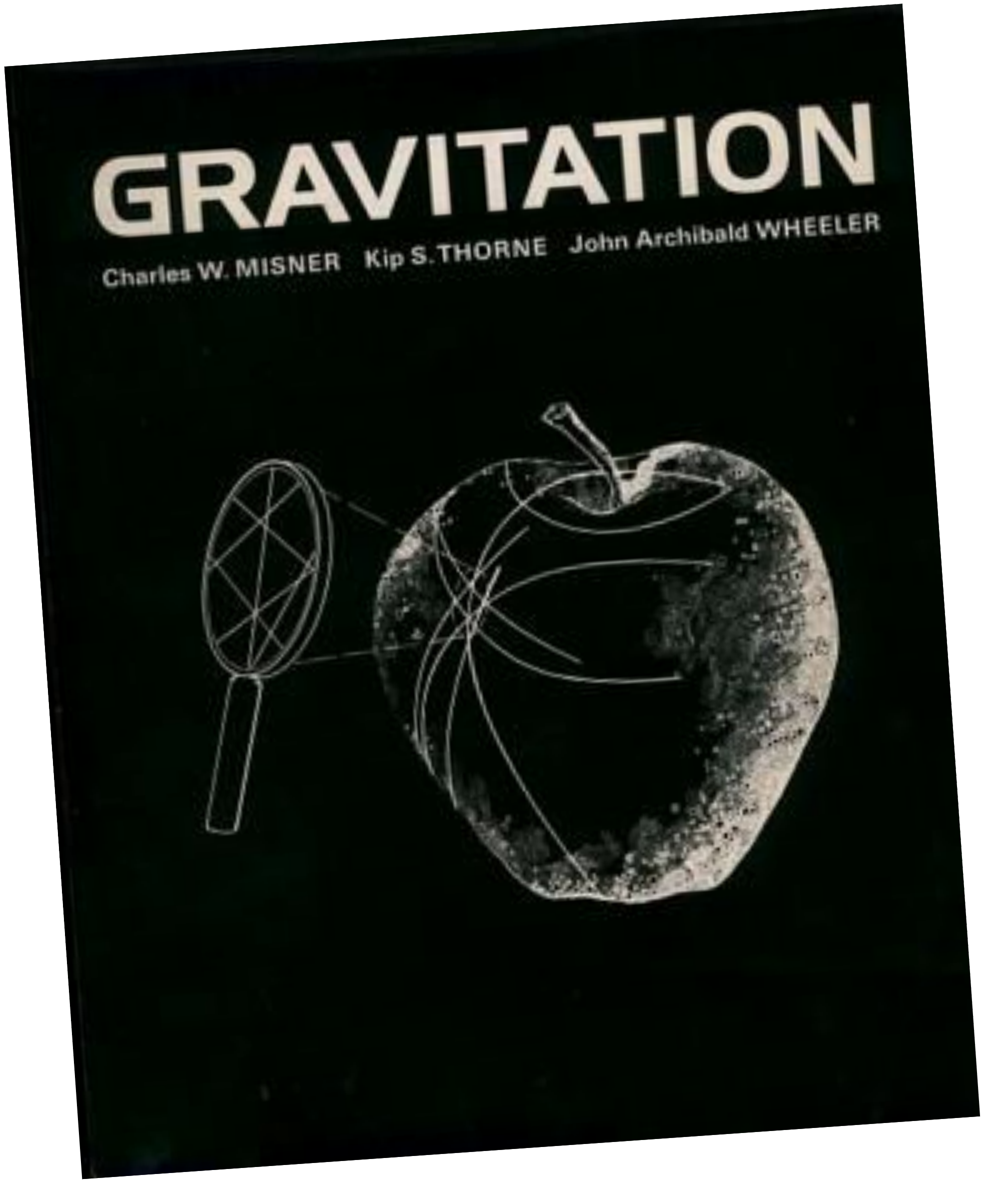


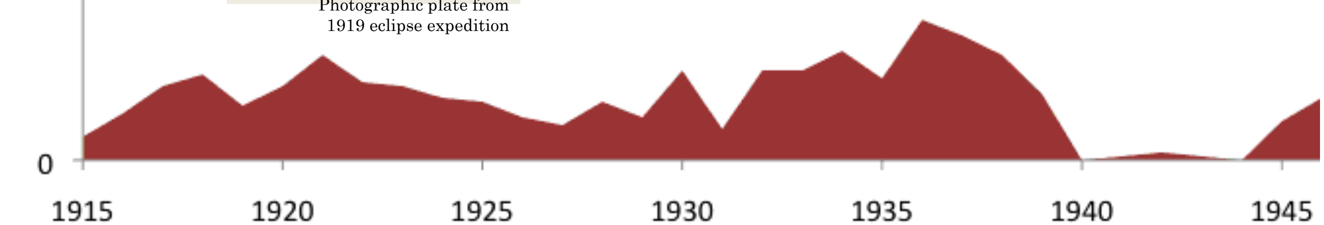
Misner, Thorne, Wheeler, ***Gravitation***:

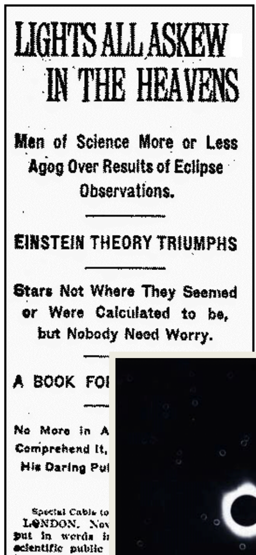
A 50-Year Anniversary Celebration

David Kaiser

The Ups and Downs of Gravity

Worldwide publications on general relativity





LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

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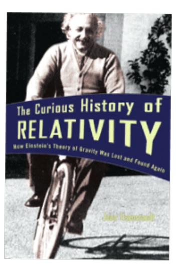
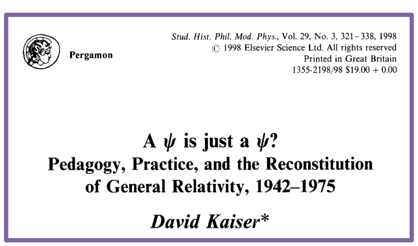
1919 eclipse expedition

American Institute of Physics





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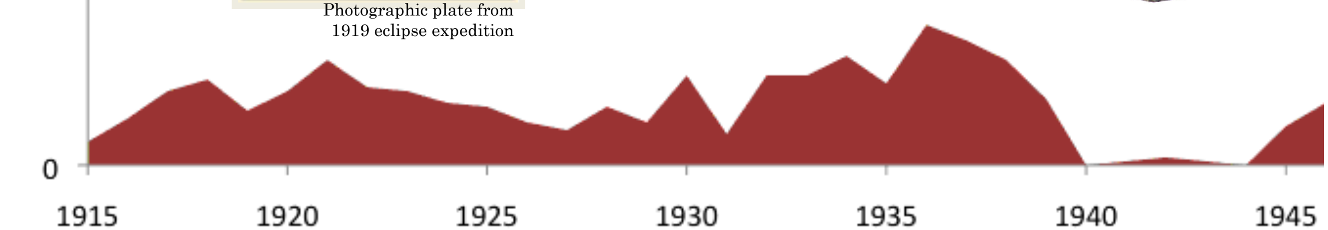

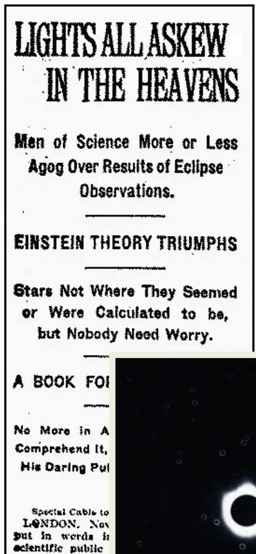

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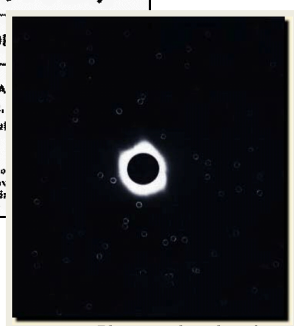

Photographic plate from 1919 eclipse expedition

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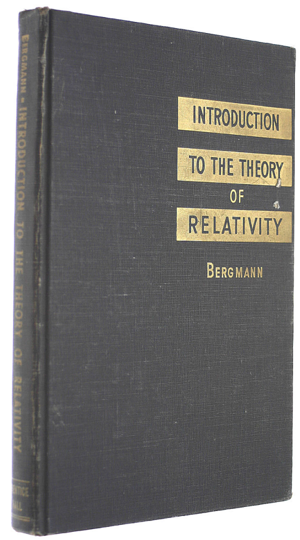
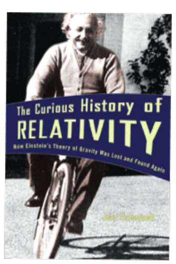
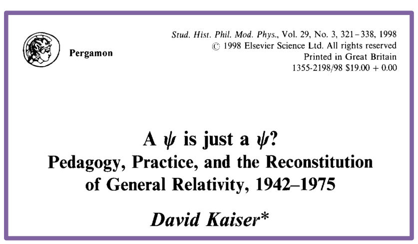
Einstein's foreword in Bergmann's 1942 textbook



Throughout the 1950s, most physics PhD programs in the US neither required nor recommended coursework on general relativity, nor included GR on graduate students' qualifying exams.





