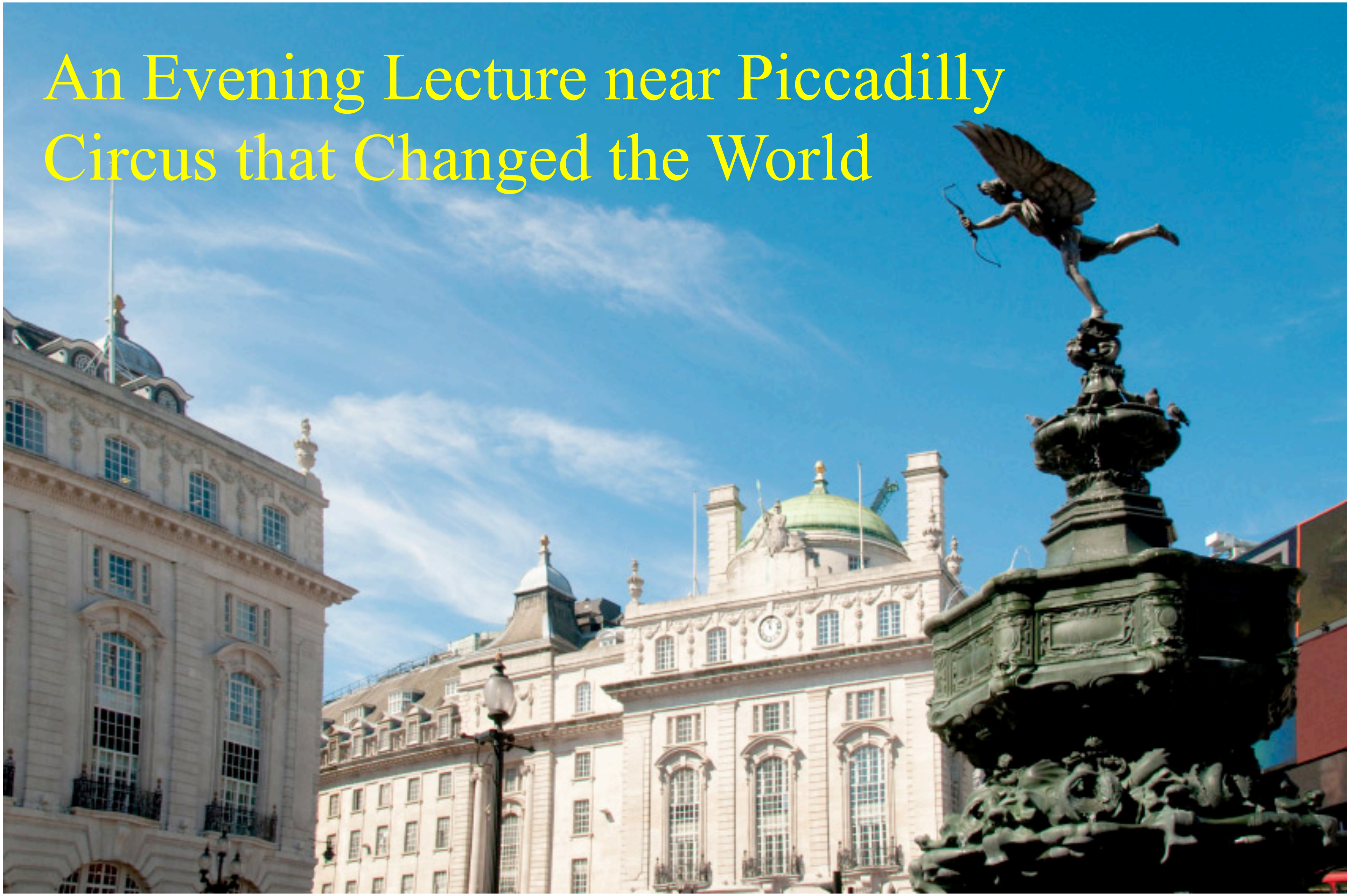

An Evening Lecture near Piccadilly Circus that Changed the World

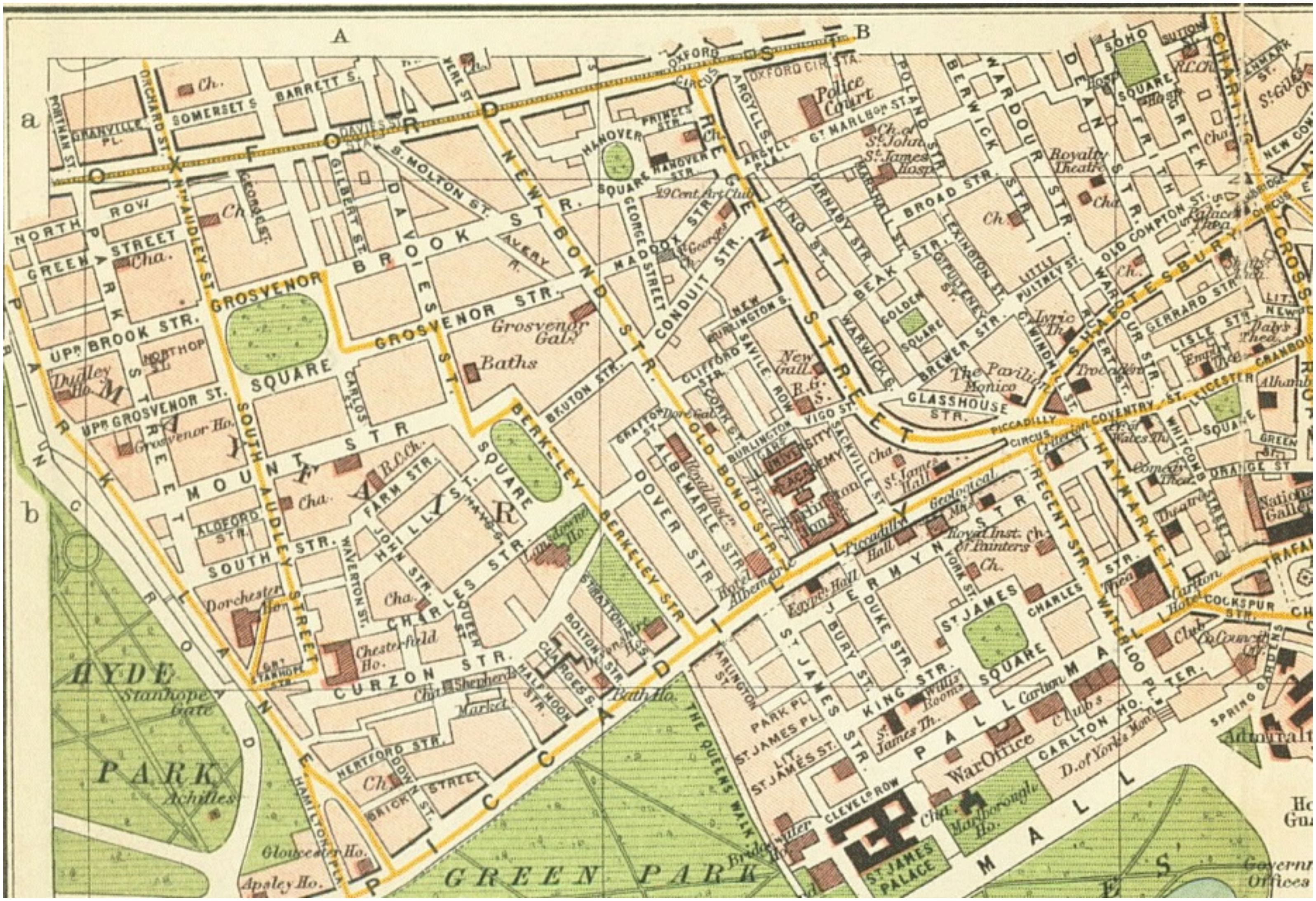
Public Lecture organized in connection to QMath13, with special thanks to:

EMORY UNIVERSITY

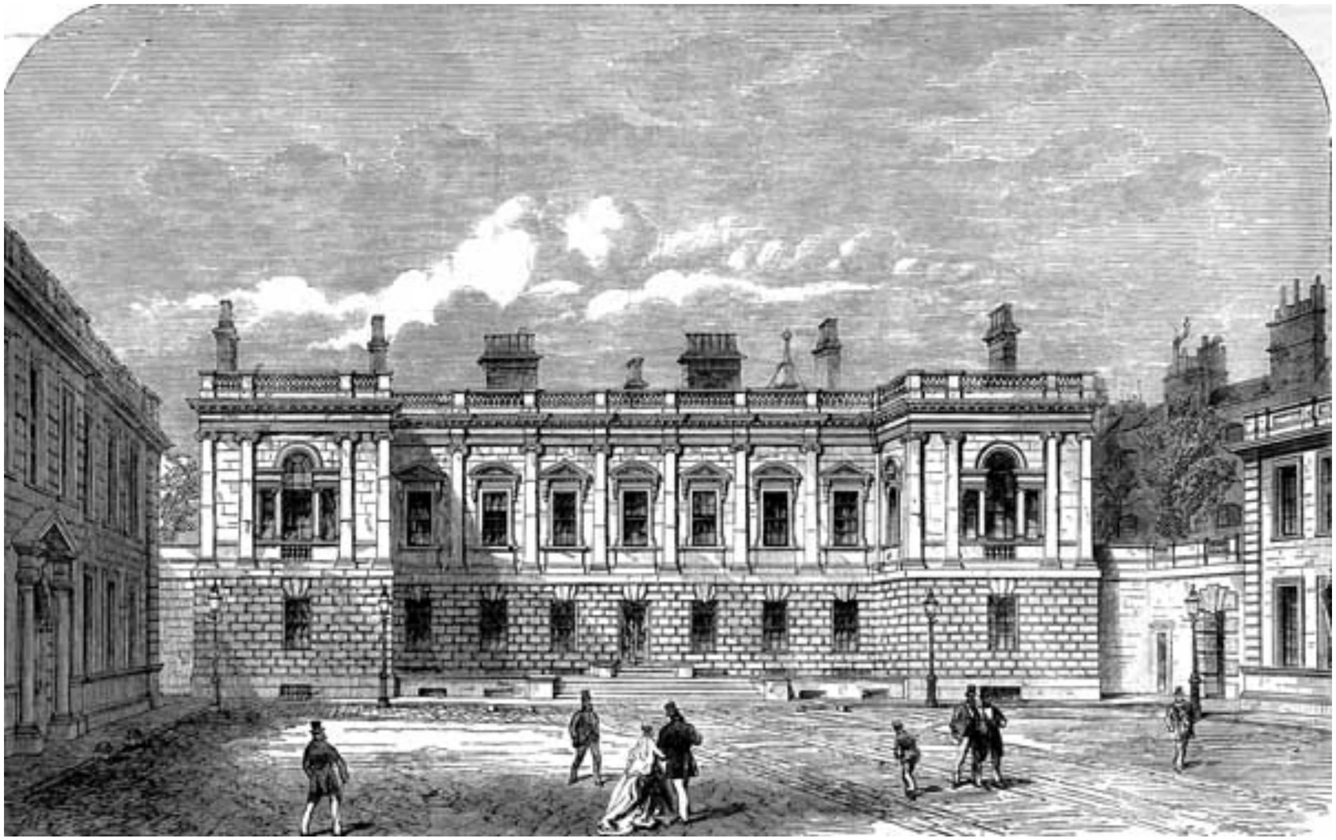
ATLANTA Science Tavern
More science, more often, in more places

