Einstein on the firing line

General relativity has survived for fifty years but not without competition; we can use a "theoretical framework" to eliminate those theories that disagree with experiment.

Clifford M. Will

An astronomer detects mysterious pulses in the light from a star at the center of the Crab Nebula, and theorists speculate that the source is a rotating neutron star (a "pulsar"). Massive aluminum cylinders in Illinois and Maryland are suddenly and simultaneously set into vibration, and theorists suggest that a gravitational wave has just passed through the solar system. Radio astronomers discover that space is filled with blackbody radiation at a temperature of about 3 K, and theorists say that it is a by-product of the initial "big bang" of the Universe. X-ray astronomers discover aperiodic fluctuations in the x-ray emission from Cygnus-X1; optical astronomers discover that Cygnus-X1 is associated with a single-line spectroscopic binary star: from this evidence theorists speculate that the x rays come from a black hole in orbit around a normal star.

But when the theorists sit down and begin to construct detailed models for these phenomena, they suddenly pull up short. All the phenomena, they notice, involve "relativistic" gravitation in a very crucial way. Newton's theory of gravitation is certainly inadequate to describe these phenomena quantitatively, and two of them (black holes and gravitational waves) it cannot describe even qualitatively. Experimental tests in the solar system up to 1960 seem to confirm Einstein's relativistic theory of gravity, so maybe that is the theory to use in model building. But these experiments were of such low accuracy (only 20% precision in most cases), that they also seem to confirm several alternatives: Whitehead's theory, the Belinfante–Swihart theory, Dicke–Brans–Jordan theory, Yilmaz's Theory, Papapetrou's theory, ... Theorists are hamstrung. Unless they have some strong reason for believing one of these theories over the others, they can have little confidence in the models that they build to explain the various astrophysical phenomena.

Fortunately, the same advances in laboratory and space technology that made possible the discovery of these astrophysical phenomena will also, in the coming decade, give the theoretical astrophysicist stronger experimental reasons for believing only *one* theory of gravitation. The technology of the 1960's has handed us a set of high-precision tools for testing gravitational theories in the 1970's: radar ranging to planets and satellites, with accuracies better than 15 meters; laser ranging to the moon, accurate to better than 30 cm; long-baseline interferometry, capable of measuring angles down to 3×10^{-4} seconds of arc; atomic and molecular clocks, stable to one part in 10^{14} over periods as long as a year; gravimeters, able to measure changes in acceleration on the earth as small as $10^{-10}\,g$, and many others.

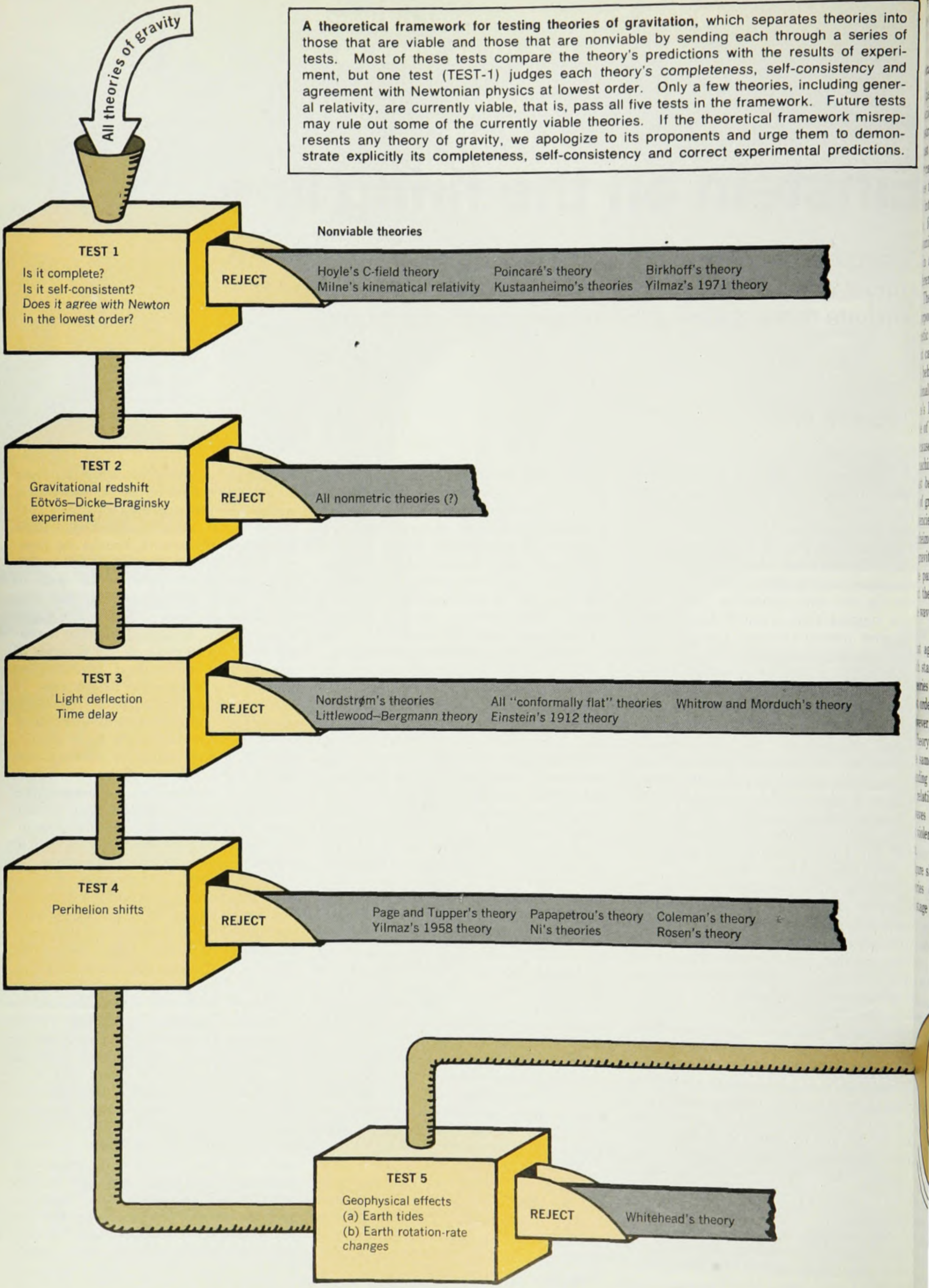
These developments—discoveries in astronomy and astrophysics, and advancing technology—have made the systematic, high-precision testing of gravitation theories an important and exciting task for the 1970's.

