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Worldviews, Wranglers, and the Making of Theoretical Physicists

8.225 / STS.042, Physics in the 20th Century
Professor David Kaiser, 14 September 2020

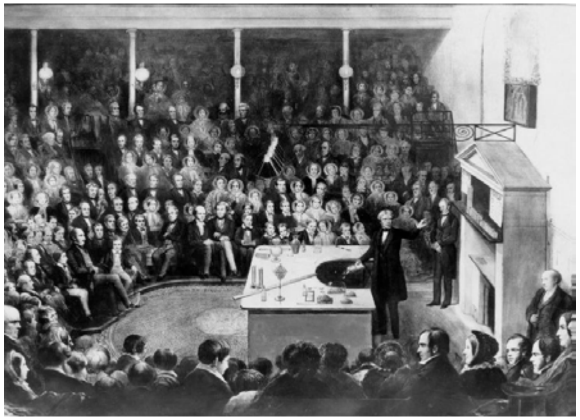
1. Maxwell's Equations, Then and Now

2. Training Cambridge Wranglers

3. The Electromagnetic Worldview

4. Institutions and Theorists

Recap: Faraday, Thomson, Maxwell



Faraday delivering Royal Institution "Christmas Lecture," 1855

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Michael Faraday had little formal education; he was first apprenticed as a bookbinder, and then as a natural philosopher at the Royal Institution.

Partly inspired by his Sandemanian faith, he was fascinated by the *interconvertibility* of forces and an underlying *unity of nature* — a unity made possible by an all-pervasive *luminiferous ether*.

He introduced *lines of force* and then *fields* to characterize the state of the ether. In place of Newtonian "action at a distance," Faraday emphasized local effects. *The birth of field theory!*

William Thomson and James Clerk Maxwell trained in mathematics at Cambridge University in the 1840s-50s. They formalized many of Faraday's ideas, and found *mathematical analogies* between electromagnetic phenomena and mechanics: a "mechanical worldview."

Maxwell found that disturbances in the ether propagated at the *speed of light*: light was just "transverse undulations" of **E** and **B** in the ether.

Cambridge University, King's Parade, ca. 1870

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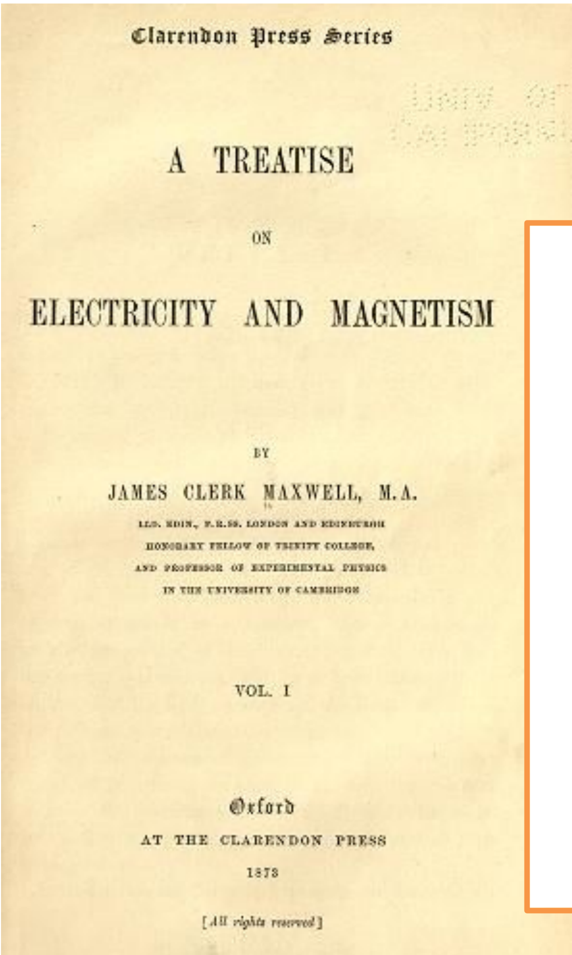
Maxwell's Equations, Then and Now


Clarendon Press Series

A TREATISE

ON

ELECTRICITY AND MAGNETISM

BY

JAMES CLERK MAXWELL, M.A.

LL.D. EDIN., F.R.SS. LONDON AND EDINBURGH
HONORARY FELLOW OF TRINITY COLLEGE,
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VOL. I

Oxford

AT THE CLARENDON PRESS

1873

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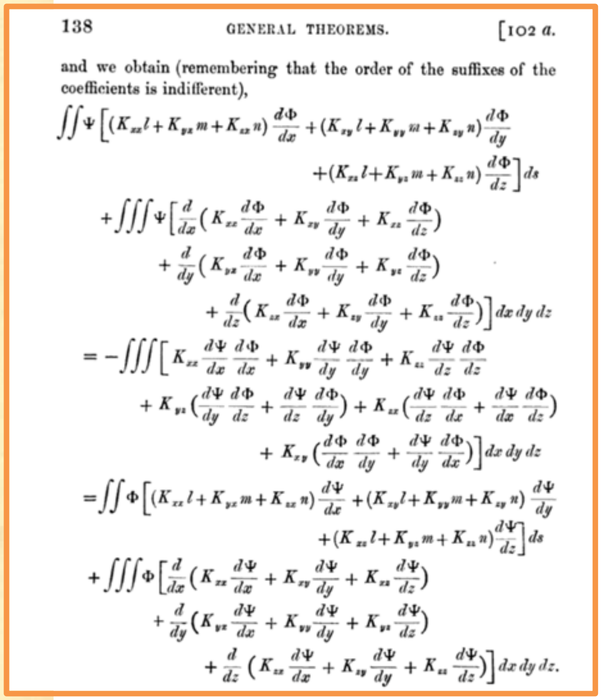
In his two-volume 1873 *Treatise*, Maxwell described his new theory of electricity and magnetism. He introduced what we call "Maxwell's equations," in full Cartesian-component form.