Georgia Institute of Technology
School of Mathematics

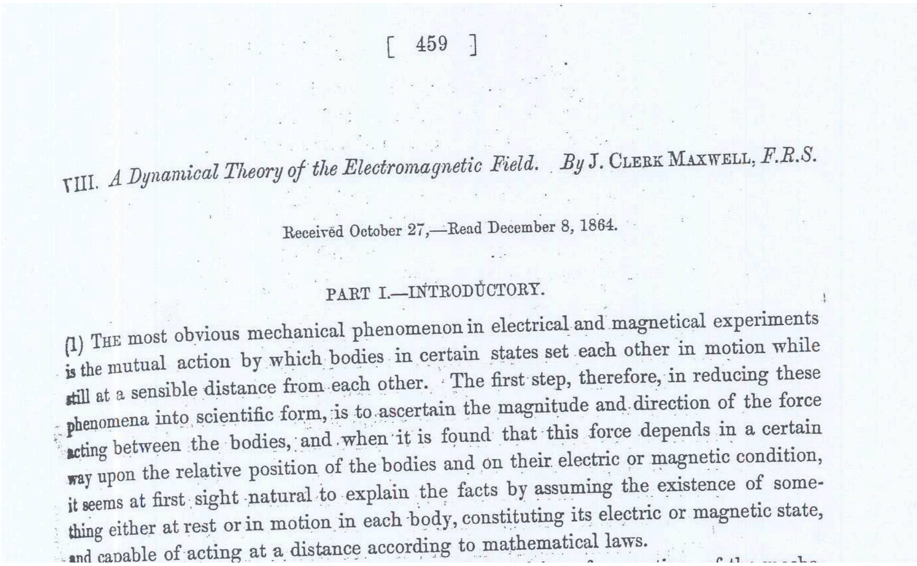
Mayfair, London



A bit over 150 years ago, on December 8, 1864, at the (then) site of the Royal Society at "Burlington House"...



Burlington House, Londres, ca. 1866



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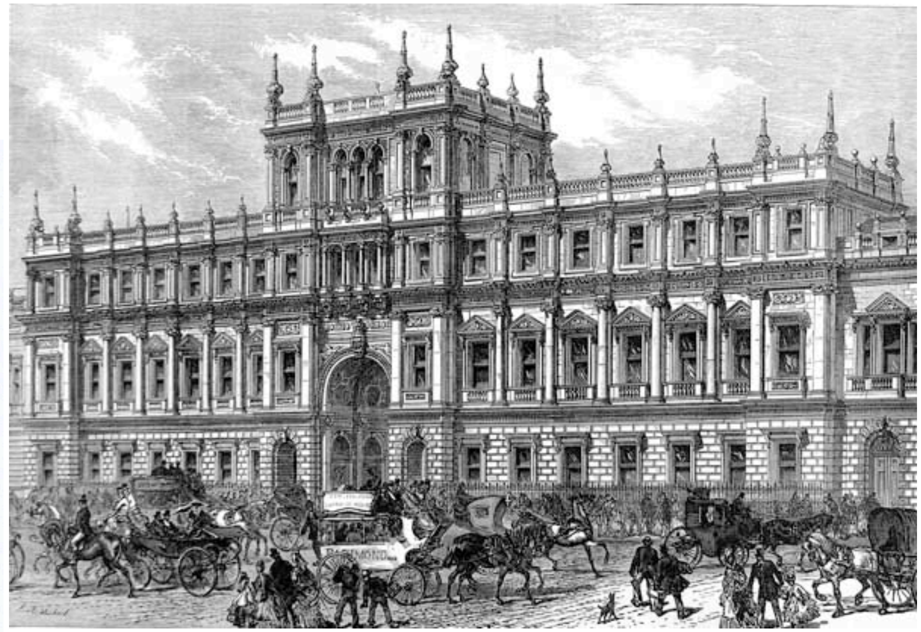
VIII. *A Dynamical Theory of the Electromagnetic Field.* By J. CLERK MAXWELL, *F.R.S.*

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.



Burlington House, Londres, ca. 1873

...at the weekly evening meeting of the Royal Society, James Clerk Maxwell read his work: A Dynamical Theory of the Electromganetic Field.

Proceedings of the Royal Society of London,
vol. 13, pp. 520-536 (1864)

The fascinating development of Electricity and Magnetism: 1785-1864

Public Lecture, QMath 13, Atlanta, Georgia, October 9, 2016

Brief Timeline of Electricity and Magnetism:

1600: William Gilbert

1785: Coulomb's Law

1800: Volta's Battery

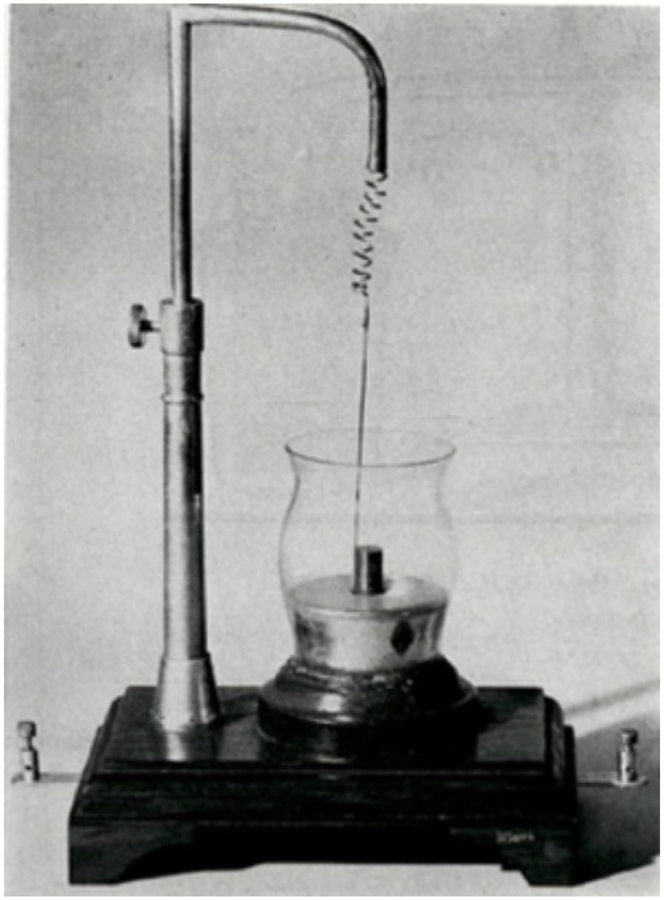
1820: Oersted Experiment

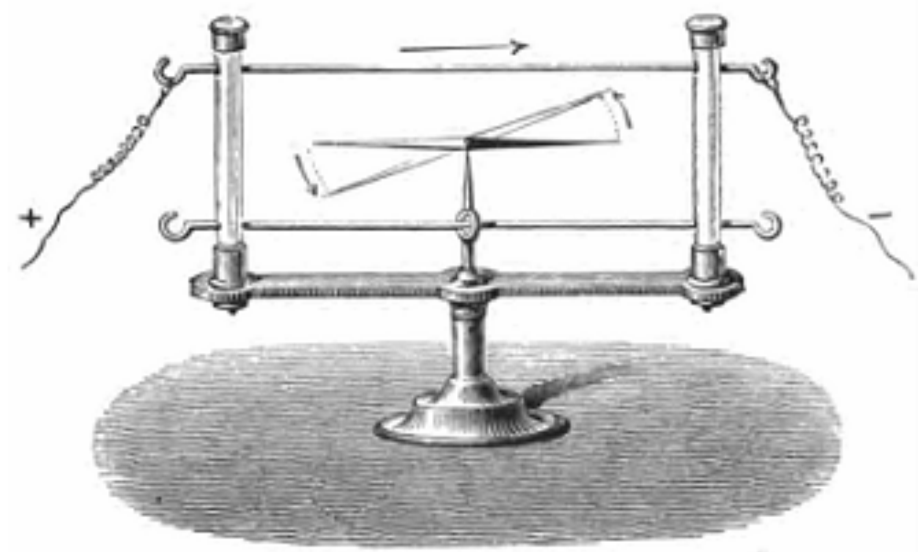
1821: The Invention of the Electric Motor

1820-1831: Development of Electromagnetism (Biot-Savart-Ampere)

