Berenice Abbott, the Physical Science Study Committee, and Visual Pedagogy in Cold War America

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American photographer Berenice Abbott is well known for her 1920s portraiture and her 1930s documentary series *Changing New York*. Scholars have paid much less attention to her subsequent turn to science as a photographic subject, even though this defined the latter half of her career.[1] Her scientific photographs appeared in magazines, books, and exhibitions from 1939 onward, and ranged in scope from biology and physics to industry and technology. Of particular interest is her work with the scientists of the Physical Science Study Committee (PSSC) at MIT in the late 1950s, making images for a new physics textbook that would be part of a reformed high school physics curriculum. These photographs were included in the PSSC text, which was published in 1960, used by hundreds of thousands of students and eventually translated into 17 languages.[2] These images, as well as others Abbott made in the years immediately after leaving MIT, were also circulated as an exhibition, and published in books for a more general audience, titled *Magnet* (1964), *Motion* (1965), and *The Attractive Universe* (1969). In these images, Abbott mobilized the relationship between light and her camera to provide concrete forms for forces that underlie the workings of the universe, such as gravity, wave motion, and magnetism, leading to situations in which viewers learned physics via understandings of photographic image-making. In the multiple-flash exposure of a bouncing ball published on the cover of the 1960 PSSC textbook, for example, the image of the ball repeats, appearing on the film not just as a ball but as a path of the ball's motion in four diminishing arcs (Figure 1).[3] The visible indication of the photographic process privileges the viewer's understanding of photographic technology as a key to accessing scientific content.

In the context of 1950s and 1960s America, photography was often thought of as the "language" of the twentieth century. It connected technological and scientific progress with modern visual idioms, and the ideals of an American liberal democracy in which all citizens are ostensibly empowered with the ability to access information and act upon it. As Terri Weissman has argued, Abbott believed firmly in photography's linkage to participatory democracy and saw her science work as furthering this potential. Abbott indicated her goals in this vein as early as the late 1930s, arguing that the general public needed to be able to appreciate the advancements of science if it was going to benefit society. She focused her energies on "the task of photographing scientific subjects and endowing them with popular appeal and scientific correctness" because "[science] needs to speak to the people in terms they will understand," meaning through photography.[4] This paper explores how exactly, in Abbott's collaboration with the PSSC, visual pedagogy using photographic technology could be understood to shift knowledge-making power over to the viewer. In many contexts at this time, photography was thought to be able to do this in a particularly modern and democratic way, allowing citizens to learn and digest information actively, rather than passively receiving it from a source. This was crucial to ideologically fighting the specter of communism, and to assuaging anxiety about the power of new technology in the context of the Cold War. By framing photography as intimately related to the process of active human observation and experimentation, Abbott positioned her images as a form of human control over new science. Her work affirmed that individuals could enact their agency and their subjectivity in the modern world by viewing and using photographs.

A multiple-flash image that operates similarly to the PSSC cover image appears inside the textbook in a section about vectors, which are quantities involving both magnitude and direction, usually depicted by a line segment (Figure 2). As explained in the chapter, "The length […] gives the magni-

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1 Monographs on Abbott include Hank O'Neal, *Berenice Abbott: American Photographer* (New York, NY: McGraw-Hill, 1982); Julia Van Haaften, *Berenice Abbott, Photographer: A Modern Vision* (New York, NY: New York Public Library, 1989); and recent volumes published by Steidl, spearheaded by Ron Kurtz. Scholars of Abbott who focus on the portraiture and *Changing New York* include Peter Barr, Sarah Miller, and Bonnie Yochelson. In-depth treatments of the science work include Terri Weissman's *The Realisms of Berenice Abbott* (Berkley, CA: University of California Press, 2011), chapter five, and a 2012 exhibition at the MIT Museum entitled "Berenice Abbott: Photography and Science: An Essential Unity" curated by Gary van Zante.

2 See E.P. Little, "PSSC: A Physics Program," *Educational Leadership* 17, no. 3 (December 1959): 167-169, 192, and James R. Killian, Jr., *The Education of a College President: A Memoir* (Cambridge, MA: MIT Press, 1985), 166-173.

3 Physical Science Study Committee, *Physics* (Lexington, MA: D.C. Heath, 1960).

4 Letter to Charles C. Adams, 1939, known as her "manifesto." Berenice Abbott Papers, Manuscripts and Archives Division, The New York Public Library, folder 6.28.

tude, and its direction specifies the direction in space."[5] To make this image, a mechanism at top left released two balls at the same time, one toward the right side of the frame and one straight down, in front of a black background. Strings were positioned so that the balls passed them as they fell and the camera was positioned so that it looked straight on at the scene. A strobe light was used to create a multiple exposure photograph, which was then cropped so that the setup is only partially visible. The photograph operates not as a witness, but as an analytical tool. The caption explains that horizontal strings traverse the image six inches apart, information that can be used along with measurements of the spatial displacements and the flash speed to calculate velocity and analyze the motion of the balls in terms of vectors. Abbott presents mathematics and the technological traces of photography as interconnected. The students then make calculations on the photograph, which actually becomes the object of investigation.[6]

As with the bouncing ball photograph, one needs to able to recognize these traces of the photographic process here in order to learn the concept at hand. Students would have learned that because of how light affects film, if an object appears multiple times on a print, they should understand that it was in motion, and that the photograph was representing a section of time. This photographic convention was strategically employed here by Abbott and her collaborators to support the pedagogical process. The full caption to this image in the PSSC text asked, "why do the strings appear to be in the foreground?" instructing students not just in the subject matter, but also in photography.[7] The students were led to surmise that the strings stayed still while the ball moved; they were thereby exposed for longer and thus appear brighter and closer. An instruction in how photographic technology works accompanied instruction about the natural laws, presenting photography's visual quirks as coherent with a broader explanatory system for physics. In Abbott's work, light delineated space in the imaginary world of the photograph, and signaled to the viewer a physical force of the universe that could be used to access, in measurable form, things beyond human observation. A photograph was thus carefully framed as a space that was both accessible and universal.

