principles are disregarded. And who is to be held responsible for the present situation? Those who created the problem? Or those who are the victims?

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The letter above was dictated by telephone to D. B. Spalding of Imperial College, London, and transmitted to PHYSICS TODAY *by Spalding at Levich's request.*

Theories of gravitation

The article by Clifford Will (October 1972, page 23) gives a timely and interesting account of the separation of viable and nonviable theories of gravitation. However, in a parenthetical statement, which I assume referred to the recent around-the-world flying-clock experiments of Richard Keating and myself, Will states: "Cesium-beam clocks flown recently on commercial jets detected only the time dilation in relative motion—a *special*-relativity effect; the gravitational red-shift effect was at the limit of their precision." This statement is incorrect, and I would like to set the record straight for those readers who have not read our reports.[1]

Time gains for round-the-world flying clocks

	Time gains (nanoseconds)	
	Eastward	Westward
Red shift	144 ± 14	179 ± 18
Kinematic Dilatation	−184 ± 18	96 ± 10
Predicted	−40 ± 23	275 ± 21
Observed mean	−59 ± 10	273 ± 7

The Table lists values (in nanoseconds) from our reports for the gravitational red-shift effect, the kinematic dilatation effect, and their sums, which give the predicted relativistic time gains for the flying clocks. It can be seen that the red-shift produced a positive time gain for both circumnavigations, while the kinematic effect had opposite signs—a result that is primarily due to the rotational motion of the earth. Because the red-shift and dilatation effects were comparable in absolute magnitude, near cancellation occurred for the eastward trip where the kinematic contribution was negative, but a relatively large positive time gain was predicted for the westward trip. In this case, the red shift represented about 65% of the predicted value.

Also listed in the Table are the means of the four measured time gains with their corresponding standard deviations. It can be seen that the measured mean for the westward trip agreed with the predicted value to within about 0.7%, and that the standard deviation (or precision of the measurement) is about 3% of the mean. In fact, the greatest uncertainties reside in the predicted values, whose error estimates were two to three times the precision in the measured values. Clearly the measurements contained both the red-shift and dilatation effects in comparable proportions, with neither at the limits of our precision.

In this context it is interesting to note that these experiments provided more than an empirical resolution of the "clock paradox" of special relativity; they also resolved an issue on the behavior of photons in a gravitational field. The red shift is often described as being due to a loss of energy (and frequency) of the photon as it climbs out of the gravitational field. Another less common explanation, but actually the one Einstein suggested, is that the clocks (or atoms or nuclei) have different frequencies at different gravitational potentials. E. T. Jaynes has argued that without an experimental distinction this issue involves only the meaning of words, and is not a question of physics.[2] Møller, on the other hand, claims that we should regard the frequency of the photon as being constant along its path of motion, with the red shift arising from a difference in the frequencies (or energy levels) of the atoms at different potentials.[3] Our flying-clock experiments have proved conclusively that the atoms that regulated the clocks had different frequencies at different altitudes.

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THE AUTHOR COMMENTS: I would like to apologize for having given the wrong impression of the Hafele–Keating

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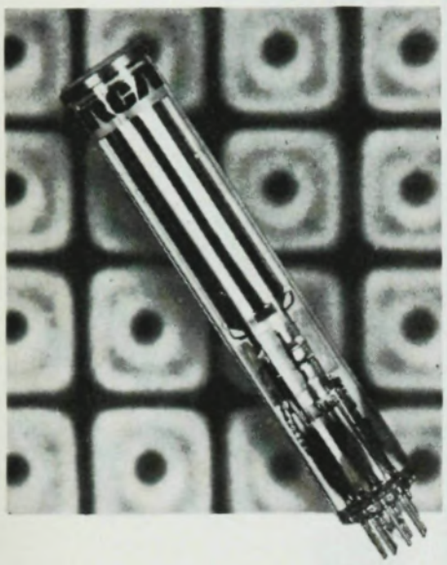