138 GENERAL THEOREMS. [102 *a*.

and we obtain (remembering that the order of the suffixes of the coefficients is indifferent),

$$\iint \Psi \Big[(K_{xx} l + K_{yx} m + K_{zx} n) \frac{d\Phi}{dx} + (K_{xy} l + K_{yy} m + K_{zy} n) \frac{d\Phi}{dy} + (K_{xz} l + K_{yz} m + K_{zz} n) \frac{d\Phi}{dz}\Big] ds$$

$$+ \iiint \Psi \Big[\frac{d}{dx}\Big(K_{xx} \frac{d\Phi}{dx} + K_{xy} \frac{d\Phi}{dy} + K_{xz} \frac{d\Phi}{dz}\Big) + \frac{d}{dy}\Big(K_{yx} \frac{d\Phi}{dx} + K_{yy} \frac{d\Phi}{dy} + K_{yz} \frac{d\Phi}{dz}\Big) + \frac{d}{dz}\Big(K_{zx} \frac{d\Phi}{dx} + K_{zy} \frac{d\Phi}{dy} + K_{zz} \frac{d\Phi}{dz}\Big)\Big] dx\, dy\, dz$$

$$= -\iiint \Big[K_{xx} \frac{d\Psi}{dx}\frac{d\Phi}{dx} + K_{yy} \frac{d\Psi}{dy}\frac{d\Phi}{dy} + K_{zz} \frac{d\Psi}{dz}\frac{d\Phi}{dz} + K_{yz}\Big(\frac{d\Psi}{dy}\frac{d\Phi}{dz} + \frac{d\Psi}{dz}\frac{d\Phi}{dy}\Big) + K_{zx}\Big(\frac{d\Psi}{dz}\frac{d\Phi}{dx} + \frac{d\Psi}{dx}\frac{d\Phi}{dz}\Big) + K_{xy}\Big(\frac{d\Phi}{dx}\frac{d\Phi}{dy} + \frac{d\Psi}{dy}\frac{d\Phi}{dx}\Big)\Big] dx\, dy\, dz$$

$$= \iint \Phi \Big[(K_{xx} l + K_{yx} m + K_{zx} n) \frac{d\Psi}{dx} + (K_{xy} l + K_{yy} m + K_{zy} n) \frac{d\Psi}{dy} + (K_{xz} l + K_{yz} m + K_{zz} n) \frac{d\Psi}{dz}\Big] ds$$

$$+ \iiint \Phi \Big[\frac{d}{dx}\Big(K_{xx} \frac{d\Psi}{dx} + K_{xy} \frac{d\Psi}{dy} + K_{xz} \frac{d\Psi}{dz}\Big) + \frac{d}{dy}\Big(K_{yx} \frac{d\Psi}{dx} + K_{yy} \frac{d\Psi}{dy} + K_{yz} \frac{d\Psi}{dz}\Big) + \frac{d}{dz}\Big(K_{zx} \frac{d\Psi}{dx} + K_{zy} \frac{d\Psi}{dy} + K_{zz} \frac{d\Psi}{dz}\Big)\Big] dx\, dy\, dz.$$

A later Maxwellian, Oliver Heaviside, invented vector notation (**E**, **B**, div, grad, curl) *expressly* to ease the manipulation of Maxwell's huge *Treatise*!

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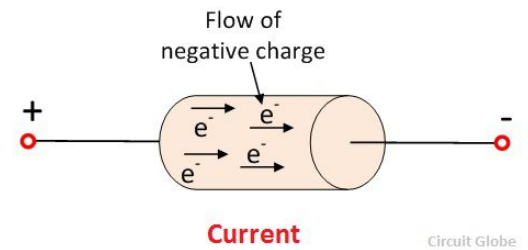
Maxwell’s Equations, Then and Now

More than just differences in *notation*. To Maxwell and his peers, Maxwell’s equations were founded on a fundamentally different idea of *what the world is made of* than our modern views.

To *us*, Maxwell’s equations describe the behavior of fundamental charged particles (electrons, ions). Electric charge is *conserved*: a fixed amount of charge is attached to each microscopic charge-carrier. Electric *current* is nothing more than fundamental charge-carriers in motion.



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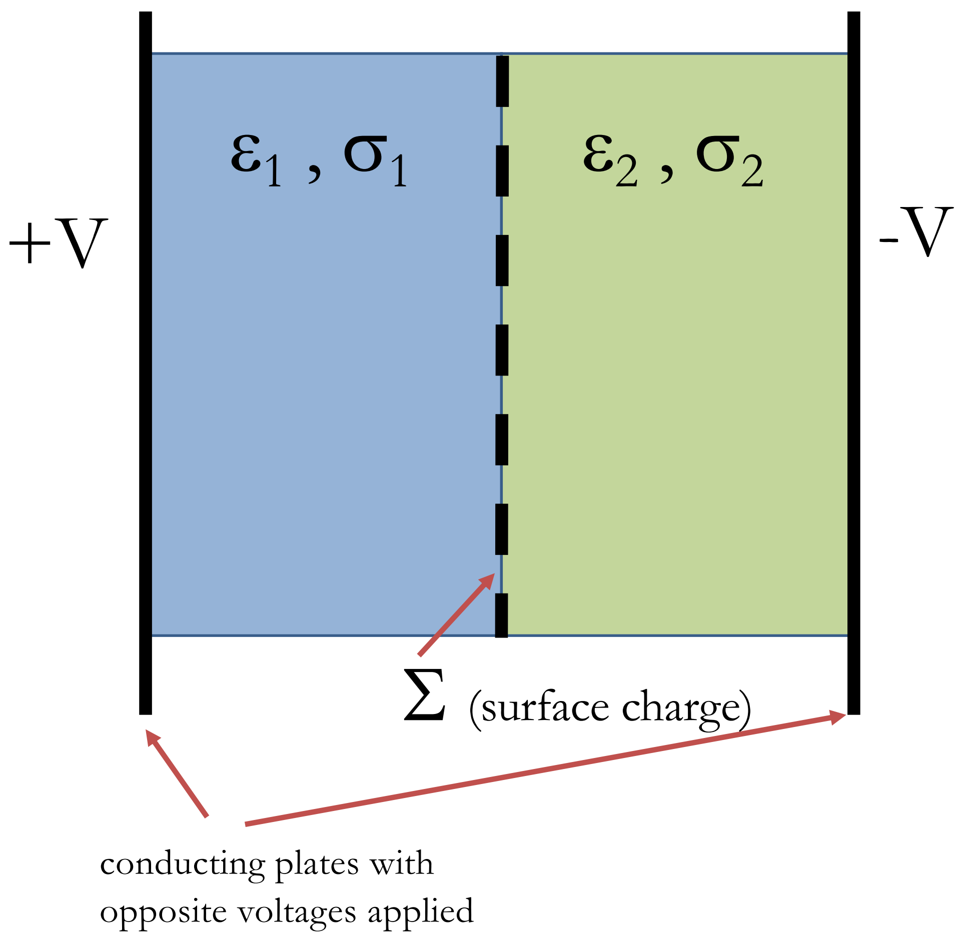
To Maxwell, *none of this was true!* (The electron wasn’t discovered for another 20 years after publication of his *Treatise*.) To the Maxwellians, the world was a *continuum*, not a collection of discrete point particles. They were “inverted atomists”: “Instead of building the world out of atoms, they built atoms out of the world.” (Buchwald)