In *The Attractive Universe*, one of the books published after the PSSC text, Abbott explored another strategy for photographic indication of motion. Instead of a strobe exposure, one long, time-lapse exposure is used, and the ball appears as a continuous blur— a solid, golf ball-textured line representing its path (Figure 3).[8] A ball's speed is represented by density instead of by distance between separate images of the same ball. In order to understand this, one must again think through the process of photography as it has been designed. A fainter line indicates faster movement, and a more solid line represents slower movement. Density could, theoretically, be measured and used to calculate speed. A trait of the photographic process, often thought of as unhelpful in terms of accuracy, is called upon as illustrative, and is only intelligible based on knowledge about photography. Abbott used a similar strategy in the book *Magnet*. In a photograph of a hanging bar magnet above a compass, two smeared pie slices, a prominent blur, indicate to the reader the movement of the magnet (Figure 4). The text explains, "the magnet will spin slowly back and forth—as we can see from the blur in the photograph—until it finally comes to rest pointing north-and-south."[9] A shape appeared on the film that has no existence apart from the film, but was made to signify a physical event.

In *Magnet,* a galaxy-like image is featured on a double-page spread (Figure 5). The caption explains, "a desert of iron filings is sculpted into a beautiful design by the presence of a magnet."[10] Abbott shot with the camera pointed downward at iron filings on a flat surface that were being attracted and repelled by a magnet beneath the support. She then printed the image in negative, so the iron filings appeared white on a black background. Magnetism, as a non-visual property or principle, was thus given a dramatic shape through the specific visual traits of photographic technology. This page spread is an example of how much space the photographs were given in relation to the text in the general audience books, which was not the case in the PSSC textbook. Here Abbott had far more input in the overall project, and helped to construct specific relationships between the photographs and the accompanying narrative.

Abbott's tactic in applying photography to wave motion, a set of principles that describe the behavior of light and sound as well as subatomic particles, was to clarify what one sees in a ripple tank experiment, a common classroom demonstration. To do this, she adapted the technique of the photogram, in which objects on photo-sensitized paper are exposed directly to light without a camera. To photograph waves, the paper was exposed while directly underneath the tank (Figure 6). As with the above images, aesthetic priorities fit together with an educational emphasis on clarity of basic visual elements, as well as with the principles of regularity in laws of physics. Abbott strove for a balanced composition, a play between light and dark, and crisp focus. These visual qualities do not appear when looking at a ripple tank

5 *Physics*, 83.

6 In this way, Abbott's work resonates with other examples of scientific photography in which knowledge is produced, rather than revealed, by the camera. See Josh Ellenbogen, "Camera and Mind," *Representations* 101 (Winter 2008): 86–115, or Robin E. Kelsey, "Viewing the Archive: Timothy O'Sullivan's Photographs for the Wheeler Survey, 1871–74," *Art Bulletin* 85, no. 4 (Dec. 2003): 702–23.

7 Ibid.

8 E.G. Valens, *The Attractive Universe: Gravity and the Shape of Space* (Cleveland, OH: The World Publishing Company, 1969) 27-28.

9 E.G. Valens, *Magnet*, (Cleveland, OH: World Publishing Company, 1964), n.p.

10 Ibid.

in person, only in the photograph. Here again, the text explained the photographic process so that the viewer knew to treat the photograph as a diagram of the results of a ripple tank experiment. Students were encouraged to measure the changing distances between ripples in order to calculate using formulae and learn various laws.[11]

An image of a spinning wrench demonstrates that the center of mass of an object remains stable as the object spins (Figure 7).[12] This is a property of objects in motion, and Abbott gave the property a form, transforming the object's motion into a geometric expression of the law by swinging her camera around following the wrench's movement. Her photographic process resulted in an image in which points on the print symbolize, in a way, points in the path of motion of an object. Black crosses mark the center of the mass of the wrench (towards the top of the handle). The PSSC text used this image to explain, "The parts of a body may move with respect to each other…No matter what these internal motions, the center of mass of the body moves as though all the mass were there."[13] A caption drafted for the display of this image in an exhibition put it this way, "…A ruler laid across the photograph lines up the cross on the handle in a straight sequence. The law expressed is that of constant velocity."[14]

In *The Attractive Universe*, Abbott presented a series of photographs as part of an explanation of relativity. A series of six images portrayed a double-star system (Figures 8-10).[15] We see a ball move through space, then move in a path that shows how space is warped by the presence of another ball, which in turn moves in response to the curvature of space caused by the first ball. The repeating balls, along with the textual explanation that they move on a piece of pliable rubber, invisible in the photograph, demonstrated how outer space can be warped by objects and their gravity. The analogy of balls moving around on a rubber sheet is a standard way to teach a general and simplified version of the concept of space-time.[16] Here, the "stars," as they are called in the book, were made to draw shapes in the two-dimensional space of the photograph, generating a visual form for an idea that again is rooted in photographic conventions for depicting motion. The images teach relativity using the viewer's knowledge of photography, interweaving visual traces of that technology into a mental concept of bending space-time. Negatives from the Abbott archive seem to show trials conducted to achieve these images, in which the balls refuse to create smooth arcs around each other, indicating that Abbott required a specific formal result.[17] These aesthetic concerns and the others that characterize Abbott's science images should not be seen as separate from how the images worked with text and math to allow viewers to access complex knowledge. On the contrary, they should be understood as a set of visual references that cued the viewer to the knowledge contained in the image, i.e. consistent rules that govern a logical, elegant universe, accessible through a technology that was available to everyone. Abbott's formal goals were thus essential to her educational ones. Abbott wrote: "Here in physics is primal order and balance, its universal implications extend limitlessly. Both scientists and artists are humble before its reason and proportion."[18] It was in this way that Abbott saw her photographic visualizations as so essential to the study of physics.

In these works, it was Abbott's process that created a specifically photographic form for the concept at hand, offering up a material scenario for the viewer to analyze. In mid-century America, as new technologies shaped global power dynamics and altered everyday life with increasing speed, many reacted by finding ways to position technology as a natural extension of human faculties. In particular, it was important for new media to appear to expand the human sensorium, but also remain tethered to human values, needs, and goals. It was common for thinkers in many fields to assert that the interdisciplinary interpretation and active production of visual material was the secret to securing this dynamic between human mind and technologies, keeping the viewer in the driver's seat and ensuring social progress. As New Bauhaus educator and artist Gyorgy Kepes wrote in reference to twentieth-century science and technology, "We may suffer from exposure to the new scale, but we have to go forward and meet it…Our central faculty in performing this task, as we have suggested, is visual sensibility."[19]

The PSSC, the context in which Abbott had her most direct opportunity to explore this type of photography, specifically concerned itself with this power of visual media to educate in ways that ensured a student's democratic subjectivity. It was launched by MIT scientist Jerrold Zacharias and MIT president James Killian, who around the same time were appointed as science advisors to President Eisenhower, in the context of the government's increasing concern about the ability of the US to compete with the Soviets in science and technology, while also promoting democratic political values. In the 1958 State of the Union address, Eisenhower declared

11 *Physics*, 177, 271, and back cover.

