell à sa théorie. Il dit l'avoir déduite des travaux de Faraday et n'avoir fait que traduire sous une forme mathématique les vues de ce célèbre physicien ; or, Faraday avait adopté les idées de Mossotti (Cf. Experimental Researches, Faraday, série XIV, § 1679). Ajoutons que, ainsi que nous le verrons bientôt, l'intensité des courants de déplacement n'a pas la même valeur dans la théorie de Poisson et dans celle de Maxwell. Nous montrerons cependant comment on peut faire concorder les deux théories.

Fig. 9 – Page 36, proposition 44 in (Poincaré 1901) where Poincaré affirms that Maxwell's displacement currents idea originated from Poisson and Mossotti ideas on dielectric polarization.

With ε and ε_0 the permittivity of the dielectric and of free space, respectively, N_A is Avogadro's number, α is the polarizability of the dielectric, that is, the ratio of the induced dipole moment of an atom or molecule to the electric field that produces this dipole moment, ρ_m the dielectric density and M its molecular mass.

The left-hand term in (1) is known as the Clausius-Mossotti factor, which, when extended to the more general case of a generic dielectric sphere p embedded in an homogeneous medium m is:

$$K(\omega) = \frac{\bar{\varepsilon}_p - \bar{\varepsilon}_m}{\bar{\varepsilon}_p + 2\bar{\varepsilon}_m} \qquad (2)$$

being $\bar{\varepsilon} = \varepsilon - j\sigma / \omega$.

Indeed this is, the first appearance of the concept of effective, homogeneous medium in the theory of heterogeneous solids. As pointed out many authors (Markow 1999, Brown 1956), Mossotti's paper (1850) does not explicitly contain the formula for the effective dielectric constant, while Clausius' book does (Fig. 12). That is why Hendrik Antoon Lorentz [Arhnem, NL, 18 July 1853 – Haarlem, NL, 4 February 1928] (Fig. 11) attributed the formula to Clausius and Mossotti (Lorentz 1909), even if Clausius did not cite Mossotti in his book (Clausius 1879).

Mossotti's deep understanding of dielectrics led him to a second achievement still bearing his name, the Clairaut-Mossotti doublet. This was an aplanatic cemented doublet lens, able to correct for axial chromatism, spherical aberration and coma (Lemaitre 2008). Alexis Claude Clairaut [Paris, France, 13 May 1713 – Paris, France, 17 May 1765], astronomer, had developed a theory of doublet lenses, that is, lenses composed of two cemented, lenses of different materials and appropriate shapes to control spherical and chromatic aberration in the period 1756-1762. Mossotti solved the fifth order equation by Clairaut, finding three real roots of which one was of practical interest (Mossotti 1855, 1858) (Fig. 13).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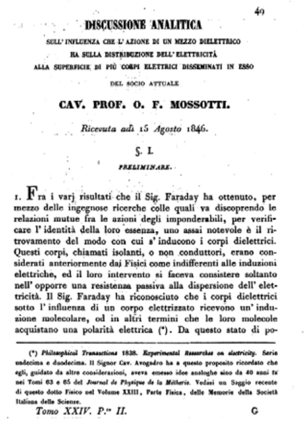
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DISCUSSIONE ANALITICA
SULL' INFLUENZA CHE L' AZIONE DI UN MEZZO DIELETTRICO
HA SULLA DISTRIBUZIONE DELL' ELETTRICITÀ
ALLA SUPERFICIE DI PIÙ CORPI ELETTRICI DISSEMINATI IN ESSO
DEL SOCIO ATTUALE
CAV. PROF. O. F. MOSSOTTI.
Ricevuta adì 15 Agosto 1846.

§. I.
PRELIMINARE.

1. Fra i varj risultati che il Sig. Faraday ha ottenuto, per mezzo delle ingegnose ricerche colle quali va discoprendo le relazioni mutue fra le azioni degli imponderabili, per verificare l' identità della loro essenza, uno assai notevole è il ritrovamento del modo con cui s' inducono i corpi dielettrici. Questi corpi, chiamati isolanti, o non conduttori, erano considerati anteriormente daj Fisici come indifferenti alle induzioni elettriche, ed il loro intervento si faceva consistere soltanto nell' opporre una resistenza passiva alla dispersione dell' elettricità. Il Sig. Faraday ha riconosciuto che i corpi dielettrici sotto l' influenza di un corpo elettrizzato ricevono un' induzione molecolare, od in altri termini che le loro molecole acquistano una polarità elettrica (*). Da questo stato di po-

(*) *Philosophical Transactions* 1838. *Experimental Researches on electricity.* Serie undecima e duodecima. Il Signor Cav. Avogadro ha a questo proposito ricordato che egli, guidato da altre considerazioni, aveva emesso idee analoghe sino da 40 anni fa nei Tomi 63 e 65 del *Journal de Physique de la Métherie*. Vedasi un Saggio recente di questo dotto Fisico nel Volume XXIII, Parte Fisica, delle Memorie della Società Italiana delle Scienze.

Tomo XXIV. P.te II. G

Fig. 10 – Cover (left) and first page (right) of Mossotti's paper (1846 but published 1850).

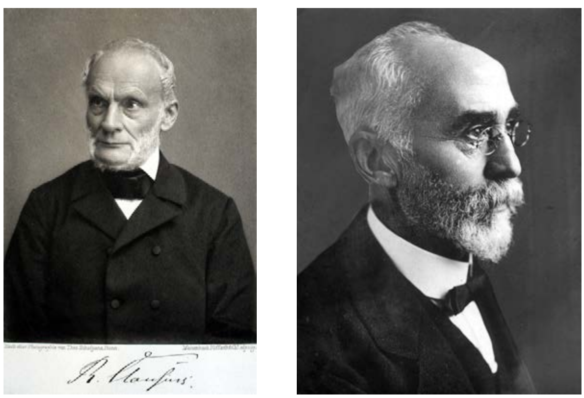
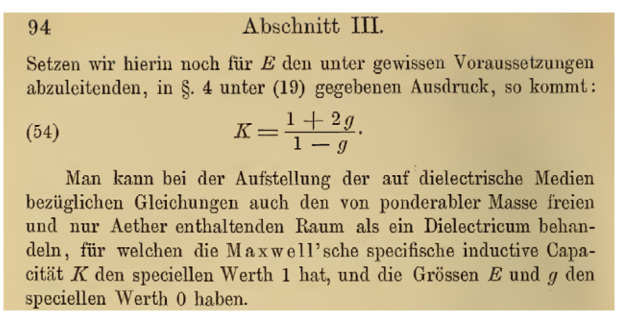


Fig. 11 – Rudolph Clausius (left) and Hendrik Antoon Lorentz (right).


94 Abschnitt III.

Setzen wir hierin noch für E den unter gewissen Voraussetzungen abzuleitenden, in §. 4 unter (19) gegebenen Ausdruck, so kommt:

$$K = \frac{1 + 2g}{1 - g}. \qquad (54)$$

Man kann bei der Aufstellung der auf dielectrische Medien bezüglichen Gleichungen auch den von ponderabler Masse freien und nur Aether enthaltenden Raum als ein Dielectricum behandeln, für welchen die Maxwell'sche specifische inductive Capacität K den speciellen Werth 1 hat, und die Grössen E und g den speciellen Werth 0 haben.

Fig. 12 – Clausius-Mossotti formula in Clausiu's book (written as the inverse as we use today) (Clausius 1879).

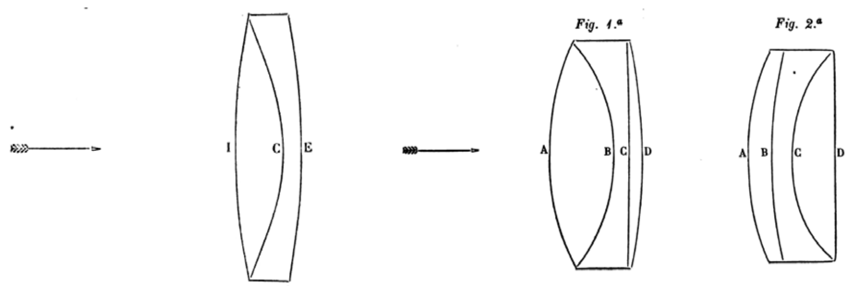


Fig. 13 – Mossotti drawings for a doublet (left) and two triplet (right) acromatic, aspherical lenses, from Mossotti 1858

Mossotti was not highly committed to publishing his results. As Enrico Betti [Pistoia, Italy, 21 October 1823 – Soiana, Pisa, Italy,11 August 1892], great mathematician and student of Mossotti, states in his obituary of Mossotti (Betti 1863), Mossotti left many ideas on scratch paper, unfinished publications and even complete papers never submitted to a journal. He even thought of using the inverse function of elliptical integrals of the first kind, years before Niels Henrik [Finnøy, Norway, 5 August 1802 – Froland, Norway, 6 April 1829] and Carl Gustav Jacob Jacobi [Potsdam, Germany, 10 December 1804 – Berlin, Germany, 8 February 1851] but left all on scratch (Betti 1863). A Complete collection of Mossotti's papers can be found in (Gabba 1942-1955).

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An unexpected Mossotti: his formula at the basis of dielectrophoresis in modern molecular biology[1]

Federico Carpi[2]*, Stefano Maddio*[3]*, Benedetta Pelosi*[4]

Biomolecular separative techniques, also called "chromatography", have always been widely applied in the field of clinical analyses, of which they have always been one of the foundations, in order to isolate specific constituents within a heterogeneous sample. As the observation scale moves towards single cells, it is widely recognized how these techniques are increasingly important. A classic method of separating biological components is to exploit their different density.

Another approach to develop separative techniques is based on the use of electric and magnetic fields. The evolution of these techniques has gone hand in hand with the evolution of knowledge of electrical and magnetic phenomena.

Electrophoresis was the first of these techniques. It is based on the application of a uniform electrostatic field to a sample to be analysed. Biomolecules having a net charge, for example due to ionizable groups, migrate within the sample. Based on the charge and mobility – that is, the coefficient that links the speed of a particle to the field to which it is subjected – the electrophoretic technique allows for separating the charged biomolecules. To improve performance, a gelatinous substance (agarose gel) is usually used as a sieve.

This approach is typically used to analyse and separate DNA nucleic acids, hence the great importance of the technique.

The electrophoresis phenomenon was first described by Ferdinand Friedrich Reuss in 1807, who observed the migration of clay particles immersed in water in the presence of an external electric field. The first device to implement modern electrophoresis was however made in 1937 by the Swedish biochemist Arne Wilhelm Kaurin Tiselius (Stockholm, Sweden, 1902 - Uppsala, Sweden, 1971) (Kyle 2005). Thanks to his research on electrophoresis, Tiselius won the Nobel Prize in Chemistry in 1948 with the following motivation: "for his research on electrophoresis and adsorption analysis, especially for his discoveries concerning the complex nature of the serum proteins."

Although electrophoresis, which is a technique that has been known for two centuries and in use for more than a century (Righetti 2009), is routinely employed in biomedical labs (Fig. 1), it has a significant limitation: it cannot be applied to neutral particles, which are instead of increasing interest in modern molecular biology.

This is where Mossotti's formula comes into play. His formula, or, rather, the Clausius-Mossotti formula, was developed in 1846 but published 1850. If the particle of interest is neutral, but it is at least polarizable, there is still a possibil-

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Fig. 1 – A commercial apparatus for electrophoresis (it.vwr.com/store).

ity to exert on it a force similar to the electrophoretic one, ultimately allowing for separations of molecules, as in the case of electrophoresis.

To that aim, let us consider a polarizable particle, describable as a uniform sphere of radius and dielectric permittivity ε_p, immersed in a uniform medium of permittivity ε_m. If subjected to an electric field $\boldsymbol{e}$, the particle is polarized. The dipole moment p envisaged by the Clausius-Mossotti formula is as follow:

$$\boldsymbol{p} = 4\pi\varepsilon_m r^3 K\boldsymbol{e} = 4\pi\varepsilon_m r^3 \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m}\boldsymbol{e}$$

where the term

$$K = \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m}$$

is known as the Clausus-Mossotti factor.

It is therefore sufficient that the electric field $\boldsymbol{e}$ is non-uniform, so that the dipole moment induced on the particle can undergo a non-null force: in fact, an elementary dipole moment is sensitive to the gradient of the square of the electric field $\nabla|\boldsymbol{e}|^2$. The force generated between the dipole moment and the non-uniform applied field is exerted on the polarized bioparticle of interest. This mechanism is the foundation of «dielectrophoresis», a phenomenon by which a neutral but polarizable particle is subject to a force when immersed in a non-uniform electric field.

The intensity of the dielectrophoretic force exerted on the biomolecule is therefore dependent on its dielectric properties and on those of the medium. This force also depends on the molecule's size and the configuration of the electric field, in particular its gradient.

The history of dielectrophoresis begins, strictly speaking, as early as in the 1920s: Hatschek and Thorne described something similar to the dielectrophoretic mechanism already in 1923 (Hatschek 1923), and a patent filed in the United States in 1924 can actually be considered an electrophoretic technique (Hatfield 1924).

However, it was Herbert Pohl, a professor at Princeton University and a pioneer of the dielectrophoretic technique in the 1960s, who gave to dielectrophoresis its current form. In 1966, Pohl and Hawk published the first demonstration of electrophoresis on yeast cells: that was the first case where dielectrophoresis was applied to living structures. The used apparatus was very simple: a signal generator was connected to a pair of electrodes in the 'point and plane' configuration, that is, one of the two electrodes was needle-like whilst the other one was a classical planar plate. With their rudimentary apparatus, Pohl and Hawk showed that live cells were attracted by the electrodes, whilst dead, non-polarizable cells remained in solution. Pohl called this technique «the natural motion of neutral matter caused by polarization effects in a non-uniform electric field» (Pohl 1951).

However, the new technique was not immediately accepted, and indeed, many of Pohl's later works were refused for publication. Only in 1978, with the publication of his paper *Dielectrophoresis: the Behaviour of Neutral Matter in Nonuniform Electric Fields* (Pohl 1978), the popularity of the technique began to grow, although still remaining a niche topic.

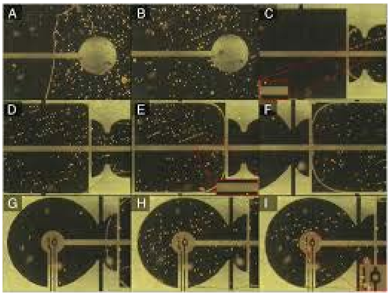

Fig. 2 – Example of an experimental dielectrophoretic device (Price 1987).