Although there are many new experimental possibilities, the cost of carrying out most in terms of manpower and money is very high. (The megabuck is a useful unit of measure for some of the tests.) For this reason, it is crucial that we have as good a theoretical framework as possible for comparing the relative values of the various experiments and for proposing new ones that might have been overlooked. This theoretical framework should be powerful enough that it can be used to analyze and assess experimental tests in detail, yet be general enough that it is not biased in favor of Einstein's general relativity. It should provide a machinery for analyzing all the theories of gravity that have been invented as alternatives to Einstein in the past 70 years, for classifying them, for elucidating their similarities and differences, and finally for comparing their predictions with the results of solar-system experiments.

Such a theoretical framework has been developed over the past several years in pace with the rapidly advancing astrophysical and technological scenes. Here we discuss one version.

We view this "Theoretical Framework for Testing Theories of Gravitation" (see figure on next pages) as a machine for the separation of theories of gravity into two bins: *nonviable theories* or theories that cannot be correct, and *viable theories* or theories that *may* be correct within the realms of twentieth-century technology. This separation involves sending each theory through a series of tests that compare the predictions of the theory with various experimental results, plus one test that *judges* the theory—is it complete and self-consistent? The reader is warned that our discussion of these tests will have a strongly theoretical flavor: We will not examine in any great detail experimental apparatus and problems, or prospects for improvement of technique, and we will play fast and loose with experimental numbers and uncertainties. For anal-

Clifford M. Will is an Enrico Fermi Fellow at the University of Chicago; this article was prepared while he was an instructor in the physics department at the California Institute of Technology, Pasadena.



A theoretical framework for testing theories of gravitation, which separates theories into those that are viable and those that are nonviable by sending each through a series of tests. Most of these tests compare the theory's predictions with the results of experiment, but one test (TEST-1) judges each theory's *completeness*, *self-consistency* and agreement with Newtonian physics at lowest order. Only a few theories, including general relativity, are currently viable, that is, pass all five tests in the framework. Future tests may rule out some of the currently viable theories. If the theoretical framework misrepresents any theory of gravity, we apologize to its proponents and urge them to demonstrate explicitly its completeness, self-consistency and correct experimental predictions.

yses of these problems from an experimenter's point of view, the reader is referred to a number of other review articles.[1,2]

Theoretical-framework machine

Any theory of gravity that is to be taken seriously at all must satisfy certain constraints:

▸ It must be complete. That is it must be capable of analyzing from first principles the outcome of every experiment of interest. It is not enough, for example, for the theory to postulate that atomic clocks at two different heights in a gravitational field run at two different rates (gravitational redshift). The theory must mesh with and incorporate a complete set of electromagnetic and quantum-mechanical laws that can be used to calculate the detailed behavior of atomic clocks in gravitational fields. For example, E. A. Milne's Kinematical Relativity[3] is incapable of making a redshift prediction, because it lacks sufficient theoretical machinery.