12 *Physics*, 379, and Valens, *Attractive Universe*, 109.

13 *Physics,* 378.

14 Smithsonian Institution Archives, Record Unit 290, Smithsonian Institution, Traveling Exhibition Service, Records.

15 Valens, *Attractive Universe*, 168-174.

16 For an explanation of the analogy and the ways in which it simplifies the theory but is useful for teaching it, see J.B. Kennedy, *Space, Time, and Einstein: An Introduction* (New York, NY: Routledge, 2014), 140-143.

17 See the Berenice Abbott Archive, Ryerson Image Centre, Ryerson University, negative box 18.

18 Berenice Abbott, "The Image of Science," *Art in America* 47, no. 4 (Winter 1959): 76.

19 Gyorgy Kepes, ed., *Education of Vision*, in the *Vision and Value* series (New York, NY: George Braziller, 1965), iv. While Kepes' and Abbott's approaches to visual pedagogy were very different, Kepes' ideas exemplify the broader context in which Abbott's efforts resonated. Kepes also worked at MIT, launching his Center for Advanced Visual Studies there in 1967.

the federal government's commitment to science education that did not create "pawns," but "free men and women," articulating the political urgency that was attached both to scientific progress and the notion of freedom of thought during this era.[20] Zacharias and Killian also happened to be very committed to the use of photography, TV, and film in education, and worked toward this throughout their careers. The PSSC curriculum reform project was conceived from the beginning as a media project and involved the production of films featuring actual scientists that could be shown in classrooms, which Zacharias described in his 1956 proposal, "Movie Aids for Teaching Physics in High Schools." When launching the PSSC, MIT scientists called upon experts in the highest levels of the film and photographic industry to serve on the steering committee, individuals such as Edwin Land of Polaroid and filmmaker Frank Capra.[21] This broader context for the project helps to illuminate Abbott's specific goals and account for the lasting power of these images. It is clear that the stakes for educational photographic media were high, involving the advancement of American science, freedom of thought, and the affirmation in the eyes of the American public of liberal democracy over communist ideology.

Abbott's images made use of the viewer's understanding of photography and marshaled this understanding towards the comprehension of other things. In working on these books, she and her colleagues were using photography to improve viewers' abilities to understand the medium itself, while simultaneously teaching science. They used the educational context to bolster photography's status as a knowledge-making tool at the same time as they drew on the connotations of photography for their audience. Abbott's work encouraged viewers to become active agents in learning science, and specifically invited them to integrate the process of photography with their thought processes. This form of visual pedagogy had power because of specific mid-century questions about the role of an individual mind as part of a social unit, and the role of technology in that formulation. Abbott offered viewers a way to actively use photography for intellectual purposes at a time when science and technology, as disciplines, but also as social forces, were rapidly changing everyday life, and had strong political connotations. Work such as hers contributed to a link that Americans were increasingly making between the use of modern visual media, the ideals of liberal democracy, and scientific progress.

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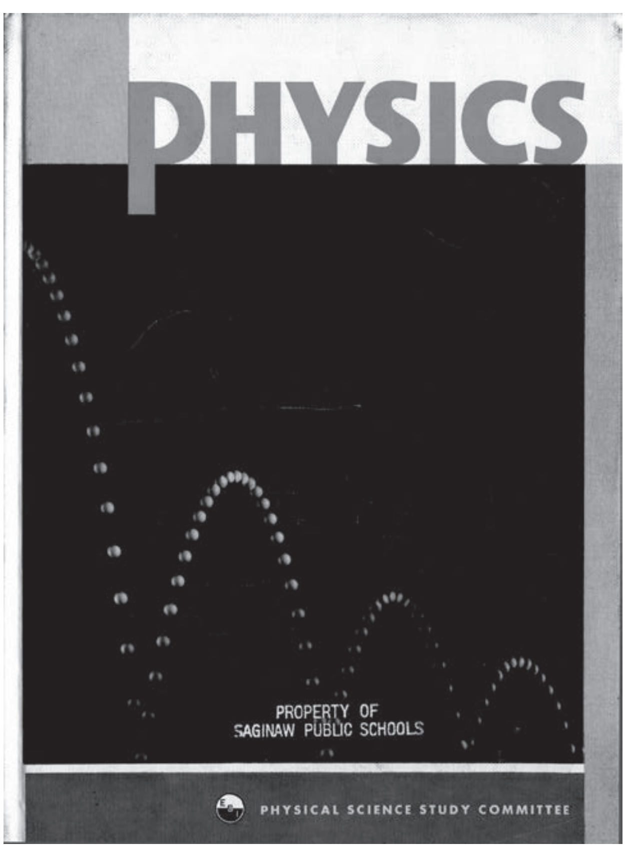
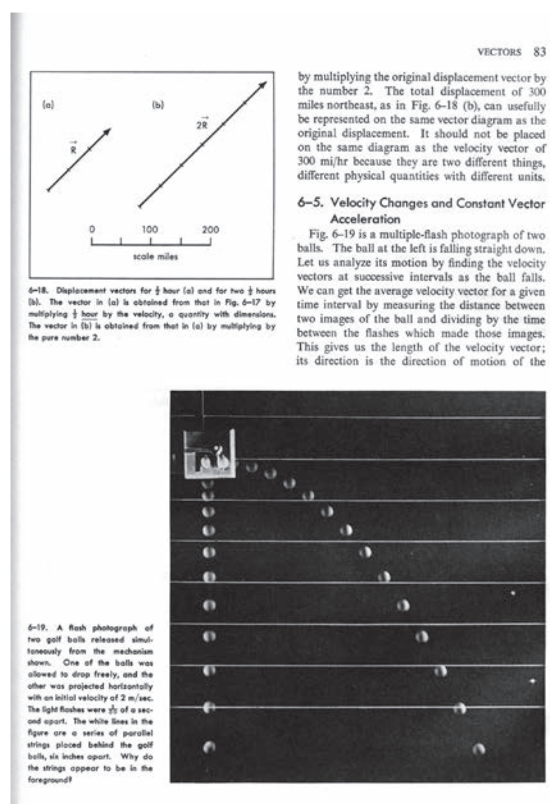
20 Dwight D. Eisenhower, "Annual Message to the Congress on the State of the Union," January 9, 1958. Online by Gerhard Peters and John T. Woolley, *The American Presidency Project*, accessed 21 December 2017, http://www.presidency.ucsb.edu/ws/?pid=11162. This online archive provides access to this document which is in the The Public Papers of the Presidents.