1831: Faraday's Induction

1864: Maxwell Equations

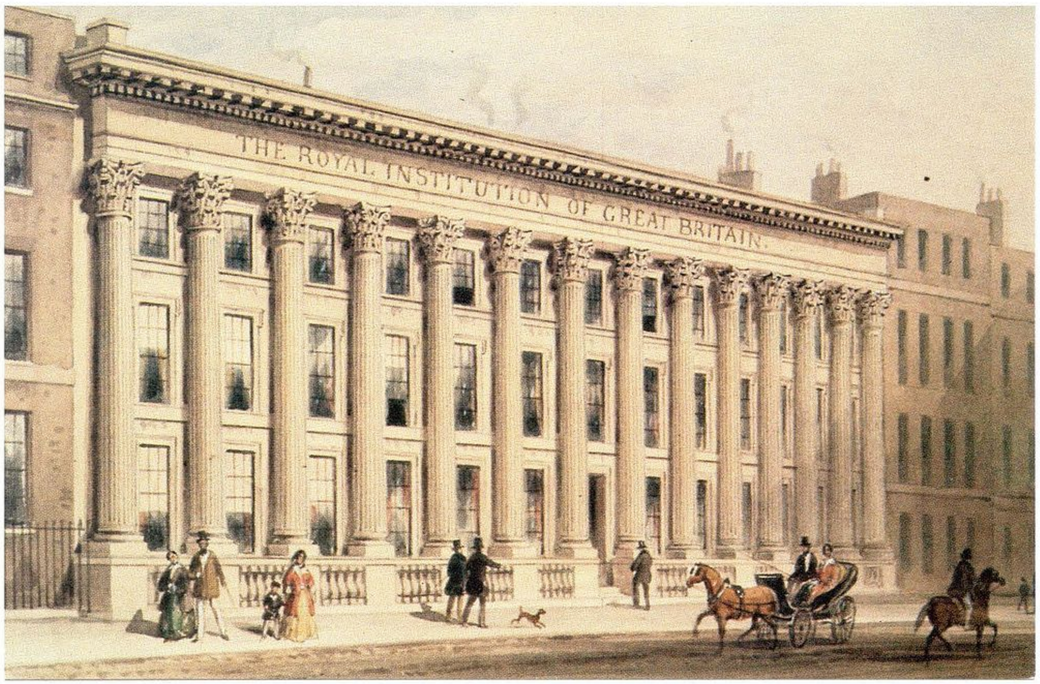




Mr. Starbuck, last night's thunder turned our compasses –that's all.
Chapter 124: *The Needle*,
"Moby Dick", de **Herman Melville** (1851).

Faraday's Electric Motor (1821*)*

Apart from the fast development on Electricity and Magnetism an interest in the connection between Electricity, Magnetism and light surged in the 1830's.



The Royal Institution, 21 Abermarle, London

Michael Faraday (1796-1867)

In 1834, Charles Wheatstone, who was interested in the use of the telegraph made the first experiment to determine the speed of propagation of electrical signals through a cable. He designed an apparatus with rotatory mirrors and determined that the speed of propagation of the signals was close to the speed of propagation of light.

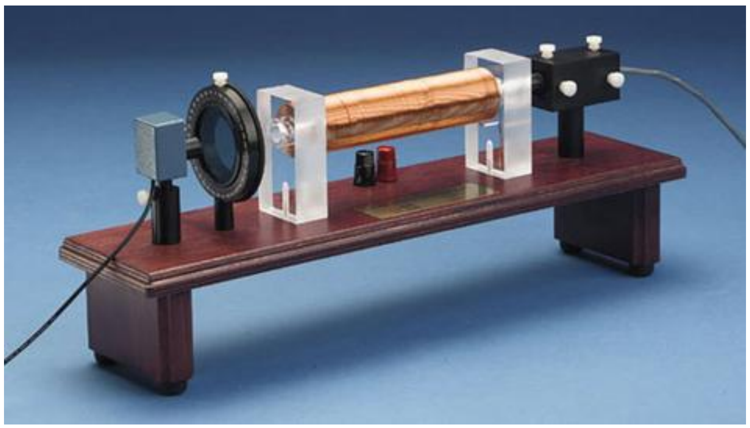
A similar method was later used by Fizeau (1848/49) and Foucalt (1850/52) to make the first laboratory measurements of the speed of light.

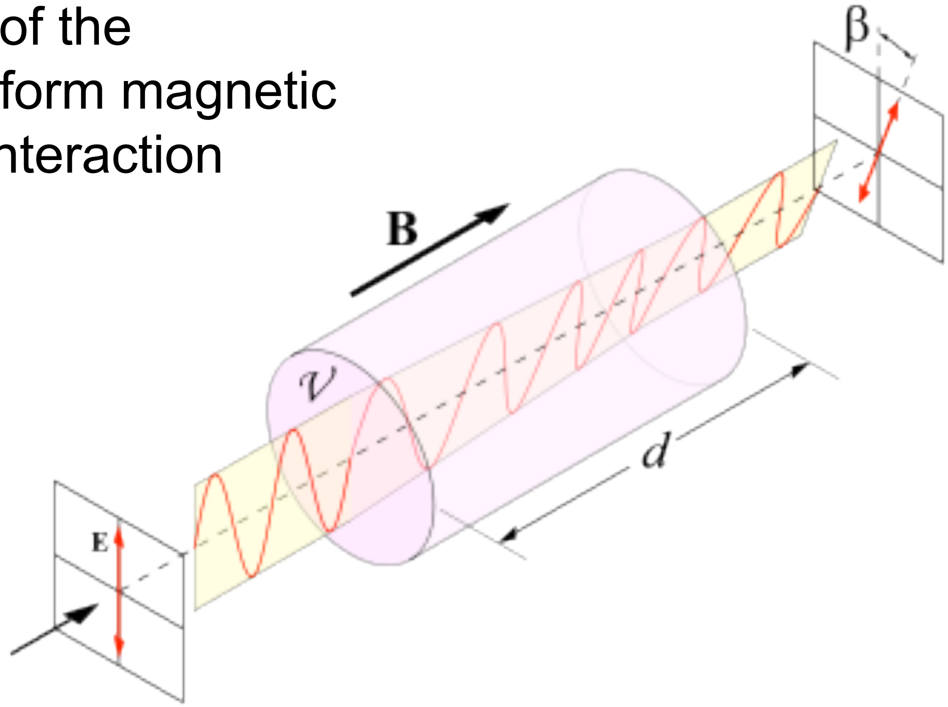
Charles Wheatstone (1802-1875)

Interaction between Light and Magnetism:

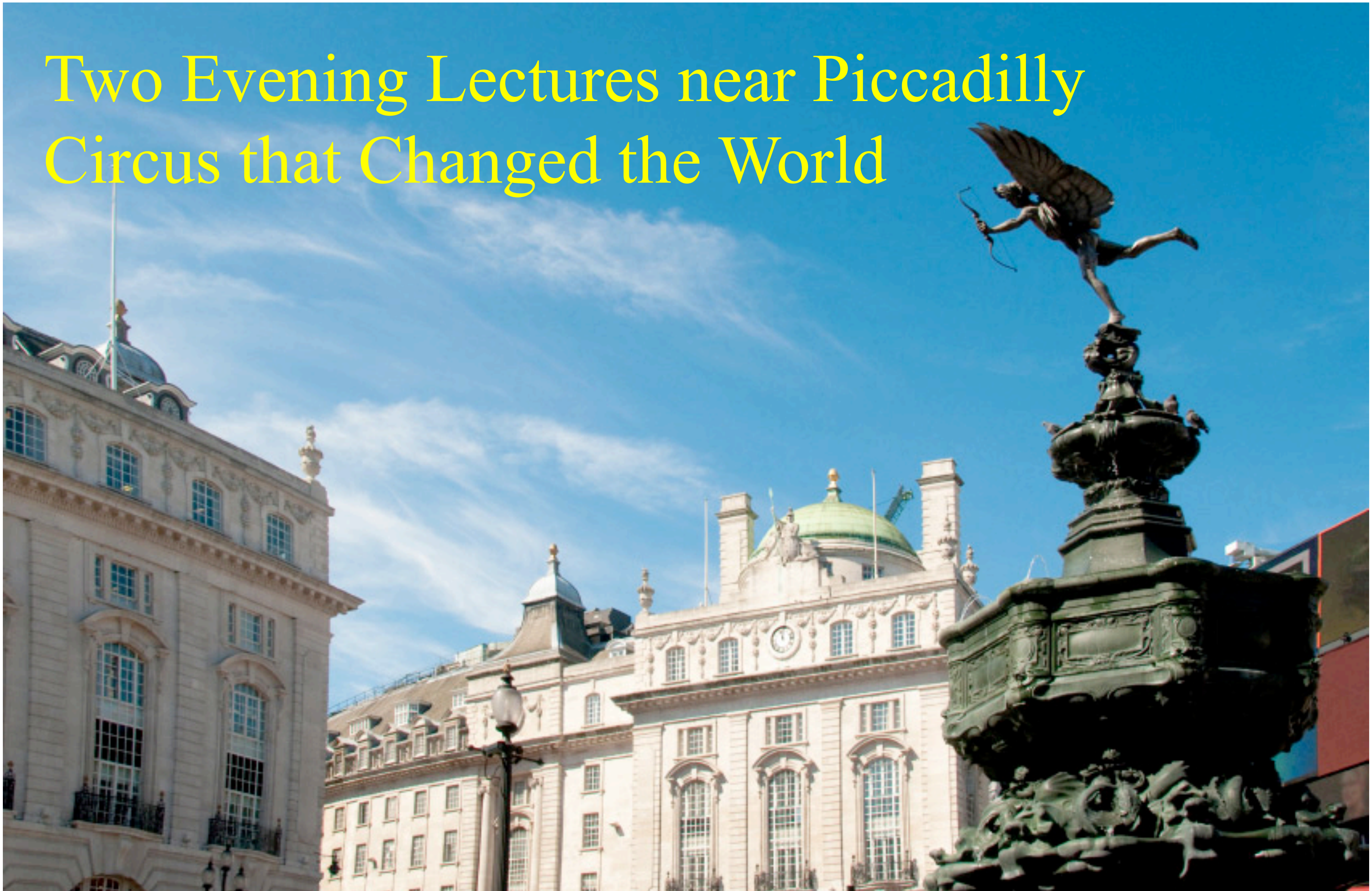
In 1808, Etienne Malus discovered the polarization of light.

