Electrodynamics: Rebirth of an Experimental Science?*

Thomas E. Phipps, Jr.
908 S. Busey Ave.
Urbana, Illinois 61801

Two quite different experiments are discussed that have independently verified the existence of longitudinal electrodynamic forces (denied by the "accepted" Lorentz force law) associated with currents flowing in closed circuits. Both employ versions of a simple "inertial modulation" method whereby current flowing within circuit portions of low effective mass exerts reduced observable force actions of those low-mass portions upon a separate test portion of greater mass—as a result of *recoil energy* taken up by the low-mass portions. By suitable design such variations of force-application effectiveness around a circuit can be exploited to spoil the exactness of differentials of force action between current elements, allowing violations of those classical theorems that assert indistinguishability of the Lorentz law from alternatives proposed by Ampère and others. In effect the classical theorems apply strictly only to immobilized (non-recoiling) circuits, *e.g.*, to those of infinite mass in all their parts. This force modulation approach offers a powerful and practical observational method of "violating" theorems of

* This essay was originally published in the *Proceedings of the Natural Philosophy Alliance*, Volume 2, 2005. It is reproduced here by permission of the last sitting President of the NPA. No suitable copies of figures were available for inclusion.

classical electrodynamics that assert the impossibility of distinguishing force laws differing by exact differentials. We discuss two entirely independent experimental confirmations of this concept and its successful use to verify semi-quantitatively the Ampère law, and empirically to show that the Lorentz force law does not tell the whole electrodynamic force story.

Introduction

Advanced modern theoretical physics is a beautiful, towering cloud castle of speculation and analogy founded upon the small hard rock of classical electrodynamics (Maxwell's equations plus the Lorentz force law). But when the rock in question is examined microscopically it is found, like other rocks, to consist mostly of empty space. In other words, physics is a fractal: Classical electrodynamics is itself a beautiful, towering cloud castle of speculation and analogy founded upon the small hard rock of empirical observations by Coulomb, Ampère and Faraday. And rather precariously founded, as it happens. Faraday, for example, was bold enough to move *part* of a circuit within a magnetic field and to note the consequent generation of an *emf* within that circuit. (Thus there was no "inertial system" in which his circuit as a whole maintained a given state of motion.) For its description this necessitates the use of a total time derivative of the circuital integral … but only partial time derivatives appear in what we today call "Maxwell's equations" (which Maxwell never wrote nor saw). It was and remains mathematically mysterious how Faraday's total time derivatives became partial ones in Maxwell's equations. All attempts at "derivation" ignore what Faraday actually observed in his laboratory.

Not content with betraying Faraday, modern physics has given Ampère a double dose of the same medicine. His original law of ponderomotive force action exerted by an infinitesimal element of neutral current $I_2 d\vec{s}_2$ upon another element $I_1 d\vec{s}_1$, having the form [1,2]

$$\vec{F}_{21(Ampere)} = \frac{\mu_0}{4\pi}\frac{I_1 I_2 \vec{r}}{r^3}\left[\frac{3}{r^2}\left(\vec{r}\cdot d\vec{s}_1\right)\left(\vec{r}\cdot d\vec{s}_2\right) - 2\left(d\vec{s}_1\cdot d\vec{s}_2\right)\right], \quad (1)$$

where $\vec{r} = \vec{r}_1 - \vec{r}_2$ is the relative position vector of the elements and $\left(\mu_0 / 4\pi\right)$ is a units factor yielding force in Newtons for current in amperes, is symmetrical between 1 and 2 subscripts, and proportional to $\vec{r}$. Thus it rigorously obeys Newton's third law of equality and colinearity of action-reaction between current elements, which requires $\vec{F}_{21} = -\vec{F}_{12}$ on a detailed element-by-element basis. Eq. (1) is the only force law having this property and conforming to all known observations of neutral current interactions. Maxwell (in his *Treatise*) said that it "must always remain the cardinal formula of electro-dynamics." Yet today it appears in no textbooks and is virtually forgotten by physicists, most of whom will never have laid eyes on it. Instead they opt for the Lorentz force law, which, when similarly expressed, takes the form [1]

$$\vec{F}_{21(Lorentz)} = \frac{\mu_0}{4\pi}\frac{I_1 I_2}{r^3}\left[-\left(d\vec{s}_1\cdot d\vec{s}_2\right)\vec{r} + \left(d\vec{s}_1\cdot\vec{r}\right)d\vec{s}_2\right], \quad (2)$$

a "law" curiously asymmetrical in subscripts 1 and 2, and not proportional to $\vec{r}$, so that it disobeys Newton's third law in two ways.

The two candidate laws, (1) and (2), can be shown to differ by a quantity that is an exact differential. This means that when integrated around closed circuits (to calculate current interactions) the difference between the two laws goes to zero and is thus unobservable. Since the Ampère law obeys Newton's third law on an element-by-element basis, integrating that law around circuits must yield agreement with the third law for circuit interactions as a whole. And since the loop-integrated difference of the Lorentz law from the Ampère law is zero, the Lorentz law must also obey Newton's third law *on a loop-integrated basis*. It is by this slim grace—and the fact that neutral current is generally thought to flow only in closed circuits—that the Lorentz law has always failed observably to distinguish itself from the Ampère law and has hence been entitled to claim no observable conflict with Newton's third law.

But there is now new hope to remedy this situation by removing the ambiguity of force laws. Let us return to the basics. By definition, "electrodynamics" concerns a kind of dynamics—which is to say, an aspect or variety of the science of mechanics. It is a feature of mechanics that it concerns the relationship of force to mass. So mass (as expressing an impediment to mobility) is a concept that has a basic, ineradicable place in dynamics of any kind. Yet you will find that in today's "electrodynamics" there is no acknowledged place for mass. The reason is readily discovered: Invariably, anything resembling an electrical conductor or circuit is either assumed to be immobile (in effect, infinitely massive), so that as a whole it is in a permanently stationary state of motion, or is assumed to be in some other given (inertial) state of motion, consistently again with infinite mass. In a word, the reason mass does not enter into the modern electrodynamicist's description of circuits is that the masses of all circuit parts are *assumed* to be effectively infinite. The question of action-reaction never arises, because infinite mass exhibits *zero recoil* under force action of any kind. Therefore it could be said that the electrodynamics we have inherited from our forefathers is a "science" shielded from all outside-the-box questions of action-reaction by a tacit assumption universally agreed upon.

It would be useful for electrodynamicists to begin thinking outside their box to the extent of considering what happens when non-infinite mass (finite mobility) properties are assigned to electrical circuits. In particular, suppose various finite masses are assigned to different *parts* of a circuit—as may well be arranged in the real world. What are the implications for force actions and reactions between circuits when their inertial (mass) properties vary around the circuits? This whole class of problems, concerned with variable dynamical "recoil," has been neglected in the modern curriculum. The assumption has been made that such considerations can have no conceivable effect upon the classical theorems on which the subject is founded. But in fact nothing is farther from the truth. It will be my task in what follows to make this apparent to the unbiased reader … that is, to make it clear that electro*dynamics* is largely undeveloped territory. The effects of recoil upon portions of a circuit have been studied extensively [5] from the standpoint of basic mechanics and need not be reviewed here. Suffice it to say that, when a force exerter of mass m acts upon a test object of mass M, the latter responds measurably not to the full "formula force" $\vec{F}$ (applicable when $m=\infty$) but to the "reduced force" $\Omega\vec{F}$, where Ω is a factor of *observable force reduction*, a mass ratio,

$$\Omega \equiv \frac{m}{m+M} \leq 1, \tag{3}$$

which we may refer to as an "inertial modulation" factor on force of any kind. (Perhaps "mobility modulation" might be a more apt term, as the "masses" m and M must be regarded as *effective values* enhanced by any external influences that act upon the bodies to reduce their mobility. Thus if mass m is "anchored" to the earth the effective value of m becomes earth's mass, and $\Omega \approx 1$.) The reason for this force reduction, as explained in [5], is that recoil motion of the force exerter "steals" energy from the interaction. In what follows we shall take this principle as given and show through experimental evidence how it allows resolution of the Ampere vs. Lorentz force law issue.