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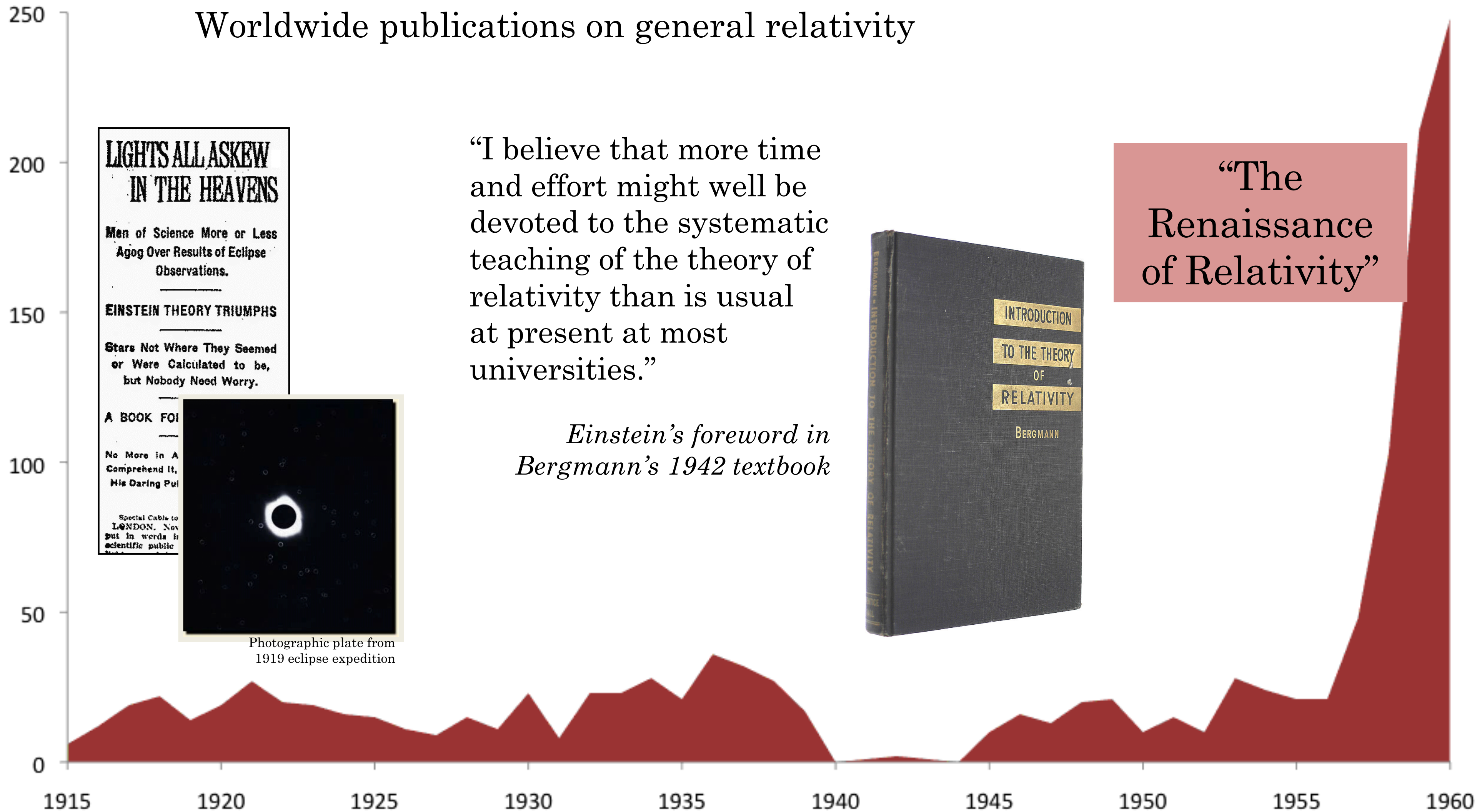

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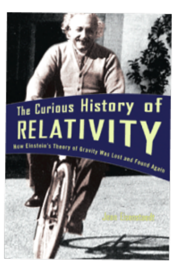

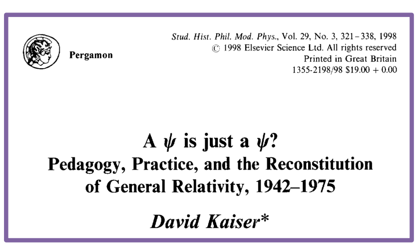

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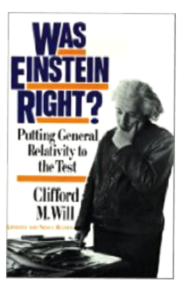
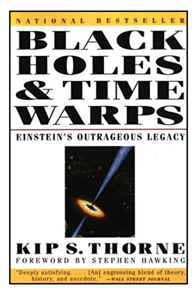
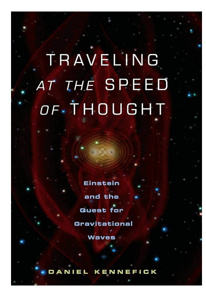
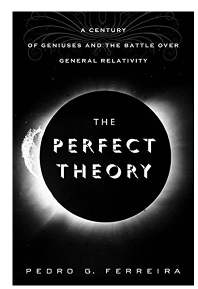
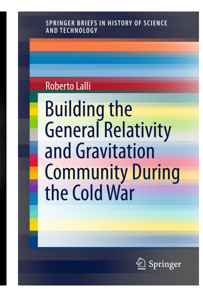
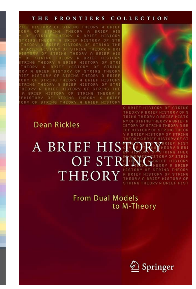