21 See James R. Killian, Jr., *Education of a College* President, 166-173, and Jack S. Goldstein, *A Different Sort of Time: The Life of Jerrold R. Zacharias, Scientist, Engineer, Educator* (Cambridge, MA: MIT Press, 1992).





VECTORS 83

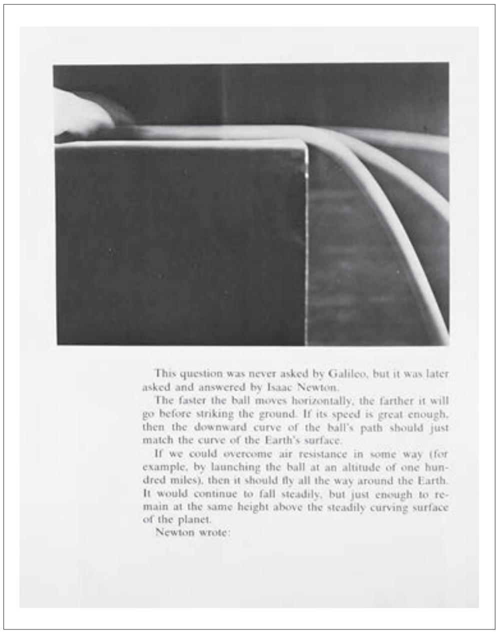
6–18. Displacement vectors for $\frac{1}{2}$ hour (a) and for two $\frac{1}{2}$ hours (b). The vector in (a) is obtained from that in Fig. 6–17 by multiplying $\frac{1}{2}$ hour by the velocity, a quantity with dimensions. The vector in (b) is obtained from that in (a) by multiplying by the pure number 2.

by multiplying the original displacement vector by the number 2. The total displacement of 300 miles northeast, as in Fig. 6–18 (b), can usefully be represented on the same vector diagram as the original displacement. It should not be placed on the same diagram as the velocity vector of 300 mi/hr because they are two different things, different physical quantities with different units.

6–5. Velocity Changes and Constant Vector Acceleration

Fig. 6–19 is a multiple-flash photograph of two balls. The ball at the left is falling straight down. Let us analyze its motion by finding the velocity vectors at successive intervals as the ball falls. We can get the average velocity vector for a given time interval by measuring the distance between two images of the ball and dividing by the time between the flashes which made those images. This gives us the length of the velocity vector; its direction is the direction of motion of the

6–19. A flash photograph of two golf balls released simultaneously from the mechanism shown. One of the balls was allowed to drop freely, and the other was projected horizontally with an initial velocity of 2 m/sec. The light flashes were $\frac{1}{30}$ of a second apart. The white lines in the figure are a series of parallel strings placed behind the golf balls, six inches apart. Why do the strings appear to be in the foreground?



This question was never asked by Galileo, but it was later asked and answered by Isaac Newton.

The faster the ball moves horizontally, the farther it will go before striking the ground. If its speed is great enough, then the downward curve of the ball's path should just match the curve of the Earth's surface.

If we could overcome air resistance in some way (for example, by launching the ball at an altitude of one hundred miles), then it should fly all the way around the Earth. It would continue to fall steadily, but just enough to remain at the same height above the steadily curving surface of the planet.

Newton wrote:

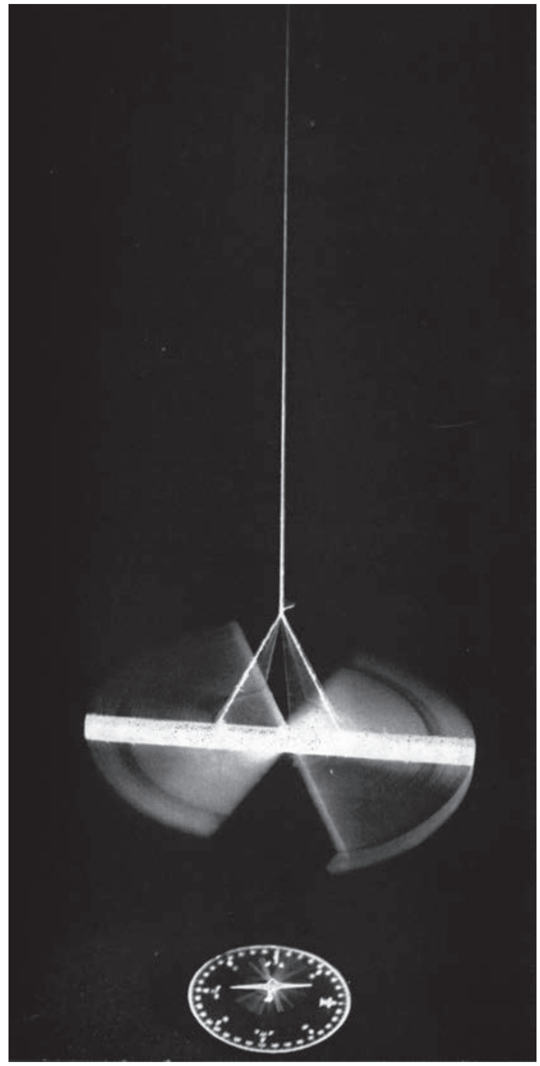
◀Figure 1 [*facing page, left*]. Physical Science Study Committee, *Physics* (D.C. Heath, 1960) with Abbott's "A Bouncing Ball in Diminishing Arcs" on front cover.