Maxwell's Equations, Then and Now



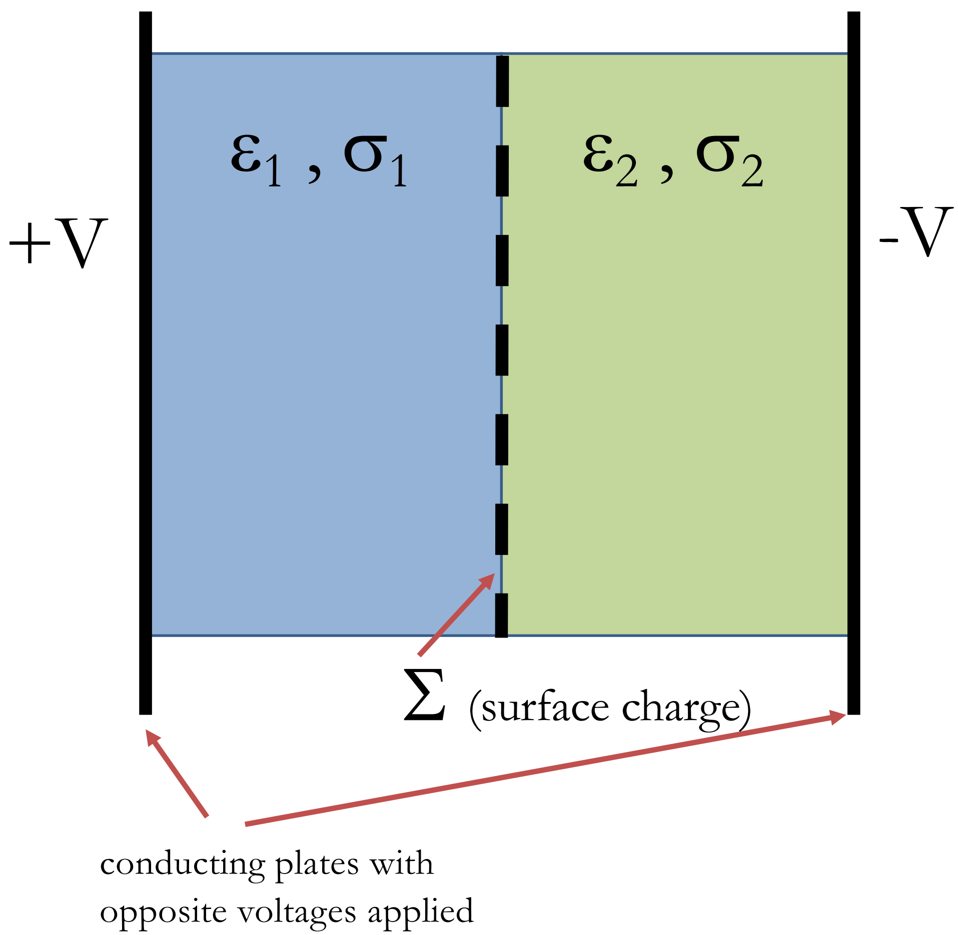
To the Maxwellians, charge could drift in and out of existence, depending on the state of the medium. It was a local manifestation of dissipative strains in the ether.

Charge as surface effect: two different materials fill the space between two conducting plates. The applied voltage puts the underlying ether under *tension*. The potential energy stored in the ether would be dissipated at a rate controlled by the local medium's *elastic capacity* [dielectric constant] and *conducting capacity* [conductivity]. Dissipation rate: $\tau = \varepsilon/\sigma$.

ε: how easy is it to store potential energy
σ: how easy is it to release the stored tension

$$\Sigma \propto \left(e^{-\sigma_1 t/\varepsilon_1} - e^{-\sigma_2 t/\varepsilon_2}\right)$$

Maxwell's Equations, Then and Now



To the Maxwellians, charge could drift in and out of existence, depending on the state of the medium. It was a local manifestation of dissipative strains in the ether.

We would say: both materials consist of fundamental charges, which can be moved around or *polarized* when the voltages are applied, leading to a surface charge Σ. The parameters ε and σ characterize how easily the fundamental charges can be rearranged.

For us, *charge comes first*. For the Maxwellians, *charge was a secondary effect of the state of the medium.*

$$\Sigma \propto \left(e^{-\sigma_1 t/\varepsilon_1} - e^{-\sigma_2 t/\varepsilon_2}\right)$$

Maxwell Summary

Although we still use "Maxwell's Equations" (thank you, Oliver Heaviside!), the way we *interpret* those equations is almost exactly the opposite of how the Maxwellians did.