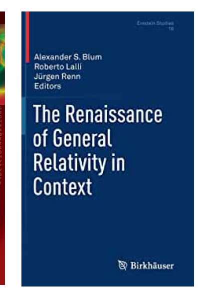




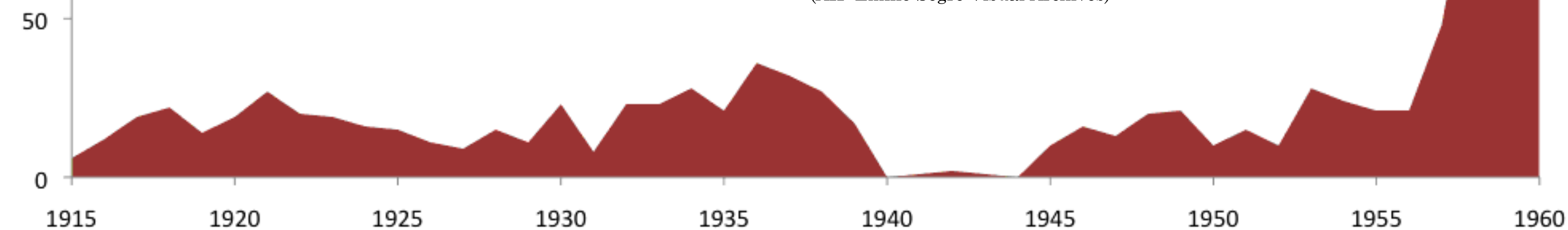








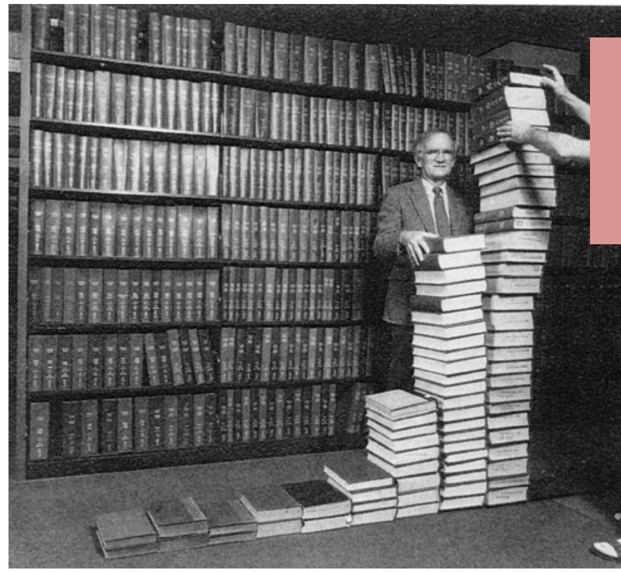
The Ups and Downs of Gravity



After 1945, publications on GR grew at a *faster rate* than the overall (exponential) increase across physics.

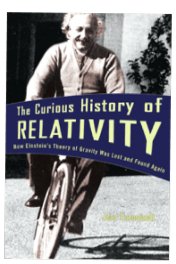
The rapid rise began *before* the new experiments (Pound-Rebka gravitational redshift, Shapiro time-delay) or astrophysical discoveries (quasars, CMB).

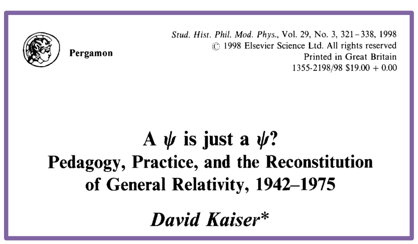
The timing underscores the importance of *institutions, networks,* and *influential teachers*.



Val Fitch with *Physical Review* by decade, 1890s-1970s
(AIP Emilio Segrè Visual Archives)

"The Renaissance of Relativity"





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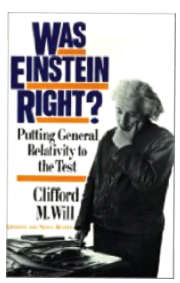

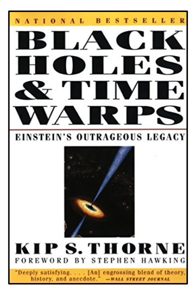

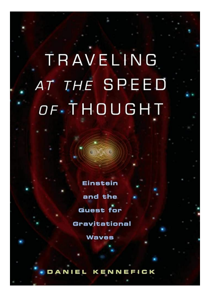

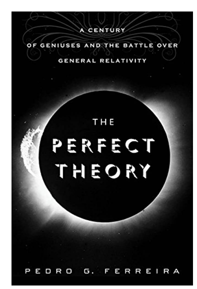

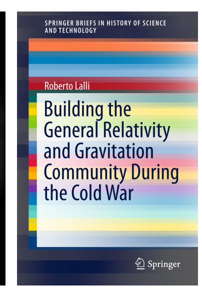

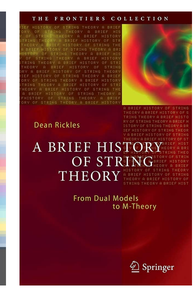

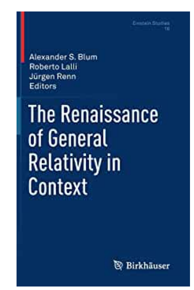

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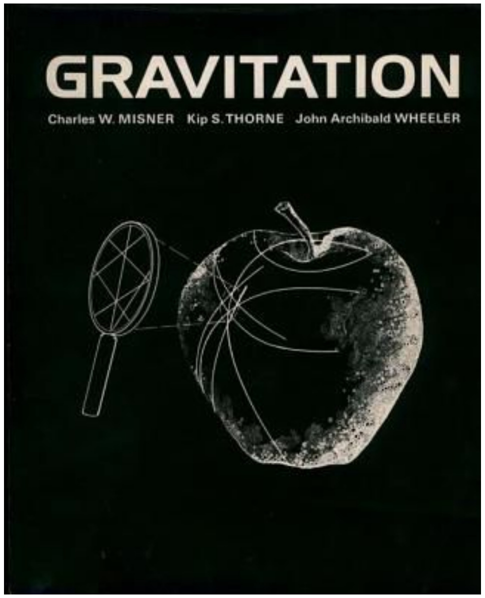

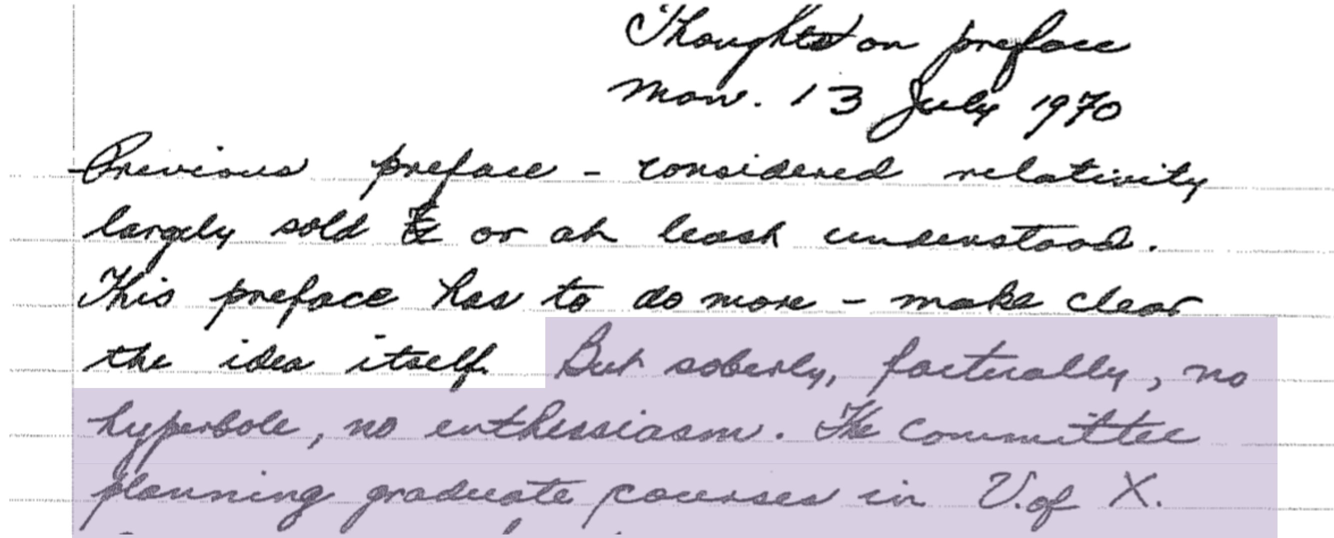

Thoughts on preface
Mon. 13 July 1970

Previous preface - considered relativity largely sold [illegible] or at least understood. This preface has to do more - make clear the idea itself. But soberly, factually, no hyperbole, no enthusiasm. The committee planning graduate courses in U. of X.