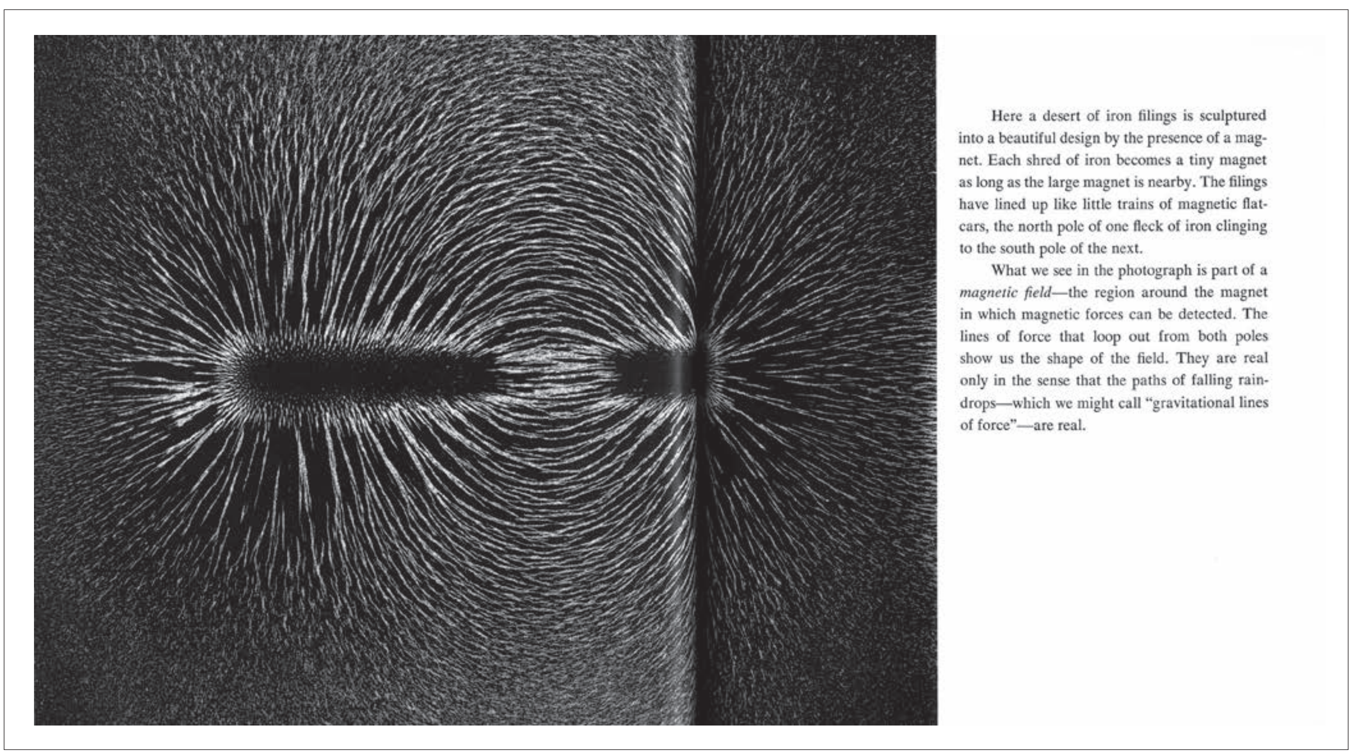
◀Figure 2 [*facing page, right*]. Physical Science Study Committee, *Physics* (D.C. Heath, 1960), 83.

▲Figure 3. [*above*] E.G. Valens and Berenice Abbott, *The Attractive Universe* (Cleveland: World Publishing Company, 1969), 43.

▶Figure 4 [*right*]. E.G. Valens and Berenice Abbott, *Magnet* (Cleveland: World Publishing Company, 1964), n.p.

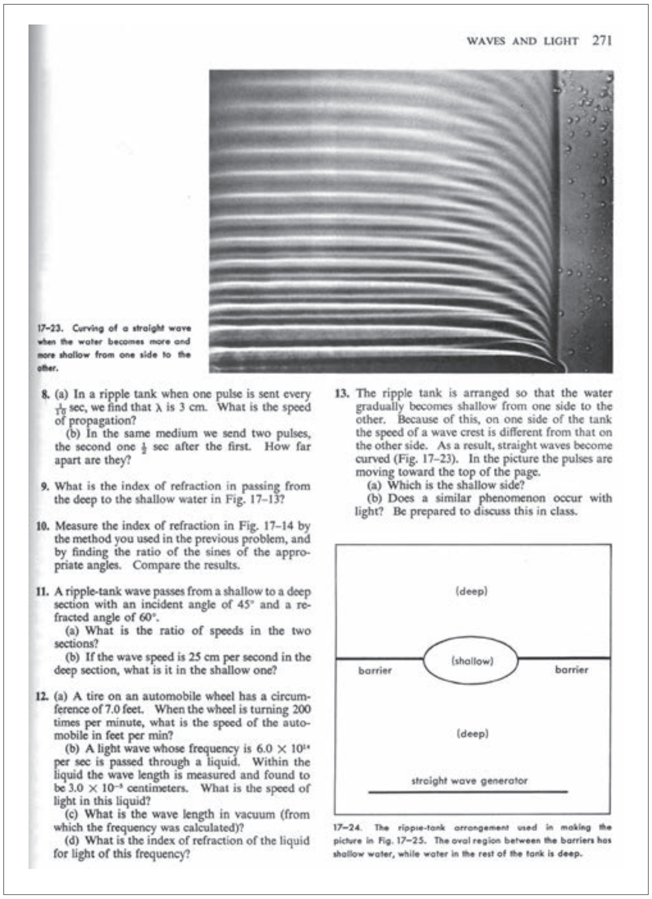
▼Figure 5. E.G. Valens and Berenice Abbott, *Magnet* (Cleveland: World Publishing Company, 1964), n.p.





Here a desert of iron filings is sculptured into a beautiful design by the presence of a magnet. Each shred of iron becomes a tiny magnet as long as the large magnet is nearby. The filings have lined up like little trains of magnetic flatcars, the north pole of one fleck of iron clinging to the south pole of the next.

What we see in the photograph is part of a *magnetic field*—the region around the magnet in which magnetic forces can be detected. The lines of force that loop out from both poles show us the shape of the field. They are real only in the sense that the paths of falling raindrops—which we might call "gravitational lines of force"—are real.



WAVES AND LIGHT 271

17–23. Curving of a straight wave when the water becomes more and more shallow from one side to the other.

8. (a) In a ripple tank when one pulse is sent every $\frac{1}{10}$ sec, we find that λ is 3 cm. What is the speed of propagation?
(b) In the same medium we send two pulses, the second one $\frac{1}{2}$ sec after the first. How far apart are they?