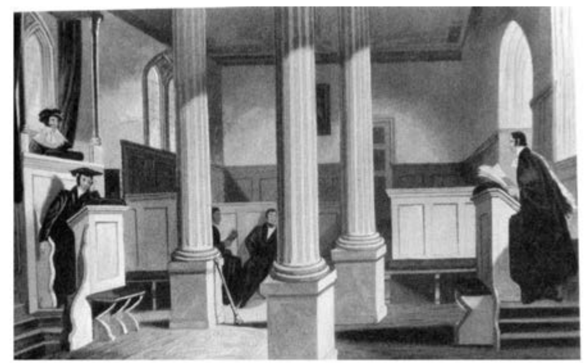
For Maxwell, like Faraday and Thomson, the ether came first. Theirs was a *mechanical worldview*. Continuity was the key: all of physics came down to the behavior of a continuous elastic medium, which supported contiguous local actions. No point particles, no fundamental charges — all (time-varying) states of the ether.

Questions?

Training Cambridge Wranglers

Michael Faraday had practically no mathematical training. By the mid-19th century, there began a massive shift in the *training* of natural philosophers, centered at Cambridge University.

New shift to *paper* and *written examinations.* Students previously had to bring their own slate, chalk, compass, and ruler for lessons in Euclid — and then dispute geometrical proofs *orally*, in *Latin*!



Oral disputation (in Latin), Cambridge, early 19th century

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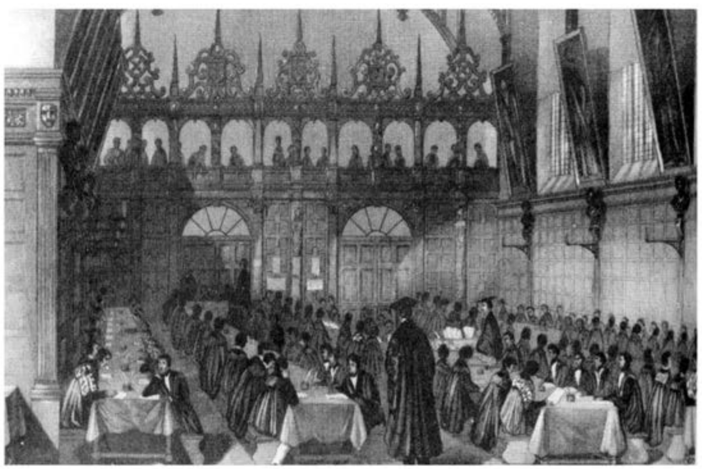

Written "Tripos" examination at Cambridge, mid-19th century

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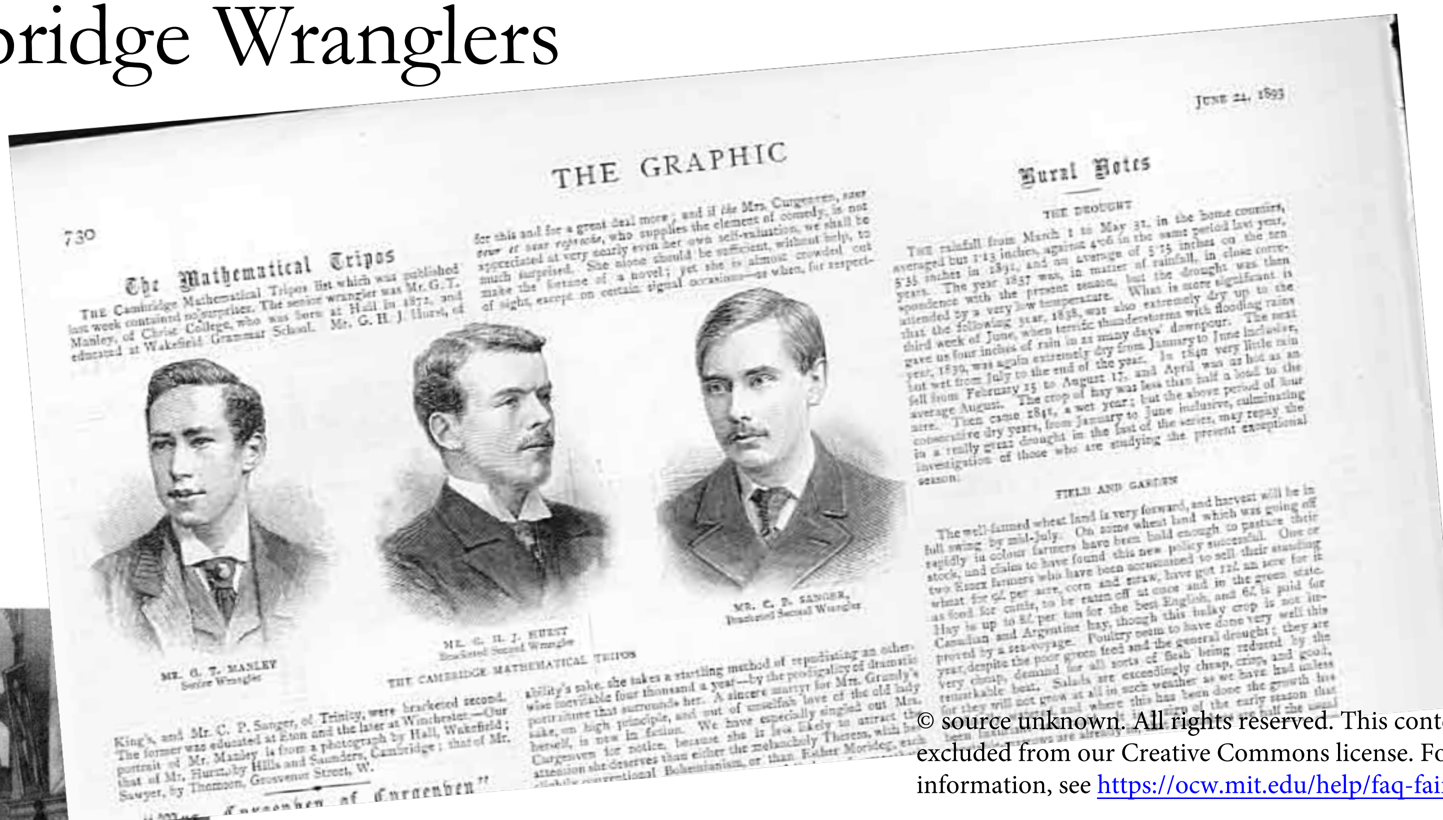
In place of a public oral disputation, students now took a silent, timed problem-solving exam on paper. Their entire undergraduate studies culminated in a grueling, 3-day written exam that determined their graduation ranking: the *Mathematical Tripos* exam.