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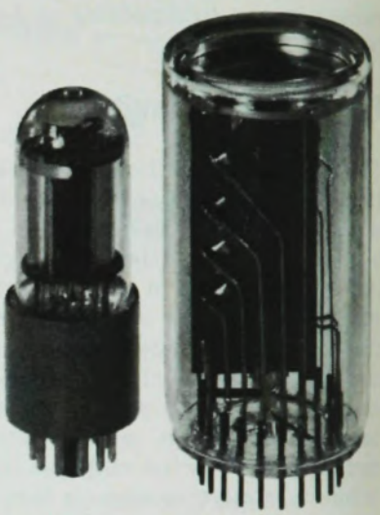

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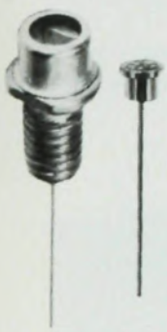

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around-the-world flying-clock experiment. The cesium-beam clocks indeed detected the gravitational red-shift effect, along with the kinematical time dilatation of special relativity. However, as a high-precision test of the gravitational redshift, it does not compare with the more accurate Pound-Rebka-Snider experiment (1% test), or the proposed rocket redshift experiment (10^{-3}% test). Instead, the importance of this experiment lies in its use of macroscopic clocks rather than gamma rays or elementary particles to verify these effects.

CLIFFORD M. WILL
University of Chicago

•

I should like to add a few comments to Will's very interesting article. These are concerned primarily with the theory of gravitation that the author considers to be "on the firing line," Einstein's meaning of general-relativity theory, and the author's discussion of "Test-2."

Firstly, Einstein clearly emphasized that his theory of general relativity is not restricted to a theory of gravity, and that the latter development from the theory was only a consequence of the solutions of a formalism that was "a makeshift to give the general principle of relativity a preliminary closed expression."[1] The theory itself (rather than its mathematical expression) is a hypothesis about the laws of nature, expressed in terms of this principle, that is, the assertion that the laws of nature (of any type!) must be objective with respect to reference frames that are distinguished by arbitrary types of relative motion in space-time.

From Einstein's own point of view, then, the "meshing" of his law of gravity with the other laws of physics is *logically necessitated* by the axiomatic basis of his theory. Indeed, this was the primary motivation for his pursuit (during 40 years or so of his career) toward a unified field theory. That is, it was not simply for the aesthetic pleasure that might be gained in unifying electromagnetism with gravity. Einstein anticipated that such a unification would lead to the further incorporation of the fundamental features of matter in the microscopic domain.

Thus, an important *test* of general-relativity theory that Will did not emphasize is its implications in the microscopic domain of elementary-particle physics. This is not to say that the gravitational force, *per se*, is important in this domain. But according to general-relativity theory, the "inside of an elementary particle" must necessarily be characterized by a highly curved space-time, which in turn would have profound effects on many of its physical properties. A recent review summarizes work in this area.[2] One of the important results, which is sensitive to the curvature of space-time in the microscopic domain, is the prediction of an explicit field relation between the inertial mass of an "elementary particle" and the geometry of space-time, as determined by all of the remaining matter of a closed system—the full incorporation of the Mach principle in general-relativity theory. A recently reported application of this result led to the inertial masses of the electron and the muon, predicted as a mass doublet, in terms of the curvature properties of space-time,[3] and the lifetime of the muon state of this doublet.[4] These theoretical results are then claimed to be successful tests of general relativity (as the theory is defined by Einstein) applied to the elementary-particle (rather than the astronomical) domain. The necessary incorporation of all domains of interaction in this theory was discussed in an earlier article in PHYSICS TODAY.[5]