John A. Wheeler papers,
American Philosophical Society

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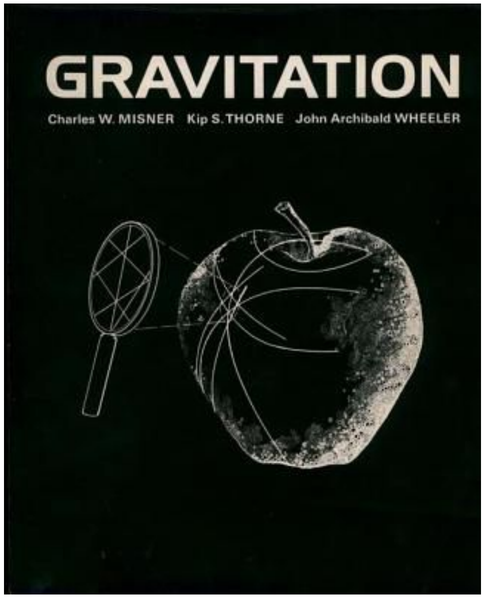

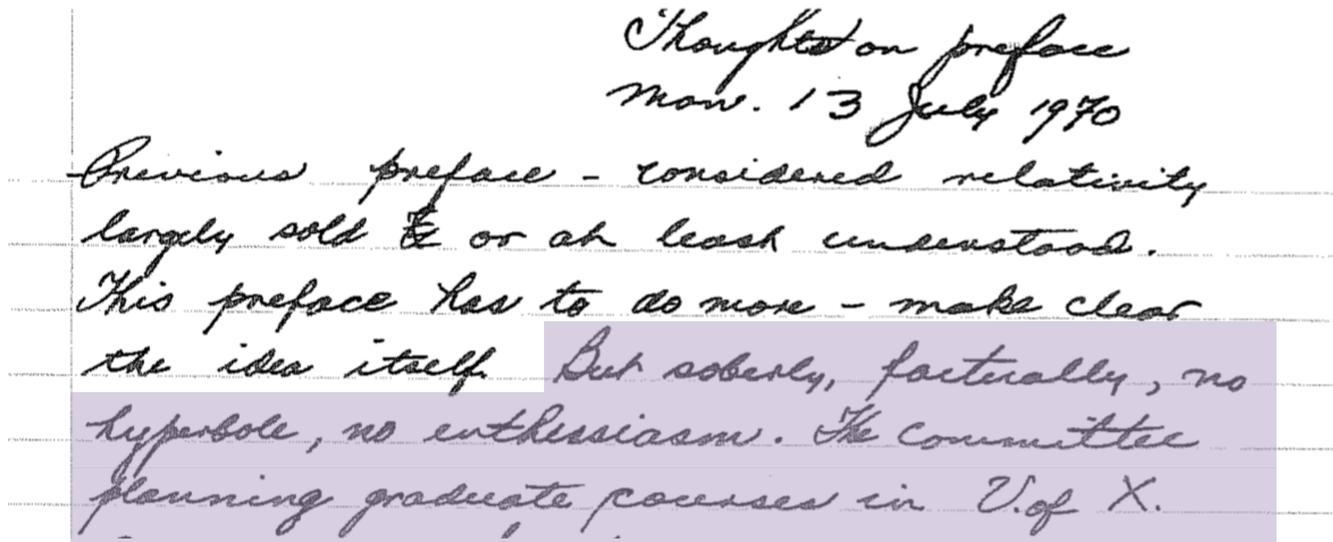

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2. Tensors in All Generality 74
3. Three-Plus-One View Versus Geometric View 78
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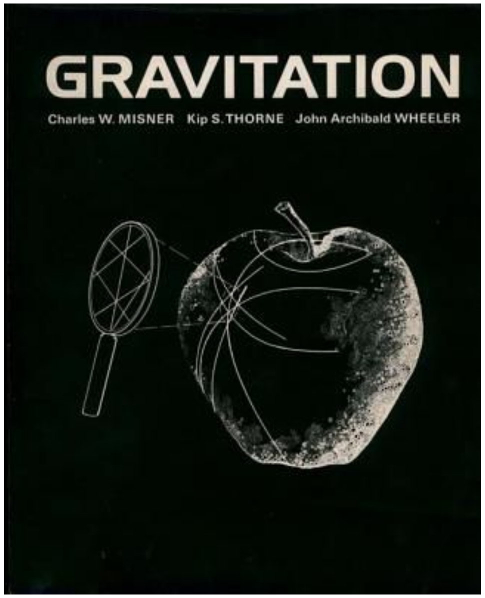
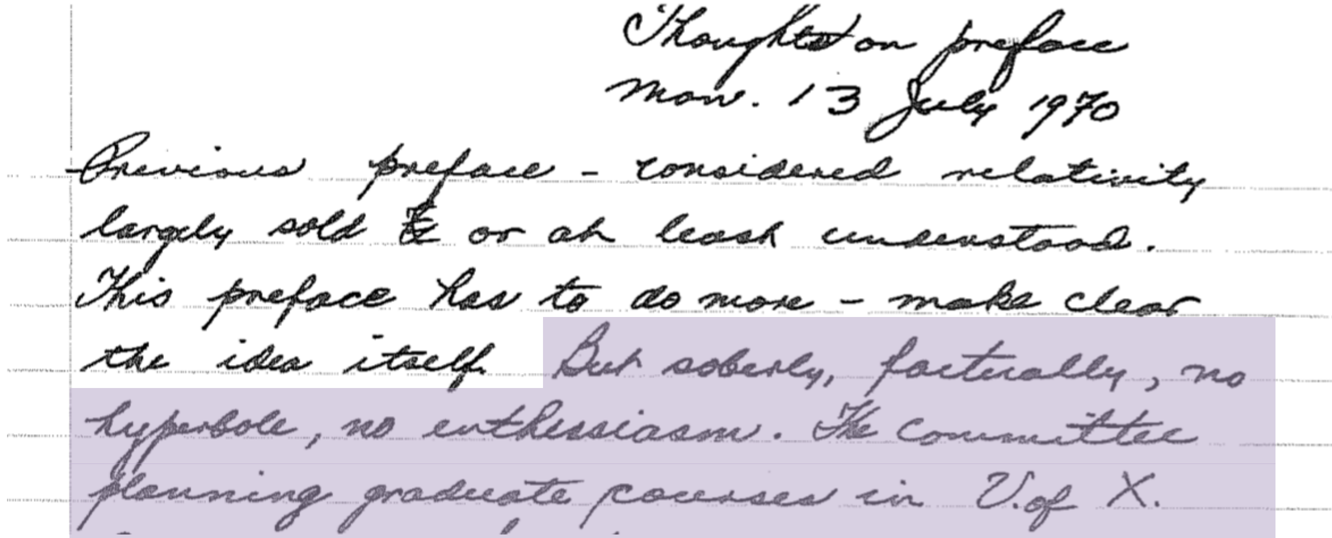
What Kind of Book is MTW?