Training Cambridge Wranglers



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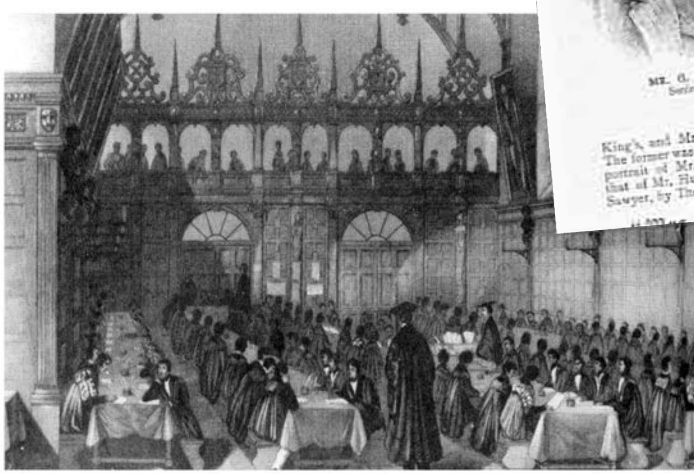

Written "Tripos" examination at Cambridge, mid-19th century

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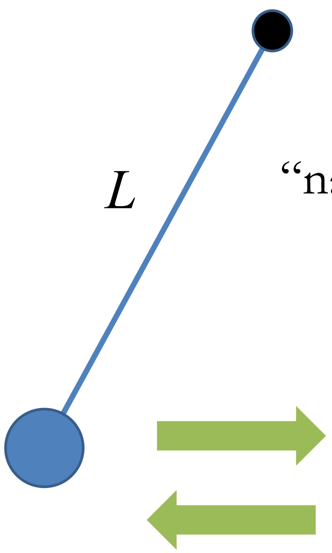
Rank-ordered results of the Tripos were published in the newspapers. The top scorers were called "wranglers." First place: "Senior Wrangler." (Both Thomson and Maxwell were Second Wranglers.)

James Ward's 1875 diary:

1. To be out of bed by 7:35 (or on Sundays 8:45)
2. To do 5 hours work before hall [lunch]
3. At least one hours [athletic] *exercise* after hall
4. Three hours work after hall
5. Finish work by 11 and be in bed by 11:30 (except on Saturday when it is 12)
6. A fine of 3d to be paid for the first rule broken on any day and 1d every other rule broken on the same day
7. A halfpenny to be allowed out of the fund to every member waking another between 6:35 and 7:35 on weekdays and between 7:45 and 8:45 on Sundays
8. Work before 8am may count either for morning or evening work of the day
9. Time spent at Church Society meeting counts for half the same time's work and also allows the member attending to work till 11:30 and stay up till 12
10. These rules binding till further notice and any alteration of them requires unanimity.

Solve for the motion of a pendulum ...



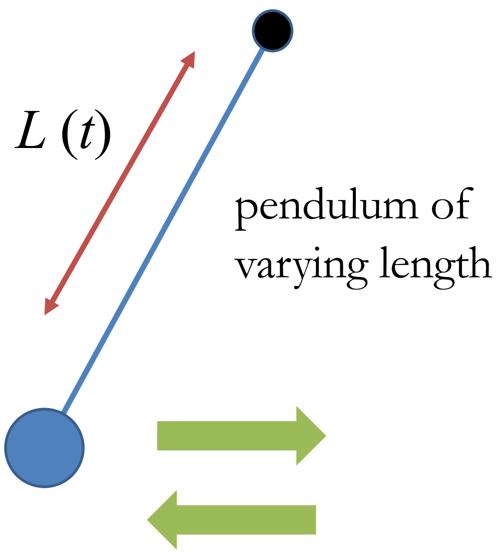
"natural frequency":
$\omega^2 = g / L$

"Simple harmonic oscillator":

$$\left[\frac{d^2}{dt^2} + \omega^2\right] \phi(t) = 0$$

$$\longrightarrow \phi(t) = A\cos(\omega t) + B\sin(\omega t)$$

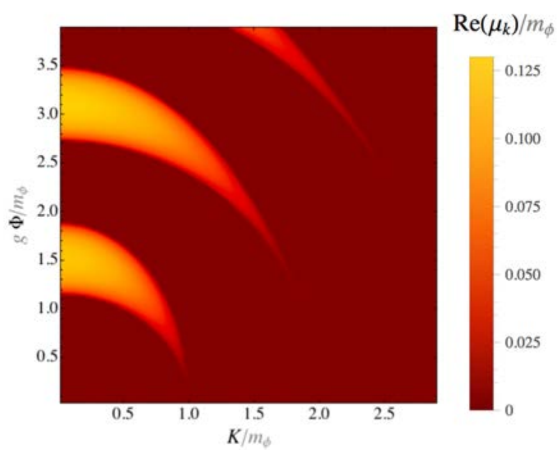
Solve for the motion of a pendulum ...