In 1845, Michael Faraday discovered experimentally the now called “Faraday Rotation” (of the polarization of light caused by a uniform magnetic field) showing for the first time the interaction between magnetism and optics



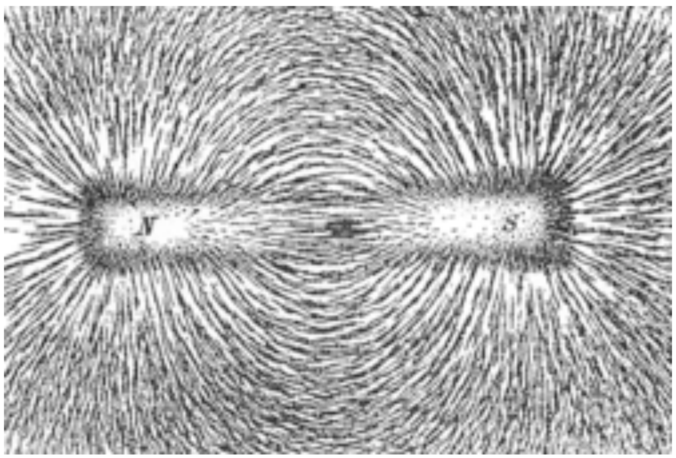


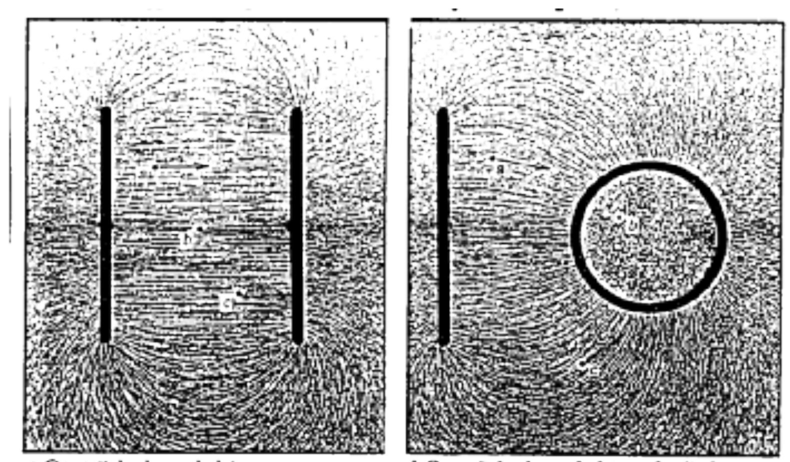
Two Evening Lectures near Piccadilly Circus that Changed the World



Public Lecture, QMath 13, Atlanta, Georgia, October 9, 2016

On Friday April 3, 1846, at the Royal Institution, Michael Faraday gave a lecture on the "Chronoscope" (invented by Charles Wheatstone. Towards the end of his talk, Faraday elaborated on his thoughts about the nature of light and the possible variations of the electromagnetic field.





c. Oppositely charged plates

d. Oppositely charged plate and cylinder

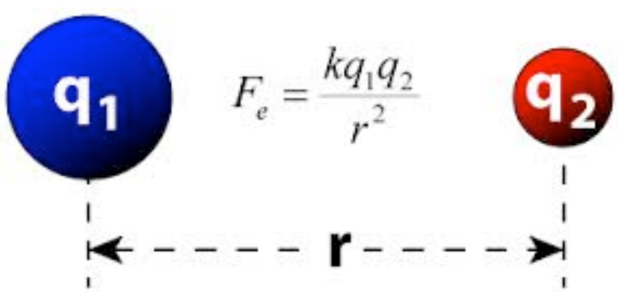
Michael Faraday: **Thoughts on Ray Vibrations,**
Philosophical Magazine 1846.

Michael Faraday: **On the Physical Character of the Lines of Magnetic Forces,**
Philosophical Magazine 1852.

Electricity, Magnetism, and the speed of light:

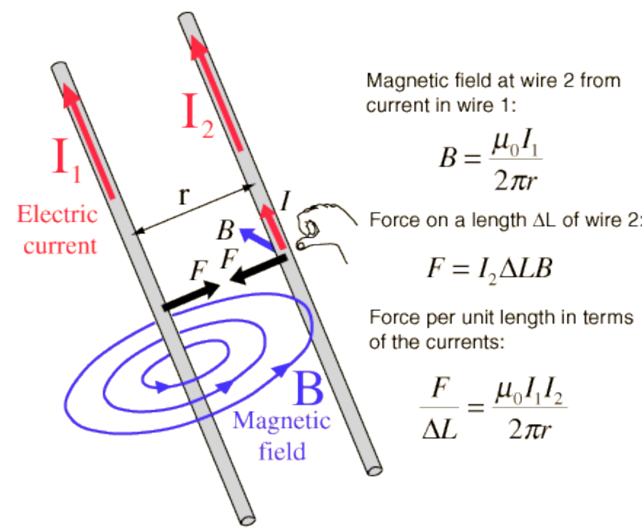
Measuring the force bwteen two electric charges (Coulomb's Law) one can determine ε_0 and measuring the force between two parallel currents (Ampère's Law) one can determine μ_0. In his famous paper Maxwell determined that the speed of propagation of his proposed electromagnetic waves was

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}.$$



Coulomb's Law

$$k = \frac{1}{4\pi\varepsilon_0}.$$



Ampere's Law

Letter to his cousin Charles Cay:

"...I have also a paper afloat, containing an electromagnetic theory of light, which, till I am convinced to the contrary, I hold to be great guns."

PART VI.—ELECTROMAGNETIC THEORY OF LIGHT.

(91) At the commencement of this paper we made use of the optical hypothesis of an elastic medium through which the vibrations of light are propagated, in order to show that we have warrantable grounds for seeking, in the same medium, the cause of other phenomena as well as those of light. We then examined electromagnetic phenomena, seeking for their explanation in the properties of the field which surrounds the electrified or magnetic bodies. In this way we arrived at certain equations expressing certain properties of the electromagnetic field. We now proceed to investigate whether these properties of that which constitutes the electromagnetic field, deduced from electromagnetic phenomena alone, are sufficient to explain the propagation of light through the same substance.

light in this, that the ... tion, and such waves may have all the properties of polarized light.

(96) The only medium in which experiments have been made to determine the value of k is air, in which $\mu=1$, and therefore, by equation (46),

$$V=v. \qquad (72)$$

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

$$v=310{,}740{,}000 \text{ metres per second}$$

is the number of electrostatic units in one electromagnetic unit of electricity, and this, according to our result, should be equal to the velocity of light in air or vacuum.

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

$$V=314{,}858{,}000;$$

according to the more accurate experiments of M. FOUCAULT‡,

$$V=298{,}000{,}000.$$

The velocity of light in the space surrounding the earth, deduced from the coefficient of aberration and the received value of the radius of the earth's orbit, is

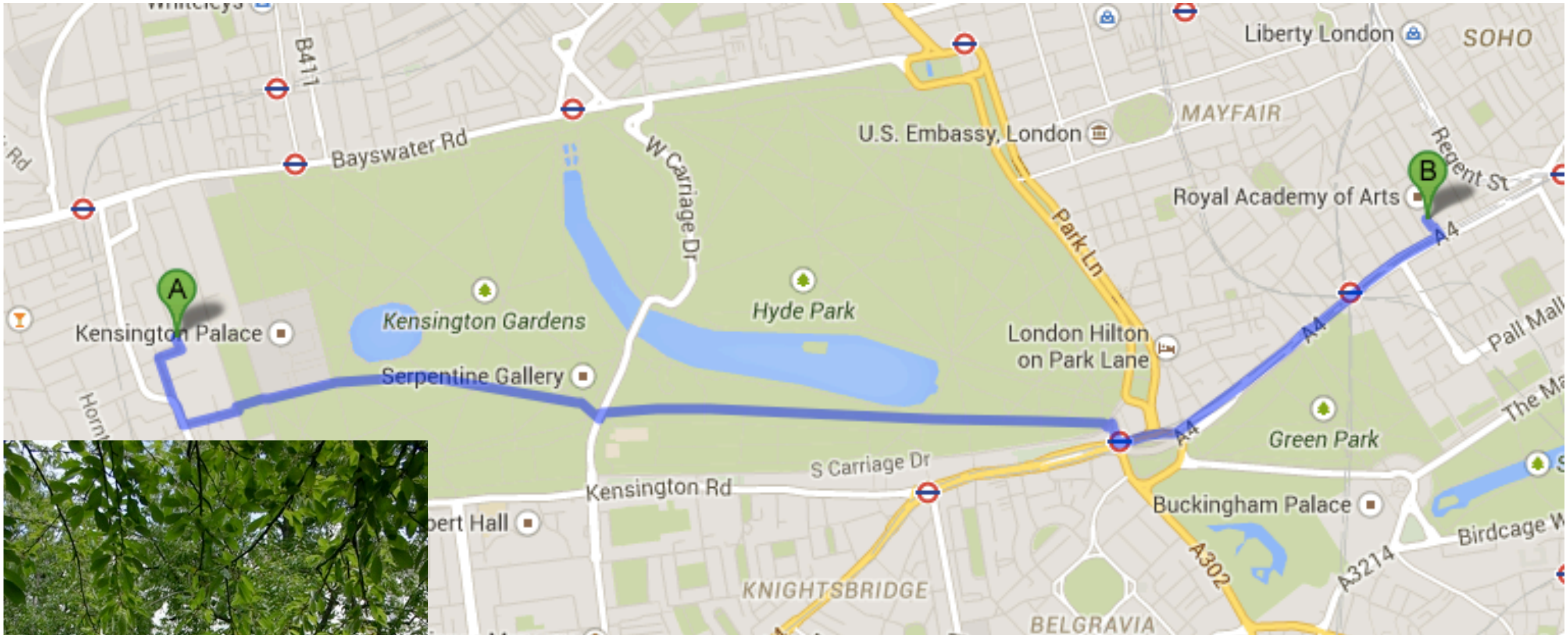
$$V=308{,}000{,}000.$$

(97) Hence the velocity of light deduced from experiment agrees sufficiently well

Piccadilly, from Coventry Street London. Original steel engraving drawn by T. H. Shepherd, engraved by T. Barber. 1830.

Maxwell was not foreign to the Royal Society. Already in 1860, at 29, he had obtained the *Rumford Medal* "...for his research on the composition of colors and other articles on optics..."

And in 1861 he had been elected as member, (i.e., "Fellow of the Royal Society").



Maxwell's house in London,
Located at 16 Palace Gardens Terrace, Kensington,
where he lived from 1860 until 1865.