Fortunately, a new generation of researchers appeared in the limelight later on, including Ronald Pethig, who was among the protagonists of a further refinement of the technique (Price 1987). Pethig would later become one of the world's greatest experts on the subject (Pethig 2017).

It is interesting to note that, in the current form developed by the generation following Pethig, many tricks have been introduced, such as the use of specific gels like agar-agar. Furthermore, various configurations/shapes of the electrodes (Fig. 2) have been described (Tsai 2011).

One of the interesting features of the Clausius-Mossotti factor is the fact that it can change according to the actual combination of the particle's and medium's permittivities.

In recent times, the use of a wide range of frequencies has emerged more and more. In fact, depending on the frequency, the Clausius-Mossotti factor can significantly vary, and in particular it the magnitude and sign of the dielectrophoretic force depends on the difference between the polarizability of the particle and of the medium, as it is apparent considering the term $\varepsilon_p - \varepsilon_m$ (Green 1997).

Therefore, using fields characterized by specific frequencies, it is possible to manipulate particles of interest with high selectivity, obtaining very specific effects: cellular filtering with high specificity and without marking, entrapment and identification of the electrical characteristics of unknown particles. Such results are difficult to obtain with traditional non-electrical chromatographic techniques and are also even more interesting than the results of classical electrophoresis.

These properties are typically used to identify cancer cells camouflaged between healthy cells, allowing for rapid and minimally invasive diagnoses.

It is worth mentioning that there exists an effect similar to dieletrophoresis for magnetizable molecules, such as some blood constituents. The effect is known as «diamagnetophoresis», as the driving source is a magnetic field. The development of this recent approach allows for operating directly on red blood cells, which are sensitive to the magnetic fields thanks the susceptibility of haemoglobin (Maciej 2003).

Finally, it is also worth noting that the two techniques can be used in combination: in this case, of the technique is referred to as «dielectro-magnetophoresis». This strategy promises to be a harbinger of even more interesting developments in the field of molecular biology.

This is really an unexpected consequence of the work pioneered by Ottaviano Fabrizio Mossotti.

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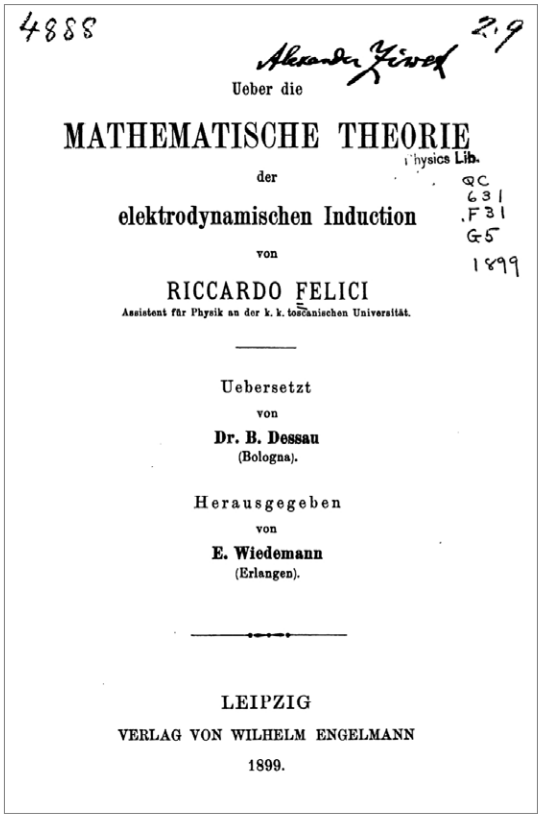
On Riccardo Felici



Ueber die

MATHEMATISCHE THEORIE

der

elektrodynamischen Induction

von

RICCARDO FELICI

Assistent für Physik an der k. k. toscanischen Universität.

Uebersetzt

von

Dr. B. Dessau

(Bologna).

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von

E. Wiedemann

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LEIPZIG

VERLAG VON WILHELM ENGELMANN

1899.

Fig. 1 – First page of a book by R. Felici (Ref. [F.62] in the list contained in this section) published in Germany, being the German translation of a previous work – in two parts – by Felici published in Italian in 1854 ([F.13] and [F.14]).

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Riccardo Felici was born in Parma (or in Pisa?)[1] in 1819. He studied in Pisa, where he was awarded his degree in 1843 and where he later became assistant to Carlo Matteucci (1811-1868). Felici was a pioneer in Electrochemistry and Electrophysiology, a friend of J.C. Maxwell and editor of *Il Cimento* [The Endeavour], a Journal of Physics, Chemistry and Natural History (1844). Later, he founded *Il Nuovo Cimento* [The New Endeavour] (1855) which is still a major Physics Journal in Italy.

Riccardo Felici directed the *Gabinetto di Fisica* [Physics cabinet] of the University of Pisa from 1859 up to 1893. The first contribution in this part outlines his life and scientific contributions.

It should be noted that Riccardo Felici had among his students and assistants Antonio Ròiti (1843-1921), who was later made a professor at the Istituto Tecnico Toscano in Florence and at several other institutions in his life. In Palermo, Ròiti, met the young Vincenzo Rosa (1848-1908), whom he appreciated, so he brought Rosa to Florence as his assistant. Later, Rosa was then a teacher to Guglielmo Marconi (1874-1937), whom he influenced deeply, in Livorno. Indeed, Vincenzo Rosa was remembered by Marconi in his Nobel Prize Lecture (1909). This progression traces an uninterrupted line from Matteucci, Mossotti e Felici, through Maxwell, to Marconi and radiotelegraphy (Grandin 2012, Selleri 2019).

This part also reproduces a list of Felici's scientific papers compiled by Antonio Ròiti himself, for Felici's obituary.

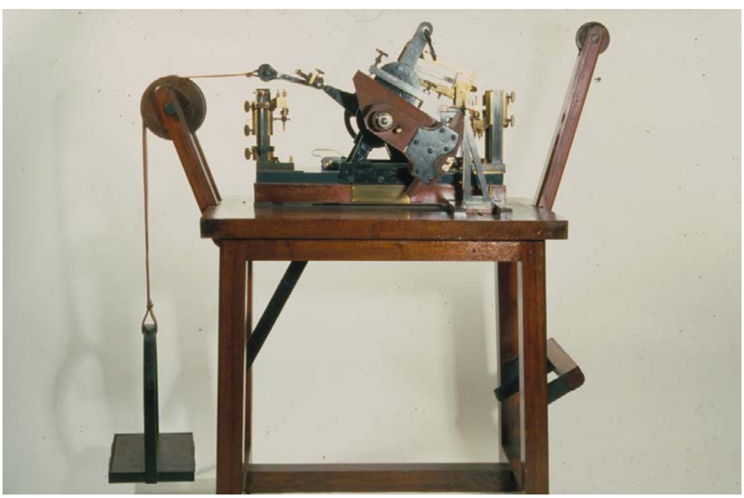

Fig. 2 – Bartoli-Felici switch, built in Florence, Italy by the Officine Turchini in 1894. The switch, from a design devised in 1874 ([F.50] in Felici's list of publications in the following) was aimed at fast opening/closing of circuits for induction experiments (University History Museum, University of Pavia).

1 Commonly the birthplace of Felici is reported to be Parma, but he possessed a baptism certificate (with some errors) issued in Pisa. See the following contribution by Paolo Rossi for details.

Fig. 3 – From left to right: the only known photograph of Antonio Ròiti; Vincenzo Rosa; and a young Guglielmo Marconi.

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The figure and the work of Riccardo Felici

Paolo Rossi[1]

1. Felici's biography

According to some sources and to the literature, Riccardo Felici (Fig. 1) was born in Parma on 11 June 1819, but the circumstances of his birth are somewhat uncertain, since there is no trace of his birth in original Parma Municipal documents, while there is an act of baptism (Archivio Riccardo Felici) requested by Felici himself, and attesting the birth in Pisa, on that same date, of Rinaldo Felice (*sic*), son of unknown parents. Some circumstances lead us to believe that Felici was the illegitimate son of the Pisan noblewoman Isabella Roncioni, whose stormy biography would make the hypothesis plausible. Certainly, there is a 'fraternal', albeit cautious, correspondence with Enrichetta Bartolommei, Isabella's daughter, and the choice of Isabella's name for Felici's only daughter does not seem casual either (Ferrero 2014).

Certainly, however, he spent his apparently uneasy childhood and adolescence in Parma, and he enrolled first, on November 30, 1838, at the local University – where he followed, among others, the teachings of Elementary Mathematics, Sublime Mathematics and Elements of Astronomy, Mechanics applied to Architecture, Statics and Hydrodynamics, Theoretical and Practical Physics, Experimental Physics – until when Professor Michele Leoni (1776-1858), who had been a lover of Roncioni in the past, prompted him to move, the following year, to the degree course in Mathematical Sciences at the Faculty of Sciences of the University of Pisa, as a pupil of Filippo Corridi, Vincenzo Amici, Luigi Pacinotti, Ottaviano Fabrizio Mossotti and Carlo Matteucci.

In his articulated study plan both Physics and Mathematics teachings appeared, together with various other technical and scientific subjects, up to his degree awarded on 12 July 1843, achieved in just three years instead of the usual four for the ordinary courses of studies.

In 1846, having already published some scientific works, Felici was appointed as assistant to the Chair of Experimental Physics held by Matteucci, as well as examiner and preparer for the exams.

From 1848 to 1849, he took part in the First War of Independence, together with his masters Matteucci and Mossotti, enrolling with the rank of lieutenant and fighting valiantly in Curtatone (Puccianti 1919).

On his return to Pisa, due to his political ideas, he was opposed by the Church in resuming his post as assistant at the university. It was only through the intercession of Professor Silvestro Centofanti, with whom he shared many political ideas and maintained friendly relations, that Felici soon succeeded in restoring his initial academic role.

[1] University of Pisa.

Fig. 1 – Riccardo Felici [1819-1902], from the photographic archive of the University of Pisa; the handwriting on the photo reads: «Riccardo Felici full professor of Physics at King's University of Pisa, July 10, 1887».

In 1852, he held both courses and seminars at the Scuola Normale Superiore in Pisa, and in 1853 he was appointed repeater. In 1854 he became adjunct professor and married Elisa Frullini, from Pisa. Their only daughter, Isabella, was born in 1856 and married Carlo Paladini.

In 1859, due to the increasing political commitments of Matteucci, Felici became a full Professor and took over the Chair of Experimental Physics – also holding the annexed Cabinet.

It is worth noticing that his salary went down twice, in 1862 and 1865, and it kept increasing every five years only starting from 1873. In 1868 he was appointed as an extraordinary member of the Higher Council of Public Education. In 1873 the Ministry proposed him to be appointed as a professor at the Higher Institute of Florence, but he finally rejected the offer.

In 1870/71 and in 1882/83, Felici was also Rector of the University of Pisa, taking on various other organizational and managerial positions – including the presidency of the Faculty of Sciences and the position of councillor of the Scuola Normale Superiore – that brought him to abandon active physical research. At the end of 1893 he left university teaching, and a few months later, in 1894, he was appointed professor emeritus of the University of Pisa (Archivio storico dell'Università di Pisa).

He had friendly relationships and collaborated with several Italian scientists of the time, as well as with scientists from other European countries. In 1897, together with several other university professors (including Battelli, Ròiti, Blaserna, Righi and Beltrami) he proposed the establishment of the Italian Physical Society and was the director of his main journal *Il Cimento* (founded in 1844, and then, renamed *Il Nuovo Cimento* in 1855).

Fig. 2 – The Monumental Cemetery of Pisa, begun 1278, completed 1464, placed in the Piazza dei Miracoli, close to the cathedral and the leaning tower. Felici, Mossotti and many other Italian preeminent people are buried there.

Many were also the acknowledgments for his career: he was a member of various other Italian and foreign scientific societies and academies, including the Società Italiana delle Scienze of Modena (1861), the Physical Society of London (1868), the Accademia delle Scienze of Bologna (1873), the Physicalisch-Medicinische Gesellschaft of Wurzburg (1874), the Accademia dei Lincei (1875), the Istituto Veneto (1875), the Accademia delle Scienze of Turin (1881), the Istituto Lombardo di Scienze e Lettere (1882), the Accademia di Scienze, Lettere e Arti of Lucca (1883), as well as various honours by chivalry orders (cavaliere dell'Ordine Civile di Savoia, cavaliere dell'Ordine dei Ss, Maurizio e Lazzaro, cavaliere, ufficiale, commendatore e Grand'Ufficiale dell'Ordine della Corona d'Italia). He also received official invitations by Italian and foreign associations among which, in 1899, the Royal Institution of Great Britain. (Archivio Riccardo Felici, Archivio storico dell'Università di Pisa).

He died in the locality of Sant'Alessio di Lucca, on July 20, 1902. His body was then buried at the monumental Camposanto of Pisa (Fig. 2).

Felici was one of the best Italian researchers and professors of experimental physics in the second half of the nineteenth century, educated at the first Italian school of physics in the nineteenth century, in Pisa, which had as its main masters Mossotti, Luigi Pacinotti and Matteucci, who was the first to give an experimental character to the school, also by his pioneering research work. There is often a certain continuity of methods and views within a school of thought, even more so in the scientific field, but this cannot be said of Felici with respect to his teacher Matteucci.

In fact the peculiarities of Matteucci's character were undoubtedly the origin of these many and rapid initiatives taken both in the political, organizational and institutional context as well as in the practice of research, where his trend was often towards the immediate experimental discovery, while he showed much less interest in theoretical and mathematical formalizations.

Quite different was Felici's temper, described by Pochettino 1930 as

> of a calm, modest, constant character; methodical spirit, crystalline, ingeniously sharp and disciplined, cautious, balanced, sometimes even skeptical, and balancing the experimental and the mathematical element in his research. A man of reasoning, Felici did not tie his name to a phenomenon he discovered; but his fundamental researches on the induction currents were conducted with such perfection of method that they deserved the honor of being included in the Klassiker der exakten Wissenschaften collection (Felici 1899) published by Ostwald.

Early references to Felici's human and scientific biography can be found in Roiti 1902, Battelli 1902 and Occhialini 1914. More recent contributions are Reeves Buck 1980, Maiocchi 1996, Vergara Caffarelli 2018 and Rossi 2018.