2. Electrodynamic Force

We now turn attention specifically to the "electrodynamic" variety of force and consider first the actions of the current elements comprising a given closed filamentary circuit C_2 on an external test element T. Let s be a length parameter measured along the loop C_2 of conducting material and associate with each value of s a linear density of effective mass $m(s)$. [Effective mass of an element $m(s)ds$ measures that element's *degree of immobilization*—whether due to inertial mass, wire stiffness, friction, viscosity, attachment to extra inert mass, etc. … *i.e.*, due to *whatever inhibits recoil motion*.] Let $M(s')$ be the effective mass of our external test element T, considered to be a small, straight, mobile conducting portion of a separate closed circuit C_1, parameterized by s', which carries an independent current. Then from Eq. (1) the observable action of C_2 on the test element T is reduced by the force modulation factor

$$\Omega(s,s') = \frac{m(s)}{m(s)+M(s')} \tag{4}$$

for any point pair (s,s') on the two circuits. The total observable force exerted by the loop C_2 on the test element at s' is then

$$\vec{F}_{obs}(s') = \oint_{C_2} \vec{F}\left(\left|\vec{r}_{s'} - \vec{r}_s\right|\right)\Omega(s,s')\,ds\,, \tag{5}$$

where $\left|\vec{r}_{s'} - \vec{r}_s\right| = r$ is the separation of current elements (one on the force exerter circuit and one on the test element) and $\vec{F}(r)$ is the "formula force."

Suppose we have two rival candidate "formula force" laws *differing* by some quantity δF that is an exact differential; *i.e.*,

$$\oint_{C_2} \delta\vec{F} ds = 0 .$$

It is traditionally concluded that this equality to zero proves the unobservability of the difference between the two laws. However, it is apparent that in general for $\Omega < 1$ anywhere on C_2 (reflecting the existence of appreciable recoil effects) we have from (3)

$$\delta F_{obs} = \oint_{C_2} \delta F \Omega\left(s, s'\right) ds \neq 0 ,$$

because the extra factor of Ω in the integrand—which plays a role formally analogous to a "Green's function"—spoils the integrand's exactness. For example, if the two "formula force" laws of electromagnetic force between current elements are those of Lorentz and Ampère, it is well-known that their difference $\delta\vec{F}$ is an exact differential. Consequently, when inertial modulation of force occurs, the theorem that asserts unobservability of the difference between these two laws is violated and it becomes possible to observe physical effects of the difference: The integrand representing the observable difference is no longer exact and distinctions between the two element-on-element force laws can be detected. To put this into practice requires deliberate manipulation of Ω as a basic feature of experimental design.

The required cleverness of manipulation is not very great. If some portions *P* of the force-exerter circuit C_2 can be made very mobile, *e.g.*, flexible or fluid and light-weight (while retaining electrical conductivity), so that $m\left(s\right)$ is small on such portions, and if the test element *T* in the test circuit C_1 is much more massive, $M(s') >> m(s)$, then from Eq. (2) we see that $\Omega\left(s, s'\right)$ can be made very small, $\Omega \approx 0$ for s on *P*. The rest of C_2 can be immobilized by "anchoring" it to a massive object such as the earth, so that $\Omega \approx 1$ for s on the non-P portions of C_2. Thus to some rough approximation the circuit C_2 in which current flows can be considered to possess portions P that exert zero force on T [$F(r)\Omega \approx 0$] and portions non-P that exert full formula force [$F(r)\Omega \approx F(r)$]. This means that a circuit roughly equivalent to the closed circuit C_2 is (for mechanical force-exertion purposes) an *open circuit* with missing gaps corresponding to the portions P, while the whole C_2 nevertheless carries current, so that it is electrically closed. The current flowing in the gaps fails to contribute much observable ponderomotive force (because of recoil of the light-weight current-carrying materials in those gaps). In short this offers a practical way—realizable in any laboratory—to approximate that fabulous nonesuch, a *current-carrying open circuit* … and of course if current could be caused to flow in an open circuit everyone would agree that a crucial experiment could readily be designed to distinguish the Lorentz law from its many classical rivals.

It is convenient terminology to refer here to the light-weight, mobile portions P of the circuit (in which the force-exerting capabilities of current are reduced below their "formula" value) as "weak links." Thus the test element T in C_1, a short, straight segment of conductor, can itself be considered to be set off from the immobile part of that circuit by weak links at each end of it, to allow it relative mobility. This permits T to respond by detectable motion to inductive forces applied by current in the external circuit C_2. T can move parallel to its length only if longitudinal forces exist (*i.e.*, only if the Lorentz force law is non-physical). Moreover, it can move in that manner under electrodynamic force action only if the force-exerting external circuit C_2, acting on the portion T of C_1, itself contains one or more weak links—since the classical theorem, to which we have previously alluded, asserts that an external circuit C_2, immobile in *all* its parts, acting on T, can exert no longitudinal force (only transverse force) for the Lorentz force law or any other force law differing from it by an exact differential. Thus any observed longitudinal motion of T correlated with current flow in the external circuit C_2 would not only confirm the existence of longitudinal forces but would simultaneously confirm the concept of inertial modulation of electrodynamic forces.

An experiment of this general nature was done by Neal Graneau and published [6] in 2001. We give a summary account of it below, and describe also an experiment [5] done by the present author to confirm qualitatively both the presently claimed “inertial modulation” concept and the existence of electrodynamic longitudinal forces. The latter experiment was done with low-current, low-frequency alternating current, whereas the Graneau experiment was done with a single high-voltage, high-current rapidly-oscillating pulse. Since the two experiments, of such entirely different experimental types, agree perfectly in confirming both the inertial modulation principle and the existence of longitudinal forces, the conclusion in favor of these (and related Newtonian) concepts seems difficult to evade. These experiments surely warrant repetition by independent investigators.

3. The Experiment of Neal Graneau

A single circuit is employed containing a vertical test element T, which is a tungsten-tipped copper rod of mass 17.7 grams and length 5.5 cm., referred to as the “armature.” At each end of T is a conductive “weak link” consisting of a variable-length arc gap. The sum of the gap lengths is fixed at 20.5 mm. The bottom gap can be varied from 0 to 10.25 mm.—the top gap varying reciprocally. The armature rod is statically supported in the chosen gap configuration by means of leaf-spring supports that allow it to move upward but not downward. The fixed electrodes defining the arc gaps are similar tungsten rods, centered coaxially above and below the armature. By a "shape-independence theorem" [7] it has been established that the shape of the external circuit portion fixed in the lab (forbidden to recoil), connecting the fixed electrodes adjacent to the gaps, is irrelevant to the observable vertical force exerted on the armature. Therefore we need not discuss it. [Consider two alternative shapes of conductor connecting the two fixed electrodes. These two shapes taken together define an immobile closed-circuit configuration external to the test element *T*, in which we know that a circuital current would exert zero longitudinal (vertical) force on *T*. From this the stated result can be deduced.] The fixed external circuit portion contains heavy-duty capacitors, a switch, meters, etc. Care is taken to assure cylindrical symmetry of the circuit portion near the armature, so that no net sideways forces are exerted.

When the switch is closed the capacitors discharge at sufficient voltage (33 kV) to generate arcs that span the air gaps. The conductive matter (plasma) within these arcs is of such light weight and "fluid" consistency that the effective conductor mass $m(s)$ within the gaps is much less than the $M(s')=$ 17.7 gram mass of the armature. That is, $m(s) \ll M(s')$, so $\Omega \approx 0$ in the arc gaps. According to Newtonian mechanics, and proximity considerations, the main force exerters acting on the armature are the two electrodes of the (non-recoiling) fixed circuit. Since Newton forbids bootstrap-lifting, the current within the armature cannot act upon itself to lift the armature, and only the action of external circuit portions, omitting the gaps, need be calculated [2] in order to predict total force acting to move the center of gravity of the armature. The Lorentz law, which allows only forces transverse to the armature, predicts no vertical motion of the armature when a pulse of current flows.