The Scientific Content of this discovery

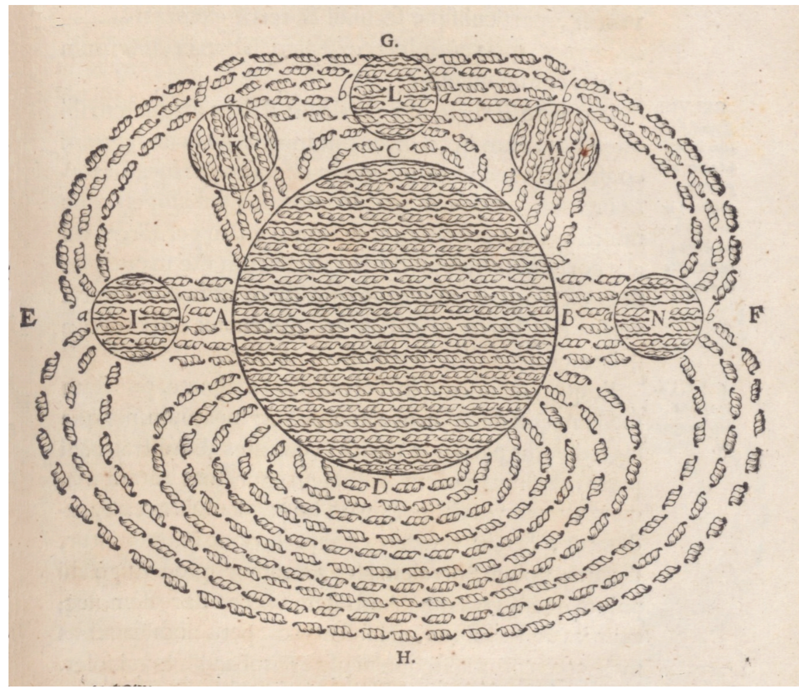
i) The Idea of a Field

ii) Interaction between Light and Electromagnetism

In some sense the first Field Theory was the Gravitational Law of Newton, published in the "Principia" (1687) [Mathematical Principles of Physics]. Newton's Laws and his Law of Gracitation were so successful that they had a huge implication in science.

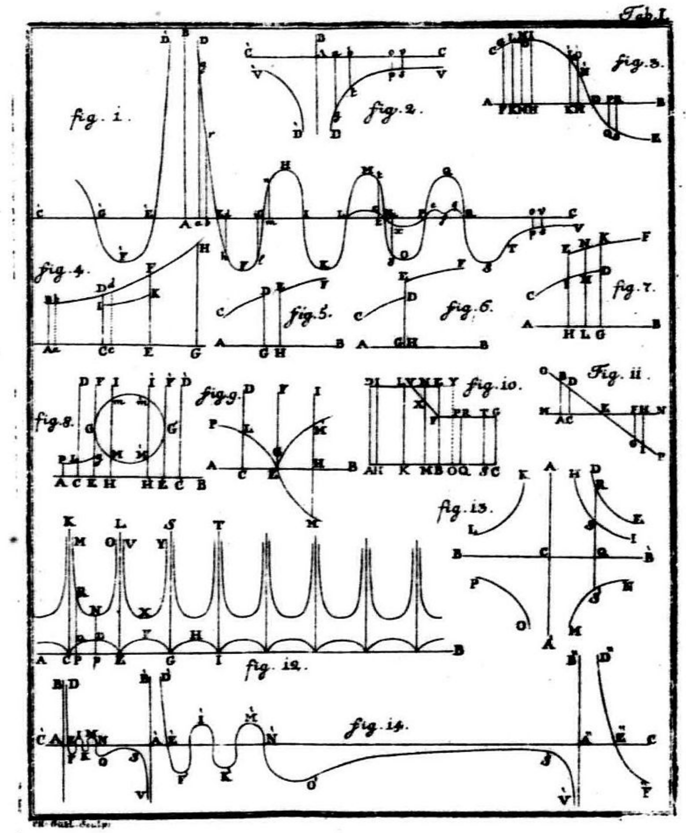
However, even before, several people were studying another Field (the magnetic Field which had a big impact even in the common language).

R. Descartes,
Principia Philosophiae, 1644.
"Line Forces of the Earth
Magnetic Field".



Roger Boscovich (1711-1787) was so taken by the "Principia" that he set himself the task of proposing an interaction of the same form between atoms. He wrote his "Philosophie Naturalis" (1758) with the idea of explaining, among other things, the different phases of matter.

Roger Boscovich (1711-1787)



Maxwell was interested in electromagnetism for a long time.

His first work on the subject was

"On Faraday's Line of Forces" Transactions of the Cambridge Philosophical Society, (1855/1856)

Between 1855 and 1865 he published many articles on the subject.

Finally in 1873 he published his famous Treatise on Electricity and magnetism.

...before I began the study of electricity I resolved to read no mathematics on the subject till I had first read through Faraday's Experimental Researches in Electricity.

The electromagnetic waves predicted by Maxwell were confirmed experimentally by David Hughes in 1879, and finally by Heinrich Hertz in 1887 at the University of Karlsruhe.

"On Electromagnetic Effects Produced by Electrical Disturbances in Insulators" (1887).

Heinrich Hertz (1857-1894)

... I wrote these equations (i.e., the dynamical equations for the electromagnetic field) in the countryside (i.e., at his family house in Glenlair) before I had any idea about the fact that the speed of propagation of the magnetic perturbations they predicted were so close to the speed of light [From a letter to William Thomson, December 10, 1861].

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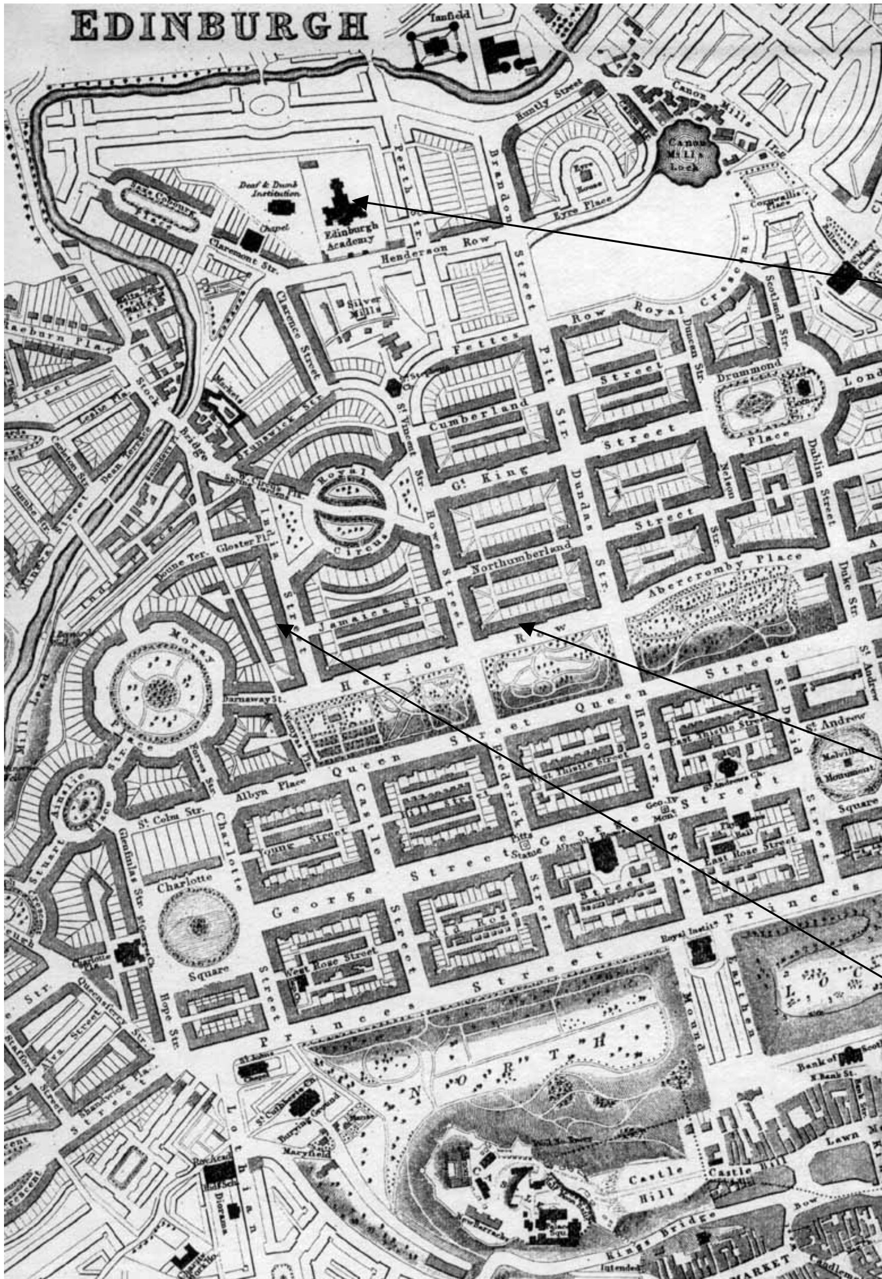
James Clerk Maxwell was born here, at 14 India Street, Edimburgo, on June 13, 1831

The main entrance to Maxwell's House as it is today.



Edinburgh Academy

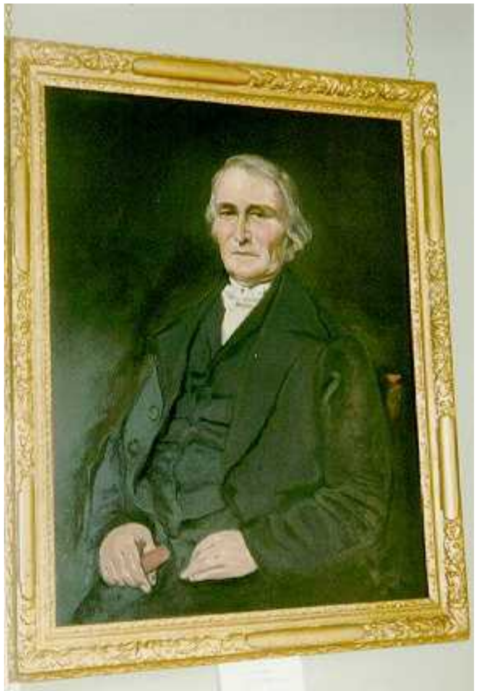
Heriot Row

14 India Street

Today, Maxwell's House is the site of the

"James Clerk Maxwell Foundation",

A Research Institute in Mathematical Physics in Edinburgh



John Clerk Maxwell *Jane and Frances Cay* *James Clerk Maxwell*

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Dining Room

Peter G. Tait (1831-1901).