It has also followed from this research that Will's distinction between Einstein's theory and the scalar-tensor theory of Dicke-Brans-Jordan is not as clearcut as he indicates. According to the principle of general relativity, the most general explicit form of the invariant differential metric is not in terms of its square, $ds^2 + g_{\alpha\beta}dx^\alpha dx^\beta$, as expressed by Will. In accordance with the symmetry group of this theory (the 16-parameter Lie group that underlies the invariance of ds) the space-time metric field must entail the solutions of 16 field equations at each space-time point, rather than ten.[6] Because the irreducible representation of this group obeys the rules of a quaternion algebra, I have started with the quaternion invariant metric $q_\alpha dx^\alpha$, where q_α is a four-vector field, and each vector component is, algebraically, a quaternion rather than a real number. I have derived the field equations in q_α and find that in an iterated form, ten of these equations are in one-to-one correspondence with Einstein's symmetric tensor equations, thus predicting all of the physics that is predicted by the tensor formalism. But there are six more field equations—thus the formalism predicts more. In particular, it was found that in a linear approximation, where $v/c \ll 1$ (as in the case of Mercury's motion relative to the sun) the six remaining field equations reduce to one important equation—which solves the scalar field equation—and five other equations that are unimportant in the first approximation. In this limit, then, the formal structure of this theory is iden-

tical with a truly "scalar-tensor theory," but only as approximation to a formalism that is the most general (that is, irreducible) expression of Einstein's general-relativity theory.[7]

Finally, I do not believe it is strictly true within Einstein's theory that "in local reference frames all non-gravitational laws of physics take on their standard special relativity forms." For, if space-time is curved anywhere, it must be curved everywhere, in accordance with the transformation properties of such a space-time. Thus the field variables associated with laws other than gravity are still mapped in a curved space-time—even though in special "local" applications they can be approximated by fields *mapped* in flat space-times that are the tangent planes to the points of observation in the actual curved space-time. Such a difference in the *exact* fields of the non-gravitational law does indeed influence their structures; for example, ordinary derivatives become covariant derivatives, thus necessitating the addition of certain non-zero geometrical field variables in the field equations. That is to say, the predictions of an *exactly* flat space geometry (with special relativity) and those of the curved space geometry (general relativity) are not *precisely* the same, even in the "local limit."[5] It is my belief that in the coming decades these differences may become detectable, not only in astronomical experimentation, but also (and perhaps more sensitively) in high-energy physics experimentation.

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We should all be thankful to Clifford Will for his concise and informative article concerning the present state of theory and experiment in gravitation. It is interesting to see that gravity, after a long lull, has become alive again, with exciting prospects of experimental inquiry and theoretical construction. This letter is intended to clarify the issue of viability of our 1971 theory.[1] Although quite unconventional in its philosophical setting, this theory is found viable under several physical interpretations of its equations. Two extreme positions that one could take and still have the theory viable are:

(a) Consider the theory as a direct generalization of special relativity, where Einstein's second postulate is extended into noninertial frames by the statement: "As measured in a sufficiently small laboratory the signal velocity is a universal constant, independent of any field of acceleration that may be present in that laboratory." Here the "signal velocity" means the velocity of massless fields including gravity, and the universality is to be maintained despite the presence of gravitational fields and their first derivatives. The statement implies that the metric structure of special relativity is being taken over into noninertial frames in the local sense above, although the geometry is, in general, curved. If accelerations vanish everywhere, the theory becomes globally special relativistic in the sense that the laboratory can be as large as desired. This implies that in the process of parallel transport the absolute values of the fields are unobservable, hence only the differences, $\phi_{\alpha\beta}(x) \rightarrow \phi_{\alpha\beta}(x) - \phi_{\alpha\beta}(x')$, where x' is the position of the observer, are relevant.[2] To make the signal velocity independent of the gravitational accelerations we require the d'Alembertian be independent of the derivatives of $\phi_{\alpha\beta}(x)$. This implies[3] that $dg_{\mu\nu} = A(g_{\mu\nu}d\phi - g_{\mu\lambda}d\phi_{\nu}{}^{\lambda} - d\phi_{\mu}{}^{\lambda}g_{\lambda\nu})$, $\partial_{\nu}\phi_{\mu}{}^{\nu} = 0$. Then the principle of equivalence yields $A = 2$; hence the local equations of $g_{\mu\nu}$ are determined. These equations are equivalent to some field equations that can be derived by simply calculating the Ricci tensor. One finds $R_{\mu}{}^{\nu} - (1/2)\,\delta_{\mu}{}^{\nu}R = 8\pi(\sigma u_{\mu}u^{\nu} + t_{\mu}{}^{\nu}/4\pi)$, where $\Box^2\phi_{\mu}{}^{\nu} = 4\pi\sigma u_{\mu}u^{\nu}$ and $t_{\mu}{}^{\nu}$ is the canonical stress-energy tensor, corresponding to the field Lagrangian, $L_f = -\partial^{\lambda}\phi_{\alpha}{}^{\beta}\partial_{\lambda}\phi_{\beta}{}^{\alpha} + (1/2)\partial^{\lambda}\phi\partial_{\lambda}\phi$. Thus the theory is a locally Lorentz invariant field theory of gravity where the gravitational part $t_{\mu}{}^{\nu}$ contributes to the geometric curvatures. Since $g_{\mu\lambda}g^{\lambda\nu} = \delta_{\mu}{}^{\nu}$, the equations can be iterated into the (matrix) form, $\tilde{g} = \tilde{\eta} \cdot \exp 2(\phi - 2\tilde{\phi})$, where $\tilde{\phi}$ is the field matrix $\phi_{\mu\nu}$, ϕ is the diagonal matrix $\tilde{1} \cdot$ trace $\tilde{\phi}$, and $\tilde{\eta}$ is $\phi_{\mu\nu}$. Although this solution is exact everywhere in the local sense above, it must be regarded as an ordered integral for finite differences $\phi_{\alpha\beta}(x) - \phi_{\alpha\beta}(x')$ due to possible noncommutativity of finite contributions. It is, however, found that in the first and second order there is no problem even for finite differences. Ex-

continued on page 55

letters

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panding in first and second order, and noting that in the weak and quasistatic limit (which is the case for all the experiments discussed by Will) two of the terms cancel; one has $g_{\mu\nu} = \delta_{\mu\nu}(1 + 2\phi + 2\phi^2) - 4\phi_{\mu\nu}$. This corresponds to $\beta = \gamma = 1$, $\alpha_1 = \alpha_2 = \alpha_3 = 0$; hence the theory's post-Newtonian limit agrees with current experiments. The usage of $\phi_{\alpha\beta}(x) - \phi_{\alpha\beta}(x')$ instead of just $\phi_{\alpha\beta}(x)$ is something new, but this does not cause any serious problem. It is found that the $\phi_{\alpha\beta}(x')$ term might, in fact, be of value in the interpretation of Sagnac-type experiments, where the issue of the local velocity of light has traditionally been quite unsatisfactory.

(b) If the above interpretation, in which the solution is exact but the interpretation is unconventional, is regarded too drastic we can view the theory as given by its field equations and, in a more conventional way, search for a PPN-type solution, $g_{\mu\nu} = \delta_{\mu\nu}(1 + A\phi + B\phi^2) + C\phi_{\mu\nu} + D\phi\phi_{\mu\nu} + E\phi_{\mu\alpha}\phi_{\alpha\nu}$. This is perfectly legitimate and can be done for the Einstein and Dicke-Brans-type theories as well. One finds the coefficients: Einstein (2, 3/2, −4, −7/2, 4); Dicke-Brans (2 − 2/ω, 3/2, −4 + 2/ω, −7/2, 4); Present (2, 2, −4, −8, 8). Substituting back into g_{μ} one finds again that, in the post-Newtonian order, the theory is the same as Einstein's theory, hence viable. Note that in this interpretation the special-relativistic correspondence is achieved in the sense of $g_{\mu\nu} \to \delta_{\mu\nu}$, $\phi_{\alpha\beta} \to 0$; hence the iteration solution is not necessarily exact beyond second order, although in the static limit it yields again an exact solution. An interesting feature is that the first-order coefficients A and C determine the second-order ones as $B = A^2/2$, $D = AC$, $E = C^2/2$. A combination of local validity of special relativity and the principle of equivalence further yields $A = -C/2 = 2$, and implies the validity of iteration to fourth order in the quasistatic limit; but these are not important for our present purpose.