What is observed is that when the switch is thrown, to allow discharge current to flow, the armature jumps up vigorously. The smaller the lower gap the more vigorously it jumps up. When there is no bottom gap at all, so that no bottom arc forms initially, the vertical (longitudinal) force observed is a maximum. (This was further verified by soldering the bottom of an armature to the lower fixed electrode, so that no gap for initial bottom arc formation could exist. The armature nevertheless jumped up, breaking the weak solder bond.) A non-electrodynamic explanation has been offered by critics appalled by the devastating implications of this result for conventional electrodynamics. They have suggested *ad hoc* new physics in the form of a proposed concept of "arc explosion," whereby the armature jumps up as if driven by a chemical explosion, not because the Lorentz force law is invalid in electrodynamics. Unfortunately, this seems inconsistent with the observations. Longer arcs contain more energy, and in the zero bottom-gap configuration the top gap is maximal, hence the hypothesized "arc explosion" should drive the armature down, not up. Clearly, when there is zero bottom gap initially, hence no bottom arc, hence no initial bottom arc explosion, such a bottom arc explosion (if it existed) could develop only after the armature has already started to jump up from some other cause. (A piled-on hypothesis is that the "other cause" is a *bounce* of the armature. This "bounce" conjecture ignores the armature supports that are designed to *prevent* downward motion of the armature. Before an upward bounce can occur, a downward motion must be allowed.) We seem forced to the conclusion that the longitudinal forces observed are electrodynamic—a diagnosis confirmed by all ancillary evidence, such as proportionality of jump-up height to current-squared, etc. The endless and bottomless ingenuity of such "explanatory" hypotheses shows the remarkable ability of conventional thinkers to think unconventional (politically neutral) thoughts in order to avoid unconventional (politically incorrect) thoughts. The strategy is known as "damage limiting."

Neal Graneau made quantitative observations and calculations. His conclusion was that the data supported the Ampère force law (implying longitudinal repulsion of collinear current elements, Newtonian mechanics, and Newton's third law of equality and collinearity of action–reaction) and none other. The electrodynamic force formula (in more convenient units) is

$$\frac{F_{dynes}}{100 I_{amps}^2} = k = \int_{Armature} ds' \int_{External} K ds, \tag{6}$$

where F_{dynes} is the magnitude of the vertical force component acting on the vertical armature T, measured in dynes (1 dyne = 10^{-5} Newton), I_{amps} is current in amperes (taken to be the same in both force-exerter and test circuit, since the two are here the same) , k is a dimensionless "force constant," and K, proportional to the vertical force component, depends on the force law. The ds integration extends over the fixed external "force exerter" portion of the electrical circuit (omitting gaps), the ds' integration over the armature test element T only. For the original Ampère force law we have from (1)

$$K ds ds' = \frac{\hat{j}\cdot\vec{r}}{r^3}\left[\frac{3}{r^2}\left(d\vec{s}\cdot\vec{r}\right)\left(d\vec{s}'\cdot\vec{r}\right) - 2\left(d\vec{s}\cdot d\vec{s}'\right)\right], \tag{7}$$

where $\hat{j}$ is a unit vector in the vertical direction, $\vec{r} = \vec{r}_{s'} - \vec{r}_s$ is the directed distance between integration elements on the armature and the external circuit, $d\vec{s}'$ is an increment of distance in the direction of current flow within the armature, and $d\vec{s}$ is a similar distance increment in the direction of current flow within the fixed portion of the external circuit (the force exerter).

The Lorentz force law (2), which allows only transverse (horizontal) force on the test element, predicts rigorously zero vertical force on *T* and thus is ruled out. Further analysis [7] of the Graneau data confirms the superiority of the Ampère law to another candidate law, predicting non-zero longitudinal force, proposed by Riemann and discussed by Whittaker [1]; namely,

$$Kdsds' = \frac{1}{r^3}\left[\left(\hat{j}\cdot d\vec{s}\right)\left(\vec{r}\cdot d\vec{s}\,'\right)+\left(\hat{j}\cdot d\vec{s}\right)\left(\vec{r}\cdot d\vec{s}\,'\right)-\left(\hat{j}\cdot\vec{r}\right)\left(d\vec{s}\cdot d\vec{s}\,'\right)\right]. \tag{8}$$

This can be seen from Fig. 1, which shows Graneau's data (reduced to equivalent *k*-values) as starred points for comparison with theoretical *k*-values for the Ampère and Riemann laws calculated by a Monte Carlo method [7] using the above formulas and various assumptions about current filament distributions over the conductor cross sections. The Lorentz law is not shown in Fig. 1 because, as remarked, it predicts zero force on the armature in the vertical (longitudinal) direction for all gap sizes. The agreement of theoretical Ampère force law predictions between the Monte Carlo calculations [7] and the entirely independent finite-element calculations of Graneau [6] was close to perfect.

The scatter of data points with respect to theory shown in Fig. 1 is seen to be considerable, presumably because repeated high-voltage "shots" caused arc ablation of the tungsten electrodes (primarily the top electrodes for small bottom gaps). The resulting electrode pitting enhanced the tendency of arc current to flow in concentrated filaments at "hot spots"—a well-known feature of arcs. Such non-reproducible variations of current density distribution necessarily caused a spread in the data. (According to theory, more concentrated flows increase the force exerted.) Still, the comparison of theory and experiment, shown in Fig. 1, speaks for itself. To do the experiment more reproducibly might require the use of fresh electrodes for each shot … but even that could hardly prevent variations of hot spots. To do better is a challenge to any investigators who follow.

It is of interest to put the Neal Graneau experiment in historical context. In 1992 Robson and Sethian [8] reported in the *American Journal of Physics* (a publication of the American Association of Physics Teachers) an experiment having geometry very similar to that described above for the Graneau experiment, but with the crucial difference that their arc gaps were symmetrical (of equal length, top and bottom) whereas their external fixed circuit was asymmetrical with respect to the armature. They argued that the latter type of asymmetry was sufficient to assure that if Ampère longitudinal forces were present they would not cancel out. They reported total absence of any evidence for Ampère forces, thus triumphantly validating the Lorentz force law—the good news all the physics teachers took for granted but were tolerantly willing to allow to be published, since it confirmed their teachings.

Unfortunately, the symmetry reasonings of Robson and Sethian had things exactly backwards. The "shape-independence theorem" alluded to above [7] and reviewed in Appendix B, shows that whether the external fixed circuit is symmetrical or not with respect to the armature makes no difference whatever. What makes the difference is arc gap asymmetry—without which Ampère repulsive forces cancel. So, Robson and Sethian, with their symmetrical gaps, painstakingly set up exactly those unique experimental conditions in which Ampère longitudinal forces precisely cancel out … and thereby achieved their proof of Lorentz forces. Moreover, this was given a free pass by all referees of the ponderous and majestic peer review system, through which the physics teachers exclude heresies in favor of their foreknown truths. When Graneau did his correction of the Robson-Sethian experiment (using asymmetrical arc gaps), and sought to publish in the same outlet used by those previous workers, truth's guardians reacted according to form: Needless to say, there was no room in the inn.

Fortunately, science in Europe has not yet been completely Americanized, and Graneau, after trying British publications in vain, finally found an outlet for his paper in the *European Physical Journal D* [1], a lineal descendant of the famous and honorable Italian physics journal *Il Nuovo Cimento*, of fond memory. However, Europeans (not being all that other-worldly) know enough instinctively to ignore anything that might threaten the world-girdling Einstein intellectual empire … so ignoration has been the universal response. That is plainly a prescription for the end of science. For half a century under the ever-tightening grip of academia's "Standard Theory"—a form of thousand-year Ptolemaic physics based on adjustable parameters, wherein perfect fields (the foreknown philosophically-correct descriptive elements), rather than perfect circles, roll on each other—we have been able to forget the idea of *progress in understanding* of fundamental particle physics. Now it seems we must forget the idea of physics altogether and accept an operational definition of physics as whatever the people who call themselves physicists choose to teach.