James Clerk Maxwell, as a child, with his mother, Frances Cay.

He is a very happy man, and has improved much since the weather got moderate; he has great work with doors, locks, keys etc., and 'Show me how it doos' is never out of his mouth. He also investigates the hidden course of streams and bell-wires, the way the water gets from the pond through the wall and a pend or small bridge and down a drain ...

Maxwell as a child.

Jemima Wedderburn (Blackburn) (1823-1909)

Watercolors and early ink work from Birds from Nature – Blackburn's "greatest ornithological achievement."

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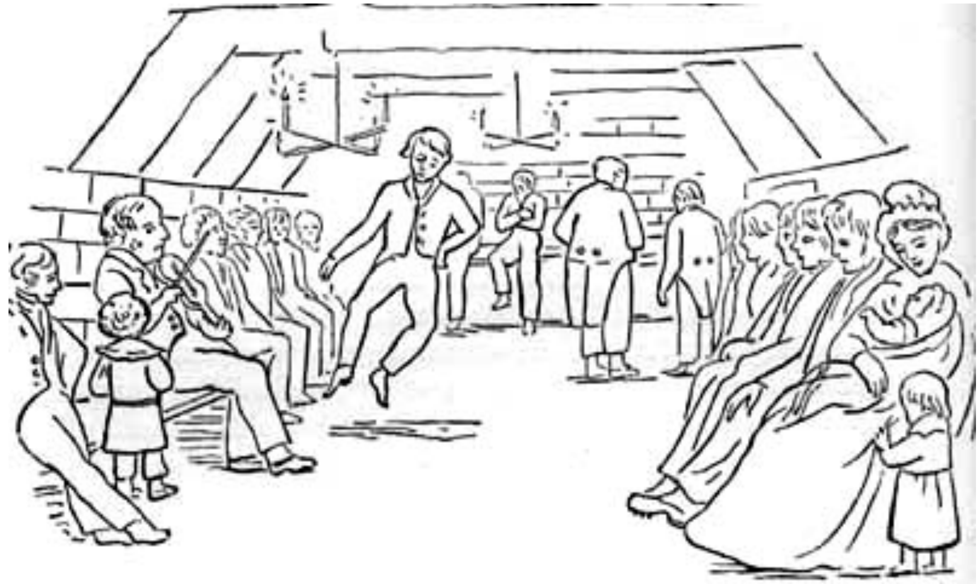
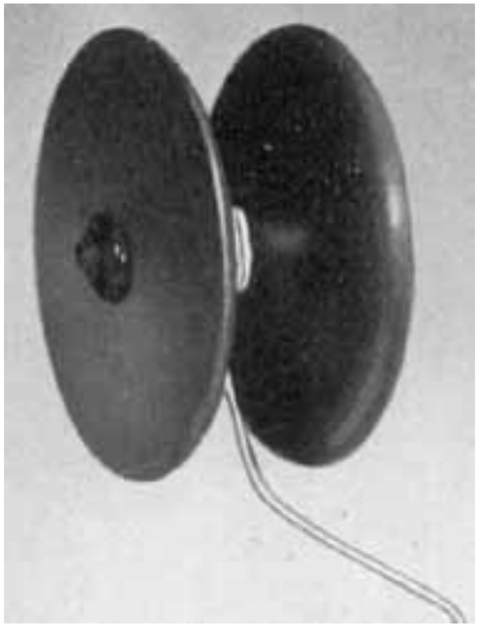


James with his father

James with his father

James playing in Glenlair in 1841 with Jemima and his tutor.



The Zoetrope of James C. Maxwell with sequences of figures drawn by himself.

1841

Water color by Jemima Wedderburn.
Notice the Ursa Minor

A stop in Newton on the way back to Edinburgh, November 13, 1841

Arriving at 31 Heriot Row, Edinburgh, November 18, 1841

James Clerk Maxwell studied at the Edinburgh Academy from November 1841 until June 1847.

View of the Edinburgh Academy, in 1828.
It was co-funded by Walter Scott in 1824.

In July 1845 Maxwell was awarded the Medal of Mathematics at the Edinburgh SAcademy, and according to Peter G. Tait,

…About the middle of his school career however he surprised his companions by suddenly becoming one of the most brilliant among them, gaining prizes and sometimes the highest prizes for scholarship, mathematics, and English verse composition. From this time forward I became very intimate with him, and we discussed together, with schoolboy enthusiasm, numerous schoolboy problems, among which I remember particularly the various plane sections of a ring or tore, and the form of a cylindrical mirror which should show one his own image unperverted.

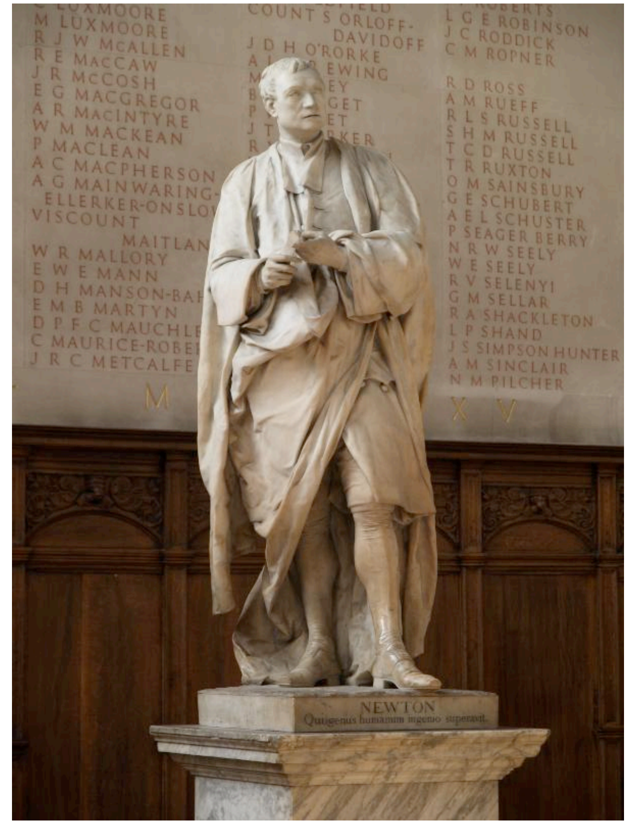
When Maxwell was 14 years old he published his first paper dealing with multifocal ovals in the Transactions of the Royal Society of Edinburgh: *Oval curves, and those having a plurality of Foci.*

After graduating from the Edinburgh Academy, Maxwell studied at the University of Edinburgh where he graduated in 1850.

Engraving from Modern Athens - published 1829

Edinburgh University - South Bridge Street

TRINITY COLLEGE, CAMBRIDGE UNIVERSITY: 1850-1854



After graduating from the University of Edinburgh he joined the Trinity College in Cambridge. He graduated from Cambridge in 1854 as Second Wrangler and shared the Smith Prize with the Senior Wrangler Edward Routh.

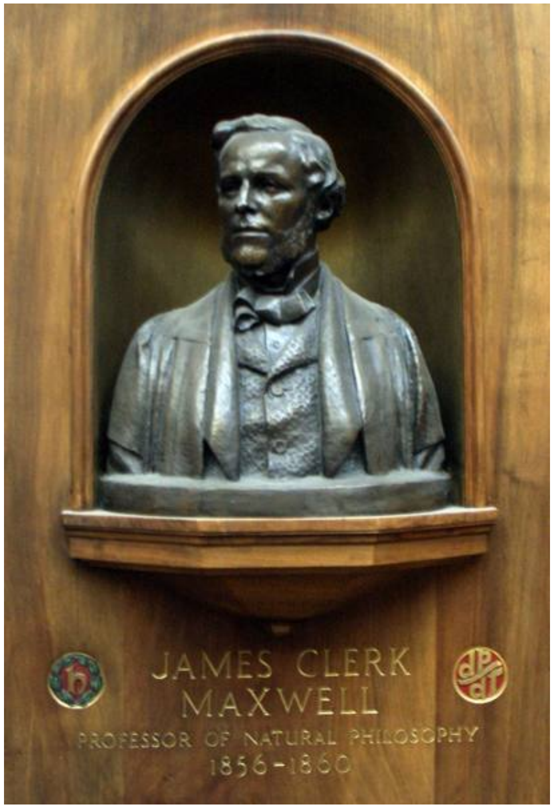
Between 1855 and 1856 Maxwell is a fellow of Trinity College. In that period he writes the two articles:

i) “Experiments on Colour, as perceived by the eye, with remarks on Colour Blindness” (1855),

ii) “On Faraday’s line of forces” (1855-1856).

In the last artcle Maxwell interprets Faraday’s Law of induction in its present setting, i.e., as:

$$\varepsilon = -\frac{d}{dt}\int \vec{B} \cdot d\vec{S}.$$



In November 1856 Maxwell joined the Marischal College at the University of Aberdeen.

Maxwell's father died in April 1856.

On June 1859, Maxwell gets married to Katherine Mary Dewar.

In 1860 he has to leave Marischal College.

He applies to an open position at the University of Edinburgh but the place is given to Peter Guthrie Tait.

His London Period: 1860-1865:

Between 1860 and 1865 he was the Chairman of the Natural Philosophy Department at King's College, London.

From 1865 until 1871 he returns to Glenlair.

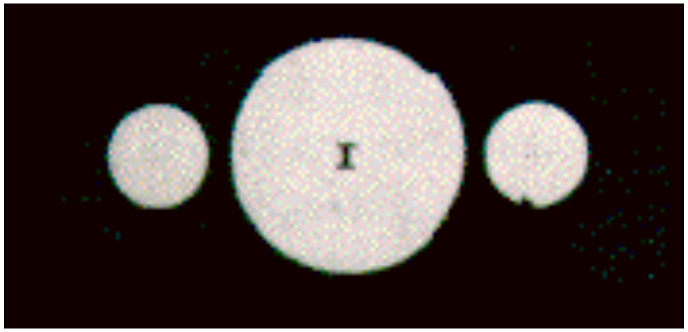
In 1871 he is appointed Professor of Experimental Physics at the Cavendish Lab., Cambridge, where he stays until his death.

James Clerk Maxwell's grave, Parton Parish near Glenlair.

Loch Ken, Scotland. In one of his shores is the village of Parton.