▸ It must be self-consistent. Several theories of gravity suffer from internal inconsistencies. For example, Paul Kustaanheimo's theories predict the correct gravitational redshift for light when the particle version (photon) is used but they predict a zero redshift when the wave version (Maxwell theory) is used.

▸ It must agree, in first approximation, with standard Newtonian theory. Most theories of gravity agree, at least to lowest order, with Newtonian physics. However, one that doesn't is Birkhoff's theory. Even though it predicts the same gravitational redshifts, light bending and perihelion shift as general relativity, it demands that sound waves travel at the speed of light, in violent disagreement with experiment.

The figure shows the results of sending theories of gravity through the TEST-1 stage of the framework. (For a discussion of how the rejected theories fail this first test, and for references to many of the theories of gravity I will mention here, see reference 3.)

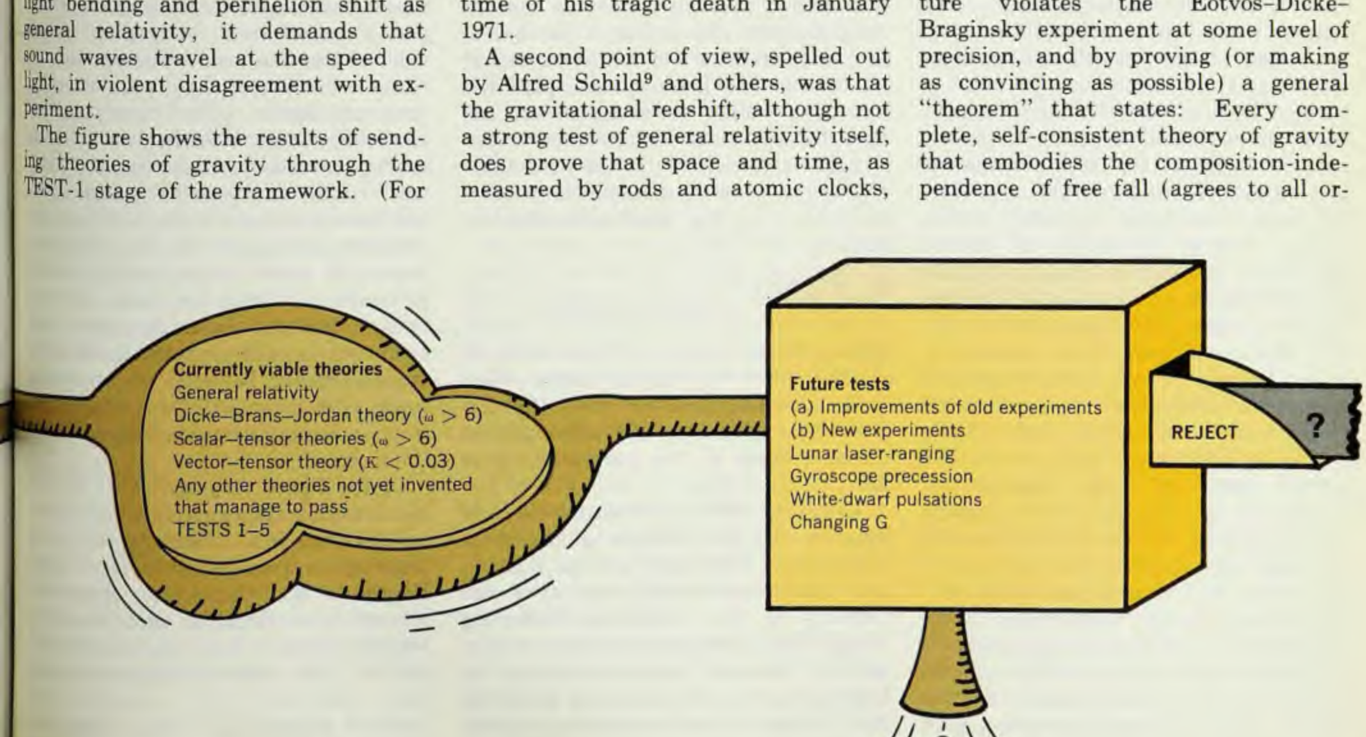
Although Einstein considered the gravitational redshift one of the most important of the predictions of general relativity, it was not until 1965 that a truly accurate confirmation of the redshift could be made. That year, Robert Pound and Joseph Snider,[4] using an improved version of the experiment performed five years earlier by Pound and Glen Rebka, confirmed the gravitational redshift of photons climbing up the Harvard tower through the earth's gravitational field. Their accuracy of one percent was made possible by the use of the Mössbauer effect (recoilless emission and absorption of photons). However, in the intervening years, the interpretation of the redshift experiment had changed.