2. The scientific work of Riccardo Felici

His first physics work date back to the years immediately following his graduation, with a first memoir, dated 1844. In this publication he expressed his critical considerations, basically on theoretical grounds, regarding research conducted by the French physician, biologist and physiologist Henri Dutrochet on certain hydrodynamic phenomena that the latter explained by introducing ad hoc a new force, while Felici brought them back to the action of capillary forces.

Appointed as Matteucci's assistant in 1846, Felici was immediately able to make use of direct experimentation, supported by the precious work of the laboratory technician Mariano Pierucci. The latter provided invaluable support for Felici's theoretical considerations, which he published, in 1846, along with a more experimental work in 1846 on certain phenomena of the thermoelectricity of mercury, which shows that electrolytic conductivity could be established not only in the presence of a thermal gradient but in any case in conjunction with phenomena of ionization of the conductive substance.

The following year, continuing with studies and research on electrochemical phenomena, he published a third work on electrical circuits formed by galvanic elements. In 1850, he published a work on the propagation of electric current inside a spherical conductor. Then, in 1851, in continuation of what had already been done in previous research, he published another paper on electrochemistry in which he also studied the effect of thermal phenomena on electrical conduction in liquids. In this work, for the first time, Felici was able to determine the mode of variation with the temperature of the polarization emf. These were purely experimental works, with the addition of non-formal theoretical considerations.

In the same year 1851, a first paper was also published focusing on the explanation of electrodynamic induction phenomena, later translated into French and republished the following year in the famous *Annales de chimie et de physique*, and also known to Maxwell. This last publication marked the beginning of the main sequence of works on electrodynamic induction, which would end in the early 1860s, consecrating Felici among the great masters of the discipline.

In the early 1850s, therefore, Felici undertook a study of electromagnetic phenomena according to an experimental approach similar to that used in the 1820s by André-Marie Ampère in studying the phenomena of attraction and repulsion between linear elements of electrical circuits. Felici began with a series of experiments in which he systematically investigated the possible variations in the intensity of inducing and induced currents with the variation of nature, greatness, relative position and shape of inducing and induced electric circuits. Thus, he reached a new theory of electromagnetic induction that contributed much to completing the theoretical framework in which to place the phenomena of electromagnetic induction, to which, above all, M. Faraday, F.E. Neumann, W.E. Weber and H.F. Lenz also contributed, in addition to numerous others.

But what most distinguishes Felici's work from the clearly notable contributions of the other authors, is the working method with which he reached the formulation of its theory. Indeed, the theories of Neumann, Lenz and Weber were based on particular *ad hoc* hypotheses, having a more *a priori* nature and justification than a reasonable physical motivation.

Instead, on the preliminary basis of simple and elementary but crucial physical experiments, Felici, similarly to the method followed by Ampère in the 1820s, arrived at the formal construction of a general theory of electromagnetic induction, avoiding recourse to prior artificial hypotheses, which had not been not experimentally proven. His main experimental results are the following (Agastra 2012):

1. The induced electromotive force is proportional to the inducing current intensity;
2. The induction caused by *n* currents of intensity *i/n* is the same as that caused by a single current of intensity *i*;
3. A conductor's effects is the same as the summation of the effects of the elementary currents into which it can be decomposed;
4. The induced electromotive force is proportional both to the number of coils of the inductor and the number of the induced circuits;
5. The currents originated in a moving closed circuit is equal to the difference of the currents that would be induced in that same circuit if, open, it was closed in its original or final position;
6. The mutual induction of two identical, coaxial, circular circuits is proportional to their diameter;
7. The current induced in a closed circuit from a solenoid (or a magnet) depends only on the relative position of the circuit's and of the solenoid's (or magnet's) extremities;
8. If the axis of a solenoid (or a magnet) forms a closed loop, then its induction is zero unless the circuit is concatenated with the axis.

Felici's law, according to which «it is possible to calculate the total charge that passes in a circuit subject to an induced current as the difference between the final flux of the magnetic field and the initial one divided by the electrical resistance of the circuit», was then resumed from J.C. Maxwell in constructing his general theory of electromagnetism, as also from A. Roiti, L. Puccianti and G. Polvani, which further confirmed many aspects of Felici's work.

Thanks to these important results, in 1859, Felici became full professor of experimental physics.

And precisely during the period in which the pioneering research on induction currents was conducted, Felici published works in which he explained, through the delay of electromagnetic induction, the presence of a certain lack of symmetry in mechanical actions intervening between a given rotating conductive sphere and a magnet placed perpendicular to the axis of rotation of this solid conductor, in the case where the angular velocity increased considerably. And it is precisely from these studies, even admitting hypotheses not directly linked to experimental facts – and this was the only case of a mathematical rather than theoretical treatment of an empirical problem by Felici – he also arrived at an ingenious theory of diamagnetism.

From the early 1860s onwards, he directed his interests towards other questions of electro-magnetism, acoustics and optics. With his work during the years between 1862 and 1866, Felici prepared, on the basis of previous work on the subject, laboratory experiments for estimating the speed of electric current. At the same time, he succeeded in describing some details of the phenomenology of electric sparks, their nature and duration, through congenial technical-experimental apparatuses prepared by himself. In those same years he published, on the basis of what his teacher Carlo Matteucci had already begun, some papers concerning some laboratory experiences on the physical behaviour of dielectrics in the presence of other electrified bodies. For this purpose, he constructed his own special electromechanical system based on a torsion balance. This research paid particular attention to the case of insulating material inserted between the two conductors of a capacitor, as also published in other remarkable works on the possibility of having dielectric polarization phenomena. This latter hypothesis had already been advanced by Amedeo Avogadro, and was then taken up and further developed by G. Belli, M. Faraday and above all by Mossotti but from a more theoretical than empirical point of view. The numerous questions that remained unanswered, being the focus of Felici's experimental work, which lasted until the last years of his research activity, were resolved with acumen and originality, thus bringing the polarization of dielectrics from a simple ad hoc hypothesis to an experimentally assessable physical reality, which however confirmed many theoretical aspects of Mossotti's physical-mathematical theory.

In the 1860s and in the early 1870s Felici published some memories on the determination of the geometric shape of some surfaces of liquids modelled by the action of capillary forces.

Later on, in the mid 1870s, for the study of the demagnetization law of certain ferromagnetic materials (a more complicated case than that of diamagnetic and paramagnetic substances), Felici thought and conceived, with the help of Mariano Pierucci, his laboratory assistant, a special switch that produced rapid intermission (at intervals of 1/20,000 seconds) in the currents induced between two concentric solenoids in which an iron cylinder was inserted.

One battery was connected to one solenoid, the other to a galvanometer, so that, by closing the circuit of the battery, the iron would be magnetized, thus inducing an electric current in the other solenoid connected to the galvanometer.

The switch prepared by Felici, with the technical support of Pierucci, made it possible to adjust the opening and closing times of these two circuits specifically to be able to estimate and adjust the magnetization and demagnetization times of the iron rod. Then, the intensity of the various currents in play, which obeyed laws taking the form $A\exp(-\alpha t)$ with A and α numerical constants were evaluated.

These experiences, which would also be taken up and extended by some of Felici's students can be considered historically as forerunners of subsequent research and theories on the demagnetization of ferromagnetic materials, which are mainly based precisely on the use of alternating magnetic fields of decreasing intensity, which made this last step necessary since the occurrence of magnetic hysteresis phenomena.

Finally we should also recall some minor works, carried out in the 1870s and in 1880s, related to laboratory experiences:

1. the study of the potential of a moving conductor under the influence of a magnetic field;
2. the propagation of electricity in a conductive sphere with electrodes on its surface;
3. the investigation of other phenomenological aspects of electromagnetic induction;
4. the study of electromagnetic phenomena in moving fluids;
5. the 'Amperian' forces;
6. the study of string vibrations.

There were also some memoirs on thermodynamics, acoustics and optics, many of which constituted the thesis topics of his students.

From a retrospective examination of the list of his works, we note that special attention was paid by Felici to the particular and indissoluble relationship between mathematics and physics, not seen from an axiomatic perspective of a physical-mathematical type, such as was assumed for example by Neumann, Weber, and Lenz in their research on electrodynamic induction, but rather from a more properly physical-theoretical perspective, which took the moves from theoretical hypotheses with a clear and precise experimental basis and noted in an a priori way.

This epistemological position of Felici probably arose from a fruitful combination of the teachings received from Mossotti and Matteucci, from which he developed a sure, firm and profound conviction of the necessary union between mathematics and physics, more according to the Galilean prescriptions for modern physics than from the axiomatic perspective typical of mathematical physics.

Felici renewed the Galilean tradition in its most typical methodological aspects of study, research and experimentation, starting above all from the work

Soient :

ds, ds' les longueurs des deux éléments, induits et inducteurs ;

r la distance de leurs points du milieu ;

θ, θ' les angles que ds et ds' font avec un même prolongement de la distance r ;

k une constante dépendante de la force de la pile ;

E la force électromotrice élémentaire. On aura

$$E = k \frac{ds \, . \, ds'}{r} \cos\theta \, . \cos\theta' .$$

Fig. 3 – Felici's formula for the induced electromotive force, from [F.9 in Felici's bibliography by A. Ròiti (see following contribution)].

on electromagnetic induction, and with this he gave birth to a true school of Pisan Physics alongside the contemporary birth of an equally important school of mathematical physics – that of Enrico Betti and Vito Volterra, who were very much affected by the influence of Felici.

Faced with the limited number of publications by Felici (almost all of them, however, having a character of completeness), one cannot certainly forget, alongside the figure of the researcher, that of a teacher: indeed for many years, in Italy of that period, as Pochettino 1930 writes:

> There was only one physical Institute, that of Pisa, directed by Felici, and the school could not have been better because from him, equally eminent both from the mathematical point of view and from the experimental point of view, the youth could well learn to know the true way of working in the field of physics; that is, to balance the theoretical element with the experimental one in a proper measure, so that the inappropriate over-dominance of one over the other does not lead to either abstruse metaphysics or disordered empiricism.

Despite this, Felici's pioneering work did not have a direct academic following in Pisa, partly due to Felici's own motives and dispositions, which led to a sort of diaspora of his students in many parts of the country, resulting in some discontinuity in some way rectified only in 1917 with the call of Luigi Puccianti, who always held Felici's teaching, his studies and his research in great esteem.

He explicitly attested that, with Felici, the school of Physics in Pisa reached the highest level of scientific research, thus renewing the great Galilean tradition. Recalling the famous maxim of *Il Saggiatore*, «philosophy is written in this great book», Puccianti 1939 wrote that

> perhaps no modern physicist like ours has ever conformed to the famous Galileo maxim with equal severity. [...] But if it is easy to admire the profound truth contained in this maxim, and to see in it a general and invariable norm of the method, it is very difficult to follow it rigorously, without being discouraged by the logical abstractness of those pure mathematical entities, or allowing oneself to be led to transform them with fantasy (as too often happened in the history

of science) into fictitious physical entities, attributing to them an imaginary concreteness, which gives them the comforting illusion of treating real things by treating them: from which precisely it refused the mentality of R Felici, who [...] while sitting in the chair of experimental physics was no less a mathematician than an experimenter.

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Felici's papers

Antonio Ròiti[1]

The bibliography of Riccardo Felici reported here below, extracted from Ròiti's work, is supplemented with translations of the titles.

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Maxwell and Italy, after *A Dynamical Theory of the Electromagnetic Field*


FIRENZE IN TASCA

ovvero

UNA GITA DI PIACERE

ALLA CAPITALE

GUIDA ECONOMICO-PRATICA.

Florence tout entière est une galerie!
MERY. *Scènes de la Vie italienne.*

FIRENZE E GENOVA
Tipografia Litografia e Zincografia dei Fratelli Pellas
Via Borgo Ognissanti, Palazzo Bonaini.
1867.

Fig. 1 – Cover page of a traveller's guide to Florence, edited in 1867, the year in which Maxwell was in the city.

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Between the publication of Maxwell's *A Dynamical Theory of the Electromagnetic Field* and the transatlantic radio link which marked the definitive affirmation of radiotelegraphy there were at least two other interactions between J.C. Maxwell and Italy.

Though it is not well known, since it was only reported in Campbell 1882, Maxwell travelled to Italy in 1867 to visit Rome and to meet Carlo Matteucci in Florence. The initial two contributions focus on the year 1867, with the first based on recent archival research carried out by the authors, seeking some further documentary proof of Maxwell's voyage, which was described in Campbell 1882. Instead, the second is an extract of a longer paper describing the known documents relating to this voyage. Further research is merited, both in Leghorn (Italy), and in Marseille (France), the latter being somewhat impaired for that year due to a pandemic outbreak.

The following contribution is on Carlo Matteucci himself and is of a more international nature, since it describes his links with European scientists of the era and, in particular, with Michael Faraday.

Also overlooked outside Italy is the fact that Maxwell was awarded a laurea honoris causa by the University of Pavia – where Mossotti studied – in 1878. It was sadly an ill Maxwell who received the news, and so, could not travel again to Italy. The last contribution focuses on this Honorary Degree and also contains the reproduction of two letters by Maxwell to the Rector of the University of Pavia which were only recently discovered and published, here for the first time. These letters were missing from the fundamental collection Harman 1990.

It is worth pointing out that Campbell 1882 has been digitalized and reprinted, thanks to the work of J.C. Rautio, and can be downloaded from the Sonnet website, as well as being available in paperback, hardcover or Kindle editions Campbell 2020.