6. Tuning Fork Experiment

The Graneau experiment employed high pulsed currents. It seemed desirable that the inertial modulation and Ampère force ideas be tested independently under entirely different physical conditions, at low alternating currents (AC) and under quasi-static conditions—for which heating and inductive effects should be minimal. Let it be noted, however, that AC experiments are not readily adapted to determining force *sign*, so that Ampère repulsion could not be specifically verified—only the existence of longitudinal force. By contrast, the Graneau experiment confirmed Ampère longitudinal *repulsion* as well as force approximate magnitude. The low alternating currents implied very small forces (because of the current-squared character of electrodynamic forces). Hence, some way of amplifying small signals was needed. Three mutually-supporting methods were used: (1) Mechanical resonance amplification was exploited by use of a low-frequency tuning fork electrically driven by the AC at an electrical frequency that was half the mechanical resonance frequency, (2) synchronous phase-locked loop amplification was exploited by use of a digital lock-in amplifier (LIA), (3) optical amplification was used in a manner to be described. The LIA (Stanford Research Model SR850) supplied from an internal oscillator the synchronizing frequency for fork-driving and phase reference. It was tuned to second harmonic to match the fork oscillations, which were detected as intensity modulations of a partially focused laser beam (optical focusing providing the third kind of amplification, at the cost of enhanced sensitivity to environmental "noise") half-cut by a razor blade attached to a fork prong, picked up by a photodiode and fed to the LIA as synchronous "signal." The laser and fork were set up on an optical bench to minimize unwanted vibration effects. Because of current-squared rectification of wave form by the electrodynamic force, each electrical cycle corresponded to two force pulses and two mechanical oscillations of the fork—hence the second-harmonic tuning of the LIA.

Fork driving was accomplished (presumably) by action of Ampère longitudinal forces on two test elements *T*, which were small-diameter straight copper tubes, each hard-epoxied to the end of a fork prong. These two *T*-elements were aligned with each other in the plane of the prongs and perpendicular to them, so that only longitudinal forces parallel to the test elements could excite fork resonant oscillations. (See photo, Fig. 2.) The main driving force was that exerted at the center where the Ampère longitudinal forces of the aligned current elements *T* in closest proximity acted twice per AC cycle.

Different types of forks were used, one with rectangular metal prongs and one all-fused-quartz with cylindrical quartz rods for prongs (Fig. 2). No significant differences in the results were noted due to fork material or construction. Data obtained with the quartz fork are described here. Current was fed into one of the test elements *T* by conduction through a loose bundle of 12 fine silver wires in parallel, and out of the other by a similar bundle. The central electrical connection between the two aligned and adjacent *T*-elements was similarly accomplished with fine wires in the case of the metal fork, but was done through a drop of mercury in the case of the quartz fork (using small tungsten rods driven into the ends of the copper tubes for the mercury contacts—as sketched in Fig. 3). Fork driving was (presumably) accomplished primarily by repulsive action of longitudinal Ampère forces acting between the two *T*-elements whenever current flowed in both of them. If only Lorentz transverse forces existed, such driving would not occur.

Fig. 4 indicates the general nature of the experimental setup. The fork resonated sharply near $f_0 = 118$ Hz. The LIA, tuned to second harmonic f_0, provided a fundamental reference frequency of $f_0/2$ (the electrical frequency) output to an audio amplifier (Techron 7541), which, through a dummy load L consisting of two 4-ohm power resistors in parallel, provided alternating current to the “Fork-driving circuit” C_1 shown on the left side in Fig. 4. The significant part of C_1 is the two test elements *T* fixed to the tuning fork prongs. The T-elements are allowed mobility through their attachment to the above-mentioned flexible bundles of fine silver wires, shown as dotted in the figure, and through the mercury drop in the center. When the frequency of applied AC is swept past half the mechanical resonance frequency f_0, classic resonance curves are traced out, as exemplified in Fig. 5.

The maximum amplitude of the resonance curve oscillations is affected not only by the strength of the current I input to circuit C_1 but also by electrodynamic force (inductive) actions of the adjacent "external force-exerter circuit" C_2, shown to the right of the fork circuit in Fig. 4. We point out (a) that if Ampère-like forces did not exist it would be difficult to explain the empirical observation of driven resonance curves such as those shown in Fig. 5, since only longitudinal force action on and between the T-elements attached to the fork prongs can plausibly explain the vigor of their oscillation, (b) that if inertial modulation effects did not exist it would be difficult to explain how current flowing or not flowing in the external closed circuit C_2 could have any effect on the amplitude of the resonance curve, as shown by the two curves in Fig. 5, for the case $I = 2$ amps rms at frequencies swept from 58.3 to 59.7 Hz. In fact, if the external closed circuit C_2 were "anchored" throughout its length so that it was completely immobilized, the well-known classical theorem to which we have several times alluded would guarantee that no observable force effect could be exerted by current in C_2 on any of the current elements of C_1. Once more as a reminder: This is because in that case the Ampère and other likely force laws (when loop-integrated) would be equivalent to the Lorentz law, which asserts that *only transverse forces* can be exerted on the external test elements T. Transverse forces would act in the horizontal plane, and could not accomplish vertical driving of the T-elements. Such forces could therefore explain neither the resonance effect shown in Fig. 5 nor the alteration of that effect when current is applied to the external circuit.

How, then, are the empirical observations of Fig. 5, revealing a difference of fork running when current flows or does not flow in the external ("force-exerter") circuit C_2, shown on the right in Fig. 4, to be explained? By the fact that, although largely immobilized, C_2 is not wholly so, but contains in close proximity to the tuning fork a "weak link" W, responsible for the inertial modulation effect previously discussed. W consists of a loose, untwisted bundle of four fine copper magnet wires (#38, 0.1-mm diameter, thinly insulated), each 23 cm long, carrying current in parallel. These are connected at both ends to heavier wires immobilized in the lab, as is the entire remainder of the circuit C_2. The two ends of the weak link W were fixed in close proximity (about 1-mm gaps) to the top and bottom of the fork-driver *T*-elements in circuit C_1. The light weight and flexibility of the weak-link conductors renders them suitable for taking up recoil and illustrating inertial modulation effects, which are plainly shown in Fig. 5 by the existence of two distinct curves, corresponding to alternating current $I = 2$ amps rms turned on (upper curve) and turned off (lower curve) in the external circuit C_2, *without changing current I* in the fork-driving circuit C_1. The two curves reflect differences of total electrodynamic force exerted on the *T*-elements—where the classical circuit theory of fully immobilized circuits would predict no difference. The mere existence of this non-vanishing difference confirms the validity of the inertial modulation concept (and presumably of the Newtonian mechanics that predicts it—including the much-maligned Newton's third law, applied on a current element-by-element basis in the case of the Ampère law).

Note that the 1-mm gaps between the lab-fixed parts of the external "force-exerter" circuit C_2 and the top and bottom of the

T-elements in C_1 are symmetrical. Previously we argued that asymmetrical gaps would be required in order to show an observable force effect. Are we contradicting ourselves? No. In this case the "test element" is actually two separate mechanical elements moving synchronously (near resonance) but 180° out of phase (one moves up when the other moves down), by the nature of balanced oscillation of the mechanical fork. The gaps at the two ends of either one of these separate mechanical elements are in fact extremely asymmetrical (a mercury gap of about 0.5 mm, and fine silver wire bundles bridging spatial gaps of several cm). The same AC is used in both circuits (C_1 and C_2), so both amplitude and phase of current in the two circuits are the same. Hence a repulsive (Ampère) force exerted by the fixed upper terminus of the weak link W in C_2 at a given instant upon the top of the upper test element and acting downward on it will be accompanied by a simultaneous repulsive force acting upward on the bottom of the lower test element, so that driving energy is fed into both prongs of the fork simultaneously. Whether this effect of C_2 works to enhance or decrease fork oscillation *amplitude* depends on the synchronous forces applied at the top (bottom) of the *T*-elements, added to those main driving forces that are applied through the mercury (mutual repulsive forces between current elements near the bottom of the upper *T*-element and near the top of the lower one). Empirically, it is seen from Fig. 5 that turning on current in C_2 somewhat inhibits fork oscillation. (Qualitatively, this is what would be expected for simultaneous strong repulsive up-pushes from below due to C_1 driving current in the mercury and weaker repulsive down-pushes opposing them from above induced by current flow in the external circuit C_2, acting on the upper driving element, and conversely for the lower driving element, in accordance with the Ampère law. No attempt has been made to quantify this.)