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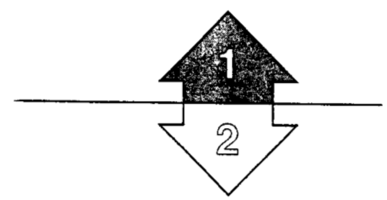
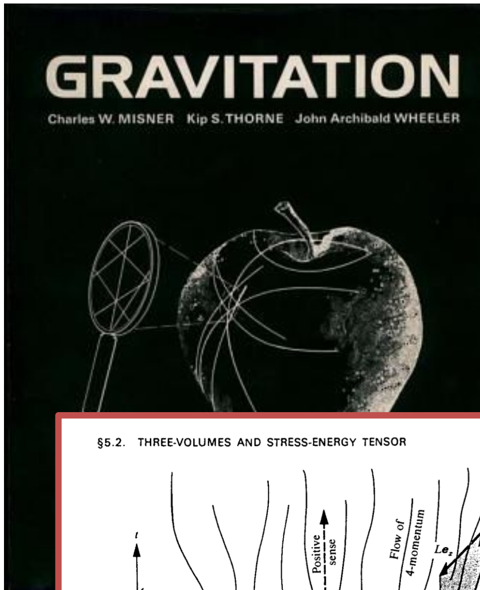
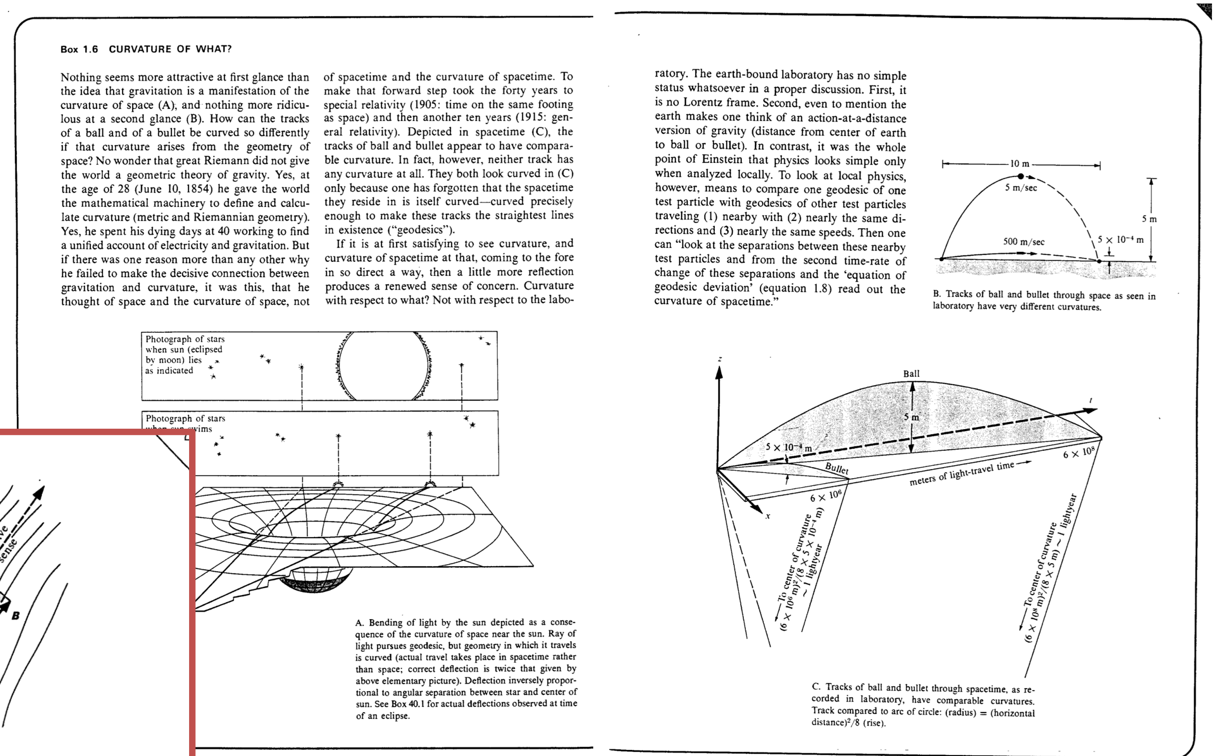


The rest of this chapter is Track 2.
It depends on no preceding Track-2 material.
It is needed as preparation for Chapter 20 (conservation laws for mass and angular momentum).
It will be extremely helpful in all applications of gravitation theory (Chapters 18–40).

What Kind of Book is MTW?





Box 1.6 CURVATURE OF WHAT?

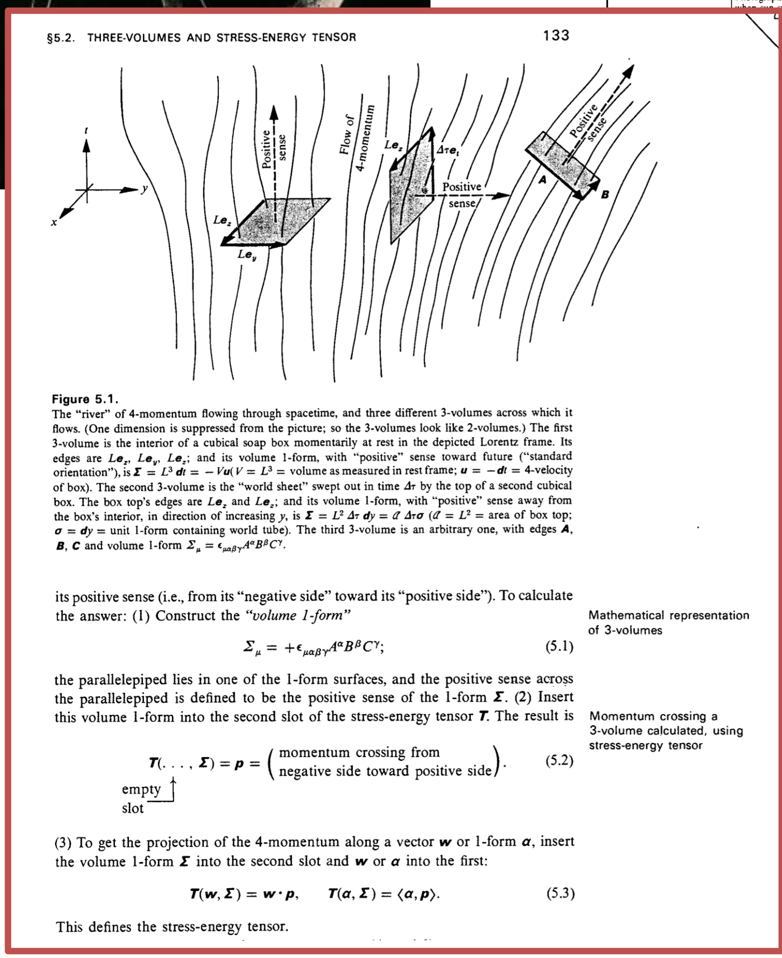
Nothing seems more attractive at first glance than the idea that gravitation is a manifestation of the curvature of space (A), and nothing more ridiculous at a second glance (B). How can the tracks of a ball and of a bullet be curved so differently if that curvature arises from the geometry of space? No wonder that great Riemann did not give the world a geometric theory of gravity. Yes, at the age of 28 (June 10, 1854) he gave the world the mathematical machinery to define and calculate curvature (metric and Riemannian geometry). Yes, he spent his dying days at 40 working to find a unified account of electricity and gravitation. But if there was one reason more than any other why he failed to make the decisive connection between gravitation and curvature, it was this, that he thought of space and the curvature of space, not of spacetime and the curvature of spacetime. To make that forward step took the forty years to special relativity (1905: time on the same footing as space) and then another ten years (1915: general relativity). Depicted in spacetime (C), the tracks of ball and bullet appear to have comparable curvature. In fact, however, neither track has any curvature at all. They both look curved in (C) only because one has forgotten that the spacetime they reside in is itself curved—curved precisely enough to make these tracks the straightest lines in existence ("geodesics").

If it is at first satisfying to see curvature, and curvature of spacetime at that, coming to the fore in so direct a way, then a little more reflection produces a renewed sense of concern. Curvature with respect to what? Not with respect to the laboratory. The earth-bound laboratory has no simple status whatsoever in a proper discussion. First, it is no Lorentz frame. Second, even to mention the earth makes one think of an action-at-a-distance version of gravity (distance from center of earth to ball or bullet). In contrast, it was the whole point of Einstein that physics looks simple only when analyzed locally. To look at local physics, however, means to compare one geodesic of one test particle with geodesics of other test particles traveling (1) nearby with (2) nearly the same directions and (3) nearly the same speeds. Then one can "look at the separations between these nearby test particles and from the second time-rate of change of these separations and the 'equation of geodesic deviation' (equation 1.8) read out the curvature of spacetime."

A. Bending of light by the sun depicted as a consequence of the curvature of space near the sun. Ray of light pursues geodesic, but geometry in which it travels is curved (actual travel takes place in spacetime rather than space; correct deflection is twice that given by above elementary picture). Deflection inversely proportional to angular separation between star and center of sun. See Box 40.1 for actual deflections observed at time of an eclipse.

B. Tracks of ball and bullet through space as seen in laboratory have very different curvatures.

C. Tracks of ball and bullet through spacetime, as recorded in laboratory, have comparable curvatures. Track compared to arc of circle: (radius) = (horizontal distance)^2/8 (rise).