If the length of the pendulum changes periodically, then we must solve the *Mathieu Equation*:

$$\left[\frac{d^2}{dt^2} + \left(\omega_0^2 + \lambda f(\omega t)\right)\right]\phi(t) = 0$$

$$\longrightarrow \phi(t) = P_1(\omega t)\ \exp[\mu(\lambda, \omega_0, \omega)t] + P_2(\omega t)\exp[-\mu(\lambda, \omega_0, \omega)t]$$



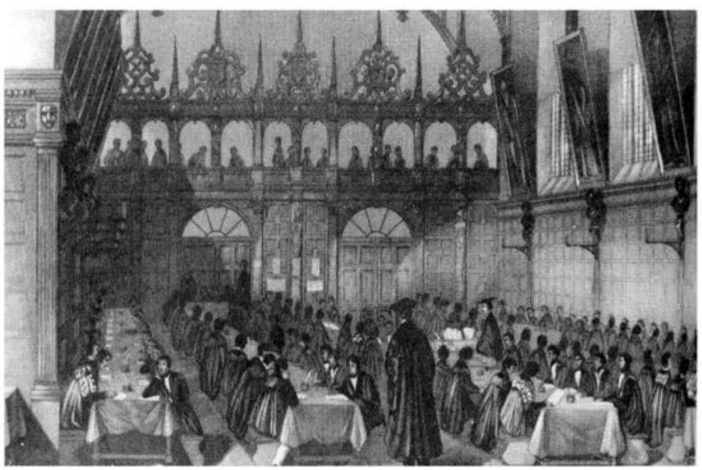
Complicated behavior: periodic oscillations for some values of the parameters; exponential instabilities for other values...

Training Cambridge Wranglers

This intense mathematical training was not only for would-be physicists; it was considered an ideal way to discipline the mind *for everyone*! As the British Empire expanded rapidly, there was a need for large numbers of disciplined civil servants. If they could master the Mathieu equation on a timed exam, they could handle complex problems of economics, governance, logistics...

As a *side effect*, a critical mass grew of Tripos-trained scholars who actually sought a scientific career. The Maxwellians came mostly from this Cambridge Tripos tradition.

The professionalization of mathematically trained physicists in Britain was driven in part by the demands of *empire*: supplying research problems (like telegraphy) and prioritizing an elite educational infrastructure.



Written "Tripos" examination at Cambridge, mid-19th century

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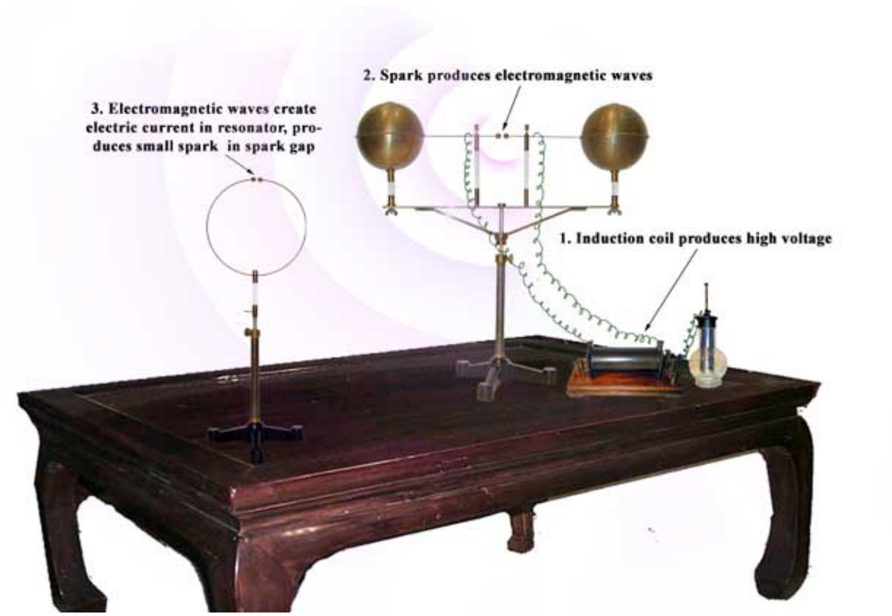
Questions?

Electromagnetic Worldview



Heinrich Hertz's 1888 apparatus, demonstrating Maxwellian waves

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Maxwell's electromagnetic theory became popular on the Continent, especially in the late 1880s, after Heinrich Hertz successfully generated and detected "Maxwell waves" in what we would now call the radio portion of the spectrum.

Yet in Germany, most physicists did not interpret Maxwell's equations the same way that the British Maxwellians did — another divide over Maxwell's equations, this time across space and not just over time.

Whereas the British considered electromagnetic effects to be grounded in a mechanical ether, to the Germans, electromagnetic effects came to seem truly fundamental: perhaps *mechanics* itself was nothing but applied electromagnetism. An *Electromagnetic Worldview*.

Electromagnetic Worldview

Consider the origin of *mass*. Instead of assuming that objects have some mass (based on their mechanical composition), what if mass itself arose from electromagnetic interactions?

A hydrodynamical analogy: the kinetic energy T of a body of mass m_0 moving with velocity v through an incompressible fluid (like dragging a beach ball under water).

outside the medium

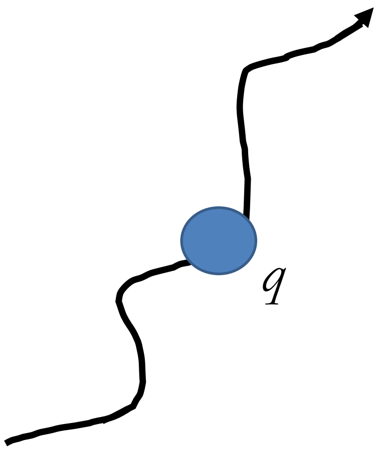
$$T = \frac{1}{2} m_0 v^2$$

within the medium

$$T = \frac{1}{2} \left(m_0 + m' \right) v^2$$

Within the medium, the ball's motion may be described by an *effective mass*, $m_{\mathrm{eff}} = m_0 + m'$, where m' is the mass of the displaced fluid.