It will be understood that *any* effect of this sort confounds classical thinking, because the current I in the fork-driving circuit C_1 does not change in the least when current is turned on or off in C_2, and the latter is an external closed circuit. As we have said, according to the traditional theorem (which ignores inertial modulation effects) C_2 can exert only transverse forces on the T-elements, and thus cannot affect the fork oscillation amplitude or influence fork resonance in any way. As far as today's education of physicists and electrical engineers extends, it should make no difference in fork running what the conductors in the external circuit C_2 are shaped like, what their inertial mass-distribution properties are, whether or not they carry current, etc. (Some cross-mode energy migration might occur due to imperfect alignment of the T-elements, small radial current flows in them, etc., but such effects would be expected to be far less than those observed. Also, such a mechanism is refuted by further evidence discussed below.)

Why can we refer to C_2 as a circuit "external" to C_1, when the two are electrically connected and use the same current source? Referring to Fig. 4, we see that the connection between the two circuits carries current between the points marked C and A in one direction and between B and D in the opposite direction. In the actual circuit construction the wires carrying these counter-flows are twisted together, so no external effects of the twisted pair are to be expected. An effective mutual isolation of the two circuits is thus achieved, and we are justified in viewing them as separate circuits carrying a common amplitude and phase of AC.

Repeated frequency scans of the sort illustrated in Fig. 5 were made, with results entirely consistent with those shown. However, amplitude variations of the resonance did occur between scans, as a result of secular variations not under control, such as temperature drifts. Each complete data run, scanning from

58.3 to 59.7 Hz (done automatically by the LIA, with automatic recording), consisting of 501 data points equally spaced in frequency with a time constant of 1 sec. and a dwell time of 4 sec. per point, took 33.4 minutes. There were generally longer time intervals between runs. Hence there was a possibility that drift effects were acting during those intervals, so that the apparent correlation of decreased fork vibration amplitude with external circuit activation, shown in Fig. 5, could instead be a chance result of inter-run drifts. To eliminate this possibility, the remote switch shown in Fig. 4 was manually thrown at one-minute intervals (during the 33.4-minute automatic frequency scan) between the connections marked "O" and "X" in Fig. 4. In the "O" position current flowed only in the fork-driving circuit C_1; in the "X" position it flowed in both C_1 and the external force-exerter circuit C_2. (Through the presence of the indicated resistance R, equal to the resistance of W, in the "O"-position circuit, equal total impedance was "seen" by the amplifier in both switch positions, so the $I = 2$ amp rms current amplitude was unaffected by throwing the switch.) This procedure amounted to turning on and off at one-minute intervals any effect of inertial modulation of electrodynamic force on the fork-driving elements.

The result, shown in Fig. 6, dramatically demonstrates that two distinct, stable statistical populations are present, each being repeatedly sampled at the one-minute intervals, corresponding to the two switch positions. With switch in position "O" the upper-curve population of stronger fork oscillation is sampled; with switch in position "X" the lower-curve population of inhibited oscillations. The consistency of the indicated samplings effectively refutes the hypothesis that secular drifts between scans are responsible for the difference in the two curves of Fig. 5.

Fig. 6 shows a maximum effect of inertial modulation because the "weak link" W in C_2 is at its closest proximity to the fork (gaps minimal) and is at its *weakest*—that is, the four fine wires comprising this link are untwisted (most "floppy") and supported only at their fixed ends. If there is anything in the inertial modulation concept, it should be true that stiffening this link and/or decreasing its proximity to the fork should decrease the force modulation effect. To test this, the wires were loosely wound on a mandrel and the separation distance of W from the tuning fork was increased to 6-7 cm. Nothing else was changed from the previous run of Fig. 6. The resulting run is shown in Fig. 7.

Comparison of Figs. 6 and 7 shows exactly the anticipated effect of decreased inertial modulation due to decreased proximity and also due to increase of the "effective mass" $m(s)$ of the force-exerting weak link W. (There was no change in the actual mass of the conductors of W, but a wire stiffening due to loose attachment to the massive mandrel caused *effective mass* to increase, or recoil mobility to decrease.) There is now much less difference between the two curves, but the effect of throwing the switch between "O" and "X" can still be plainly seen.

Finally, *without changing proximity* to the fork, the weak link W was tightened as much as possible on the mandrel and the fine wires were taped onto its surface (with masking tape) to further reduce their mobility. The intention was to eliminate the inertial modulation effect entirely. Fig. 8 shows that this intention was largely realized. Only a hint (on the high-frequency side) remains of the effects of throwing the switch. This brings our observations into substantial agreement with classical expectations based on the theorem (applicable to the Ampère law, the Lorentz law, and most others proposed in the past) so often mentioned here: that *when all parts of a closed external circuit are completely immobilized* current flowing in it can affect a test element only through transverse forces upon that element. The fact that this theorem is well-honored here, incidentally, refutes any conception that the fork-driving observed is not due to longitudinal electrodynamic forces *per se* but to cross-mode migration of energy from transverse Lorentz action to longitudinal driving action. If such energy migration (purely a function of fork-and-driver geometry) were happening, it would persist when the external circuit is immobilized, as in the data run of Fig. 8, because the fork-and-driver geometry does not change. Instead, we see that in the case of immobilization of the external circuit any transverse force action on the fork driving elements does *not* migrate into longitudinal action of any appreciable amount; so the hypothesized energy migration is not happening.

This same consideration refutes the idea that radial current flows in the *T*-elements may be occurring and producing Lorentz force action affecting fork driving. The fact that the proximity of W to the fork was not altered between the runs of Figs. 7 and 8 shows that the substantial difference between these two curves is due solely to the change in degree of mobility (susceptibility to recoil) of the conductors comprising W. In Fig. 7 the wires of W were loosely wound on the mandrel; in Fig. 8 they were tightly wound. No other change was made in the experimental conditions, and the runs were consecutive. The raw data sequence of Figs. 6-8 is as near to direct observational *proof* of the inertial modulation concept as experiment is likely to be able to furnish.

7. Caveat Concerning Fine Wires as "Weak Links"

An unsuccessful attempt (unreported elsewhere) has been made by the present author to use fine wires as weak links in a low-current DC experiment with a torsion balance. A test element T on the torsion arm was connected by fine-wire bundles to a circuit C_1, and a force-exerter element was similarly isolated as a weak link in an external circuit C_2. Direct current of a few amperes in these circuits proved inadequate to show any evidence of force action between the circuits. Since the straight element T was oriented transverse to the torsion arm, this showed a failure of longitudinal forces to make their appearance. Two explanations suggest themselves: First, the static-deflection torsion balance was orders of magnitude less sensitive to force than the phase-locked type of AC amplification. Secondly, the fine wires have obvious shortcomings as "weak links" in the DC context.

Transiently, fine wire bundles might serve, but under a steady push the wires must yield and suffer displacements that cause them in effect to stiffen and become less mobile—hence to exhibit an increasing effective m-value. Although it is doubtful that the m-value could increase indefinitely, the evidence suggests that it can increase sufficiently to reduce any evidence of longitudinal force action at low currents below the threshold of observability. And, of course, fine wires demand low currents, so they appear intrinsically poor candidates for weak links in DC experiments aimed at exploring electrodynamic force laws.

Even at resonance the tuning forks never produced an audible hum. Hence it is likely that the oscillation amplitudes were in the sub-micron range. This suggests that the effective Ω-value was never near zero, as hoped, but possibly only a little less than unity. If so, it would be hopeless to use fine wire bundles as the weak links employed with a torsion balance. Mercury, with high direct currents, would be needed. That would introduce further problems of heating, vapor, and surface tension. I have worked with mercury, never with satisfactory results … and must leave that to more skillful experimentalists.