§5.2. THREE-VOLUMES AND STRESS-ENERGY TENSOR 133

Figure 5.1.
The "river" of 4-momentum flowing through spacetime, and three different 3-volumes across which it flows. (One dimension is suppressed from the picture; so the 3-volumes look like 2-volumes.) The first 3-volume is the interior of a cubical soap box momentarily at rest in the depicted Lorentz frame. Its edges are $\boldsymbol{Le}_x$, $\boldsymbol{Le}_y$, $\boldsymbol{Le}_z$; and its volume 1-form, with "positive" sense toward future ("standard orientation"), is $\boldsymbol{\Sigma} = L^3\,\boldsymbol{d}t = -V\boldsymbol{u}$ ($V = L^3$ = volume as measured in rest frame; $\boldsymbol{u} = -\boldsymbol{d}t$ = 4-velocity of box). The second 3-volume is the "world sheet" swept out in time $\Delta\tau$ by the top of a second cubical box. The box top's edges are $\boldsymbol{Le}_x$ and $\boldsymbol{Le}_z$; and its volume 1-form, with "positive" sense away from the box's interior, in direction of increasing y, is $\boldsymbol{\Sigma} = L^2\,\Delta\tau\,\boldsymbol{d}y = \mathcal{A}\,\Delta\tau\boldsymbol{\sigma}$ ($\mathcal{A} = L^2$ = area of box top; $\boldsymbol{\sigma} = \boldsymbol{d}y$ = unit 1-form containing world tube). The third 3-volume is an arbitrary one, with edges $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ and volume 1-form $\Sigma_\mu = \epsilon_{\mu\alpha\beta\gamma}A^\alpha B^\beta C^\gamma$.

its positive sense (i.e., from its "negative side" toward its "positive side"). To calculate the answer: (1) Construct the *"volume 1-form"*

Mathematical representation of 3-volumes

$$\Sigma_\mu = +\epsilon_{\mu\alpha\beta\gamma}A^\alpha B^\beta C^\gamma; \qquad (5.1)$$

the parallelepiped lies in one of the 1-form surfaces, and the positive sense across the parallelepiped is defined to be the positive sense of the 1-form $\boldsymbol{\Sigma}$. (2) Insert this volume 1-form into the second slot of the stress-energy tensor $\boldsymbol{T}$. The result is

Momentum crossing a 3-volume calculated, using stress-energy tensor

$$\boldsymbol{T}(\ldots, \boldsymbol{\Sigma}) = \boldsymbol{p} = \begin{pmatrix}\text{momentum crossing from} \\ \text{negative side toward positive side}\end{pmatrix}. \qquad (5.2)$$

empty slot

(3) To get the projection of the 4-momentum along a vector $\boldsymbol{w}$ or 1-form $\boldsymbol{\alpha}$, insert the volume 1-form $\boldsymbol{\Sigma}$ into the second slot and $\boldsymbol{w}$ or $\boldsymbol{\alpha}$ into the first:

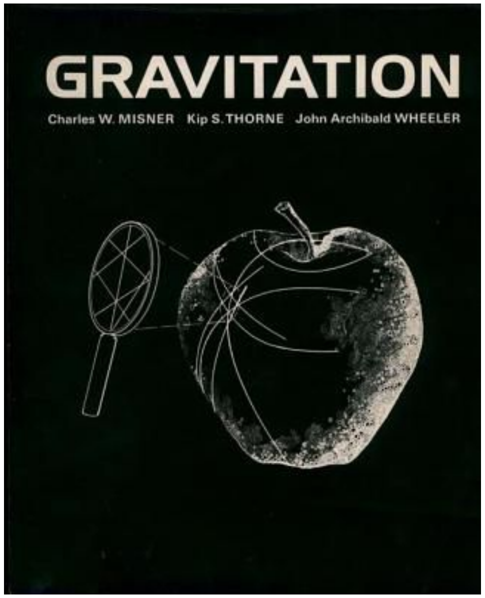
$$\boldsymbol{T}(\boldsymbol{w}, \boldsymbol{\Sigma}) = \boldsymbol{w}\cdot\boldsymbol{p}, \qquad \boldsymbol{T}(\boldsymbol{\alpha}, \boldsymbol{\Sigma}) = \langle\boldsymbol{\alpha}, \boldsymbol{p}\rangle. \qquad (5.3)$$

This defines the stress-energy tensor.

"Several features of the manuscript will require special typesetting problems." They would require *at least* 6 distinct typefaces, perhaps as many as 8. **"The extreme complexity of the typography"** meant that equations from the original edition should be photographed and pasted in to foreign-language editions, rather than attempting to retypeset them.

Kip Thorne to Earl Tondreau (editor at W. H. Freeman), October 14, 1970; Thorne to Ya. B. Zel'dovich and I. D. Novikov, June 21, 1973.

What Kind of Book is MTW?



"I was rather shocked to learn from Bruce [Armbruster, the editor] that the people at [W. H.] Freeman are so out-of-touch with our book that they have not been regarding it as a textbook, but rather as a technical monograph. I suppose that the enormous size of the book has something to do with it. [...] Freeman had not been expecting to pick up the textbook market with this book" at all, but rather to prepare an expensive hardcover edition for sale to libraries.

Kip Thorne to John Wheeler and Charles Misner, February 17, 1972

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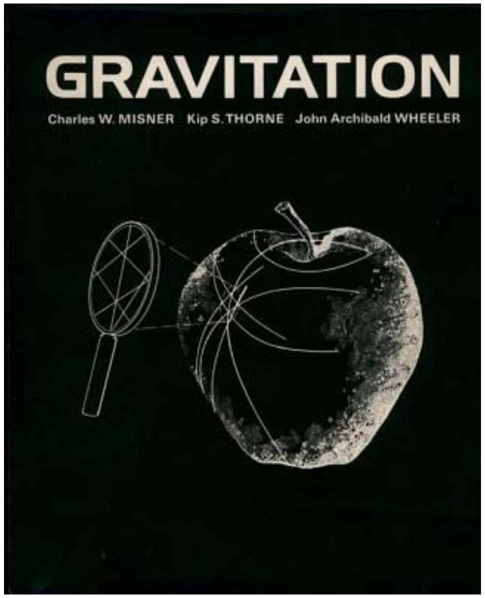

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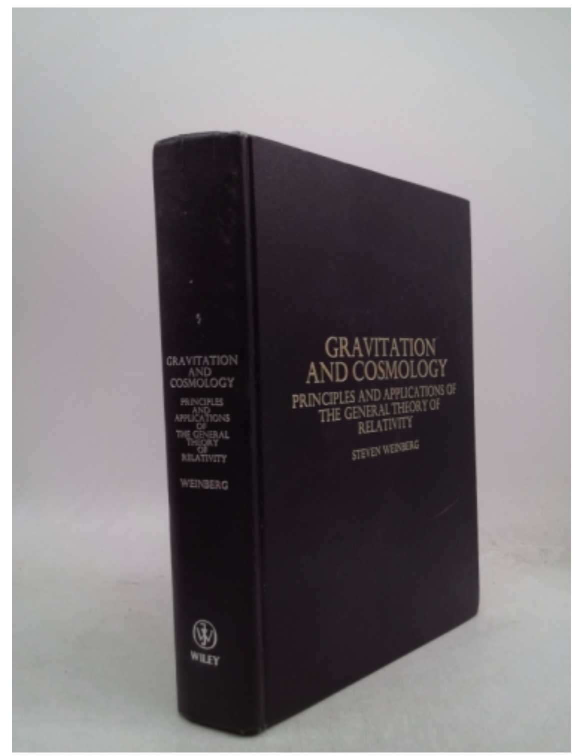
After some frenzied negotations over pricing and royalty rates, the publisher agreed to publish a sturdy paperback edition priced at $19.95 [around $130 today], so that the ***paperback*** edition of ***MTW*** would remain comparable in price to the ***hardcover*** edition of **Steven Weinberg's *Gravitation and Cosmology*** (1972).



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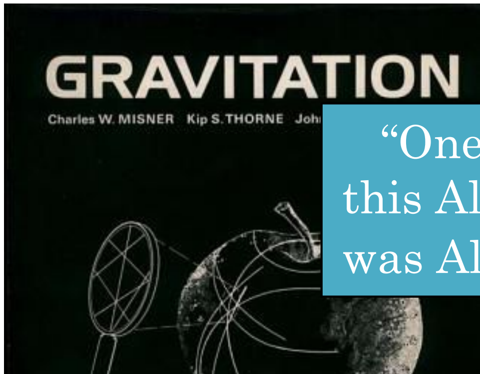
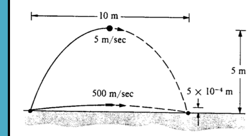


"A pedagogic masterpiece."