Electromagnetic Worldview



Now consider an electrically charged object in motion, interacting *with its own electric and magnetic fields*. The self-field effects act like a fluid, generating resistance to changes in the object's motion.

$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$

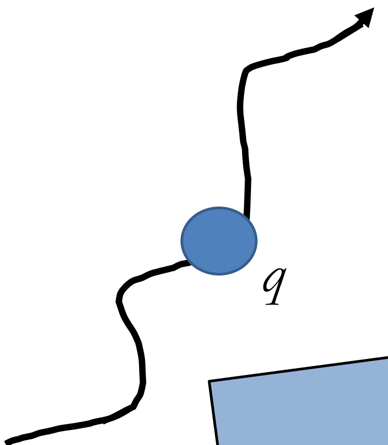
$$T = \frac{1}{2}\left[m_0 + \frac{\mu q^2}{a^2}\right] v^2$$

Effective mass: $m_{\text{eff}} = m_0 + \frac{\mu q^2}{a^2}$

μ = magnetic permeability of the medium
a = radius of the charged object

But unlike the beach ball, an electric charge can never be "outside" of its "medium" (its self-field). So what if $m_0 = 0$, and *all* mass arose from electromagnetic effects?

Electromagnetic Worldview



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Wilhelm Wien, 1900: "the possibility of an electromagnetic foundation for mechanics"

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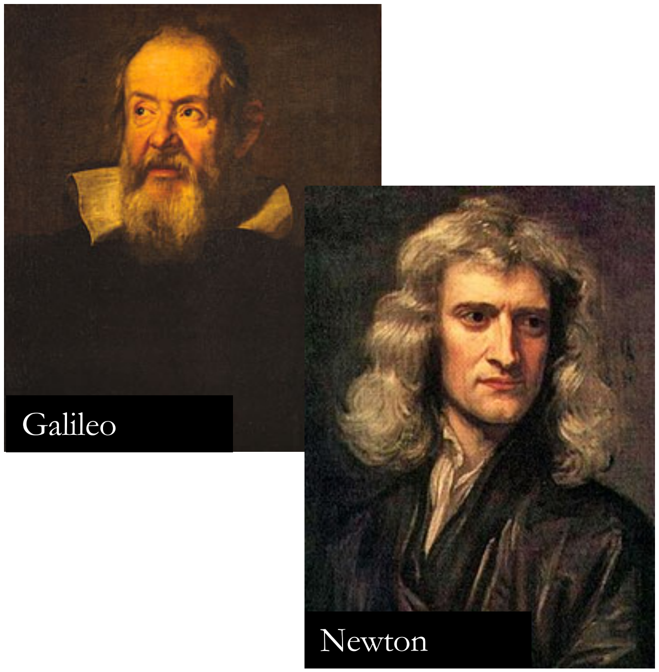
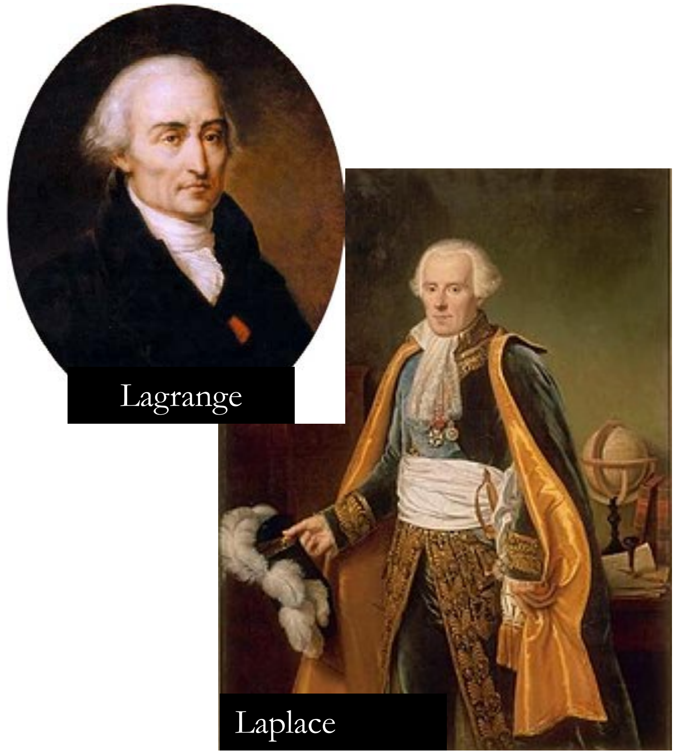
Questions?

“Theoretical Physicist”?



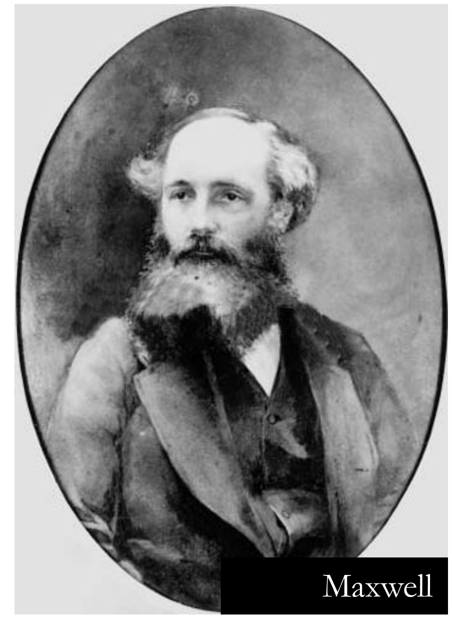
“mathematician,”
“philosopher”

1600s



“mathematician,”
“astronomer”

1700s



“physicist”

1800s

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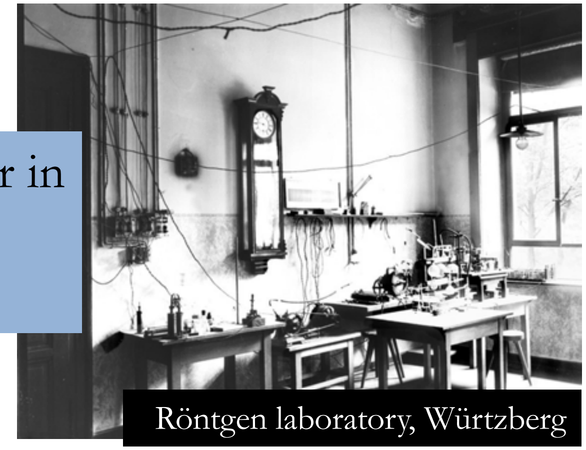
“Theoretical Physicist”

German university system: a single “Ordinarius” professor in a given field. In physics, the ordinarius was in charge of all experimental apparatus for the department.