8. Summary: Theory

From consideration of Newton's laws we showed that, if a force exerter is sufficiently mobile to be subject to appreciable recoil, its "formula force" F (valid in the limit of no recoil) is effectively reduced by a factor $\Omega = m/(m+M)$, where m is force-exerter effective mass and M is test-body effective mass. It is the reduced force ΩF that must be used in determining the *observable motion* of the test body under action (whether distant or contact) of the force exerter. This elementary and perfectly general result of classical mechanics is in accord with the simplest intuition. Thus if a test body, an automobile of mass M, is moved when pushed by a strong enough man of mass m standing firmly on the earth and exerting muscular force F, there is no question that the motion is described by $F = Ma$, a being the observable acceleration of the auto and F (the "formula force") a measure of the development of the man's muscles. But if the same man stands on wet ice the observable motion is quite different. It is given by $\Omega F = Ma$, where $\Omega = m/(M+m)$ and $\Omega \ll 1$, so the auto barely moves. The reason is, of course, that the wet ice affords no purchase, no "anchorage," to the force-exerter; so he is largely decoupled from the earth. There is thus no way he can avail himself of the huge mass of the earth to help him. The force he exerts accelerates him much more than the auto. In fact we see that the latter equation of motion ($\Omega F = Ma$, with Ω not specialized to unity) is the more fundamental one, in that when anchorage to the earth is restored—as by putting ashes on the ice or giving the man hob-nailed boots—we can consider the man to acquire extra effective mass through improvement of his connection to the earth—so that m, an "effective" value, becomes that of earth-and-man combined, $m \to \infty$; consequently $\Omega \to 1$. Only in this limit of force-exerter immobilization can $F = Ma$ be rigorously asserted as the equation that describes the *observable* motion of a test body in classical physics. Note that the man not only exerts less "push" force on the automobile while standing on wet ice, but also feels less reaction force on his palms. That is, action and reaction remain always the same: *Observable force action is limited by sustainable reaction*.

From this line of reasoning we extrapolated to suggest that in electrodynamics $\Omega(s,s')=m(s)/(m(s)+M(s'))$ plays a role analogous to a Green's function that enters integrands describing the force action of element s on s' and spoils the exactness of certain differentials that have hitherto been doctrinally treated as necessarily and eternally exact, with the effect of protecting the Lorentz force law from observations that might unmask its non-physicality. Thus our message here will hardly be greeted with jubilation by theorists. For experimentalists, however, it should be welcomed as a message of hope; for now it becomes clear that they have a "new" experimental parameter to play with—the "force modulation" factor Ω. In the above example, as noted, the man on wet ice is not without resources. He can don hobnail boots, spread ashes on the ice, etc., all with the objective of increasing his coupling to the earth by increasing Ω. In the same way a whole world of possibilities opens up for experimental ways to spoil exact differentials by deliberate manipulation of electrical circuit portion mobilities.

9. Summary: Experiment

Two experiments that pioneer the exploration of this new world of possibilities have been described here. In both, electrical coupling is maintained within a complete conductive circuit, while mechanical coupling is decreased on circuit portions we have termed "weak links." In the Neal Graneau experiment [6] (a repetition of the Robson-Sethian experiment [8] with corrected geometry) these weak links are asymmetrical (unequal) arc gaps filled with conductive plasma of very low mass m compared to test element (armature) mass M. In the gaps, therefore, according to Eq. (4), we have $\Omega \approx 0$; so force-law circuit integrations can in effect be carried out over incomplete circuits instead of complete ones. Integrations of this sort, in conjunction with Graneau's observations of armature jump-up in the direction from narrow gap to wider gap, have confirmed semi-quantitatively the law of (longitudinal) force between current elements originally proposed by Ampère. The latter law has the unique feature that it rigorously obeys the (relativistically "discredited") third law of Newton, asserting that action and reaction between current elements centers are equal, opposite, and collinearly aligned. Such observations decisively refute the key Lorentz force law, whereon depends the relativistic dogma of "universal covariance," which is manifestly violated by the Ampère law. The Lorentz law predicts only transverse forces on the armature and thus offers no electrodynamic explanation, even of a qualitative sort, for the observed jump-up phenomenon. Given an adequately funded and credible (*i.e.*, academically sanctioned) research project, the techniques of Graneau should in principle be adaptable to *quantitative measurements* that would settle the validity (or not) of the Ampère law for all time.

The second experiment discussed here also demonstrated the existence of longitudinal electrodynamic forces through the fact of AC longitudinal driving of a tuning fork. This experiment was addressed primarily to demonstrating the phenomenon we have termed "inertial modulation" of electrodynamic force, whereby suitable circuit design allows $\Omega \ll 1$ on chosen circuit portions. We showed in the context of alternating current of only 2 amps rms near 59 Hz that weak links, consisting of bundles of fine wires in parallel, not only *do* (as predicted) modulate the force exerted by a closed external circuit on a straight current-carrying test segment (the tuning fork driving element), but do so in exactly the way predicted by Newtonian theory. That is, when the weak link in the external circuit is progressively stiffened, so that the effective *m*-value of the force-exerter is steadily increased, Ω increases steadily and the resulting observable effect of inertial modulation decreases—going to zero, as it should, in the limit of perfect "anchoring" of the whole external force-exerting circuit ($\Omega \rightarrow 1$).

10. Summary: Broader Implications for Physics

In commenting on the tuning fork observations, it might be said that the surprising thing revealed by them is how hard it is in practice to rid all force observations of small (generally unwanted) inertial modulation effects. It could be thought from the total absence of mention of such effects in the whole of the existing electrodynamic physics literature that they must be very small, esoteric, and difficult to observe. In fact, when looked for by methods of adequate sensitivity, they proved rather difficult to eradicate. So, as sometimes happens, the impediment lay not in seeing but in deciding to look. It is interesting to reflect on the state of a science in which such impediments to empiricism are essential to the prospering of a status quo. The hallmark of this type of science is that, when finally somebody bothers to look, nobody listens. Whether physics is in such a condition today may be judged by the fact that Graneau's report [6] (after multiple rejections over six years through successive refereeing processes on two continents) has been in the public domain now for four years with no attention paid to it, nor any likelihood of attention ever by the authorities whose preemptive interests currently define physics. Similarly my own report [5] has been out for eight barren years (admittedly in a more obscure location—for an obvious reason consistent with my theme).

If the whole sad business is not forgotten entirely, it will only be because some indefatigable scholar happens to cite the one relevant publication that ever saw light of official sanction through publication in a first-line journal. This was the experiment of Robson-Sethian [8], published in 1992 in *Am. J. Phys.*, which was built upon precisely those fundamental conceptual errors that were needed to guarantee obtaining the foreknown right answer (universal validity of the Lorentz force law). Thus, although the inertial modulation concept was used in the Robson-Sethian experiment (through introduction of arc-gap "weak links"), it was used in the one way that could have failed to reveal longitudinal (non-Lorentz) force effects. That is, the experiment was tried *only* with arc gaps of equal length, so that any longitudinal forces present had to cancel by symmetry. These experimentalists reasoned that arc gap asymmetry was unnecessary because they made separate provision instead for *shape asymmetry* of the external circuit portion outside the arc gaps. Unfortunately, there is a simple theorem [7] (proven in Appendix B), evidently unknown to them, which asserts the "shape-independence" of forces exerted by such external partial circuits. So, they used the wrong kind of asymmetry to test the physics … or the uniquely right kind to achieve publishability under the aegis of established physics authority.

The inescapable conclusion that "universal covariance" fails for electromagnetic forces leaves theoretical physics in chaos—a condition well-earned through generations of wrong choices and bad judgments, all supported by "consensus" and lovingly perpetuated by the self-validating machinery of higher education. Thus stands the discipline at the onset of the new century.

References and Notes

[1] E. T. Whittaker, *A History of the Theories of Aether and Electricity* (Harper, New York, 1960), Vol. 1.

[2] P. and N. Graneau, *Newtonian Electrodynamics* (World Scientific, Singapore, 1996).

[3] P. T. Pappas and T. Vaughan, "Forces on a Stigma Antenna," Phys. Ess. **3**, 211-216 (1990).

[4] As evidence that academic in-group membership, not merit, has become the criterion for scientific "publication" not only in print but now on the Internet, I offer the following response received in April, 2005 from the Cornell University sponsors of the arXiv.org archive for scientific papers on the Internet, to the question, "Does the author's lack of an institutional affiliation affect eligibility of submissions?" The answer (copied here verbatim) was: "We have revised our policies with respect to unaffiliated researchers. We insist that new submitters are part of the academia or that they are suffiently (sic) networked with it. If you have no recognized academic affiliation, then you must find someone who does, and with expertise in the relevant subject matter (your specific field of research), to endorse your registration with us. Endorsement should be informed and enthusiastic, as if that person felt comfortable being co-author of your works. It should not be granted merely to support freedom of speech or to help out a friend. See: http://arxiv.org/help/endorsement for more details."