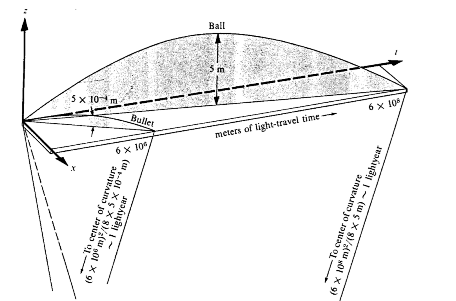
Dennis Sciama, *Science* (March 22, 1974)

"One of the great books of science, a lamp to illuminate this Aladdin's cave of theoretical physics whose genie was Albert Einstein."

Michael Berry, *Science Progress* (1975)



B. Tracks of ball and bullet through space as seen in laboratory have very different curvatures.



C. Tracks of ball and bullet through spacetime, as recorded in laboratory, have comparable curvatures. Track compared to arc of circle: (radius) = (horizontal distance)²/8 (rise).

"This is a difficult book to read in a linear, progressive fashion. [...] There is a commendable attempt at informality, but this reviewer found the breeziness irritating at times."

L. Resnick, *Physics in Canada* (June 1975)

"The variety of gimmicks is bewildering—framed headings with quotations, marginal titles, 'boxes' sometimes extending over several pages, heavy type, light type, large type, small type. Clearly the book is an experiment in presentation on a grand scale."

W. H. McCrea, *Contemporary Physics* (July 1974)

A reader would be most comfortable with *MTW* "if he is a regular subscriber to *Time* magazine—the writing of these authors has much in common with its breathless style."

Ian Roxburgh, *New Scientist* (September 26, 1974)

the parallelepiped lies in one of the 1-form surfaces, and the positive sense across the parallelepiped is defined to be the positive sense of the 1-form $\boldsymbol{\Sigma}$. (2) Insert this volume 1-form into the second slot of the stress-energy tensor $\boldsymbol{T}$. The result is

Momentum crossing a 3-volume calculated, using stress-energy tensor

$$\boldsymbol{T}(\ldots, \boldsymbol{\Sigma}) = \boldsymbol{p} = \left(\begin{array}{l}\text{momentum crossing from}\\ \text{negative side toward positive side}\end{array}\right). \quad (5.2)$$

(3) To get the projection of the 4-momentum along a vector $\boldsymbol{w}$ or 1-form $\boldsymbol{\alpha}$, insert the volume 1-form $\boldsymbol{\Sigma}$ into the second slot and $\boldsymbol{w}$ or $\boldsymbol{\alpha}$ into the first:

$$\boldsymbol{T}(\boldsymbol{w}, \boldsymbol{\Sigma}) = \boldsymbol{w} \cdot \boldsymbol{p}, \qquad \boldsymbol{T}(\boldsymbol{\alpha}, \boldsymbol{\Sigma}) = \langle \boldsymbol{\alpha}, \boldsymbol{p} \rangle. \quad (5.3)$$

This defines the stress-energy tensor.

The Weather

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97th Year ··· No. 137 SUNDAY, APRIL 21, 1974 Phone (202) 223-6000 Classified 223-6200 Circulation 223-6100 60c Beyond Washington, Maryland and Virginia 50c

Ups and Downs of 'Gravitation'

GRAVITATION. By Charles W. Misner, Kip S. Thorne, and John Archibald Wheeler. W. H. Freeman. 1,279 pp. Cloth, $39.50; paper, $19.95

By DAVID PARK

WHEN LAWS OF NATURE have been firmly established, a scientist often allows himself the pleasure of imagining what would happen, according to these laws, under wildly extreme circumstances. Archimedes, having proved (falsely, as it turns out) the law of the lever, said, "Give me a place to stand and I will move the world." Isaac Newton, at 22, wondered whether the same principles that govern the fall of an apple from a tree also govern the motion of the moon, which falls forever towards the earth but always so as to pass to one side of it. More than a century later, Pierre-Simon Laplace showed that in Newton's theory the gravitational field of an extremely massive star would suck back all light emitted from it: "A luminous star having the same density as the earth, but a diameter 250 times that of the sun, would not permit any of its rays to reach us; it is thus possible that the largest luminous bodies in the universe are by this fact invisible."

In 1915, Albert Einstein replaced Newton's theory of gravity by a new theory that did not contain the idea of a gravitational force at all, but postulated that the apple and the moon go where they go along force-free paths in a curved spacetime. The agreement with experiment was spectacular but the curvatures involved were very mild; at the earth's surface where we encounter it, the curvature corresponds to that of an arc of a circle whose center lies near the sun. Even such small effects required prodigies of mathematical effort, and the number of physicists with the time and energy to spend on working out the theory's more fanciful consequences remained small for many years, while the general public seemed to enjoy telling each other that only two, or six, or 12 men in the world understood Einstein's theory.

In 1939 there appeared papers by Robert Oppenheimer and two collaborators following up the Laplacian fantasy (though they didn't mention Laplace and probably did not know what he had written). Their stars were just as extreme as Laplace's but in another way: about as massive as the sun but only a few miles across. Using somewhat primitive arguments they showed that such a star, having the same density as an atomic nucleus, as it cools would be unable to withstand the huge force of its own gravity and would collapse still further. Any unfortunate inhabitant of such an object would find that in the course of about a day all his options vanish: he could no longer escape and even the beam of the flashlight he used for signaling would curve back and light up the ground at his feet.

Is this the destiny of every star as it cools and contracts? Or is it an absurdity produced by pushing a good theory beyond the furthest limits of its applicability? "Gravitational collapse," John Archibald Wheeler has written, "is the greatest crisis of physics to emerge from general relativity."

There are several reasons why Einstein's theory, almost 60 years after its birth, is now in a period of explosive development. There is at last a considerable group of physicists who have mastered the necessary mathematics and, in addition, computers have come to their aid. But more important, there are new phenomena to be explained.

So now books on the subject are coming out, and the one most discussed and criticized and wondered over is by Wheeler, at Princeton, and two of his former students, Charles Misner of Maryland and Kip Thorne of the California Institute of Technology. Perhaps it is strange to review here a textbook full of mathematics, a book, moreover, whose 6.7-pound bulk the young, the old and the infirm can scarcely lift. But those who read like to know what is being published and discussed.

Imagine that three highly inventive people get together to invent a scientific book. Not just write it, but invent the tone, the style, the methods of exposition, the format. Like the French *nouvelle vague* of a few years ago, but with a different mixture of purpose, resourcefulness, and energy. First, the question of tone.

The reader may have some preconceptions as to how a scientific treatise ought to sound; our authors have written, "Gravity is a great mystery. Drop a stone. See it fall. Hear it hit. No one understands why.' What a misleading statement! Mystery about fall? What else should the stone do except fall? To fall is normal. The abnormality is an object standing in the way of the stone." Electromagnetism and gravitation are compared in these words: "Electromagnetism has the motto, 'I count all the electric charge that's here.' All that bears no charge escapes its gaze. 'I weight all that's here' is the motto of space curvature. No physical entity escapes this surveillance." Reading words like these awakens hope that the fuzzy and lugubrious "style" that still spreads its gloom over so much of American science may not be in fashion forever.

There are very few stories that should be told sequentially. The *nouvelle vague* people knew that and adopted various strategies for breaking up a linear narrative, and future scientific writers may wish to consult Nabokov's *Pale Fire*. In *Gravitation*, there are two strategies. The whole book can be read on two tracks, and each page identifies its track. The reader chooses according as his curiosity and energy are bounded (Track 1) or unbounded (Track 2).