9. What is the index of refraction in passing from the deep to the shallow water in Fig. 17–13?

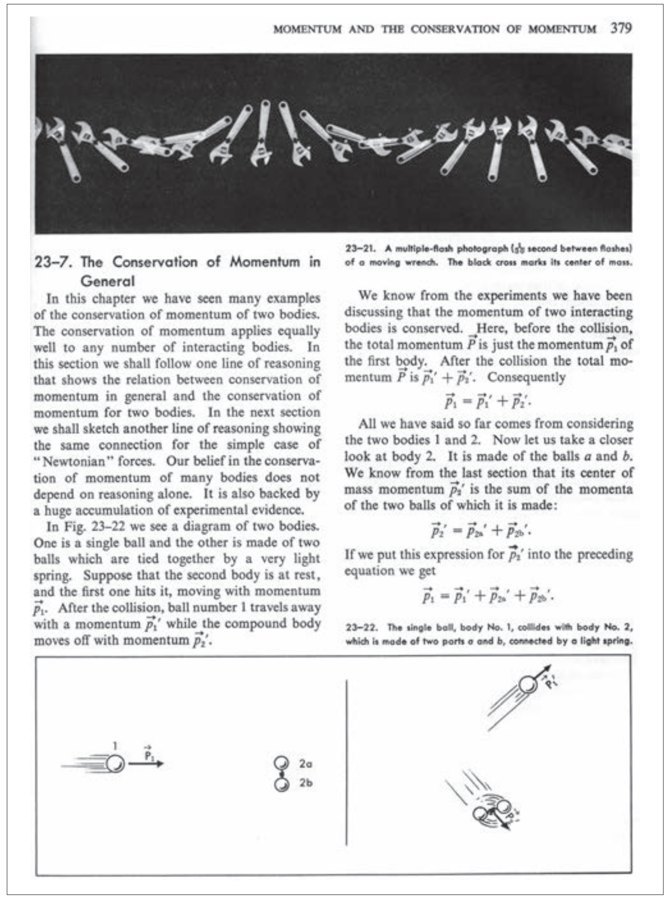
10. Measure the index of refraction in Fig. 17–14 by the method you used in the previous problem, and by finding the ratio of the sines of the appropriate angles. Compare the results.

11. A ripple-tank wave passes from a shallow to a deep section with an incident angle of 45° and a refracted angle of 60°.
(a) What is the ratio of speeds in the two sections?
(b) If the wave speed is 25 cm per second in the deep section, what is it in the shallow one?

12. (a) A tire on an automobile wheel has a circumference of 7.0 feet. When the wheel is turning 200 times per minute, what is the speed of the automobile in feet per min?
(b) A light wave whose frequency is 6.0×10^{14} per sec is passed through a liquid. Within the liquid the wave length is measured and found to be 3.0×10^{-5} centimeters. What is the speed of light in this liquid?
(c) What is the wave length in vacuum (from which the frequency was calculated)?
(d) What is the index of refraction of the liquid for light of this frequency?

13. The ripple tank is arranged so that the water gradually becomes shallow from one side to the other. Because of this, on one side of the tank the speed of a wave crest is different from that on the other side. As a result, straight waves become curved (Fig. 17–23). In the picture the pulses are moving toward the top of the page.
(a) Which is the shallow side?
(b) Does a similar phenomenon occur with light? Be prepared to discuss this in class.

17–24. The ripple-tank arrangement used in making the picture in Fig. 17–25. The oval region between the barriers has shallow water, while water in the rest of the tank is deep.



MOMENTUM AND THE CONSERVATION OF MOMENTUM 379

23–21. A multiple-flash photograph ($\frac{1}{30}$ second between flashes) of a moving wrench. The black cross marks its center of mass.

23–7. The Conservation of Momentum in General

In this chapter we have seen many examples of the conservation of momentum of two bodies. The conservation of momentum applies equally well to any number of interacting bodies. In this section we shall follow one line of reasoning that shows the relation between conservation of momentum in general and the conservation of momentum for two bodies. In the next section we shall sketch another line of reasoning showing the same connection for the simple case of "Newtonian" forces. Our belief in the conservation of momentum of many bodies does not depend on reasoning alone. It is also backed by a huge accumulation of experimental evidence.

In Fig. 23–22 we see a diagram of two bodies. One is a single ball and the other is made of two balls which are tied together by a very light spring. Suppose that the second body is at rest, and the first one hits it, moving with momentum $\vec{p}_1$. After the collision, ball number 1 travels away with a momentum $\vec{p}_1'$ while the compound body moves off with momentum $\vec{p}_2'$.

We know from the experiments we have been discussing that the momentum of two interacting bodies is conserved. Here, before the collision, the total momentum $\vec{P}$ is just the momentum $\vec{p}_1$ of the first body. After the collision the total momentum $\vec{P}$ is $\vec{p}_1' + \vec{p}_2'$. Consequently