[5] T. E. Phipps, Jr., "Inertial Modulation of Electrodynamic Force," Phys. Essays **10**, 615-627 (1997).

[6] N. Graneau, T. Phipps, Jr., and D. Roscoe, "An experimental confirmation of longitudinal electrodynamic forces," Eur. Phys. J. D **15**, 87-97 (2001).

[7] T. E. Phipps, Jr., "Monte Carlo Electrodynamic Calculations Using the Filamentary Approximation," Hadronic J. **19**, 273-301 (1996).

[8] A. E. Robson and J. D. Sethian, "Railgun recoil, Ampère tension, and the laws of electrodynamics," Am. J. Phys. **60**, 1111-1117 (1992).

Figure Captions

Fig. 1. Values of force constant *k* [Eq. (7)] vs. lower gap width (initial air gap beneath the armature before discharge) in the experiment of Neal Graneau [6], calculated by the Monte Carlo method [7] for the force laws of Ampère [Eq. (8)] and Riemann [Eq. (9)], treating current distributed across conductor cross section as a bundle of filaments. Different current distributions were assumed as follows: A1: Ampère law, current uniform over circular disc. A2: Ampère law, current uniform over skin-depth annulus. R1: Riemann law, circular disk. R2: Riemann law, annulus. Data points observed by Graneau are shown as "stars."

Fig. 2. Photograph of two tuning forks used in experiments [5] to demonstrate fork driving by longitudinal forces and inertial modulation of such forces. The upper fork is a metal one, the lower (used in experiments described here) is of fused quartz. Both are shown with current-carrying transverse "test elements" *T*, attached to ends of fork prongs, that drive the fork at electrical frequencies near half the mechanical resonance frequency. The central electrical connection between the two driving elements is made by a loop of fine wires for the metal fork, by a mercury drop for the quartz one. The razor blades shown cut a partially focused He-Ne laser beam to allow detection of sub-micron oscillations.

Fig. 3. Sketch of quartz tuning fork, indicating two-part test element *T* (attached to ends of fork prongs) and manner of connecting it into the fork-driving circuit via low-constraint "weak links" (mercury in the center, fine-wire bundles at top and bottom).

Fig. 4. Schematic of fork-driving ("test element") circuit C_1, left, and external ("force-exerter") circuit C_2, right, containing an indicated *weak link* W. The two circuits are here combined into a single circuit to allow one amplifier to supply current *I* to both. R has the same resistance as W. L is a constant dummy load, LIA the lock-in amplifier. Switch allows activating both circuits in position "X" and only the fork-driving circuit in position "O." Optical means of detecting fork vibration amplitude not shown.

Fig. 5. LIA signal raw data for two successive frequency scans across fork resonance peak. Scans are with (for lower curve) and without (for upper curve) the fork-driving current *I* (2 amps rms) flowing also in the external circuit C_2 of Fig. 4. Termini of the weak link W are located at fixed positions about 1 mm from the top and bottom ends of the test elements attached to the fork prongs.

Fig. 6. Conditions similar to those of Fig. 5, with manual switch controlling current *I* thrown at 1-minute intervals between positions "O" and "X" (Fig. 4). Wires of weak link W supported only at ends and positioned as for Fig. 5. The result is evidently successive samplings of the same two distinct data populations shown in Fig. 5. This indicates the stability of those two populations in time and the reality of the distinction between them.

Fig. 7. Same as Fig. 6 but with weak link W partially "anchored" (made less mobile) by loose winding on a mandrel and with separation distance of W from test element increased to 6-7 cm. The distinction between the two data populations being sampled is evidently decreased by this stiffening and decreased proximity of the weak link.

Fig. 8. Same as Fig. 7 but with weak link W very firmly tightened on mandrel and taped to it, with separation distance from test element unchanged from Fig. 7. The external circuit C_2 thus approximates the ideal of being immobilized (infinitely massive)—hence the classical theorem that an external closed circuit cannot affect fork running (no longitudinal forces on test element) is seen to be approximately obeyed. (Some slight residual modulation effect, however, is perceptible at the high-frequency end of the scan.)

Fig. B-1. Two filamentary partial circuits of arbitrary shapes used in proving the shape-independence theorem. The single “test element” is the straight filament segment marked *T*. Mathematical “current” *I* is imagined to flow, as indicated, from a source at *E* to a sink at E' ; also, such current flows in *T*.

Appendix A. Blowing the Whistle: A Brief Essay on the Reduction of Faraday's Law to Differential Form

It seems altogether mysterious how the full information contained in Faraday's observations of non-inertial deformations of circuits, or in the total time derivatives descriptive of them, gets thrown away to leave us with the bare bones of Maxwell's partial time derivatives that are supposed to tell mankind everything it needs to know about electromagnetism. The bare bones are perfectly compatible with purely inertial motions, as Einstein's special relativity theory—built on the covariance (or spacetime symmetry, for which partial derivatives are essential) of Maxwell's equations—confirms. So, in effect, the electromagnetic physics of a non-inertial world is mapped by Maxwell's equations onto an inertial world. Believers in this sort of magic will surely have no difficulty believing in the Tooth Fairy.

That information is thrown away in the passage from d/dt to $\partial/\partial t$ will be evident from the traditional representation of d/dt in its "convective" form,

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \left(\vec{v} \cdot \vec{\nabla}\right),$$

where $\vec{v}$ is some new velocity parameter having nothing to do with inertial frame transformations. (This expression is certainly valid when $\vec{v}$ is constant; otherwise, when it is variable, there will be additional terms of a form once considered by Helmholtz.) What "$\vec{v}$" is depends on physical context, but it is certainly a parameter expressing new and different information not contained in $\partial/\partial t$. So, there is *necessarily* extra information contained in any theory based on d/dt, as compared with $\partial/\partial t$ … and this extra (parametric) information goes beyond any associated with transformations between inertial frames, hence beyond anything to do with special relativity theory or Maxwell's equations as currently formulated.

All physics texts agree in representing Faraday's observations by

$$\oint \vec{E}\cdot d\vec{\ell} = -\frac{d\Phi_m}{dt} = -\frac{d}{dt}\int \vec{B}\cdot d\vec{S}\,,$$

where, sure enough, your eyes do not deceive you, that is indeed *d*/*dt*, not $\partial/\partial t$. So, how is it that this concise summary of observations, manifestly involving an extra parameter (the velocity, *e.g.*, of the portion of the circuit that Faraday moved non-inertially while leaving the remainder stationary), becomes part of a set of field equations suited to purely inertial description? Some expositors, such as Panofsky and Phillips [*Classical Electricity and Magnetism* (Addison-Wesley, Reading, MA, 1962), 2nd ed.] have the boldness simply to write

$$\oint \vec{E}\cdot d\vec{\ell} = -\frac{d}{dt}\int \vec{B}\cdot d\vec{S} = -\int \frac{\partial \vec{B}}{\partial t}\cdot d\vec{S}\,,$$

which takes considerable guts, even when accompanied with fast talk about "a differential expression valid for free space or a stationary medium." Indeed, if Faraday had been working in free space or a stationary medium he would not have needed that extra $\vec{v}$ parameter implied by *d*/*dt*. But since he wasn't and did, it plainly misrepresents the whole thrust of his experiment to make an elision such as that above. It throws away information and makes a travesty of mathematical "derivation," solely for the sake of getting to the foreknown goal, the "Maxwell equation"

$$\vec{\nabla}\times\vec{E} = -\frac{\partial \vec{B}}{\partial t}\,.$$

It would be more honest, better mathematics, and also wiser in physical terms, to write

$$\vec{\nabla} \times \vec{E} = -\frac{d\vec{B}}{dt},$$

as Hertz did [*cf*. T. E. Phipps, Jr., "Hertzian Invariant Forms of Electromagnetism," in *Advanced Electromagnetism Foundations, Theory and Applications*, T. W. Barrett and D. M. Grimes, eds. (World Scientific, Singapore, 1995)]. That throws away no information and also yields first-order (Galilean) inertial transformation invariance (since *d*/*dt* is invariant, whereas $\partial / \partial t$ is not). But of course it destroys the basis for the great ideological commitment of our time, "universal covariance" … also "spacetime symmetry," another of those invisible truths that define our age.