The work of Leonard Schiff and Robert Dicke[5] suggested that the redshift experiment was not a strong test of general relativity at all. The gravitational redshift, they claimed, could be calculated by appealing to conservation of energy, elementary quantum theory and the Eötvös experiment: the measurement of the composition-independence of gravitational acceleration for laboratory-sized bodies. This experiment was first performed by Baron Roland von Eötvös[6] to one part in 10^9 precision, and improved by Dicke[7] (one part in 10^{11}) and more recently by Vladimir Braginsky[8] (one part in 10^{12}). Schiff was working on what he felt would be a more convincing proof of this point of view at the time of his tragic death in January 1971.

A second point of view, spelled out by Alfred Schild[9] and others, was that the gravitational redshift, although not a strong test of general relativity itself, does prove that space and time, as measured by rods and atomic clocks, have to be curved by the presence of gravitating masses.

A third point of view has emerged from recent research by David Lee, Alan Lightman and Kip Thorne. This interpretation is in some sense an amalgamation of the other two: Every theory of gravity that passes TEST-1 must give a complete and self-consistent means of "meshing" its laws of gravity with the other laws of physics. That is, it must give machinery for calculating the response of electromagnetic fields to gravity (modified Maxwell's equations), the response of quantum-mechanical systems to gravity (modified Dirac equation), the response of nuclear forces to gravity, and so on. The high-precision results of the Eötvös–Dicke–Braginsky experiments put severe constraints on the type of machinery permitted to mesh gravity with the rest of physics. In fact, the third point of view speculates, the *only* machinery that can produce agreement with these amazingly accurate experiments is that of a curved-spacetime theory or "metric theory" of gravity. Moreover, the gravitational redshift experiment verifies that freely falling "test" bodies follow geodesics of the curved spacetime metric (geodesics are the "straight lines" of curved space).

Thus, according to this third point of view, TEST-2 (the redshift experiment and the Eötvös–Dicke–Braginsky experiments) should pass only the curved spacetime "metric" theories, and should reject all the "nonmetric" theories. Current research is groping toward a "proof" of this third point of view by demonstrating explicitly that every nonmetric theory in the literature violates the Eötvös–Dicke–Braginsky experiment at some level of precision, and by proving (or making as convincing as possible) a general "theorem" that states: Every complete, self-consistent theory of gravity that embodies the composition-independence of free fall (agrees to all or-



ders with the Eötvös-Dicke-Braginsky experiment) must be a metric theory.

What is a metric theory?

If TEST-2, the redshift and Eötvös experiments, proves that only metric theories of gravity have a chance of being correct, then we should focus on these theories and examine them carefully. In precise terms, a metric theory of gravity is one in which

- there exists a metric that governs proper length and proper time measurements in the usual manner: Given two events in spacetime separated by a coordinate interval dx^i (i = 0, 1, 2, 3), the invariant or "proper" interval ds is given by

$$ds^2 = g_{ij} dx^i dx^j$$

where g_{ij} is the metric, and a summation over i and j is assumed.

- test bodies follow geodesics of the metric.
- in local "inertial," or freely falling, reference frames, all nongravitational laws of physics take on their standard special-relativity forms.

Now, in the solar system, gravity is relatively weak; the Newtonian potential divided by the square of the speed of light is everywhere smaller than 10^{-5}. Thus any analysis of the predictions of a metric theory of gravity for the solar system can be performed using the weak-field or the "post-Newtonian" limit of the theory. But when we begin studying the post-Newtonian limits of various metric theories, we notice a surprising feature: Almost all metric theories of gravity have the same form for their post-Newtonian limits, even though their exact, strong-field limits may differ greatly. The only way any one theory differs from any other at the post-Newtonian level is in the numerical values of a set of coefficients. A given coefficient may have the value unity in one theory, zero in another, 3.7 in still another, and so on. A particular set of values for these coefficients identifies a particular theory. Because all metric theories of gravity are the same at the post-Newtonian level except for the values of these coefficients, we can assign the coefficients letter names—γ, β, α_1, α_2 and so on—with *unspecified* values, and thus obtain a "supermetric theory" of gravity. Each metric theory's post-Newtonian limit is thus a special case of this supertheory. Therefore every metric theory predicts the same kind of observable effects in the solar system; however the *size* of each effect will depend on the numerical values of the coefficients corresponding to that theory. Experiments to measure the sizes of effects can be regarded as measurements of the "true" values of these coefficients γ, β, and so on. A set of high-precision experimental measurements of these coefficient values will, we hope, allow us to pick out of the supertheory that theory of gravity that best agrees with experiment.