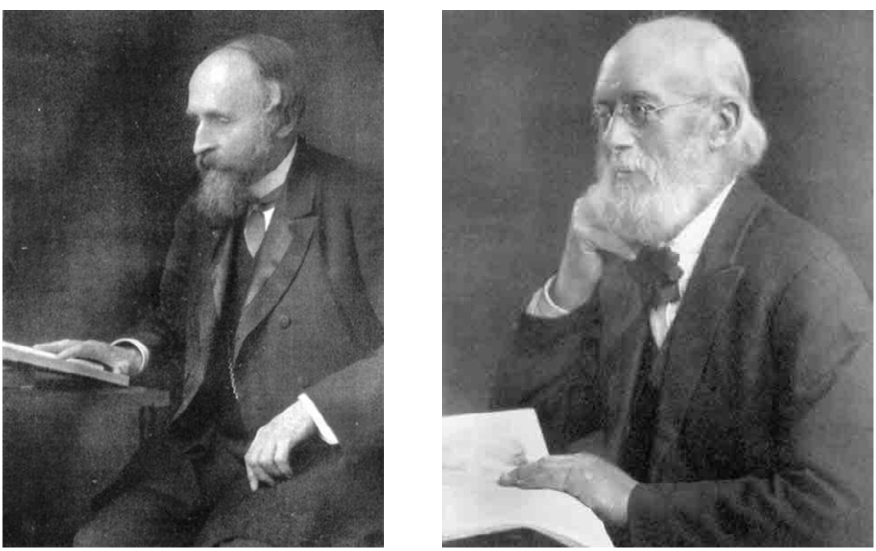
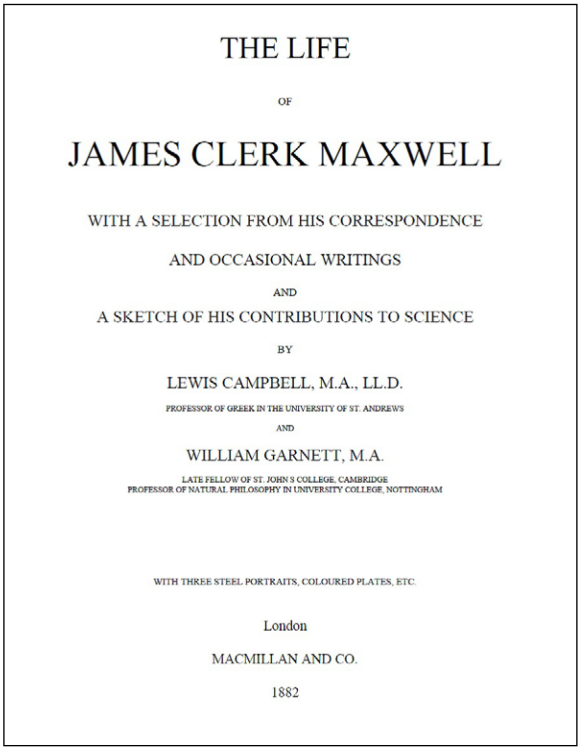


Fig. 2 – Left: Lewis Campbell (Edinburgh, Scotland, September 3, 1830 - Locarno, Switzerland, October 25, 1908). Right: William Garnett (Portsea, England, December 30, 1850 - Hampstead, England, November 1, 1932).



THE LIFE

OF

JAMES CLERK MAXWELL

WITH A SELECTION FROM HIS CORRESPONDENCE

AND OCCASIONAL WRITINGS

AND

A SKETCH OF HIS CONTRIBUTIONS TO SCIENCE

BY

LEWIS CAMPBELL, M.A., LL.D.

PROFESSOR OF GREEK IN THE UNIVERSITY OF ST. ANDREWS

AND

WILLIAM GARNETT, M.A.

LATE FELLOW OF ST. JOHN'S COLLEGE, CAMBRIDGE
PROFESSOR OF NATURAL PHILOSOPHY IN UNIVERSITY COLLEGE, NOTTINGHAM

WITH THREE STEEL PORTRAITS, COLOURED PLATES, ETC.

London

MACMILLAN AND CO.

1882

Fig. 3 – The first page of (Campbell 1882) in the digital restored copy available online (Campbell 2020).

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Steamship routes in the second half of XIX century: from Great Britain to Italy

An archival search on J.C. Maxwell's voyage to Italy was started a few years ago and is still ongoing. There are several issues in finding evidence of this voyage.

First, the fire in Maxwell's House, which destroyed many *private* letters and papers by Maxwell (Rautio 2013). What we now have are the *scientific* letters and papers, collected in three large volumes (Harman 1990) and which were kept mostly at Cavendish Laboratory. In the scientific letters we found no evidence of correspondence with Carlo Matteucci to plan a meeting. But this cannot be considered as proof against the Florentine voyage stated by Campbell 1882, since they might have exchanged letters now lost. Searches performed at the J.C. Maxwell foundation in Edinburgh and at Cavendish Laboratory at Cambridge have as yet provided no evidence.

What is of more concern is the absence, in Matteucci's biography, of any hint of a meeting with Maxwell in Florence, or elsewhere (Bianchi 1874).

So the next step was to search the archives of the port of Marseille, which is explicitly cited by Campbell 1882, and of Leghorn (Fig. 1), which would be the obvious port used to arrive at or depart from Florence.

Inquiries in Marseille were carried out remotely, due to limitations of movement caused by the recent pandemic, and gave no hints so far of the existence of registers of quarantined ships which would have been worth further investigations there.

Fig. 1 – Leghorn port (Livorno in Italian) in an 1867 map.

The State Archives in Leghorn keep all the Port Captain correspondence and several days were spent browsing the documents from 1867 and 1868 to check for late- or mis-archiving. To date no real key clues have been found.

For 1867 only monthly summaries of ships entering and leaving the port were found. An example of one of these is in Fig. 2 and 3. Sadly this was of no big help because it merely demonstrates that Leghorn was a very active port with hundreds of ships coming and going every month (590 from short distances and 135 from international ports in April 1867 – Fig. 2), and thousands of passengers (9202 from short distances and 1203 from international ports in April 1867, 509 and 671, respectively, who disembarked from a foreign steamship). Indeed what can be inferred from the previous data is that foreigners did mostly arrive by steamships instead of by sailing ships, which might be considered obvious since the former were more comfortable.

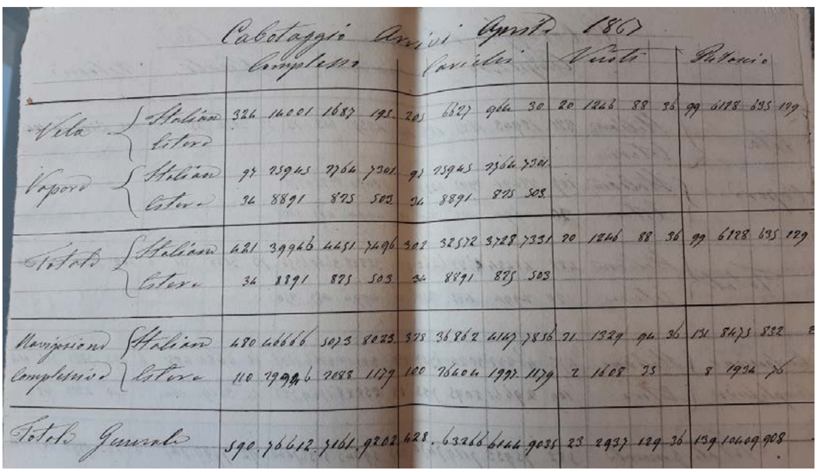
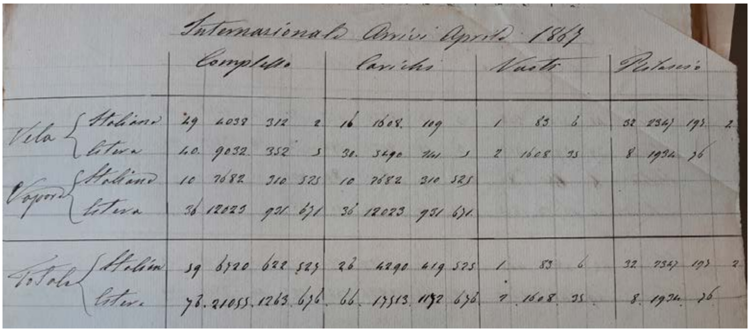


Fig. 2 – Summary for April 1867, ships entering the port of Leghorn in the month from short routes (Cabotaggio). Rows are for «sailing» (Vela) and «steam» (Vapore) ships, further split into Italian (Italiane) and foreign (Estere). Then there is a third row with the totals, again divided by type, and a last row with the grand totals. Columns are grouped in «total» (Complessivo) which is then split into «loaded» and «unloaded» in the following group of columns. Within each group the first column is the number of ships, the second the tonnage, the third the crew, the fourth the passengers [ASLi, Capitaneria di porto di Livorno, inv. n. 142, categoria XVII "Cabotaggi, arrivi aprile 1867." Courtesy of the State Archives in Leghorn, Italy].

No more detailed papers have been found up to now for 1867, though they might exist since we did find some pages dated 1866 with only the ship names, even if there is no clear indication of their port of origin. Further research might shed some light on this. That Leghorn was a major port in the Mediterranean in the second half of XIX century is also demonstrated by the chart in Fig. 4, where 5 main ports are detailed, with two, Genoa and Leghorn, being Italian.

In Fig. 4, hardly visible, the main routes connecting these ports are indicated, with Marseille to Leghorn being among these.

In any event, it appears that the preferred route from England to Marseille departed from Southampton by ferry to the north of France to then travel to Marseille by train. Then, most passengers would depart for the east Mediterranean by steamship (Frey 2019), to avoid the Atlantic and the Gibraltar strait.


Internazionale Arrivi Aprile 1867

		Complessivo				Carichi				Vuoti			Rilascio			
Vela	Italiane	29	4038	312	2	16	1608	109		1	83	6	32	2347	193	2
	Estere	40	9032	352	5	30	5490	241	5	2	1608	35	8	1934	76	
Vapori	Italiane	10	7682	310	525	10	7682	310	525							
	Estere	36	12023	921	671	36	12023	921	671							
Totale	Italiane	39	6720	622	527	26	4290	419	525	1	83	6	32	2347	193	2
	Estere	76	21055	1263	676	66	17513	1152	676	2	1608	35	8	1934	76	

Fig. 3 – Summary for April 1867, ships entering the port of Leghorn in the month from long routes (Internazionale). To be read as Fig. 2 [ASLi, Capitaneria di porto di Livorno, inv. n. 148, categoria XVII "Internazionali, arrivi aprile 1867." Courtesy of the State Archives in Leghorn, Italy].

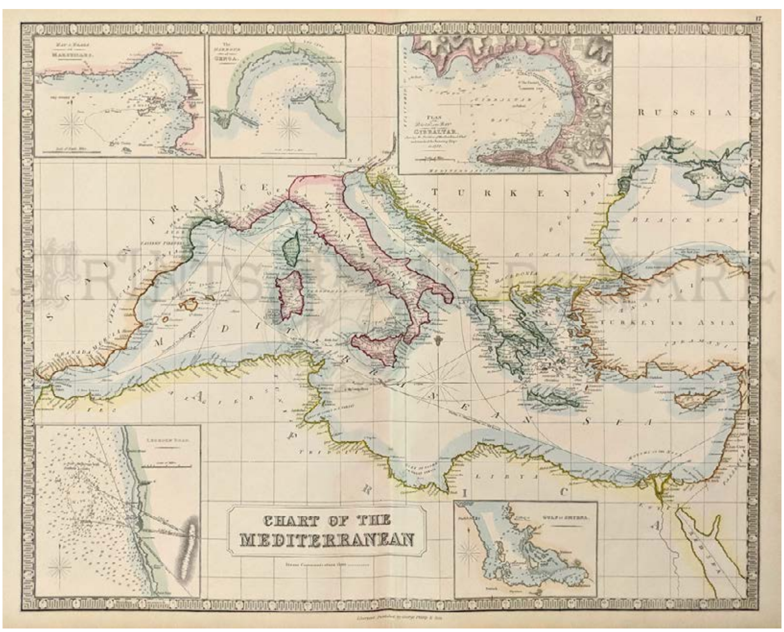


Fig. 4 – Chart of the Mediterranean (1848-1850) Showing the main ports: from top left, clockwise, Marseille, Genoa, Gibraltar, Smyrna, Leghorn.

But if, as Campbell says, J.C. Maxwell and his spouse had to quarantine in Marseille they must have arrived by boat. Although no clear maps of routes from England to Marseille have been found so far, it is known that, in 1844, the *Peninsular and Oriental Steam Navigation Company* actually invented what we now call a leisure cruise. Tourists leaving from Southampton, sailed to the Mediterranean, in particular to Alexandria and Constantinople (P&O Cruises). This line supposedly stopped in Marseille (Theodora) even though Thackeray, the writer renowned for *Vanity Fair* (1848) and *The Memoirs of Barry Lyndon* (1844), who was granted a free cruise in exchange for publicity, does not cite a stop in Marseille in his book about the cruise (Thackeray 1848).

Another company with regular lines from Southampton to the East, landing in Marseille, was the *Pacific Steam Navigation Company,* but this was founded 1870 after the opening of Suez canal and consequent revitalization of the Mediterranean routes (P&O Cruises).

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1867 - James Clerk Maxwell: The Florentine Days[1]

Giuseppe Pelosi[2], *Stefano Selleri*[3]

It is well known that since the 17th century members of the European – especially British – aristocracy and haute bourgeoisie loved to take the grand tour, a journey of discovery and learning that could last from a few months to several years. The destination of these travels was nearly always Italy (De Seta 1982).

The custom was interrupted in the period of the French Revolution and Napoleonic Empire; although it was resumed during the Restoration, it never regained the popularity of the previous century.

Italy was the favorite destination because of its Roman ruins, the works of the Renaissance and the wealth of its art and culture generally. Venice, Florence, Rome, Naples (along with Pompeii and Herculaneum) and all of Sicily were the obligatory stops.

Less common, though by no means rare, was the tour with scientific aims, undertaken to meet eminent scholars and to visit institutes and laboratories. In this case as well Italy was among the possible destinations.

Among the physicists – or more precisely natural philosophers – who visited Italy from Britain in the 19th century we would like to recall Michael Faraday and James Clerk Maxwell, focusing on their brief stay in Florence.

<…omissis…>

James Clerk Maxwell

James Clerk Maxwell (Edinburgh, Scotland, 13 June 1831 - Cambridge, England, 5 November 1879; Fig. 1) was born in the same year that Faraday conducted the critical experiment that led to the law associated with his name, one of Maxwell's four equations. Coming from an affluent family, Maxwell did not encounter obstacles in receiving a first-rate education, unlike Faraday. During his studies, Maxwell excelled in mathematics.

Maxwell led a much more settled life than Faraday. Attached to his Scottish home in Glenlair (Pelosi 2019), he left it reluctantly and then only for work, such as when he taught at Aberdeen, London and Cambridge (Fig. 2).

Only once did he travel outside Britain, and in this case as well his destination was Italy. We have much less documentation about this journey compared to that of Faraday, given that the latter made meticulous journal entries of everything he did (Blasi 2011).

[1] This is indeed an extract of a longer paper entitled "Michael Faraday and James Clerk Maxwell: The Florentine days." *Il Colle di Galileo* 8, 2(2020): 27-37.

