Electromagnetism is still fundamental science.
Recent developments in clarifying the theoretical foundations of electromagnetism.

Alberto Favaro

Department of Physics,
Imperial College London, UK.

March 21, 2011
Outline.

Main theme: electromagnetism (EM) is a testing ground.
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- Charge conservation experiments $\Rightarrow$ inhomogeneous Maxwell’s equations. Closed magnetic lines experiments $\Rightarrow$ homogeneous Maxwell’s equations.
- EM response of spacetime: linearity, zero birefringence, electric-magnetic duality measurements.
Less is more*. 

Various structures on spacetime (Figure).

Build EM so that based on experiments, not on above structures.

Make EM independent of spacetime curvature, torsion, etc. Roughly, only need continuous, smooth spacetime.

This approach: Kottler (1922), Cartan ('23), van Dantzig ('34). Related: Einstein, Mie, Sommerfeld.

Figure: Hehl and Obukhov (Birkhäuser, 2003).
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Experiments
Maxwell's Eqs.
Vac. response.

Conclusions.
Thank-you.

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- EM needs $\sim$ continuity and smoothness only. Not distance, curvature, etc. If spacetime was a globe, we would not care about distances, or the curvature.
- We would only demand a continuous, smooth surface (smooth transition between the pages of an atlas).

Figure: Charlie Chaplin, “The Great Dictator”, 1940.
Towards the experiment side of things.

A warning (but Nobody Need Worry).

Lack of assumptions: the EM response of vacuum is general (not specified until late); It’s a bit like a general material.
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- Homogeneous Maxwell equations, the other equations.
Inhomogeneous Maxwell’s Eqs., Experiment 1.

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**Vac. response.**

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- Charge conserved in $n \rightarrow p + e + \bar{\nu}_e$? Charges of $p$ and $e$ equal? Measure neutrality of gases (e.g. nitrogen).

Dylla and King (PRA, 1972). Record sound in electrically-driven gas-filled chamber. Get force at electrical drive, thus $|\left(q_e - q_p\right)| \leq 2 \times 10^{-19}$. 
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- However, variable $\alpha$ need not imply variable e-charge. See Hehl, Itin, Obukhov, arXiv:0610221.
- Measurements by Marion et al. (PRL, 2003) show that potentially $|\dot{q}_e/q_e| \leq 3.6 \times 10^{-16}$ (years)$^{-1}$. 
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- Figure: Aharonov/Bohm (PRL, 1959). Interference measures $B$-field in area enclosed by e-trajectories.
- “Step” in zero $B$-signal can be used to detect magnetic monopoles. (Proposed, Lämmerzahl et al., PRD 2005).
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Fig.: Barron/Maguire-Boyle, “Nanothechnology for the Oil and Gas Industry” (Online Collection, 2011).
Homogeneous Maxwell’s Eqs., Experiment 2.

- Homogeneous Maxw’s Eqs $\Leftrightarrow$ No magnetic monopoles.
- Measure $B$-field “step” due to monopoles, use SQUIDs.
- Screening current against external $B$-field yields accurate measurement of B-field. Search for “steps”.

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Summary: 150 years after Maxwell’s equations.

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Nonlinear vacuum response.

Nothing assumed so far about the response of vacuum. Not specified yet how $\mathbf{E}$ and $\mathbf{B}$ determine $\mathbf{D}$ and $\mathbf{H}$ in vacuum.
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- Left: Burke et al. (PRL, 1997), increased positron production due to multiphoton light-by-light scattering.
- Right: Akhmadaliev (PRC, 1998), $\gamma$ turned into virtual $e^-e^+$ pair, and scattered off nucleus to get new $\gamma$. 
Nonlinear Vacuum for Macroscopic Fields.

Macroscopic: nonlinear vacuum effects not detected yet.
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In recent years, growing number of experiments...
Electromagnetism is still fundamental science.


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Experiments

Maxwell's Eqs.

Vac. response.

Conclusions.

Thank-you.

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- Heisenberg-Euler: sensitivity not enough by factor 4800.

$\psi = \pi (n_\parallel - n_\perp) L/\lambda$
Detection by Michelson interferometry (TO DO).

- Large coil installed on one arm, modifies speed of light.
- Test will work for Heisenberg-Euler and Born-Infeld.
- Döbrich/Gies (EPL, 2009): “For our quantitative estimates, we have concentrated on the advanced LIGO, as its sensitivity goal matches with currently available field strengths”. (Figure: taken from LIGO website.)
Other requirements for vacuum response*. 

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Outline.
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Maxwell's Eqs.
Vac. response.
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Thank-you.

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Requirements for a general material*.

The requirements constraining a general vacuum can be interpreted as requirements on a general laboratory material. Actually, talking of materials...

General material to allow TE/TM decomposition.

- Lindell/Bergamin/Favaro (PIER, 2011).

Other metamaterials stuff...
Conclusions.

- Maxwell’s equations only require spacetime \(\sim\) continuous and smooth. Nothing more.
- Eliminating unnecessary assumptions puts the focus on a \(\sim\) minimal set of experiments.
- Charge conservation \(\Rightarrow\) Inhomogeneous Maxwell’s Eqs.
- No mag. monopoles \(\Rightarrow\) Homogeneous Maxwell’s Eqs.
- Vacuum response assumed late: after Maxwell’s Eqs.
- Maybe nonlinear? Remember, QED says so.
- Maxwell’s theory is still fundamental science.
Electromagnetism is still fundamental science.

Outline.
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