The use of post-Newtonian coefficients or parameters to study metric theories of gravity and to analyze experimental tests is called the "Parametrized Post-Newtonian" (PPN) formalism, and the coefficients are called PPN parameters. Primitive versions of such a formalism were studied as early as 1922 by Arthur Eddington[10] and later by H. P. Robertson[11] and Schiff[12]; more general versions have recently been used by Kenneth Nordtvedt[13] and by me.[14] In the current version of the PPN formalism[15] there are up to nine parameters, each of which describes or measures a particular physical property of metric theories of gravity. The names of these parameters and a heuristic description of their physical meaning are shown in Table 1, along with their numerical values in a few particular theories. The remaining tests in the theoretical framework have been analyzed with this PPN formalism.

Light bending and radar time delay

The bending of light rays by the sun (see figure on page 27) and the delay in the round-trip travel time of a radar signal that passes the sun both measure the parameter γ. A light ray (or photon) that passes by the sun is deflected by an angle

$$\delta\theta \approx (1/2)(1 + \gamma)\,(1.75/d) \qquad (1)$$

independent of the frequency of the light, where d is the distance of closest approach of the ray from the sun in units of solar radii and $\delta\theta$ is the deflection in seconds of arc. A radar signal sent across the solar system past the sun to a planet or satellite and returned to the earth suffers an additional non-Newtonian delay in its round-trip travel time t_t (in microseconds), given by, for a ray that passes close to the sun,

$$\delta t_t \approx (1/2)(1 + \gamma)\,[250 - 20\log(d^2/r)] \qquad (2)$$

where r is the distance of the planet or satellite from the sun, in astronomical units. Measurements of these two effects have given us our most precise measurements of the parameter γ to date.

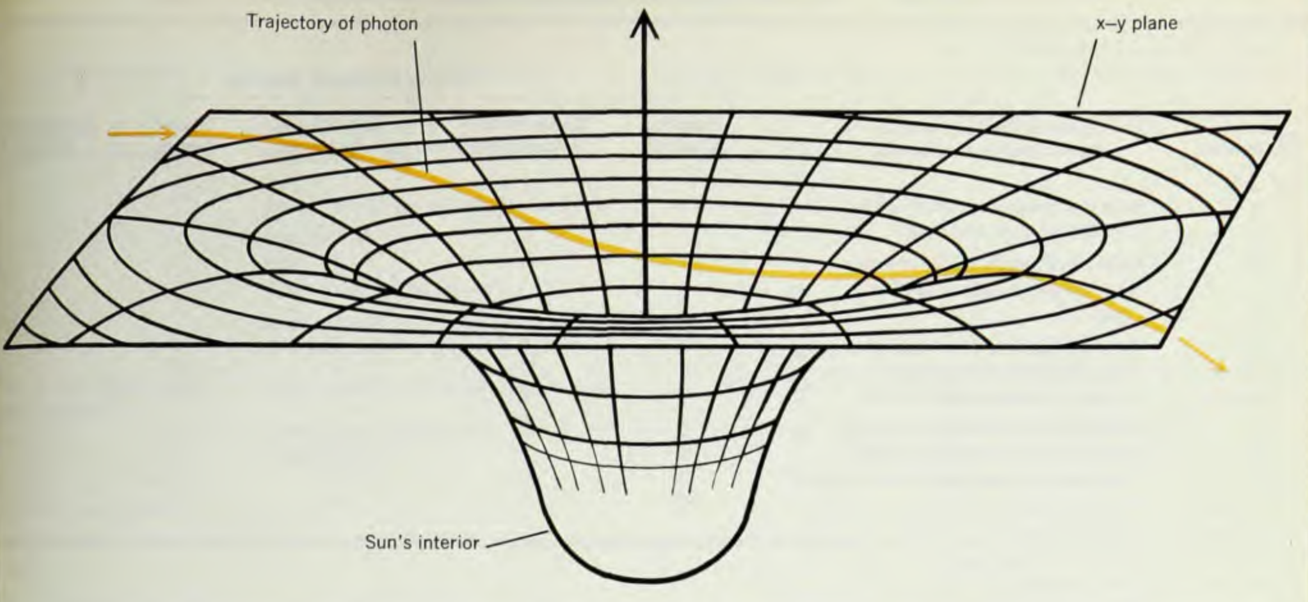
The prediction of the bending of light by the sun was one of the great successes of Einstein's general relativity. Eddington's confirmation of the bending in the first days following World War I helped make Einstein famous. However, the experiments of Eddington and his coworkers had only 30% accuracy, and succeeding experiments were not much better: The results were scattered between one half and one and a half times the Einstein value, and the accuracies were low. However, the development of long-baseline radio interferometry has altered the situation. Long-baseline and very-long-baseline techniques of interferometry can in principle measure angular separations and changes in angles as small as 3×10^{-4} seconds of arc. Coupled with this technological advance is a heavenly coincidence: Each 8 October, two strong quasistellar radio sources, 3C273 and 3C279, pass very close to the sun (as seen from the earth), in fact 3C279 actually goes behind the sun. By measuring the relative bending of the two signals from these quasars, radio astronomers over the past few years have been able to measure the coefficient $(1/2)\,(1 + \gamma)$ in equation 1, which has the value unity in general relativity. Their results[16] are seen in Table 2.