Röntgen laboratory, Würtzberg

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After German unification in 1871, the country underwent rapid industrialization …

Krupp Steelworks

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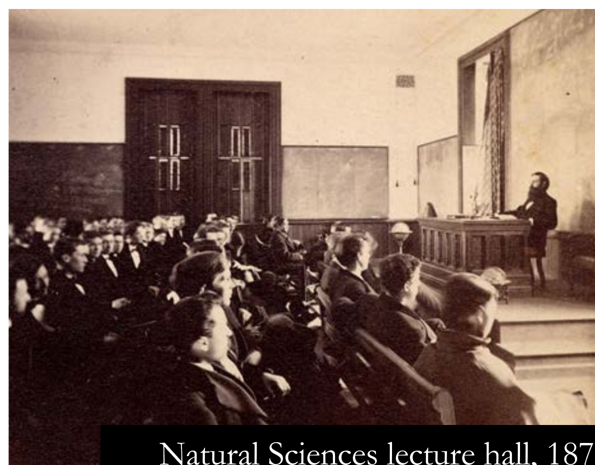
… which called for the rapid training of new physics teachers for secondary schools.



Natural Sciences lecture hall, 1876

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“Theoretical Physicist”

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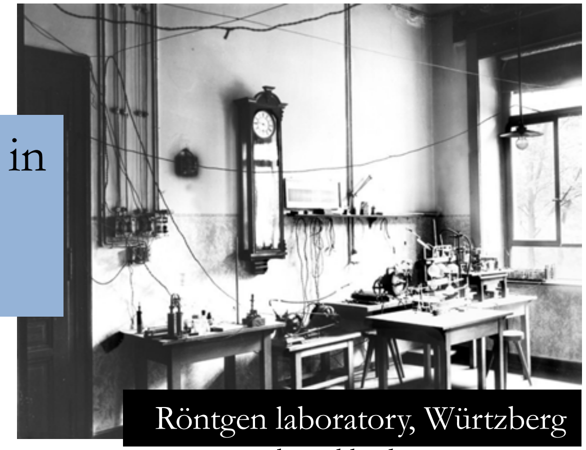
Röntgen laboratory, Würtzberg

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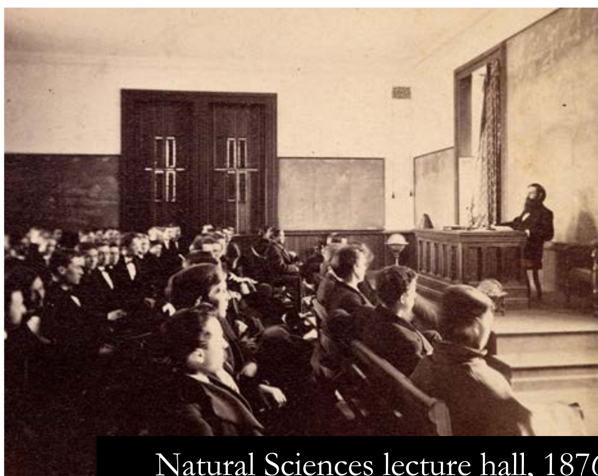
Rapid growth of junior-faculty ranks (“extraordinarius” professors) to teach the new classes.


Natural Sciences lecture hall, 1876

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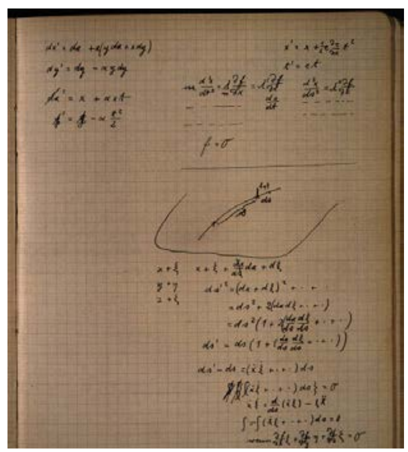
But the extraordinarius faculty *only* had access to pencil and paper.


Einstein’s Zürich notebook, 1912

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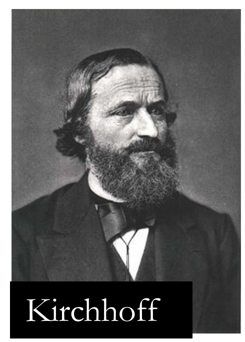
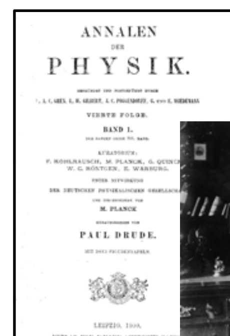
During the 1880s and 1890s, “theoretical physicist” became a recognized specialty, and job title.


Kirchhoff



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Planck

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"Theoretical Physicist"

In place of British empire-building as one main route to building up a community of mathematically trained theoretical physicists (Tripos exam!), in Germany the field of theoretical physics took root in a very different institutional context: a state-run university system with a tight limit on the highest-ranking positions.

Changing industrialization priorities and a dramatic population increase during the mid-19th century created a bulge of lower-ranked, younger scholars who had no access to experimental equipment.

Within a generation, they had created their own research journals and institutes, and even (by the 1890s) the first *Ordinarius* professorships in "theoretical physics."

It was within this institutional context in which much of modern physics — relativity and quantum theory — was crafted.

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