[2] University of Florence.

[3] University of Florence.

Fig. 1 – Left: James Clerk Maxwell. Right: Maxwell's recently restored house in Glenlair, Scotland.

The only brief mention of Maxwell's trip to Florence in 1867 can be found in his authoritative biography written by his friend Lewis Campbell, together with William Garnett (Fig. 5) (Campbell 1882). We reproduce here the extract in question:

> Maxwell's retirement [to Glenlair] was not by any means unbroken. There was a visit to London in the spring of every year. And in the spring and early summer of 1867 he made a tour in Italy with Mrs. Maxwell. They had the misfortune to be stopped for quarantine at Marseilles, and his remarkable power of physical endurance and of ministration were felt by all who shared in the mishap. True to the associations of his early days (see above, pp. 28, 121), he became the general water-carrier, and in other ways contributed greatly to the alleviation of discomforts that were by no means light.
>
> We met accidentally at Florence, and I remember his mentioning two things as having particularly struck him amongst the innumerable objects of interest at Rome. He had looked at the dome of St. Peter's with an eye of sympathetic genius[4] and his ear for melody had been satisfied by 'the Pope's band'. He acquired Italian with great rapidity, and amused himself with noticing the different phonetic values of the letters in Italian and English.[5] One of his chief objects in learning the language was to be able to converse with Professor Matteucci, whose bust now stands in the Campo Santo at Pisa. During the same tour he took special pains to improve his acquaintance with French and German. The only language he had any difficulty in mastering was Dutch.

It is worth noting that Carlo Matteucci (Forlì, Italy, 20 June 1811 - Livorno, Italy, 24 June 1868; Fig. 3), whom Maxwell met in Florence, was professor of

[4] The tone in which he spoke of this brought home to me, more than anything I have seen in books, the joy of Michael Angelo in etherealizing the work of Brunelleschi.

[5] On learning from our teacher, Sign. Briganti, the pronunciation of suolo, he said, "That is the English for rondinella."

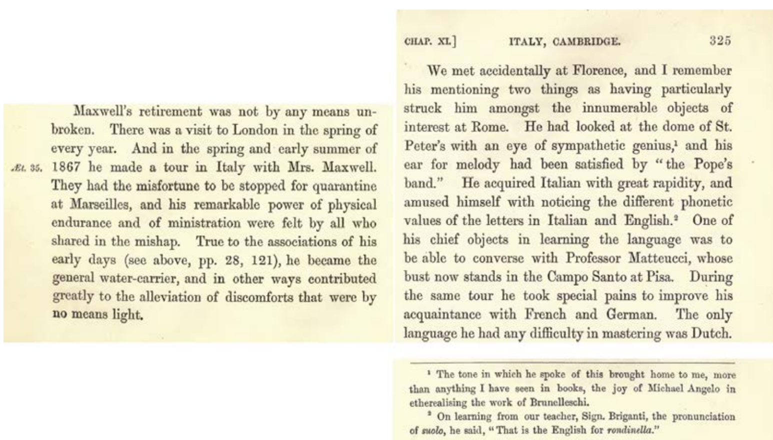
Fig. 2 – Principal locations associated with Maxwell: his native city of Edinburgh, his country home in Glenlair in the south of Scotland; the university cities of Aberdeen, London and Cambridge; the cemetery of Parton where he is buried.

experimental physics in Pisa (from 1840), Senator of the newly founded Kingdom of Italy (1860), and Minister of Education (in 1862, in the first Rattazzi government). He had close connections with Great Britain. In 1844, he won the Copley Medal, the most important prize awarded by the Royal Society of London, for his research on animal electricity; the same prize had been received by both Davy (1805) and Faraday (1832). Only two Italians had received the Copley Medal before Matteucci: Alessandro Volta (1794) and Giovanni Antonio Amedeo Plana (1834). It is, however, sad to note that James Clerk Maxwell was never awarded the prize.

In addition, in Pisa Matteucci met the Scotswoman Robinia Young, who became his wife in 1846. According to Farnetani 2008, Robinia was the daughter of the famous Thomas Young, the eminent natural philosopher, who founded the wave theory of light, Young's modulus of materials, and physical optics, and who further made important contributions to the decipherment of hieroglyphs (Pelosi 2008). The present authors, however, have not found certain proof of this supposed family relation, neither in the literature nor in the Scottish parish where Robinia was born.

Fig. 3 – Carlo Matteucci.

Unfortunately, all other documents pertaining to Maxwell's travels in Italy were almost certainly destroyed in the two fires that ravaged the house in Glenlair (in 1899 and 1929, Rautio 2013). Neither is evidence for this journey and the relationship between Maxwell and Matteucci to be found in books on the latter (Bianchi 1874).



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Æt. 35.

CHAP. XI.] ITALY, CAMBRIDGE. 325

We met accidentally at Florence, and I remember his mentioning two things as having particularly struck him amongst the innumerable objects of interest at Rome. He had looked at the dome of St. Peter's with an eye of sympathetic genius,[1] and his ear for melody had been satisfied by "the Pope's band." He acquired Italian with great rapidity, and amused himself with noticing the different phonetic values of the letters in Italian and English.[2] One of his chief objects in learning the language was to be able to converse with Professor Matteucci, whose bust now stands in the Campo Santo at Pisa. During the same tour he took special pains to improve his acquaintance with French and German. The only language he had any difficulty in mastering was Dutch.

[1] The tone in which he spoke of this brought home to me, more than anything I have seen in books, the joy of Michael Angelo in etherealising the work of Brunelleschi.

[2] On learning from our teacher, Sign. Briganti, the pronunciation of *suolo*, he said, "That is the English for *rondinella*."

Fig. 4 – Extract from Campbell 1882 describing Maxwell's journey to Florence.

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The myth of British Science through Carlo Matteucci's correspondence

Sergio Giudici[1]

Introduction

The nineteenth century opens under the sign of electricity with an all-Italian invention. Towards the end of 1799, at his residence in Lazzate (Como) the Italian scientist Alessandro Volta provided the first source of continuous current: the famous copper and zinc battery, called «artificial electric organ» in the letter sent in March 1800 to Joseph Banks, president of the Royal Society.

Unlike the common electrical machines of the time, the battery was able to deliver a continuous current and therefore allowed an «electrical fluid» of constant and adjustable intensity to flow in the circuits. Until then it had been only possible to study static or very rapid electrical phenomena like discharges and sparks. By flowing through conductors, the uniform electric fluid showed effects never seen before and led to sensational discoveries.

Ten years after Volta's invention, electrochemical pioneer Sir Humphrey Davy said that «The Voltaic battery was an alarm-bell to experimenters in every part of Europe». In fact, the scientific revolution triggered by the battery manifested itself earlier in the studies on the relationship between electricity and matter, particularly in the process now called electrolysis. Davy was able to isolate certain chemical elements that do not exist in the free state such as potassium, sodium and magnesium. Afterwards, a quantitative basis to electrochemistry was provided by Faraday and, independently, by Italian scientist Carlo Matteucci.

In 1820, Danish scientist Hans Christian Ørsted showed the correlation between electric current and magnetic field, that line of research would continue in France with Biot, Savart and Ampère. In 1831 Faraday showed that a change in magnetic flux induces electric current and the first confirmation of the effect came almost immediately from Florence where Leopoldo Nobili and Vincenzo Antinori had promptly repeated the experiment. Induction was used shortly afterwards by Matteucci in the field of bioelectricity, obtaining results that can be regarded as the basis of modern electro-physiology.

Within the European dimension in which electromagnetism developed, a particular link between Italy and Britain emerges and it consists not only in knowledge exchange and in the sharing of specific problems but also in a more cultural complex form. Such Anglo-Italian *fil rouge* is particularly evident in the friendship between Michael Faraday (1791- 1867) and Carlo Matteucci (1811-1868). Since the very beginning, Faraday appreciated the scientific works of the young Italian and later he learned Italian to correspond with him. Their correspondence spans over a period of almost three decades, from Matteucci's scientific beginnings until 1859, two years before the formation of the Italian unitary state, in which Matteucci would hold the position of senator and then minister of education.

[1] University of Pisa.

At every stage of his professional career, Matteucci found encouragement and support in the paternal loveliness granted him by Faraday. His admiration for the British scientist extended to the whole British way of life to a such degree that anglophilia can be considered a Matteucci's peculiar characteristic both in his private and public life.

Dark calorific rays and first contact with Faraday

The first contact between Matteucci and Faraday dates to the summer of 1833, when the young Italian sent the already renowned English scientist some of his works. Probably the material sent included the work on the heat (Matteucci 1832) he already presented at the Académie de France as final dissertation of the advanced course he attended at the *École Polytechnique* in Paris under the supervision of François Arago. In that work it was first shown that infrared radiation – then called *dark calorific rays* – exhibited an interference pattern like the one observed in the case of visible light.

> After these experiences repeated many times, and always with similar results, [one can conclude] that, due to the reciprocal action of two heat beams, which meet with a certain inclination in some points, an increase in heat is produced, and in others not; and that the arrangement of these calorific fringes is very identical with those of light. It is quite true, however, that in place of the dark fringes I could not see a drop in temperature in regard to the surrounding; but this must certainly depend on the difficulty of measuring in isolation with such an instrument a small space, such as that of these calorific fringes (Matteucci 1832, Author's translation).

The subject was part of the long research tradition on the nature of light. Interference figures in visible light were noticed by Grimaldi, Newton and Huygens (Pelosi 1998). At the beginning of the nineteenth century, light corpuscular theory was going to be abandoned after the experiments by Augustin-Jean Fresnel in France and by Thomas Young in Britain who convincingly demonstrated in 1801 the wave nature of light through the double-slit experiment (Pelosi 2011). In the year 1800, calorific rays were highlighted by William Herschel by placing a mercury thermometer in the spectrum created by a glass prism.

Faraday appreciated young Matteucci's first works and replied with an encouraging wish

> Sir, I am very much your debtor for your kindness in sending me your papers and for your good opinion. All such marks of goodwill are stimuli to me, urging me still forward in the course which has obtained such commendation. Being convinced you cannot refrain from pursuing science by experiment, I need not express a hope that you will do so manfully. No man of judgment can work without succeeding, and you are not likely to leave a course which has already made your name known throughout the European Continent (Faraday to Matteucci, october 1st, 1833, Lett. 682 in James 1993a)

The Italian scientist Leopoldo Nobili was of a different opinion and with a certain severity he reproached the lack of care in controlling some systematic effects due to the geometry of the heat sources used by Matteucci in his studies.

> Mr. Matteucci has dealt with this subject twice. In the first one he used a ball of flaming iron as a heat source: a source too wide to assume that his results could be conclusive, as the famous Arago already observed. In the second work he tried to remove the objection by restricting the source to that of a thin platinum wire heated with a single voltaic element [...] The idea was a happy one, but even it, I think, was not satisfactory enough for the rather serious omissions with which it was accompanied. It was not enough, for example, to reduce the heat source to a radiant point: it would have been also necessary, for the comparability of results, to ensure the constancy of that heat centre throughout the course of the experience. (Nobili 1834)

The conflicting opinions of Faraday and Nobili is a first example of how Matteucci, at least until 1840, was highly appreciated abroad but little considered by his Italian colleagues.

Electrochemistry, Induction and Torpedoes

In the early decades of nineteenth century, *science by experiment* meant making use of the Volta battery and electrolytic cells. The devices were commonly used in experimentation but a full understanding of the electrochemical phenomena taking place was still lacking. Having obtained very interesting results on the subject, Matteucci wrote a memoir entitled *Sur la force électro-chimique de la pile* published shortly afterwards in the *Annales de Chimie et de Physique*. Unaware that Faraday was working on the same topic and that he had found results identical to his own, Matteucci did not mention the English scientist in his memoir. Such a serious omission was awkwardly unnoticed by the publisher but not by German physicist Poggendorff who denounced the suspicious inspiration – bordering on plagiarism – of Matteucci's memoir.

Let us remind that Faraday's and Matteucci's results are a milestone in electrochemistry and are now known as Faraday's laws of electrolysis. The first of them establishes the proportionality between the mass produced in the electrolysis process and the total charge flowing through the electrolytic cell. In formulas it reads as

$$m = \frac{M_A}{N_A Ze} Q$$

Where M_A indicates the molar mass of the substance produced, N_A the Avogadro's number, e the elementary charge (i.e. that of the electron), Q the total quantity of flowed charge and Z the valence of the ion. The law provides the important quantitative picture of what happens in the battery at atomic level showing how the current flowing is linked to the oxidation-reduction processes at the electrodes.

In support of the real independence between the two works, it should be noted that in his memoir Matteucci mentions the silver coulombmeter he used to measure the total charge while Faraday does not say which instrument he used for the same measurement. This and other differences seem to support the hypothesis of true independence (Ehl 1954)

Fearing that the suspicion of plagiarism would disappoint Faraday's benevolence, Matteucci writes in his own defence:

> The very high esteem that I feel for you, and the friendship with which you are pleased to honour me could alone lead me, and even make it my duty to repel an unjust accusation brought against me in the Poggendorff Journal. Alluding to my memoir on Electro-Chemical force, published in the Annales de Physique et de Chimie of Messieures Arago and Gay-Lussac, I am charged with plagiarism from your most highly celebrated works on Electro-Chemistry. This imputation is too unworthy of my character, and there is no act of my life that can justify it. If the humbleness of my means and the adversity to which I am subjected, did not allow me to give to that memoir all the extension that the subject required (which science will not regret after your works) let the oblivion into which it must needs fall be sufficient penalty. (Matteucci to Faraday, March 12, 1836, Lett. 907 in James 1993a)

Faraday, probably used to episodes of this kind, did not give particular credit to Poggendorff's insinuations, but rather he investigated the referee criteria adopted by the publisher. Faraday believed in Matteucci's good faith and – as Fabio Toscano notes – both behaved like true gentlemen and «the episode did not leave the slightest trace in [their] relationships, destined, on the contrary, to become increasingly close and affectionate» (Toscano 2011).

Matteucci's work on electrolysis had a certain European resonance but not in Italy. The lamented «humbleness of my means» and the «adversity to which I am subjected» were sadly true.

Matteucci was born in 1811 in Forlì in Romagna, at that time the region had been taken away from the Church State and included in the Kingdom of Italy, vassal state of Napoleonic France. With the Congress of Vienna (1815), Romagna was returned to the Church and Matteucci became subject of the Pope. Living in the Papal state meant being on the margins of the great cultural currents and having great difficulty in keeping up to date and accessing scientific literature.