One of the major sources of error in these experiments is the solar corona, which bends radio waves much more strongly than it bent the visible light rays that Eddington observed. Improvements in dual-frequency techniques may improve accuracies by allowing the coronal bending, which depends on the frequency of the wave, to be measured separately from the gravitational bending, which does not.

The time-delay effect was not predicted by Einstein; it was 1964 when this effect was discovered by Irwin Shapiro[17] as a theoretical consequence of general relativity and of other theories of gravity (see equation 2). In the following years, attempts were made to measure this effect with radar ranging to targets passing through "superior conjunction" (target on the far side of the sun; radar signals passing close to the sun). Two types of targets were employed: planets such as Mercury and Venus, used as passive reflectors of the radar signals; and the Mariner VI and VII spacecraft, used as active retransmitters of the radar signals. Detailed analyses[18] of the measured roundtrip travel times yielded results as shown in Table 2. Here, as in the light-deflection measurements, the solar corona causes uncertainties in the measurements because of its slowing down of the radar signal; again dual-frequency ranging may help to reduce these errors.

In the figure on page 24 we see that Nørdstrøm's theory and the Littlewood-Bergmann theory predict no bending or time delay ($\gamma = -1$), and Einstein's 1912 theory (*not* general relativity) and Whitrow and Morduch's theories predict half the observed effect ($\gamma = 0$). These theories are ruled out.

Some theories are made uncomfortable but are not quite ruled out by



Curvature of space and the propagation of a light ray. General relativists like to form a mental picture of the curvature of space embodied in a metric theory of gravity by means of a so-called "embedding" diagram. Here we show the embedding diagram for the sun. The warped surface is really the x–y plane (we suppress the z-direction). If Newtonian theory were correct, this surface would be perfectly flat and the Euclidean formula for distances, $d = (x^2 + y^2)^{1/2}$, would be valid. But in curved space, the distance measured outward from the center of the sun may be longer than $(x^2 + y^2)^{1/2}$. The embedding diagram represents this by "stretching" the x–y plane near the sun. (Because of our limited senses, this stretching necessitates a three-dimensional picture.) Thus a light ray moving on the x–y plane near the sun has further to go to get across because it must cross a "stretched" region of space; that is, it must dip into the bowl of the embedding diagram. The "dip" causes part of the additional "time delay" suffered by the light ray (the rest of the delay is caused by a slowing down of the light by the sun—a special-relativity effect). The curvature of space also causes the path of the light to bend: The rim of the bowl in the embedding diagram is analogous to a banked roadway, which can change a motorist's direction without a turn of the steering wheel. This space curvature, along with the bending due to special relativity, produces the famous bending of light by the sun.

TEST-3; these are the scalar–tensor theories, of which the Dicke–Brans–Jordan theory is a special case. They contain an adjustable dimensionless "coupling constant" ω, which may vary between $-3/2$ and infinity (in the limit $\omega \to \infty$, these theories reduce to general relativity). For example, for these theories to agree with the time-delay measurements within two standard deviations, ω must be larger than six. However, the spread in values among the various experiments, and the quoted probable errors in the measurements of $(1/2)\ (1 + \gamma)$ make it impossible at present to rule out the scalar–tensor theories with confidence.

Perihelion shifts

In the past several years, the theoretical interpretation of the perihelion shifts of the planets has become more and more complex. The *measured* perihelion shifts are accurately known: After the effects of the other planets and of the "general precession" of the earth's rotation axis have been subtracted out, Mercury has a residual perihelion shift of 43 seconds of arc per century, and this shift is known to a precision of about one percent from radar-ranging data for the planets.[19] For Earth the residual shift is 4 arcsec per century, known to about ten-percent accuracy. The explanation of these perihelion shifts involves three effects: the classical, solar-oblateness and preferred-frame shifts.

According to the PPN formalism, the classical perihelion shift depends on the parameters γ and β, that is, it depends on the curvature of space and on the nonlinearity in the gravitational field produced by the sun. For general relativity, the classical perihelion shift gives complete agreement with the observations.