$$\vec{p}_1 = \vec{p}_1' + \vec{p}_2'.$$

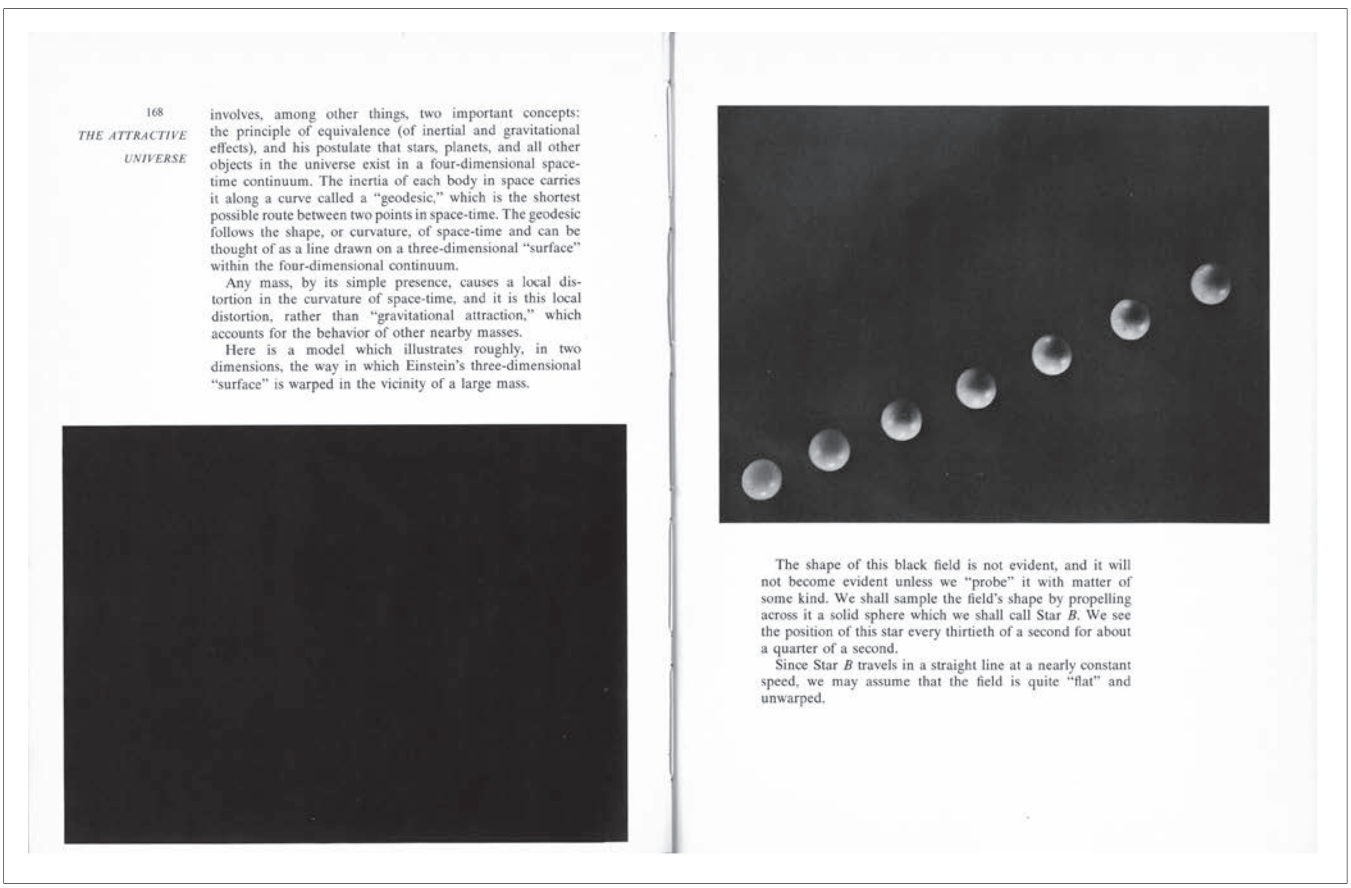
All we have said so far comes from considering the two bodies 1 and 2. Now let us take a closer look at body 2. It is made of the balls *a* and *b*. We know from the last section that its center of mass momentum $\vec{p}_2'$ is the sum of the momenta of the two balls of which it is made:

$$\vec{p}_2' = \vec{p}_{2a}' + \vec{p}_{2b}'.$$

If we put this expression for $\vec{p}_2'$ into the preceding equation we get

$$\vec{p}_1 = \vec{p}_1' + \vec{p}_{2a}' + \vec{p}_{2b}'.$$

23–22. The single ball, body No. 1, collides with body No. 2, which is made of two parts a and b, connected by a light spring.



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THE ATTRACTIVE UNIVERSE

involves, among other things, two important concepts: the principle of equivalence (of inertial and gravitational effects), and his postulate that stars, planets, and all other objects in the universe exist in a four-dimensional space-time continuum. The inertia of each body in space carries it along a curve called a "geodesic," which is the shortest possible route between two points in space-time. The geodesic follows the shape, or curvature, of space-time and can be thought of as a line drawn on a three-dimensional "surface" within the four-dimensional continuum.

Any mass, by its simple presence, causes a local distortion in the curvature of space-time, and it is this local distortion, rather than "gravitational attraction," which accounts for the behavior of other nearby masses.

Here is a model which illustrates roughly, in two dimensions, the way in which Einstein's three-dimensional "surface" is warped in the vicinity of a large mass.

The shape of this black field is not evident, and it will not become evident unless we "probe" it with matter of some kind. We shall sample the field's shape by propelling across it a solid sphere which we shall call Star *B*. We see the position of this star every thirtieth of a second for about a quarter of a second.

Since Star *B* travels in a straight line at a nearly constant speed, we may assume that the field is quite "flat" and unwarped.

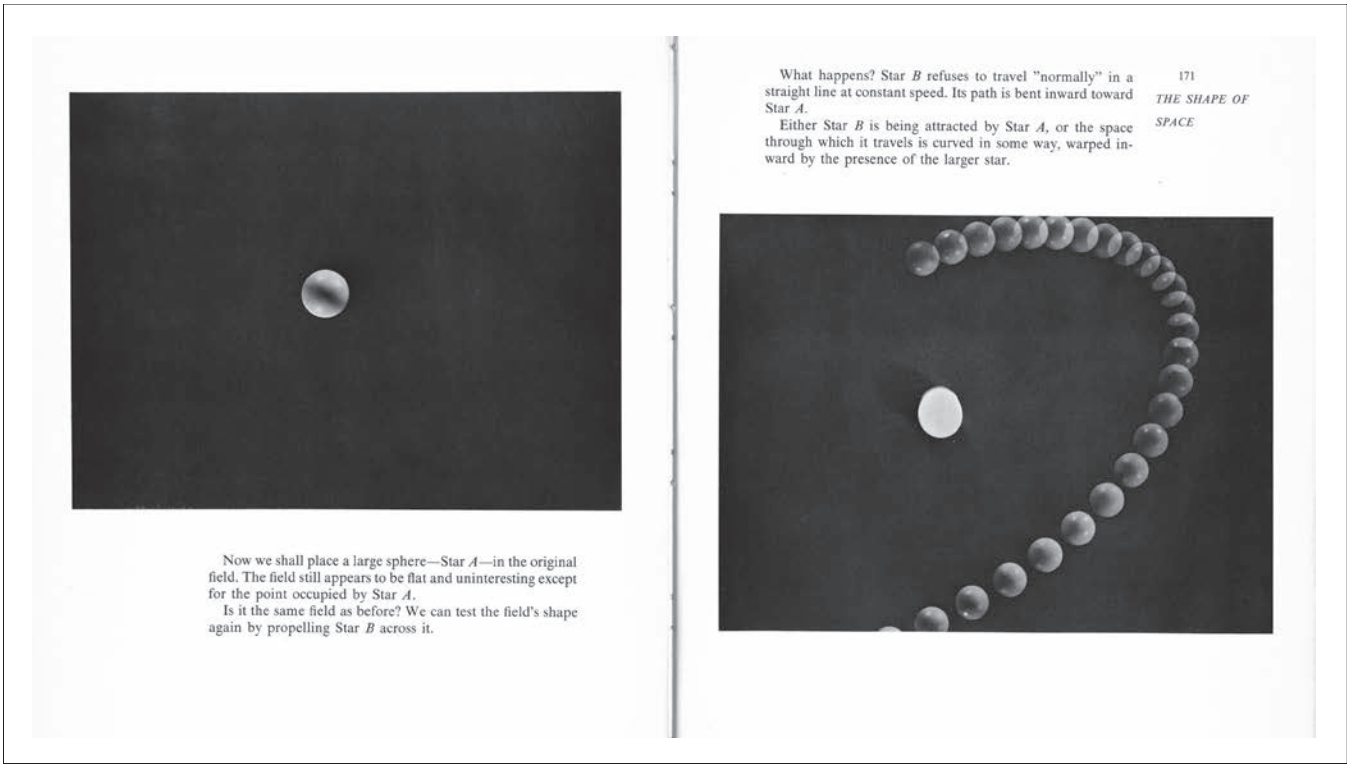
◀Figure 6 [*facing page, top left*]. Physical Science Study Committee, *Physics* (D.C. Heath, 1960), 271.