A brother expert, J. D. Jackson [*Classical Electrodynamics* (Wiley, New York, 1965), p. 173], pulls a similar swindle, reflecting similar desperation to get to the known truth of the Maxwell equation. He says, "Faraday's law can be put in differential form by use of Stokes's theorem, provided the circuit is held fixed in the chosen reference frame …" But to hold the circuit fixed in any reference frame is to disregard what Faraday learned about circuit *shape change* regardless of "reference frame." In other words it is to subordinate the physics to over-simplified mathematics for the sake of political correctness. Although mathematically correct, use of the first-order invariant operator *d*/*dt* in the so-called "differential form of Faraday's law" is politically incorrect. It torpedoes both "Maxwell's equations" and "spacetime symmetry."

Needless to say, once an invariant formulation of electromagnetism is admitted as a conceivable approach, it should be consistently pursued by using *d*/*dt* also in the other field equation that involves time differentiation. In that way a first-order invariant formulation of electromagnetic field theory is postulated that represents a covering theory of Maxwell's equations (and one that reduces to those equations in the limit $\vec{v} \to 0$, $d/dt \to \partial/\partial t$). One then requires only an interpretation of $\vec{v}$ to obtain a physical theory. This matter is treated in the above-cited Barrett & Grimes reference and elsewhere. By interpreting $\vec{v}$ as *field detector (or test charge) velocity* we achieve a way of incorporating the Lorentz force law into the field equations, thus eliminating the need to postulate a separate force law for electrodynamics—so the distinction between electromagnetism and electrodynamics disappears.

Unfortunately, although the above-recommended reform would improve the logic and consistency of the field theoretical approach to electrodynamics, it would not (as far as can readily be determined) yield a prediction of the Ampère force law. So it would not remove the disagreement of field theory with force observations, as established in the present text. The reason seems basic and ineradicable: Ampère's law is an expression and embodiment of Newton's third law. Both these laws are products of the action-at-a-distance tradition and style of physical description—which has always been at odds with the field (continuum) mode. The two have complementary strengths and weaknesses. Field theory is good at describing radiation (manifestly causally retarded) and poor at describing force action (never observed to be anything but instantaneous). Action-at-a-distance theory is good at describing force action (obviously so for gravity—and vitally so for action-reaction balance, to avoid a never-observed infinite regression of causally-delayed action-reactions!) and poor at describing radiation. The two can never be "unified" because of their conflicting premises. Academia solves this impasse by simply discarding action-at-a-distance—

pretending it isn't there—going, like Newton, into deep denial. But, then … there is quantum mechanics!

In the end, quantum mechanics will force a choice in favor of action-at-a-distance … but what a long and weary political road will have to be plodded before this possibility will be allowed to be whispered in academic halls! When that great day comes we shall perhaps be able to get rid of all fields except as expedient approximants. That will depend on discovery of a way of describing radiation consistent with the action-at-distance tradition. In our day it is useless to speculate—we are so far from such a possibility. I will merely hazard an uneducated guess that a quantum ether might be pictured, similar to Dirac's sea of negative-energy electrons, in which instant actions alert the future absorber to a quantum emission, but also alert all other particles of the sea … whereupon progressive quantum wave interferences—competitions among these many silent bidders—result in delay of process completion (observable energy transference) that is interpreted as causal *propagation*. In the "final" physics, if any, I envision no place for fields as primitive descriptors. Fields will come to populate the history-of-science books alongside the perfect circles of Ptolemy. My supposition, based on over-all performance to date, is that action-at-a-distance and point particles—given a fair chance—will prove able to carry the whole load. On this I am well aware of differing 100% from my more orthodox contemporaries in physics. I believe in pluralism. I am delighted that they keep their roads of opinion, research, and publication open. I should be even more delighted if they were to show me the same courtesy.

Appendix B. Proof of Shape-Independence Theorem

We repeat here the proof given in Ref. [7] of a theorem having application to the experiment of Robson-Sethian [8] and elsewhere in electrodynamics:

Theorem (shape-independence). *For the electromagnetic force laws [1] of Lorentz (Grassmann, Biot-Savart, Laplace, etc.), Ampère, Weber, Gauss, Riemann, and all others differing from these only by additive exact differential quantities, the net longitudinal ponderomotive force component (if any) acting parallel to the length of a straight current-carrying test element T, exerted by a fixed external current-carrying partial circuit C of arbitrary shape joining fixed endpoints* E, E' *(these points and C being nowhere coincident with T), is independent of the shape of C and depends only on the geometry of the minimum gaps ET and* $E'T$ *. (It is stipulated that T is free to respond to longitudinal force by observable longitudinal motion, but that the "fixed" external partial circuit C is forbidden to alter its state of motion in whole or in part.)*

Proof. We limit proof to idealized single-filament circuits—generalization to multi-filament circuits being readily accomplished. Also, we illustrate by a two-dimensional diagram only, the theorem's validity in three dimensions being readily inferred. Given fixed positions of endpoints E, E' relative to the test element *T*, consider two arbitrary shapes C', C'' of the fixed external partial circuit (denoted *C* in the statement of the theorem) connecting points E, E', as in Fig. B-1. Suppose that each of C', C'' carries a current *I* in the same sense—say, from *E* to E'. (*T* also carries a current. We treat these as "mathematical currents" and do not allege that such partial circuits can carry physical currents.) Let a single closed electrical circuit *CC* be formed by connecting C' and C'' at the junction points E, E'; and let the sense of current *I* in the C' portion of *CC* be reversed, so that a current loop is formed with current flowing unidirectionally (counterclockwise, as shown) in the whole circuit. Designate the reversed current in this C' portion as *–I*. To reflect this change of sign we may write $CC = -C' + C''$.

By a well-known theorem [Maxwell, *Treatise*; C. Christodoulides, *Am. J. Phys.* **56**, 357 (1988); etc.], for all force laws of the class specified in the statement of our theorem, any fixed external closed circuit carrying current exerts upon *T* the same longitudinal force as does the Lorentz force law—namely, *zero*. (That is, all these force laws differing by an exact differential, when integrated around any fixed closed circuit, are *loop equivalent* and agree with the Lorentz law that any force is rigorously transverse to the filamentary current in *T*.) So, our closed circuit *CC* exerts zero force on *T* parallel to its length. If the partial circuit C', acting alone, exerts a longitudinal force *F* on *T*, then a physical superposition of C' upon CC—which we shall denote $CC + C'$—exerts on *T* a longitudinal force $0 + F = F$. By the linearity of Maxwell's equations the superposition of oppositely-flowing currents (whereby the superposed C' coincides spatially with the $-C'$ portion of CC) is equivalent to the presence of C'' alone. Symbolically: $CC + C' = \left(-C' + C''\right) + C' = C''$. So, C' exerts *F*, $CC + C'$ exerts *F*, and C'' exerts *F*. Consequently C' and C'' exert the same longitudinal force on *T* … a force component which is therefore independent of shape of the external circuit portion in view of the arbitrariness of the shapes of C', C''; *qed*.

If the gaps *ET* and $E'T$ between the endpoints E, E' and the adjacent top and bottom of the test element are symmetrical (of equal width), then any external asymmetrical circuit shape is deformable into a symmetrical shape with respect to *T*. According to the theorem, this deformation will have no effect on the longitudinal force exerted on *T*. But in the symmetrical configuration (symmetrical external circuit portion and symmetrical gaps) obviously there is force balance for any of our force laws. Consequently we have the

Corollary. *If the gaps ET and E'T are symmetrical (of equal width) the force components balance and no longitudinal force action on T can be observed (short of the breaking of materials, as in exploding wire phenomena [2],[8]). Therefore, if a crucial experiment is to show such force action through observable ponderomotive displacement of (the center of mass of) T, it must employ gaps of unequal width.*

This corollary makes it clear why Robson-Sethian obtained a publishable null result [8], since they used arc gaps of equal width. By way of contrast, Graneau [2] obtained an unpublishable (in America) non-null result by using arc gaps of unequal width.