The sun may be slightly oblate, and this oblateness may cause an additional perihelion shift for Mercury as large as 4 arcsec per century. The smaller the oblateness, however, the smaller the additional shift.[20]

Some metric theories of gravity single out the mean rest-frame of the Universe as a "preferred" frame. Examples include the theories of C. Page and B. O. J. Tupper, Huseyin Yilmaz, A. Papapetrou, W.-T. Ni, C. J. Coleman, and Nathan Rosen, and a vector–tensor theory of gravity developed by Nordtvedt and me.[3,15] If the solar system were at rest relative to the mean rest-frame of the Universe, most of these theories would agree with general relativity in their predictions for all the "classical" tests. But the solar system probably moves through the Universe with a velocity of about 200 km per sec (due to its motion around the Galaxy and to the Galaxy's motion relative to other galaxies), and this motion should cause, according to these theories, observable solar-system effects whose sizes depend on the PPN "preferred-frame" parameters α_1, α_2 and α_3 (see Table 1; note that general relativity and the scalar–tensor theories predict *no* such effects—α_1, α_2 and α_3 are zero for these theories). One of these effects is an anomalous perihelion shift for Mercury and for the earth.[21] In fact many preferred-frame theories predict such large anomalous shifts (hundreds and thousands of seconds per century) that they can be ruled out by the observations, in spite

Table 1 Parametrization of Metric Theories of Gravity

Parameter	What it measures, relative to general relativity	General relativity	Dicke-Brans-Jordan theory	Vector-tensor theory	Yilmaz theory	Papapetrou theory
		Value in various theories				
γ	How much space-curvature is produced by a unit mass?	1	$(1+\omega)/(2+\omega)$	1	1	1
β	How much nonlinearity is there in the superposition law for gravity?	1	1	1	1	1
α_1	To what extent and in what manner	0	0	0	-8	-8
α_2	does the theory single out a preferred	0	0	κ	0	-4
α_3	Universal rest-frame?	0	0	0	-4	0
ζ_1	How much and what kind of violation	0	0	0	0	0
ζ_2	of conservation of total	0	0	0	-2	0
ζ_3	momentum does the theory predict?	0	0	0	0	0
ζ_4		0	0	0	-1	0

of the four-arc-sec uncertainty caused by the possible solar oblateness.

The uncertainty in the value of the sun's oblateness makes it impossible to rule out the scalar-tensor or vector–tensor theories (see the figure): Their predictions differ from those of general relativity by less than four arc sec per century.

Geophysical effects

Preferred-frame theories of gravity predict two kinds of geophysical effects caused by the earth's motion at 200 km per sec through the Universe, and again depending on the PPN parameters α_1, α_2 and α_3. The most important of these effects are a twelve-hour sidereal-time tide of the solid earth, analogous to the solid-earth tides caused by the moon and sun, and a yearly variation in the rotation rate of the earth. Earth-tide data obtained with high-precision gravimeters and length-of-day data obtained with atomic clocks have been shown[21,22] to put stringent limits on the sizes of these preferred-frame effects, limits so stringent that they would rule out again all the preferred-frame theories of gravity already ruled out by TEST-4. These theories thus fail on both counts. The vector-tensor theory of gravity is almost ruled out by earth-tide measurements, which put an upper limit of 3×10^{-2} on the adjustable coupling constant κ for this theory (in the limit $\kappa \rightarrow 0$, this theory reduces to general relativity).

Another theory ruled out by these geophysical tests is a theory that has been a thorn in Einstein's side since its inception in 1922 by Alfred North Whitehead.[3] Whitehead's theory, although very elegant and simple in formulation, is so complex in its mathematical details that it does not even fit into the nine-parameter PPN formalism (the only metric theory that does not, so far). Nevertheless, it agrees with Einstein in its predictions for all the classical tests and passes all the previous tests with flying colors. It has, however, been shown recently[22] to predict twelve-hour sidereal-time Earth tides, caused by the Galaxy, that are 200 times larger than observations will permit. Thus Whitehead's theory, after 50 years of life, has been killed by TEST-5.

We have discussed the theories of gravity that have been ruled out by the five tests in our theoretical framework. What about the theories that have passed these tests and are currently viable? General relativity passes all five tests with flying colors, as long as the solar oblateness is small enough that its contribution to Mercury's perihelion shift is smaller than the experimental error (± 0.4 arc sec per century). Dicke–Brans–Jordan Theory and the scalar–tensor theories pass all five tests, as long as their coupling constant ω is larger than six. Results of future light-deflection and time-delay experiments may push ω even higher.

The vector–tensor theory passes all five tests, as long as its coupling constant κ is smaller than 3×10^{-2}. Other theories, not yet invented or not yet pulled out of the literature and examined, may manage to pass all the current tests in the theoretical framework.

Future tests

There are two kinds of future tests of theories of gravity that our theoretical framework will incorporate: improvements of old experiments, and new experiments.