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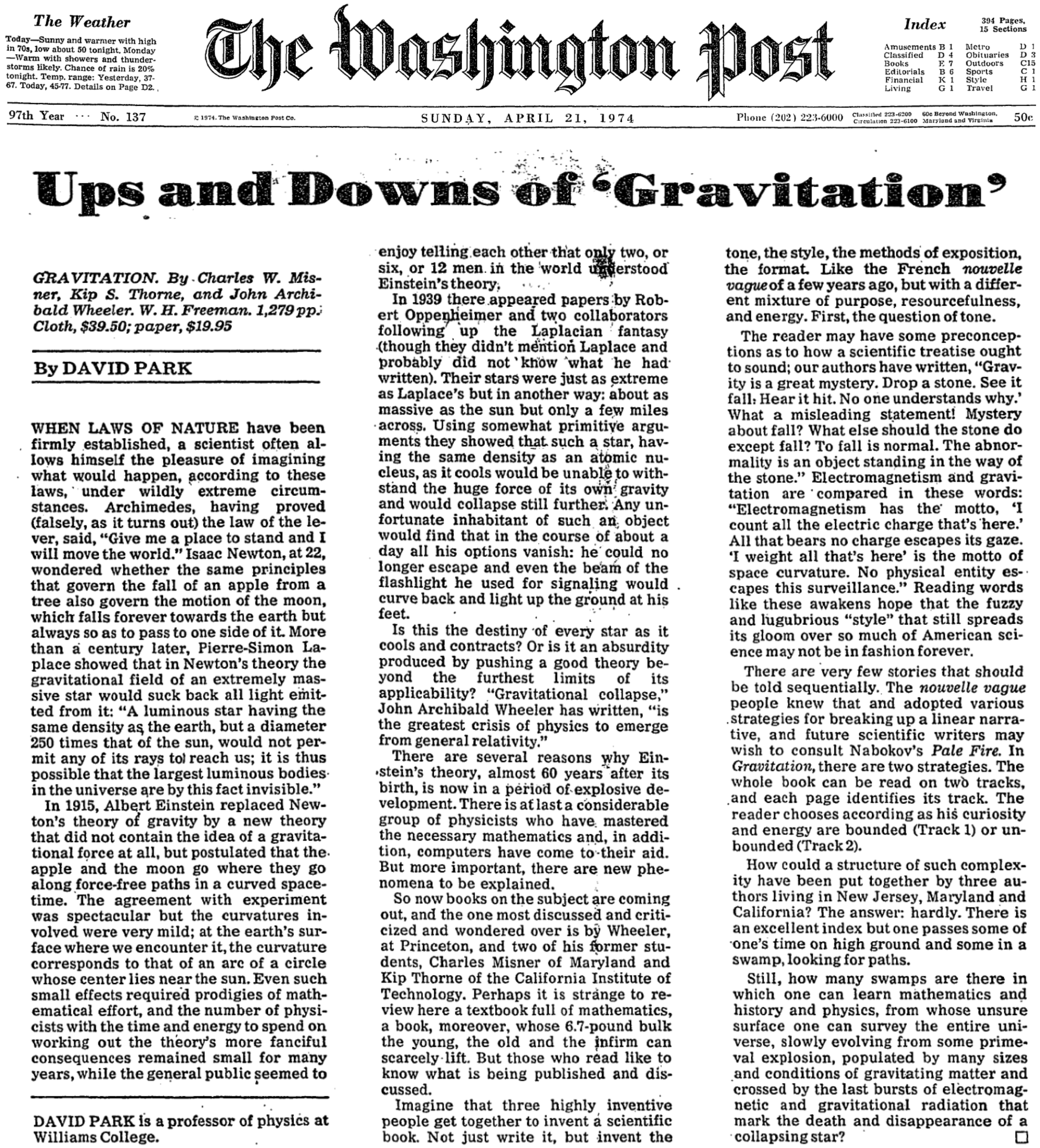

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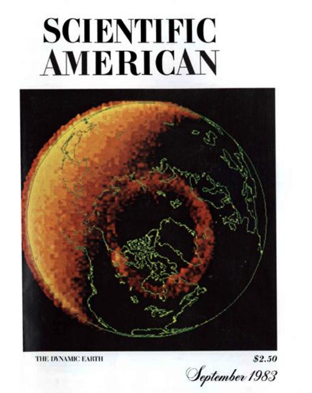

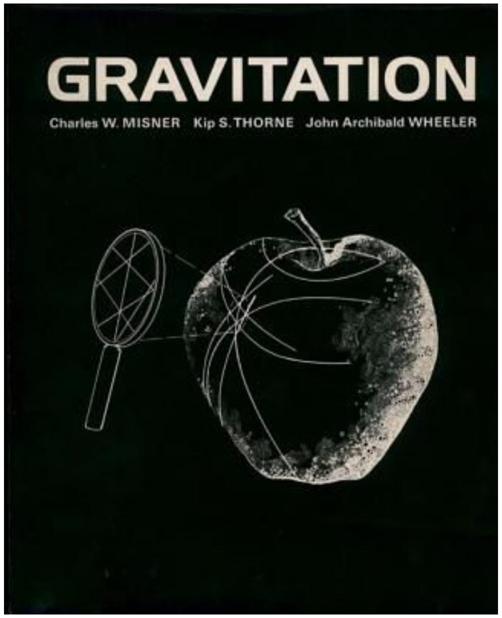

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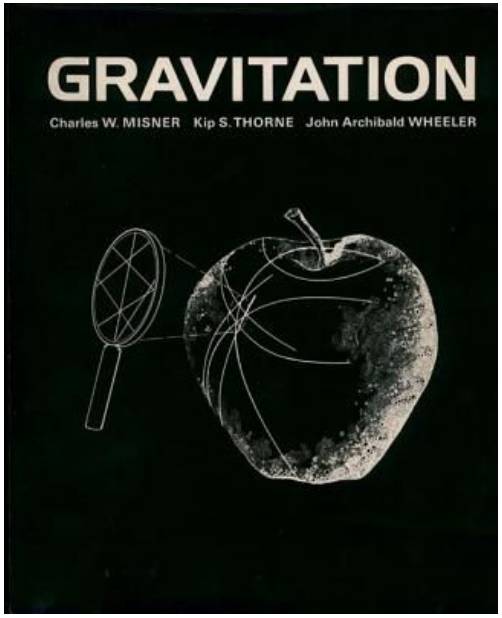
Yet he had become "obsessed" with Einstein's own question: "whether or not God had any choice in the creation of the Universe. Could God be a traveling technician whose responsibility is to supervise gravitational collapses and big bangs?"

Dan Foley to Kip Thorne, February 7, 1980



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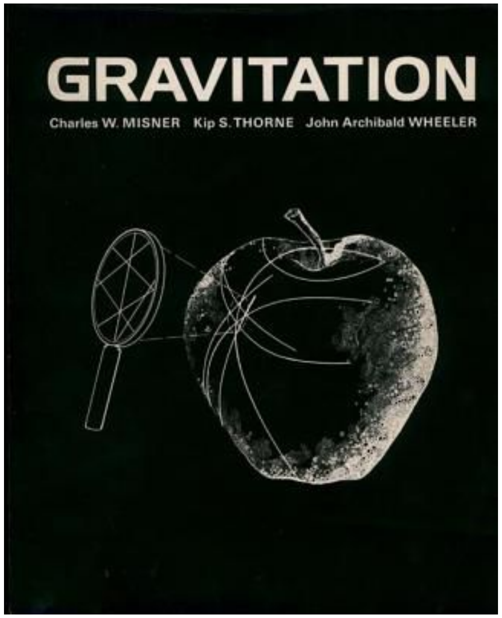
John A. Wheeler to Peter Renz (editor at W. H. Freeman), June 28, 1979

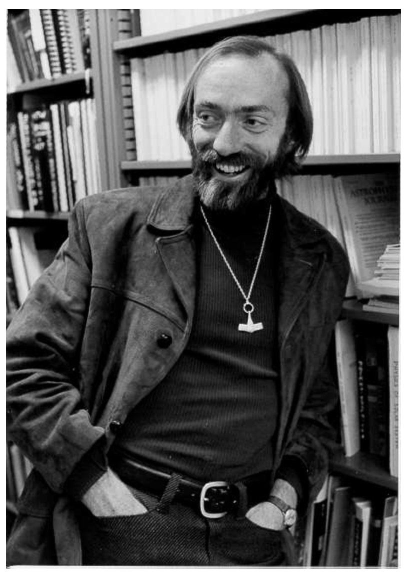
John Wheeler lecturing in Cambridge, UK, 1971
(*Physics Today* April 2009)



Since its original publication in 1973, Misner, Thorne, and Wheeler's *Gravitation* has been a fascinating and inspiring ***hybrid***: part research monograph, part textbook, and part popular book, all wrapped up in "merely" 1279 pages.

Congratulations on the book's first 50 years! And—with the 2017 reprint edition from Princeton University Press—good luck with the next 50 years!

Charles Misner
(AIP Emilio Segrè Visual Archives)



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