◀Figure 7 [*facing page, top right*]. Physical Science Study Committee, *Physics* (D.C. Heath, 1960), 379.

◀Figure 8 [*facing page, bottom*]. E.G. Valens and Berenice Abbott, *The Attractive Universe* (Cleveland: World Publishing Company, 1969), 168-9.

▼Figure 9 [*top*]. E.G. Valens and Berenice Abbott, *The Attractive Universe* (Cleveland: World Publishing Company, 1969), 170-1.

▼Figure 10 [*bottom*]. E.G. Valens and Berenice Abbott, *The Attractive Universe* (Cleveland: World Publishing Company, 1969), 172-3.



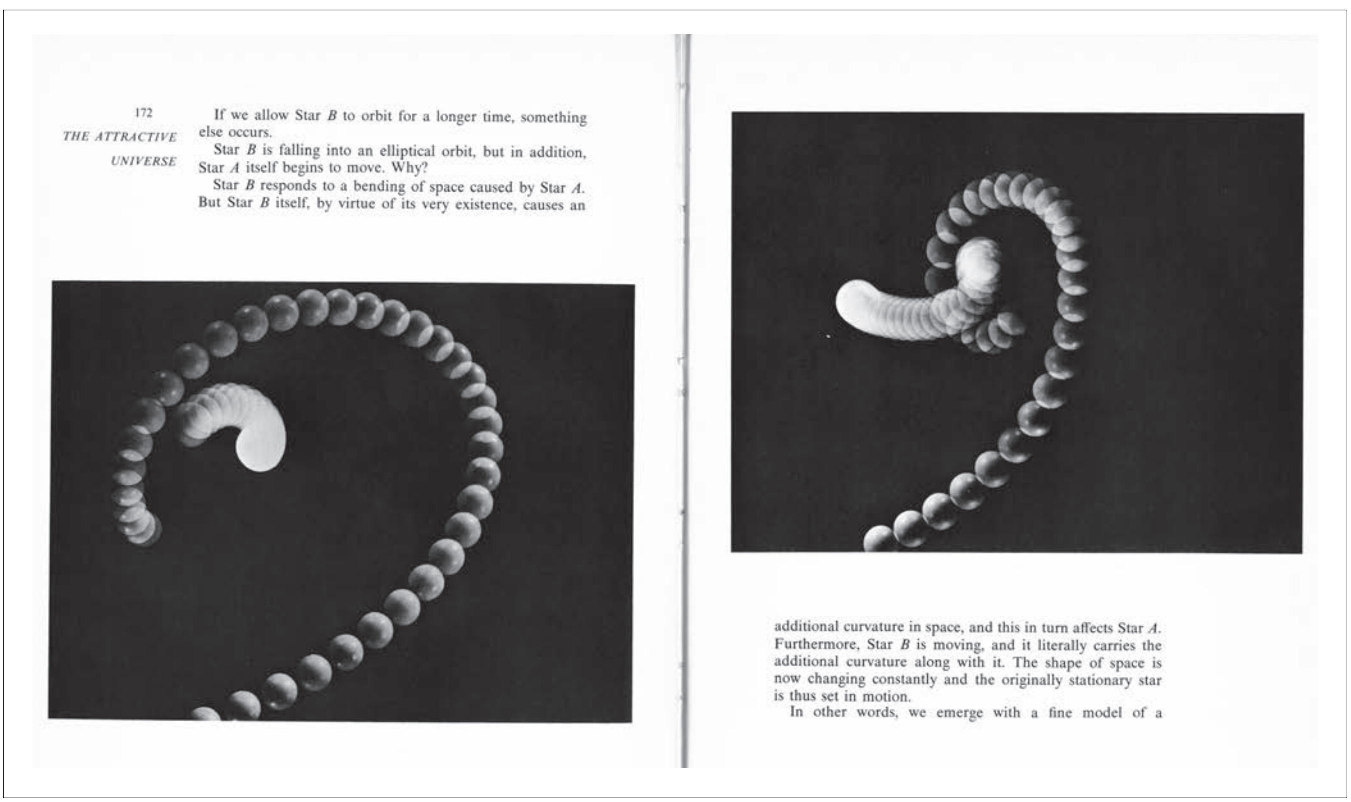
Now we shall place a large sphere—Star *A*—in the original field. The field still appears to be flat and uninteresting except for the point occupied by Star *A*.

Is it the same field as before? We can test the field's shape again by propelling Star *B* across it.

171 *THE SHAPE OF SPACE*

What happens? Star *B* refuses to travel "normally" in a straight line at constant speed. Its path is bent inward toward Star *A*.

Either Star *B* is being attracted by Star *A*, or the space through which it travels is curved in some way, warped inward by the presence of the larger star.



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If we allow Star *B* to orbit for a longer time, something else occurs.

Star *B* is falling into an elliptical orbit, but in addition, Star *A* itself begins to move. Why?

Star *B* responds to a bending of space caused by Star *A*. But Star *B* itself, by virtue of its very existence, causes an additional curvature in space, and this in turn affects Star *A*. Furthermore, Star *B* is moving, and it literally carries the additional curvature along with it. The shape of space is now changing constantly and the originally stationary star is thus set in motion.

In other words, we emerge with a fine model of a