Currently viable theories of gravity should be recycled through improved versions of TESTS-2 to 5, and a variety of improvements in some of these tests are planned in the 1970's. Hydrogen-maser clocks flown in rockets should improve the accuracy of the gravitational redshift measurement by several orders of magnitude[23] (cesium-beam clocks flown recently on commercial jets detected only the time dilation of clocks in relative motion—a *special* relativity effect; the gravitational-redshift effect was at the limit of their precision). Further improvements in the Eötvös experiment, with orbiting manned laboratories, are being studied.[24] These experiments are important because (as we have speculated) they show that the correct theory of gravity must be a "metric" theory.

The crucial test of the scalar–tensor theories is TEST-3. Planned improvements in the light-deflection and time-delay experiments include more dual-frequency measurements to reduce uncertainties caused by the solar corona, and radar-ranging to spacecraft that are either orbiting or on the surfaces of planets ("anchored spacecraft"), or to drag-free spacecraft, in order to reduce the effects of the solar wind and radiation pressure on their motions. Crucial in this effort will be the 1975 Viking mission to Mars; no other planned mission combines an anchored spacecraft with dual-frequency radar.

Continued accumulation of data on the motions of the inner planets will yield improved measurements of the perihelion shifts of Mercury and Earth, and may perhaps allow a direct measurement of the effect of the sun's oblateness on planetary orbits.[19]

A variety of new possible experimental tests of gravitation theories have been devised, and many of these tests will be carried out in the 1970's. Measurements of the secular precession of the spin axes of an array of orbiting superconducting gyroscopes are planned

Table 2 Measurement of the PPN Parameter γ

Type of experiment	Experimenter (and date)	Value of $(1/2)(1+\gamma)$
Light bending measured by radio interferometry[16]	October 1969	
	Muhleman, Ekers, Fomalont	$1.04 {+.15 \atop -.10}$
	Seielstad, Sramek, Weiler	$1.01 \pm .12$
	October 1970	
	Hill	$1.07 \pm .17$
	Shapiro and coworkers*	$1.03 \pm .2$
	October 1970 and October 1971	
	Sramek and Fomalont*	$0.94 \pm .06$
Time delay measured by radar ranging[18]	Passive radar to Mercury and Venus	$1.02 \pm .05$
	Active radar to Mariner 6 and Mariner 7	$1.00 \pm .04$

** Unpublished result*

for late in this decade by a group at Stanford University.[25] This experiment measures two kinds of precession: the geodetic precession, produced by the curvature of space around the earth, given by

$$(1/3)(1 + 2\gamma)\ (7 \text{ arc sec per year})$$

and the Lens–Thirring precession, produced by the rotation of the earth, given by

$$(1/2)(1 + \gamma + \alpha_1/4)\ (0.05 \text{ arc sec per year})$$

Hoped-for accuracy of the measurements is 0.001 arc sec.

Laser ranging to the moon with accuracies in range better than 30 cm may measure or rule out a host of gravitational effects. Among these are the effects of a breakdown in the equality of inertial and gravitational mass for the earth[26] (Nordtvedt effect), predicted by most theories with the exception of general relativity; a variety of effects predicted by preferred-frame theories of gravity, such as the vector–tensor theory,[21] and effects produced by the nonlinear superposition of the fields of the sun and the earth, which are present even in general relativity.[27]

Studies of the stability and pulsations of white dwarf stars may put even tighter constraints on preferred-frame theories of gravity, such as the vector–tensor theory, and on any others that manage to pass the five tests in our framework. These theories have been shown by Ni to predict that pulsations of white dwarf stars should grow in amplitude because of their motions relative to the Universe's mean rest-frame, in disagreement with observations. But there remain crucial uncertainties in the classical theory of white-dwarf pulsation damping.

Radar and optical studies of the motions of the planets may yield a tight upper limit on a possible secular variation in the Newtonian gravitational constant.[28] Such a variation cannot be analyzed within the PPN framework, because it is produced by variations (due to an evolving Universe) in the strengths of cosmological scalar, vector and tensor fields. Nonetheless, a tight limit on such a variation could help toward distinguishing between general relativity and the various scalar–tensor and vector–tensor theories. The current upper limit[28] of four parts in 10^{10} per year is not yet tight enough, but improvements are planned.

It has been 50 years since the creation of Einstein's general relativity, and for 50 years the theory has been on the firing line. So far, as we have seen, it has survived, but then so have several other theories. One of the key goals of the 1970's is to push experimental tests of gravitation theories to their limit, so that, finally, only one theory will remain. It may be general relativity or it may be some other theory. But only then can the theoretical astrophysicist, equipped with the correct theory of gravity, proceed with confidence in the exciting task of understanding the heavens.

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This work was supported in part by the National Science Foundation (GP-27304, GP-28027) and the National Aeronautics and Space Administration Caltech/JPL Contract No. NAS 7-100 (188-41-54-02-01) and NGR 05-002-256.

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