The theory differs from Einstein's theory in strong and nonstatic phenomena and therefore requires an extension of the usual PPN formalism, as these phenomena appear to be testable via suitable models of quasars and pulsars.[4] Here one might contemplate the coefficient of the ϕ^2 term in g_{ii} and that of ϕ^3 in g_{oo} as new PPN parameters. Likewise the interpretive difference mentioned above could possibly be parametrized by giving a coefficient to $\phi_{\alpha\beta}(x')$ in the potential difference $\Delta\phi_{\alpha\beta}$. In this connection it is interesting to note that a recent advance[5] in the measurement of light ($\delta c = \pm 1$

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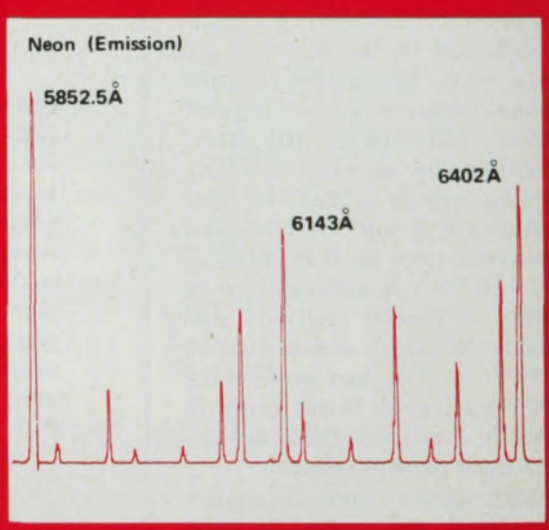

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m/s) seems promising toward a direct test of the local universality of the velocity of light in non-inertial (rotating, artificially accelerated or gravitational) frames of reference.

Finally, if the first interpretation above turns out to be valid, we can see an interesting connection with the so-called Schiff conjecture mentioned by Will. For in this interpretation $g_{\mu\nu}$ is essentially a transformation, $dx_\mu = g_{\mu\nu}dx^\nu$, between the covariant and contravariant descriptions. As such, $g_{\mu\nu}$ does not have to satisfy the commutability of finite contributions, but metricity (the existence of a nonsingular $g_{\mu\nu}$) is needed to satisfy the requirement of objectivity (equivalence) of the two descriptions. The composition independence of free-fall would then become a corollary, because a metric theory is equivalent to a kinematics where mass does not enter into the consideration of motion. Schiff's idea of a connection with quantum mechanics is then realized in the sense that only in a metric theory will the wave equation and the geodesic equations of motion yield identical results in the limit of geometric optics (for example the bending of light or aberration). Hence the wave-particle duality seems to imply, already in its classical form, the metricity of geometry. The explicit universality of the Planck constant appears, however, not necessary for the argument, although it might be crucial for the quantizability of gravity itself.

The author wishes to thank Clifford Will for his critical reading of this letter and for his suggestions that are incorporated.

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Correction

December 1972, page 53. In the review of *Color and Symmetry* by A. L. Loeb, the reviewer's name should be spelled *Donnay*. He is affiliated with Johns Hopkins University and the Université de Montreal. In the fifth line of the center column on page 53 there should be a comma after the word "rotocenters," and the first displayed equation in that column should have a closing parenthesis after the italic k. □