Between 1834 and 1836 Matteucci settled in Florence with the hope of obtaining a stable position at the Imperial-Regio Museo di Storia Naturale. At that time, the Grand Duke of Tuscany Leopold II was striving to modernize the Museum trying to make it a research and teaching centre of European level. In 1814 the Museum was visited by Davy and Faraday. For the occasion, a spectacular experiment was set up by focusing sun's rays onto a diamond target. In such a way it was demostrated that diamond can ignite like any other carbon-based substance (Pelosi 2020).

Among the most active scientists at the Florentine Museum was Leopoldo Nobili, inventor of the astatic galvanometer and author of various research on electricity and its applications. Shortly before Matteucci's arrival, Nobili and Antinori had found themselves involved in a delicate situation. The two managed to produce a spark by electromagnetic induction, inspired by a similar experiment conceived by Faraday they had been informed of. The Florentine result was published before Faraday officially published his own in the *Philosophical Transactions* of the *Royal Society* as he was supposed to do.

This was followed by an *affaire*, which fortunately became clear fairly quickly. The editor of Faraday's ponderous epistolary (James 1993a) summarizes the incident as follows:

> With this time Faraday was able to pursue electro-magnetic induction, resulting in its discovery in August 1831 25th. Faraday wrote to Hachette on 17 December 1831 announcing this discovery. Hachette, believing it to be an official announcement, read the letter to the Academie des Sciences in Paris from which Faraday's work was widely reported in the press. The misreporting of this letter allowed others, particularly Leopoldo Nobili and Vincenzio Antinori in Florence, to repeat some of Faraday's experiments and publish them before Faraday, since his paper was delayed due to the new refereeing procedures at the Royal Society. This made it appear that Faraday had been anticipated in some of his discoveries, particularly the production of a spark from an electromagnet. After this event Faraday became much more cautious about what he wrote in letters about his unpublished research. (James 1993b)

The electric arc produced by induction is a phenomenon similar to the spark triggered by abruptly interrupting the current circulating in a circuit. The phenomenon often occurs with old switches and is explained in term of great electromotive force produced by the rapid variation of self-induced magnetic flux. The result is now known as Faraday-Lenz law and reads as

$$F = -L\frac{dI}{d\mathrm{t}}$$

In case of rapid variation and/or large self-induction, the induced electromotive force can be so large to produce a spark. In the experiment carried out by Faraday and repeated by Nobili and Antinori, the spark was seen between the two poles of a horseshoe magnet by abruptly detaching a rod as shown in figure 1.

Called to review such kind of experiments at the Royal Society, John Forbes commented

> Finally, as far as yet known, no one except Signori NOBILI and ANTINORI and me have yet obtained the spark from the natural or permanent magnet. This, indeed, must be in a great measure owing to the power of the magnets we have been able to command, (no notice is given of the size of that at Florence); there is little doubt, however, from the constancy and brilliancy of the results (Forbes 1834).

The Faraday-Nobili *affaire* was resolved quickly but episodes of this kind more often gave rise to lengthy controversy, as it would happen a few years later

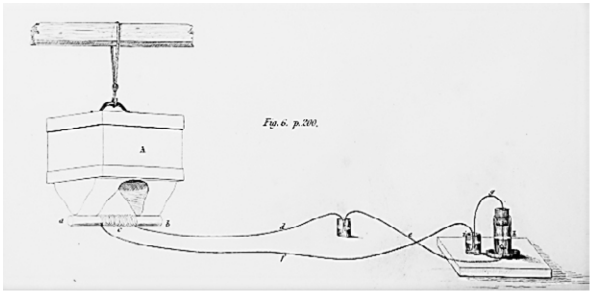

Fig. 1 – Sketch of the 'spark-experiment' shown by J. Forbes 1834 in his review on Induction.

with the dispute between Matteucci and Dubois-Raymond, in which Faraday himself would be involved in the role of referee.

> These polemics of the Scientific world are very unfortunate things they form the great stain to which the beautiful edifice of scientific truth is subject: Are they inevitable? They surely cannot belong to science itself but to something in our fallen natures. How earnestly I wish in all such cases that the two champions were friends. Yet I suppose I may not hope that you and Du bois Raymond may some day become so. Well let me be your friend at all events (Faraday to Matteucci, lett. 2647, March 3rd, 1853, in James 1993a)

These episodes had sometimes the advantage of focusing the attention on the subject of the controversy. Indeed, Matteucci meditated a lot on the spark obtained by magnetic induction and he had the brilliant idea of using the extra current produced by induction to ignite a spark in a circuit powered by the *natural electric organ* of a torpedo. Obtaining a spark from electric fishes was a relevant issue, in fact it would show that *animal electricity* does not differ from the one produced by artificial devices. It should be reminded that until the mid-nineteenth century, the various forms of electricity had not yet been unified. In principle, it could be that the atmospheric electricity, that of the battery, that of electric fish, involved distinct *electric fluids*.

The difficulty in producing a spark from torpedoes is due to the low voltage provided by the natural electric organs of the animal (i.e. about 40-50 V for Mediterranean torpedoes). It can be estimated that for such a low voltage the maximum distance, allowing the electric arc to be produced, is equal to about ten microns. Therefore, even if a spark were produced, the light effect would be invisible. Matteucci's experimental idea was to circumvent the obstacle by using induced electromotive force which greatly amplifies the voltages as Faraday and Nobili had shown.

> The torpedo diverts the needle [magnetic], the torpedo magnetises the soft iron, shakes and why should it not give the spark? And will obtaining it be such a great discovery? It is useless for me to describe it to you [the method to obtain the

spark] Read again Faraday's last work on the spark [...] and it is found (Matteucci to Santi Linari, March 12, 1836 in Bianch 1874, Author's translation).

Once back in Romagna, the experiment was successfully carried out in the spring of 1836 near Cesenatico. Immediately Matteucci informed Faraday. «With Mr. Jenkins' device, which you have studied so well, I got the sparkle of the torpedo, and still get it» (Matteucci to Faraday, May 30, 1836, Letter 921 in James 1993a).

The news is reported in post scriptum while the body of the letter contains a singular request concerning a possible stable position on the Ionian Island of Corfu.

> Deep domestic misfortunes force me to leave my country. The opportunity is propitious, and you can help me well, and I beg you not to delay a moment in doing so. It is a question of appointing in Corfu, Italian professors of Physical Sciences, Chemistry and so on. Certainly, either through personal contacts or directly you can have influence in these elections. Please use it to my advantage and as soon as you can – either chemistry or physics, but it doesn't matter. A lesson is not a discovery (Matteucci to Faraday, May 30, 1836, Letter 921 in James 1993a).

After a long Venetian past, the island became a British protectorate in 1815. In order to live in a region of British influence, Matteucci would have agreed to move to an even more peripheral place than the one where he lived[2]. Indeed, despite the notoriety earned abroad with his studies on bioelectricity, the attention of Italian academia towards him continued to be scarce. Still in 1839 Matteucci's works were practically ignored during the first congress of Italian scientists in Pisa.

A few months after Cesenatico experiments, the German naturalist Alexander von Humboldt wrote to Faraday as follows: «Since Mr. Matteucci obtained, as I had always hoped, electric sparks by irritating torpedoes, you will double your desire, I am sure, to obtain living Gymnoti» (Von Humboldt to Faraday, 26 July 1836, Lett 930 in James 1993a).

Matteucci's name circulated among scientists and his researches were appreciated. *Gymnotus* is an electric fish whose electric organ is capable to deliver about 100 V. Faraday asked the British colonial offices for help in obtaining some of these fishes, intending to repeat Matteucci experiment and encouraged his young friend to articulate the issue of bioelectricity in a more ambitious research program, «beautiful and very important subject, linking the action of electricity directly with the nervous system» (Bianchi 1874).

[2] The singular request can be related to what Italian poet Ugo Foscolo, native to the Ionian islands, anglophile and exile in London, wrote in 1817. In brief, Foscolo argued that one of the reasons why Ionians should be considered fortunate with respect to Italians is that while Lombardy and Venice had been annexed to the protectionist Austrian empire, the Ionian Islands enjoyed the benefits of British free trade, access to the markets of London and northern Europe, and the investments that British bankers would have channeled to the islands. See Foscolo 1964.

Matteucci responded by complaining the need of a theoretical framework that was still missing. In that period he was making the leap from experimenter with brilliant ideas to mature scientist capable of a broad and critical eye.

> I believe the study of electricity makes great progress; however, I see with sorrow that we are lacking a sufficiently general theory to group so many phenomena. I recognize why research of this kind has become and will become more and more difficult because of the great complication of the effects, more or less secondary, that develop alongside any chemical, physical or physiological action that one wishes to study. Despite all this, progress must be made. (Matteucci to Faraday, December 29, 1837, in James 1993a, Author's translation)

As Nobili had already experimented, in 1838 Matteucci measured the current circulating in the muscles with a galvanometer and discovered that the electricity ceased keeping the muscle in a state of contraction ('tetanus'), both spontaneously and under the action of exciting substances. This experiment highlighted the physiological nature of animal currents. Not only such electric flowing existed since the galvanometer measured it, but such current was linked to the physiology of the organ in which it flowed. This experiment as well as the improvement of the frog galvanoscope (see Figure 2) and the invention of the so-called *frogs pile* are considered the basis of modern electrophysiology (Piccolino 2011).

These scientific findings attracted the attention of the international scientific community and, above all, that of Alexander von Humboldt. The German naturalist reported Matteucci's progresses to the Grand Duke of Tuscany who in 1840 with *motu proprio* entrusted him with the chair of Physics at the Faculty of Natural Sciences of the University of Pisa.

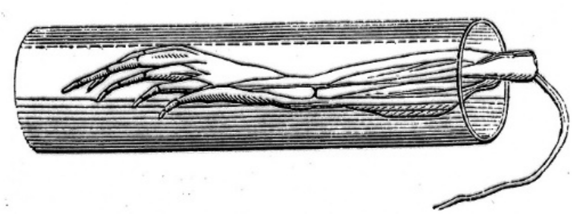

Fig. 2 – Sketch of a frog galvanoscope. The instrument was invented in 1780 by Luigi Galvani and improved by Matteucci. When the protruding nerve is connected to a circuit with electric potential, the muscles contract and the leg will twitch; it twitches a second time when the circuit is broken. The instrument is sensitive to super-small voltages and it was still used well into the 19th century when alternative tools like the electromagnetic galvanometer and gold-leaf electroscope were being introduced.

Anglophile sentiment and telegraphy

In September 1844, Matteucci arrived in London, invited to present and replicate his experiments in electrophysiology. The purpose of the visit was above all to the Italian scientist to the members of the Royal Society. Indeed, he was candidate for the prestigious Copley Medal, which he was awarded a few months later. Being in the British Empire capital for Matteucci meant above all being able finally to meet Faraday in person and to immerse himself in the British scientific community. Faraday made him visit the headquarters and laboratories of the Royal Society and, together with the astronomer John Herschel, went to York where the meeting of the British Association for the Advancement of Science was held.

«After I met you, I feel more courage in me. Next Monday, at Kings College with Todd and others, I will make my experiences; I beg you to assist me, and I am sure you will return this signaled favour» (Matteucci to Faraday, September 20, 1844, in James 1993a, Author's translation).

«I am happy, I have repeated my experiences with Todd, Wheatstone, Bowman and Miller. But I am counting on you: tomorrow, I beg you, come to Kings College» (Matteucci to Faraday, September 23, 1844, in James 1993a, Author's translation)

«How much gratitude I owe you, dear friend! God is my witness; I can never forget Him. I am staying in London until Tuesday, and I ask only one favour of you, to see you as often as possible» (Matteucci to Faraday, September 20, 1844, in James 1993a, Author's translation).

Once back in Italy, Matteucci was full of a predilection for the British way of life, and his enthusiasm was such that he made a singular request to Faraday:

> In the midst of my strange melancholy, and always looking forward to forming a family so that I might spend my life less badly, the thought had crossed my mind to ask you to choose me from among the English bridesmaids of your acquaintance who would like to be my wife. Let us not talk about it for now; but if this desire will awaken in my soul, believe that I will not change my choice (Matteucci to Faraday, October 18, 1844, in James 1993a, Author's translation).

A similar request was also sent to the chemist William Robert Grove, but no one obviously acted as a matchmaker. However, a few months later Matteucci told Grove

> I have an event that concerns me personally. You have often said to me: «it's time for you to get married with an Englishwoman». I followed your advice and my inclination. Next year I will come to London with my wife. She is a Scottish bridesmaid, whom I met by chance in Pisa. She is so good and so clever that she will certainly make my house happy. I thank Providence from the bottom of my Heart (Matteucci to Grove, April 22, 1845, in James 1993, Author's translation).

According to Nicomede Bianchi, the first meeting between Matteucci and his future wife Robinia Young took place along the road Via Aurelia between Livorno and Pisa, where Matteucci helped an English lady and her daughter, Robinia precisely, whose draft horse had gone wild.

Bianchi's testimony is surprisingly similar to the incipit of the sentimental novel *Il Dottor Antonio* by Giovanni Ruffini, in which an Italian patriot falls in love with a young Englishwoman met in very similar circumstances: an incident along the Ligurian stretch of the Via Aurelia. Published in 1855 with the intention of arousing sympathy for the Italian Risorgimento cause across the Channel, the novel was a great success.

Trace of Matteucci's genuine anglophile sentiment can be found in a letter to his future wife.

> I think you will now find your country more admirable than the one that appeared to you before you stayed on the continent. This point does not offend me. As a man of science, I too have my share of merit in England's great progress, which is largely due to science. So you need not fear to make me feel sorry to write «chez nous we do it better». We Italians have also done something in the world, and no doubt we will do something, or rather we will do something, although not much (Bianchi 1874, Author's translation).

Matteucci's Anglophilia can be considered as a particular case of the widespread «Love for England» common during Italian *Risorgimento* among liberals who considered «England's great progress due to Science» as a development model to be imitated. In this context, it is worth to recall Matteucci's passion for telegraphy. Among the various scientists he met in London there was Charles Wheatstone, who in 1837 with William Cooke patented a telegraph system paving the way for commercial exploitation. We do not know if they talked about telegraphy but, once back in Italy, Matteucci endeavoured to be appointed as director of the electric telegraphs of Tuscany. Thanks to his efficient management, in November 1847 the first Italian telegraph line was set up between Pisa and Livorno. In 1851, Matteucci published a manual on Electrical Telegraphy (Matteucci 1851). The book is an excellent text on telecommunications and, between the lines, it says more than what one would expect from a technical manual. The treatise is pervaded by a sincere positivist optimism and seems to promise the reader a near future made better by education and technology.