Maxwell’s main Scientific Contributions

Structure of the Rings of Saturn
Color Vision
Electromagnetism
Kinetic Theory of Gases
Automatic Control
Structural Analysis in Civil Engineering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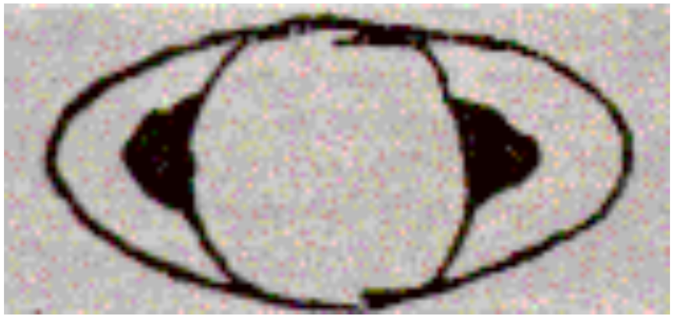
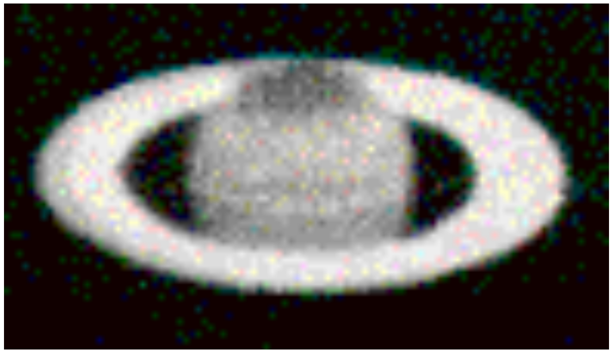



XIII


Ann. 1676
Fig 138

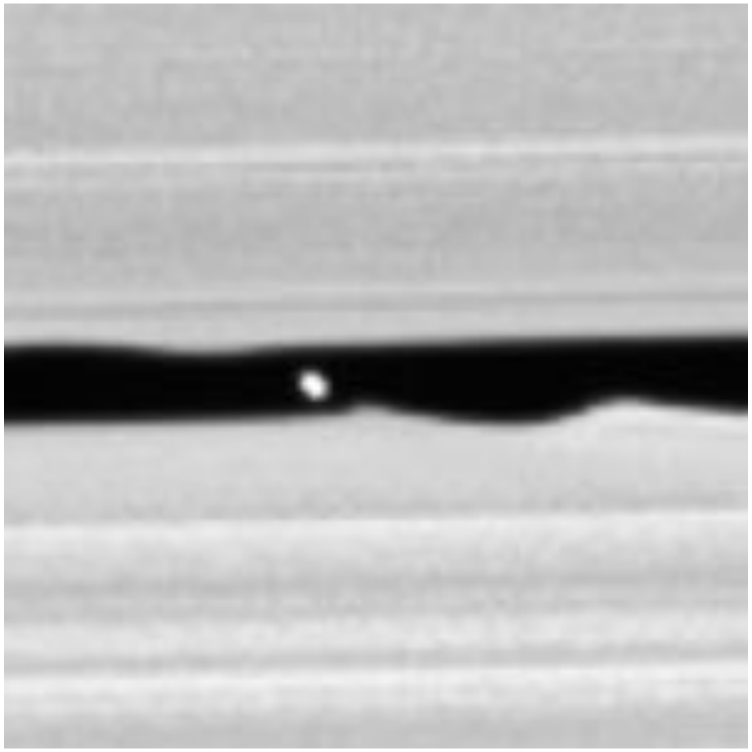


On the Stability of the Motion of Saturn's Rings (1859)
Adams Prize

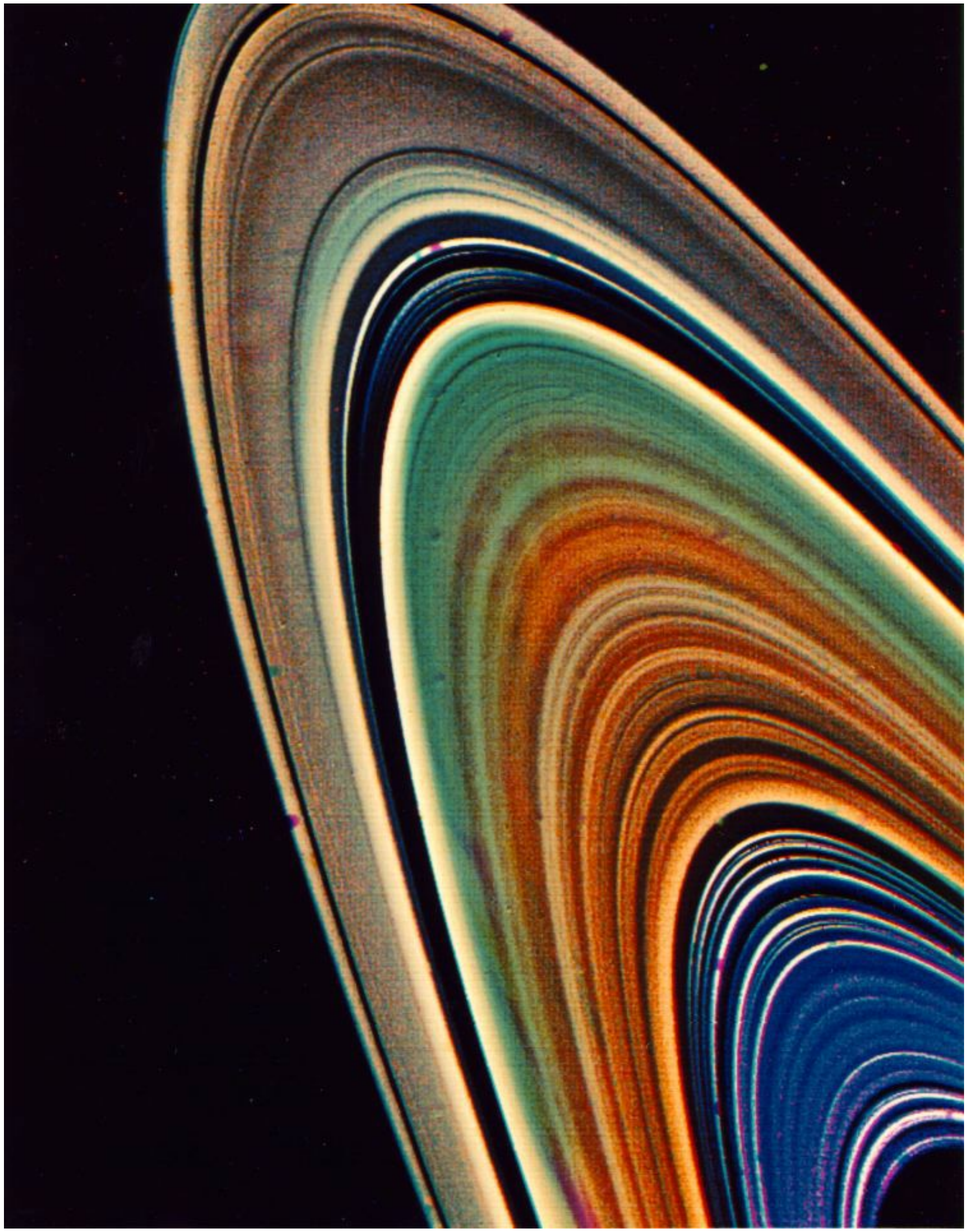
The final result, therefore, of the mechanical theory is, that the only system of rings which can exist is one composed of an indefinite number of unconnected particles, revolving round the planet with different velocities according to their respective distances. These particles may be arranged in series of narrow rings, or they may move through each other irregularly. In the first case, the destruction of the system will be very slow, in the second case, it will be more rapid, but there may be a tendency towards an arrangement in narrow rings, which may retard the process.

In 1895, Keeler spectroscopically measured the rotation speeds at different parts of the rings of the Saturn, at the Allegheny Observatory in Pittsburgh. He verified the effects mathematically predicted by James Clerk Maxwell in 1857. The velocities of rotation varied from 20 kilometers per second at the inner edge of the B ring to just under 16 kilometers per second at the outer edge of the A ring. This confirmation of Maxwell's hypothesis brought Keeler worldwide fame.

James Edward Keeler (1857-1900), American astronomer, late 1890s.



The J. Keeler division, as seen from the Cassini spacecraft in 2005.



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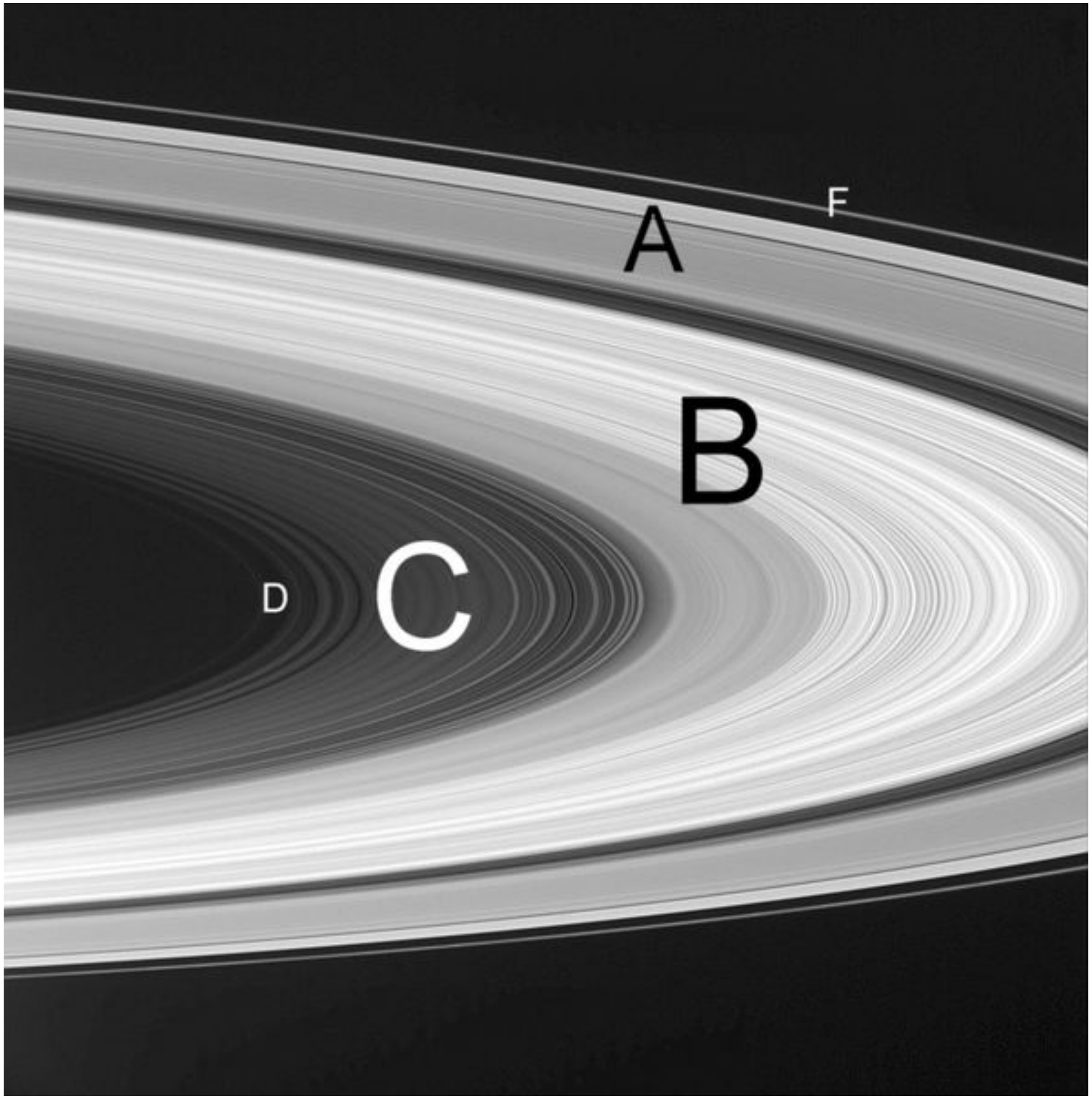