After reviewing the telegraphy of several countries, Matteucci explains why the British system is the one to be preferred and he is very proud of having made it even better «the price of a dispatch transmitted with the English system is much more than double that of a dispatch transmitted with the system we have adopted» (Matteucci 1851, Author's translation).

Discussing the speed of signal propagation, Matteucci imagines telegraph around the whole earth's globe

> If the electric circuit also made a full circle around the earth, the electric current would propagate in all points of the conductor wire in such a short time that there would not be, at least for our senses, a perceptible difference in time between the effects of the current at one point or another of this circuit, even if taken as far apart as possible (Matteucci 1851, Author's translation).

Indeed, such imagination was not so far from reality. The first attempt at a transatlantic cable was in 1857 as a joint enterprise between England and the United States.

In his treatise, Matteucci discusses public education and geo-political issues as well.

> It is appropriate for us to make people feel that scientific studies and non-ordinary qualities of intelligence are absolutely necessary to train a good electrical telegraph clerk, and we are therefore pleased to see many young people educated in mathematical and natural sciences among us, turning to this career. [...] The reasons for communication are born and multiply with the ease of communication itself, with the example of other places, for the sake of novelty, which little by little becomes a real need. Every state, whether large or small, is today so constrained by external influences under all relations, and mainly for the media, that it cannot isolate itself and make a barrier to others without greatly harming its own interests (Matteucci 1851, Author's translation).

In the five years of life, Tuscan telegraphs developed side-by-side with the railways and followed the tracks almost faithfully (Fari 2016). Similarly, Matteuci's fascination with telegraph networks is parallel to the fascination with railways of a more famous anglophile: the first Italian prime minister Cavour who wrote during his stay across the Channel: «In England there are no more distances. Communication even between distant cities, such as London and Liverpool, has become easier than between different parts of the same city. The mail leaves London twice a day for almost all directions» (From Cavour's Journal reported in Romeo 1977, Author's translation).

Both Matteucci and Cavour share the same liberal positions and both feel the inevitable charm of England, always felt by those who prefer English moderation to French excesses and by those who know well the needs of a modern industrial society. In the nineteenth and in the first half of the twentieth century, exiles with a conservative or liberal democratic tendency and with an empirical and positivist orientation in philosophy, almost always chose Great Britain as their destination (Biagini 2004).

Faraday and Britain as cultural models

During the 30s and early 40s, Matteucci was animated by a strong self-affirmation sentiment that according to Marco Piccolino may remind of Stendhal's characters but after the first Italian war of Indipendence (1848) Matteucci seems to have internalized the typically English moderation. Somehow Faraday sensed the change and wrote to him:

> Your philosophy always combines very much with my way of thinking, because I find it vigorous and at the same time cautious. I believe that this last quality is necessary no less than the first, and I am of the opinion that there is no class of people more pernicious to the progress of scientific truths than that of the vigorous without prudence (Faraday to Matteucci, November 27, 1849, in James 1993a, Author's Translation).

Faraday probably encouraged his friend to intensify his political commitment and Matteucci replied as follows:

> I think I am doing some good for my country, politically, but please don't encourage me too much on this path, because I never know where duty and patriotism end, and when vanity and selfishness begin. That is why I always have my galvanometer with me (Matteucci to Faraday, September 27, 1852, in James 1993a, Author's Translation).

In 1862, such *political galvanometer* led Matteucci to accept the position of minister of Education offered by prime minister Rattazzi (Leone 2019). The reforms Matteucci had in mind were partially inspired by the British education system. For instance, on the model of the British university campuses, he intended to reform the so-called Scuole Normali as schools of excellence for teacher training. Arguing in favour of the project he explicitly mentions Faraday's biography.

> The philosophers, the surveyors, the chemists are born, if Providence assists them by bringing them closer to a professor that cultivates science with ardor, he will discover the genius of the young student, and that genius will not perish. This is what Englishmen mean when they proudly say that Sir H. Davy's greatest discovery is the discovery of Faraday (Carlo Matteucci, Speech to the Italian Senate, February 19, 1862, in Matteucci 1867, Author's Translation).

Matteucci tried to reform – unfortunately without much success – the Italian school system by intervening on the too early bifurcation between classical and technical-scientific paths. With the intention of delaying such separation, Matteucci was at odds with the Italian idealistic tendencies that considered science nothing more than technical knowledge and, therefore, to be soon separated from the more elevated classical studies. On the contrary, Matteucci conceives learning science as a true spiritual education.

> These sciences must be taught to the people, to the middle classes, to the elected intellectuals because Faraday was right when he said that today there are notions of mechanics, hydrostatics, elementary chemistry, which are fundamental, which are the ABC of a liberal education, and which a gentleman cannot ignore. And how could it be otherwise if those sciences respond to the most natural and legitimate curiosity of our spirit, if the applications of those sciences have made the greatest economic revolution [...] if natural philosophy has provided man with the strongest and surest instrument of his intellectual education? (Matteucci 1866, Author's translation).

The correspondence between Faraday and Matteucci ends with a last affectionate letter by Faraday.

> The condition of my health becomes ever more serious and I do not know how things go on, because when I read, I cannot remember what I have read and thus I omit to read what I should. Lately, I worked for six whole weeks, straining to obtain results which I in fact obtained, but all negative. But the worst of it is that,

> looking over my previous notes, I find that I had verified by experimentation, eight or more months ago, the same facts, and I had completely forgotten them. This vexed me somewhat, not just the work but the forgetfulness, because work without memory proves to be useless. Despite all this, I have thousands of reasons to be satisfied, and if I speak of my condition, it is not to complain but to explain myself. If I could do as I wished, I would not write a letter to you unless it contained some scientific subject. Instead, the reality is that they are all devoid of interest, like the present one. However, if you do not mind, I shall continue to write to you, if for no other reason, than to thank you for your important news and to tell (Faraday to Matteucci, November 5, 1859, Lett. 3668 in James 1993a, Author's translation).

The mentioned forgotten facts concern the occasional experiments Faraday carried on despite his health condition. One of this late experiment attempted to find an electrical effect by raising a heavy weight. After the discovery of dualism between electricity and magnetism, Faradays was convinced that also gravity may be convertible into some other force, most likely electrical. No result was found and the Royal Society refused to publish his negative conclusions. About 1855, Faraday's mind began to fail as he gradually sank into senility.

As a conclusion, one can take inspiration from the passage of the last letter in which Faraday says «I shall continue to write to you» even if there is no particular scientific topic to talk about. The *other than science* Faraday would pleased to write to Matteucci is evidently something concerning their friendship and mutual esteem. However, this *other than science* springs out from science itself and confirms the existence of the *fil rouge* linking Faraday's England to Matteucci's Italy, presumed in the introduction. That link is obviously a fact of electro-science history but it is also a more complex cultural substance that resounded even in the Italian parliament. The anglophile sentiment is not a marginal aspect of Matteucci's personality, on the contrary it is part of that cultural substance. The alliance between Italian liberalism and British Empire was not only a political and diplomatic issue but also a matter of cultural resonances triggered by making science together.

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On Matteucci's death, his wife left most of her husband's correspondence to the Italian historian and archivist Nicomede Bianchi who in 1874 published a biography more attentive to the scholar's political work rather than to the scientific. In this work Bianchi quotes numerous letters, of which in many cases it is now not possible to trace the originals. Therefore I often had to refer to Bianchi instead of Matteucci's or Faraday's original correspondence. Whenever possible, I referred to the James' edition of Faraday's correspondence.

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Maxwell's Honorary Degree from the University of Pavia in 1878

Virginio Cantoni[1], *Adriano Paolo Morando*[2]

Alessandro Volta was Regius Professor of Experimental Physics at Pavia University from 1778 to his retirement in 1819. After his invention of the battery (1799) he devised many other apparatus that can be seen today in the A. Volta Physics Cabinet at the University of Pavia's History Museum. There his worktable is also kept (Figure 1).

Fig. 1 – Volta's original worktable and some of his collection of instruments of late XVIII early XIX century: batteries, condensers, electric pistol, electrophorus, electrometers, eudiometers, Leyden jars.

As well as being an outstanding scientist, Volta was an exceptional educator. His lectures were so crowded that, in 1785, Emperor Joseph II of Austria (Pavia as well as Milan and all Lombardy was then part of the Austrian empire), ordered the construction of a new lecture room for physics. The architect Leopoldo Pollack finished it in 1787. Originally the ceiling was flat but, after being damaged in 1828, it was replaced with the present impressive shell-shaped ceiling (Figure 2).

Being such an outstanding scientist, who indeed made possible all the development of electrical science thanks to his battery, a solemn centenary celebration of Alessando Volta's university chair was held at the University of Pavia in 1878 (N.A. 1878).

The Rector Alfonso Corradi decided to organize a major international event on the last Saturday of April 1878. A committee was established, comprising, among the others, Prof. Giovanni Cantoni, Dean of the Faculty of Mathemati-

[1] University of Pavia.

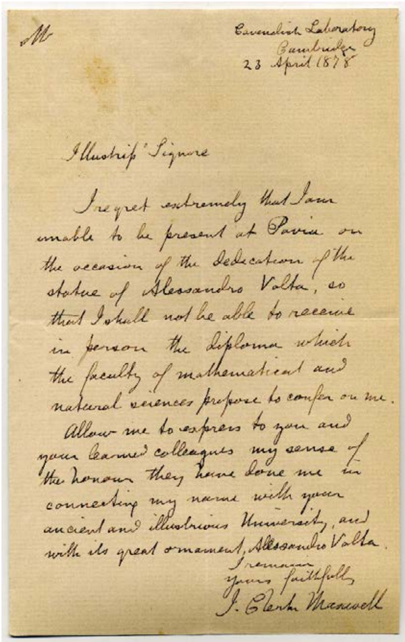
[2] Polytechnic University of Milan.

Fig. 2 – The Alessandro Volta lecture room realized by the architect Leopoldo Pollack in 1787, to admit the large audience that followed the lessons of Volta, who then taught in this classroom for over thirty years.

cal, Physical and Natural Sciences, and successor to Volta in the Chair of Physics, Eugenio Beltrami, Chair of Mathematical Physics and recently arrived from Rome, and Volta's grandson Gerolamo Gobbi Belcredi.

To celebrate this important event, Pavia organized a sumptuous ceremony with vast echoes both in Italy and abroad. To the bust of Volta, already displayed at the University, a new full-figure statue was unveiled in the University courtyard (Figure 3) by the Prime Minister, Benedetto Cairoli (an Italian unification hero), in the involvement of Francesco de Sanctis, the Minister for National Education.

Fig. 3 – The statue of Alessandro Volta by Antonio Tantardini in the courtyard of the University of Pavia, inaugurated the April 28, 1878 celebrations, as you can see walking along the main street of Pavia.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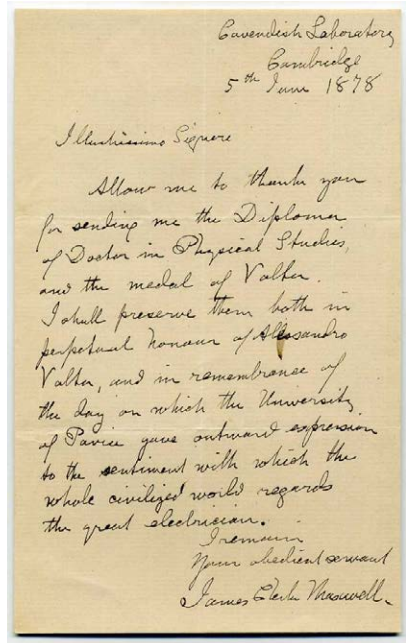
Cavendish Laboratory
Cambridge
23 April 1878

Illustriss Signore

I regret extremely that I am unable to be present at Pavia on the occasion of the Dedication of the statue of Alessandro Volta, so that I shall not be able to receive in person the diploma which the faculty of mathematical and natural sciences propose to confer on me.
Allow me to express to you and your learned colleagues my sense of the honour they have done me in connecting my name with your ancient and illustrious University, and with its great ornament, Alessandro Volta.
I remain
yours faithfully
J. Clerk Maxwell

Cavendish Laboratory /
Cambridge/23 April 1878
Illustriss. Signore (in Italian)
/ I regret extremely that I am unable to be present at Pavia on the occasion of the dedication of the statue of Alessandro Volta, so that I shall not be able to receive in person the diploma which the faculty of mathematical and natural sciences propose to confer on me.
Allow me to express to you and your learned colleagues my sense of the honour they have done me in connecting my name with your ancient and illustrious University, and with its great ornament, Alessandro Volta.
I remain / yours faithfully / J. Clerk Maxwell


Cavendish Laboratory
Cambridge
5th June 1878

Illustrissimo Signore

Allow me to thank you for sending me the Diploma of Doctor in Physical Studies, and the medal of Volta. I shall preserve them both in perpetual honour of Alessandro Volta, and in remembrance of the day on which the University of Pavia gave outward expression to the sentiment with which the whole civilized world regards the great electrician.
I remain
Your obedient servant
James Clerk Maxwell.

Cavendish Laboratory /
Cambridge / 5th June 1878
Illustrissimo Signore (in Italian)
/ allow me to thank you for sending me the Diploma of Doctor in Physical Studies, and the medal of Volta. I shall preserve them both in perpetual honour of Alessandro Volta, and in remembrance of the day on which the University of Pavia gave outward expression to the sentiment with which the whole civilized world regards the great electrician.
I remain / Your obedient servant / James Clerk Maxwell.

Fig. 4 – Two letters from Maxwell to the Rector of Pavia University, recently found in the University's Historical Archive, on the occasion of Volta's anniversary and the assignment of the diploma.

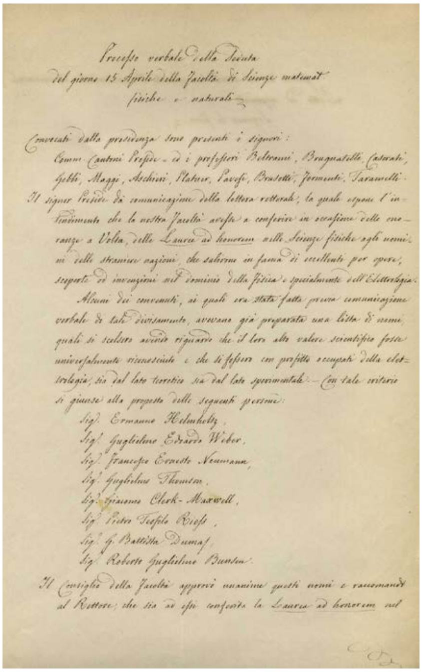
On a meeting of the committee on April 15, 1878, the members decided to award Honorary Degrees in Physics to be conferred by the University of Pavia on Europe's leading experts in electrology. Five years after Maxwell's *Treatise* but still 10 years before Heinrich Rudolf Hertz's experiment demonstrating the reality of electromagnetic waves. The choice of scientists, which were really the top scientists of the time, carefully balanced the current schools of action at distance (German: from Wilhelm Eduard Weber to Ludwig Ferdinand von Helmholtz) (Hesse 1961) and contact action (English: from William Thomson, Lord Kelvin, to James Clerk Maxwell) (Whittaker 1951). The full list is (see also Figure 5):

Helmholtz, Hermann from Berlin.
Weber, Wilhelm Eduard from Göttingen.
Neumann, Franz Ernst from Königsberg.
Thomson, William from Glasgow.
Clerk Maxwell, James from Cambridge.
Riess, Peter Theophil from Berlin.
Dumas, Jean Baptiste from Paris.
Bunsen, Robert Wilhelm from Heidelberg.

The long correspondence now fully recuperated in the University of Pavia's Historical Archive, between these outstanding scientists and Professors at the University of Pavia, certainly stirs the emotions. Figure 4 show two examples of letters from Maxwell to Adolfo Corradi, the Rector of the University of Pavia.

The celebration was a clear and undeniable sign of continuity with Volta and also sprang from Cantoni's (the true organizer of the celebrations) strong cultural affinities with Maxwell. In 1877, the Scottish physicist published his *Matter and Motion*, the text on Mechanics (Maxwell 2002) largely derived from his notes to workers attending his evening classes. By 1881, Cantoni had already published the Italian edition (Maxwell 1881). And this was not just a simple but laudable translation task: the second part of the book also collected Ottaviano Fabrizio Mossotti's writings on Mechanics (from Pavia) to which Maxwell himself, several times, made explicit reference.

Among the many interesting lectures given in this occasion in Pavia, the one by Augusto Righi, who presented a preview of his «phone that you hear at a distance» (what we now call a loudspeaker) is to be remembered. Augusto Righi was a well-known scientist, who had come under the influence of Alexander Graham Bell's recent patents (1875-1877) and who presented this invention the very same year at the Paris Expo. Sadly, he had no commercial success. Righi, a former pupil of Antonio Pacinotti, would later deal with Hertzian experiments (Hertz 1893), and electromagnetic waves (Righi 1897). Righi will then be the master of Guglielmo Marconi.


Processo verbale della Seduta
del giorno 15 Aprile della facoltà di Scienze matemat.
fisiche e naturali

Convocati dalla presidenza sono presenti i signori:
Comm. Cantoni Preside - ed i professori Beltrami, Brugnatelli, Casorati, Gobbi, Maggi, Aschieri, Platner, Pavesi, Brusotti, Formenti, Taramelli.
Il signor Preside dà comunicazione della lettera rettorale, la quale espone l'intendimento che la nostra Facoltà avesse a conferire in occasione delle onoranze a Volta, delle Lauree ad honorem nelle Scienze fisiche agli uomini delle straniere nazioni, che salirono in fama di eccellenti per opere, scoperte od invenzioni nel dominio della fisica e specialmente dell'Elettrologia.
Alcuni dei convenuti, ai quali era stata fatta previa comunicazione verbale di tale divisamento, avevano già preparata una lista di nomi, quali si scelsero avendo riguardo che il loro alto valore scientifico fosse universalmente riconosciuto e che si fossero con profitto occupati della elettrologia, sia dal lato teoretico sia dal lato sperimentale. Con tale criterio si giunse alla proposta delle seguenti persone:
Sig. Ermanno Helmholtz,
Sig. Guglielmo Edoardo Weber,
Sig. Francesco Ernesto Neumann,
Sig. Guglielmo Thomson,
Sig. Giacomo Clerk-Maxwell,
Sig. Pietro Teofilo Riess,
Sig. G. Battista Dumas,
Sig. Roberto Guglielmo Bunsen.
Il Consiglio della Facoltà approvò unanime questi nomi e raccomandò al Rettore, che sia ad essi conferita la Laurea ad honorem nel

Record of the Faculty Board Meeting
Of April 15 of the Faculty of Mathematical, Physical and Natural Sciences
The following gentlemen have been summoned by the Dean:
The Dean, Comm. Cantoni and Professors Beltrami, Brugnatelli, Casorati, Gobbi, Maggi, Aschieri, Platner, Pavesi, Brusotti, Formenti, Taramelli.
The Dean reads a letter from the Rector expressing the intention that our Faculty will award, on the occasion of commemoration of Volta, some Honoris Causa degrees in Physical Sciences to foreigners of reputation for excellence for their doings, discoveries or inventions in the domain of Physics and especially Electrology.
Some of those summoned who were pre-warned verbally of this intention, had already prepared a list of names, selected for their high, universally acknowledged, scientific value, and who have worked on electrology both theoretically or experimentally. With this criterion the proposal was put forward for the following:

Mr. Helmholtz, Hermann
Mr. Weber, Wilhelm Eduard
Mr. Neumann, Franz Ernst
Mr. Thomson, William
Mr. Clerk Maxwell, James,
Mr. Riess, Peter Theophil,
Mr. Dumas, Jean Baptiste,
Mr. Bunsen, Robert Wilhelm.

The Faculty Board unanimously approved these names and recommended to the Rector that the Honoris Causa degree be awarded on the day when the monument to the immortal physicist is inaugurated.
Read and approved (Members' signatures)

Fig. 5 – First page of the minutes of the Board Meeting of April 15 of the Faculty of Mathematical, Physical, and Natural Sciences awarding honoris causa degrees to various scientists, including Maxwell. Note that most of the board members are well known distinguished professors, e.g. the mathematicians Eugenio Beltrami (non-Euclidean geometry and Beltrami-Klein model, Laplace-Beltrami operator, etc.) and Felice Casorati (Weierstrass-Casorati theorem in complex analysis).

Indeed, to the transmission of sound, to Bell and the telephone, Maxwell dedicated his last conference, published in 1878 on Nature (Maxwell 2003, Maxwell passed away a year later, in 1879). With a little wry humour here and there, and keeping a safe distance from this invention, Maxwell said: «A method had been invented of transmitting, by means of electricity, the articulate sounds of human voice...».

And so, it was that these technological achievements came to be presented at the Volta celebrations, in a way that confirmed Volta's dually theoretical and applicative spirit. In the 'radiant days' of the end of April 1878, the least that could be done to celebrate the glories of the past and, in a fully Positivistic, view, by awarding honorary degrees to Maxwell and the other key figures of the new electrical and electromagnetic science, an opening to the technological expectations of the future was given.

The interested reader will find more detailed information in a book dedicated to the event, edited both in Italian and in English (Cantoni 2011a) and in a paper on IEEE Antennas and propagation magazine (Cantoni 2011b).

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Conclusions

The genesis of Maxwell's equation has been one of the few truly epiphanic events in science, earning Maxwell an everlasting place in the pantheon of the greatest scientists of all times, with Galileo, Newton, Einstein, just to cite a few.

The impact of the theory on our current lifestyle is impressive. Not a single modern electronic device could have been designed without it, and this has been acknowledged by hundreds of events all over the word in 2015, for the 150 year anniversary of the publication of *A Dynamical Theory of the Electromagnetic Field*.

Of course, such development cannot be considered a day's intuition of an anchorite secluded in a remote place as charming as Glenlair or any other place in Scotland, but must be the result of long personal labour and much sifting of the results and ideas of others.

This book, in its first part, hopefully has provided the reader with an overview of how extended Maxwell's network of interests was, how vast his readings were, and how much he owed to so many of his fellow scientists. We hope the reader will forgive us for the slight parochial pride with which we designed second part, dealing with an insight on Italian scientists relevant to Maxwell and his theory. However, as stated earlier, many of the French, British and German scientists are also so well known and studied that any more detailed discussion, beside the short biographical profiles in part one, would have been superfluous, whereas the three Italians are not so well known outside Italy. Therefore, we believe that the second part could be of interest for all readers.

FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

Giuseppe Pelosi, Stefano Selleri, *The Roots of Maxwell's* A Dynamical Theory of the Electromagnetic Field. *Scotland and Tuscany, 'twinned by science'*, © 2023 Author(s), CC BY 4.0, published by Firenze University Press, ISBN 979-12-215-0058-5, DOI 10.36253/979-12-215-0058-5

Afterword

During the 30 + years I was Editor-in-Chief of the *IEEE Antennas and Propagation Magazine* and its predecessor publication, the *AP-S Newsletter,* and during the more than 20 years I have been Editor of the URSI *Radio Science Bulletin,* I've had the great pleasure and support of Giuseppe Pelosi and Stefano Selleri with their historical contributions to those publications. Their writings and those of the authors they have enlisted have invariably told fascinating stories about electrical engineering and radio science, distinguished by careful and detailed research and illustrated with rare, original illustrations, photographs, and quotations that they found. This book has been an attempt to maintain and polish that tradition.

This book takes the reader through a marvellous journey tracing part of the history of James Clerk Maxwell and his equations. Particular emphasis is given to connections to the work of three Italian scientists, Ottaviano Fabrizio Mossotti, Riccardo Felici, and Giuseppe Luigi Lagrange. What is particularly interesting are the interrelationships – several heretofore unrecognized – that the editors and authors were able to establish among Maxwell, the three Italian scientists, and other European exponents in the field. In reading this Note, one may come to a much better understanding of how the science underlying Maxwell's equations developed, which is a significant contribution itself. Perhaps best of all – as is always the case with the writings of these two authors, and those whom they have enlisted in preparing this book – the book can be an enjoyable and fascinating read.

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I congratulate them on this excellent work, and I hope that we will be gifted with many more contributions of this sort from Giuseppe Pelosi and Stefano Selleri.

W. Ross Stone, PhD, LFIEEE, FURSI, FCIE
Stoneware Limited Editor, URSI Radio Science Bulletin
URSI Assistant Secretary General (Publications and GASS)
Director, European Association on Antennas and Propagation
Honorary Life Member, IEEE Antennas and Propagation AdCom
San Diego, California, USA

Postface

This book is unique among all of the many volumes that have been written about James Clerk Maxwell. This is not a biography of Maxwell, but rather provides us with the results of an in-depth search for the technical ancestry of his work. Yes, those of us who work in the field know Maxwell's electromagnetic theory well. We might even know a bit about the origin of some of the equations. Faraday's work inspired Maxwell to transform Faraday's concepts of an 'electrotonic state' into formal mathematics, yielding what Maxwell called the electromagnetic momentum that we now call the magnetic vector potential, a field that surrounds electric current and is closely related to the, today, more commonly used quantity, magnetic field. And so it goes for Ampère, Coulomb, and many others.

Few, including me, would be able to trace the genealogy of Maxwell's individual equations back to their primal origins. This book does that. With a detailed investigation of every reference in Maxwell's Treatise, the authors obtain the original papers that Maxwell referenced. Then they take it one step further. They trace back every reference listed in every paper that Maxwell referenced. We have here both the parents and the grandparents of Maxwell's theory. This is a monumental work, suitable for the ages. We are indeed fortunate to benefit from the wealth of information contained herein.

In Part II of the book, the authors detail the work of and provide brief biographies for multiple Italian researchers whom Maxwell referenced. In addition, they present what little information is available about Maxwell's trip to Italy, specifically to meet the Italian researchers he was drawing upon. As mentioned in the definitive 1882 biography of Maxwell, (modern reprint: The Life of James

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Clerk Maxwell (Illustrated), available on Amazon), we even find out that Maxwell, who was multi-lingual, learned Italian specifically for this trip.

Full disclosure: I am not a historian. My profession is numerical electromagnetics. Exploring Maxwell's life and times is a delightful hobby. But it was a real joy to read through Part II and find extensive detail, not available elsewhere, on the work of many Italian researchers of the era that all helped lead Maxwell to the shining Truth of his electromagnetic theory.

I highly recommend this book for anyone interested in the giants upon whose shoulders we stand.

James C. Rautio
Maxwell Foundation Trustee
Big Moose, NY USA

About the authors

Giuseppe Pelosi is Full Professor of Electromagnetic Fields at the Department of Information Engineering, School of Engineering, University of Florence. He is an IEEE Life Fellow «for contributions to computational electromagnetics». Among the various Institutions that have had him as a collaborator: McGill University, Montreal (QC, Canada), the University of California at Los Angeles (CA, USA), the Université de Nice Sophie-Antipolis (France) and the Center for History of Science of the Royal Swedish Academy of Sciences (Sweden).

Stefano Selleri is Associate Professor of Electromagnetic Fields at the Department of Information Engineering, School of Engineering, University of Florence. He is an IEEE Senior Member, member of the IEEE History Committee. Among the various Institutions that have had him as a collaborator: McGill University, Montreal (QC, Canada), the Université de Nice Sophie-Antipolis (France) and the Universidad Polytecnica de Madrid (Spain).

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Scientists' biographical data

People are listed with their [birthplace, birthdate – death place, death date] in brackets. In the original part of this book cities and countries are indicated with their modern names, for easier localization by the reader. In some of the works here republished cities and countries are cited with their names of the time and the relevant date. This, even if more historically accurate, makes localization somewhat more difficult, especially in Germany and Italy, which were undergoing complex modifications in XIX century. Nevertheless, we elected not to change the original papers.

Bibliographical References

References are very numerous, both in original and republished contributions. Republished ones had a style bound to the journal in which they were originally published. We chose to make references uniform, slightly changing the style of the ones in the republished material, when needed.

Due to the large bibliographical work on hard-to-find original papers, which are sometimes hard to read, some inaccuracies may have slipped through. We apologise for these in advance and would be grateful if readers would notify us of any they might find.

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The affiliations of those who contributed to the drafting of the texts are those 'photographed' on the date of preparation of the text and also reported updated to the date of pubblication if necessary.

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