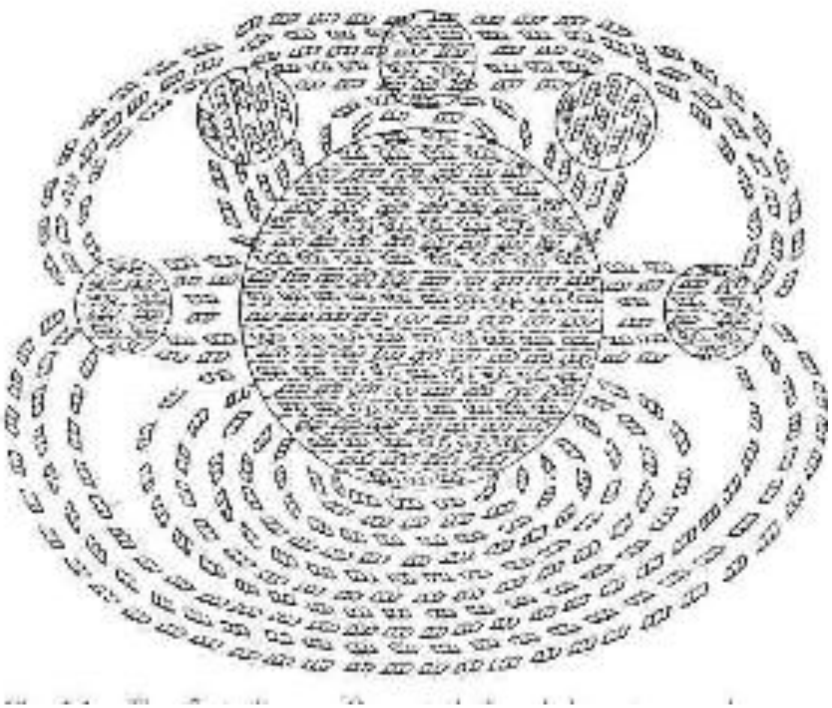
Maxwell Division between Rings B and C

Color Vision (1861):

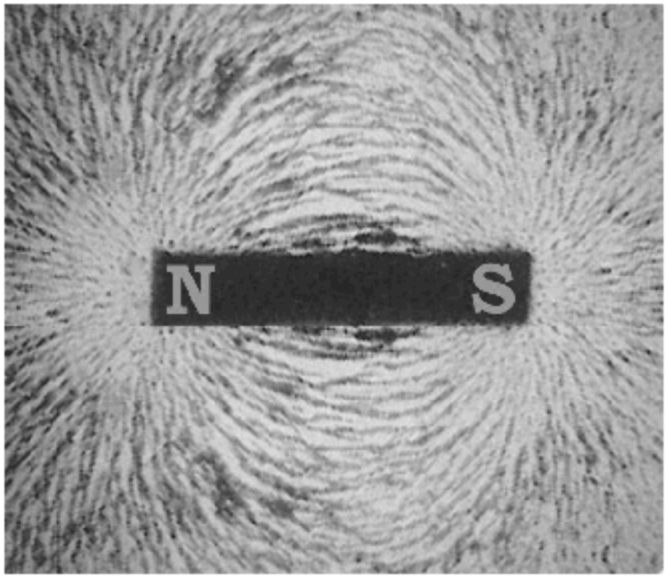
Maxwell wrote many manuscripts on the subject of color vision and produced the first color photograph (using the RGB decomposition).

The first color photograph (J. Clerk Maxwell, 1861).

Lineas de Fuerza: Petrus Peregrinus, William Gilbert, Descartes, Michel Faraday, Maxwell.



Lineas de Fuerza del Campo Magnetico, según Descartes.



Lineas de Campo Magnético, Experimentos de Faraday.

Light as Electromagnetic Phenomena (ca. 1862):

…the velocity of light in air, as determined by M. Fizeau, is …195.647 miles per second. The velocity of transverse undulations in our hypothetical medium … agrees so exactly with the velocity of light calculted from the optical experiments of M. Fizeau, that we can scarcely avoid the inference that lights consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena.

James Clerk Maxwell, "A dynamical theory of the electromagnetic field", Phil. Transactions of the Royal Society (London) 155 (1865).

Maxwell Equations (Electrodynamics):

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \nabla \cdot \vec{D} = \rho$$

$$\nabla \times H = \vec{J} + \frac{\partial \vec{D}}{\partial t} \qquad \nabla \cdot \vec{B} = 0$$

$$\vec{D} = \epsilon_0 \vec{E} + \vec{P} \qquad \vec{B} = \mu_0 \left(\vec{H} + \vec{M} \right)$$

Kinetic Theory of Gases:

J.C. Maxwell, "Illustrations of the Dynamical Theory of Gases" Phil. Mag. 19 (1860), pp. 19-32;

J.C. Maxwell, "On the results of Bernoulli's theory of gases as applied to their internal friction, their diffusion, and their Conductivity for heat", Report of the 30th Meeting of the British Association for the Advancement of Science, part 2 (1860): 15-16.

J.C. Maxwell, "Viscosity of internal friction of air and other gases", Phil. Transactions of the Royal Society of London 156 (1866), 249-268.

At the meeting of the British Association in Bradford, UK, on September 23, 1873, Maxwell delivered his talk: "Molecules", which was later published in Nature (437-441).

Bradford Hall, Sept. 1873.

The implications of Faraday's ideas and Maxwell's Equations were fundamental for the development of Physics in the XXth Century. They originated:

i) Special Theory of Relativity.

ii) The General Theory of Relativity.

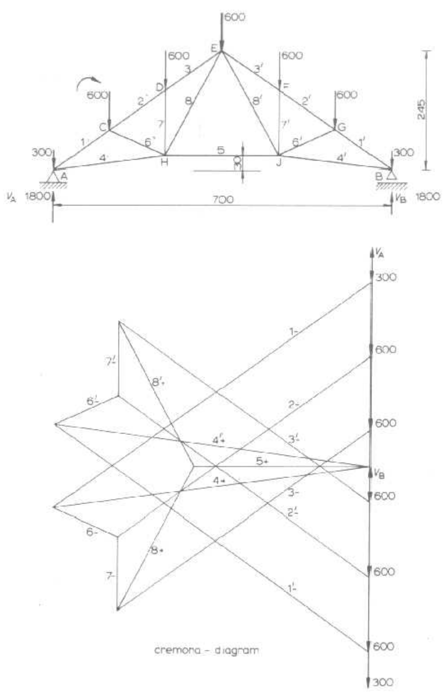
iii) Quantum Mechanics.

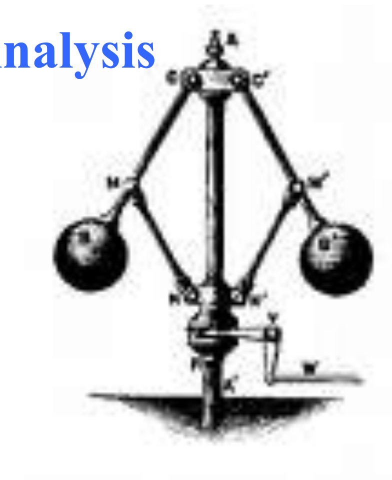
By combining Quantum Mechanics with Field Theory, Born, Jordan, Heisenberg (1925) started a whole new point of view, where at the end what is important are the Fields, and the particles are just, in some sense, excitations of these fields.

Crutial contributions to Engineering:

1. J. Clerk Maxwell, “On governors”, Proc. Royal Society, 100 (1868).
   He established the foundations of Automatic Control.

2. He deviced new methods of Structural Analysis
for Civil Engineering.





Maxwell-Cremona Diagram.

Albert Einstein (1931): On the celebration of Maxwell's centennial.

We may say that, before Maxwell, Physical Reality, in so far as it was to represent the process of nature, was thought of as consisting in material particles, whose variations consist only in movements governed by partial differential equations. Since Maxwell's time, Physical Reality has been thought of as represented by continuous fields, governed by partial differential equations, and not capable of any mechanical interpretation. This change in the conception of Reality is the most profound and the most fruitful that physics has experienced since the time of Newton.

Max Planck (1931): On the celebration of Maxwell's centennial.

… it was his task to build and complete the classical theory, and in so doing he achieved greatness unequalled. His name stands magnificently over the portal of classical physics, and we can say this of him: by his birth, James Clerk Maxwell belongs to Edinburgh, by his personality he belongs to Cambridge, by his work he belongs to the whole world.


¡Thank you!