An elementary treatment of the reverse sprinkler

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We discuss the reverse sprinkler problem: How does a sprinkler turn when submerged and made to suck in water? We propose a solution that requires only a knowledge of mechanics and fluid dynamics at the introductory university level. We argue that as the flow of water starts, the sprinkler briefly experiences a torque that would make it turn toward the incoming water, while as the flow of water ceases it briefly experiences a torque in the opposite direction. No torque is expected when water is flowing steadily into it unless dissipative effects, such as viscosity, are considered. Dissipative effects result in a small torque that would cause the sprinkler arm to accelerate toward the steadily incoming water. Our conclusions are discussed in light of an analysis of forces, conservation of angular momentum, and the experimental results reported by others. We review the conflicting published treatments of this problem, some of which have been incorrect and many of which have introduced complications that obscure the basic physics involved.

I. INTRODUCTION

In 1985, R. P. Feynman, one of most distinguished theoretical physicists of his time, published a collection of autobiographical anecdotes that attracted much attention on account of their humor and outrageousness.¹ While describing his time at Princeton as a graduate student (1939–1942), Feynman tells the following story:²

There was a problem in a hydrodynamics book,³ that was being discussed by all the physics students. The problem is this: You have an S-shaped lawn sprinkler ... and the water squirts out at right angles to the axis and makes it spin in a certain direction. Everybody knows which way it goes around; it backs away from the outgoing water. Now the question is this: If you ... put the sprinkler completely under water, and sucked the water in ... which way would it turn?

Feynman went on to say that many Princeton physicists, when presented with the problem, judged the solution to be obvious, only to find that others arrived with equal confidence at the opposite answer, or that they had changed their minds by the following day. Feynman claims that after a while he finally decided what the answer should be and proceeded to test it experimentally by using a very large water bottle, a piece of copper tubing, a rubber hose, a cork, and the air pressure supply from the Princeton cyclotron laboratory. Instead of attaching a vacuum to suck the water, he applied high air pressure inside of the water bottle to push the water out through the sprinkler. According to Feynman's account, the experiment initially went well, but after he cranked up the setting for the pressure supply, the bottle exploded, and "...the whole thing just blew glass and water in all directions throughout the laboratory ... "4

Feynman¹ did not inform the reader what his answer to the reverse sprinkler problem was or what the experiment revealed before exploding. Over the years, and particularly after Feynman's autobiographical recollections appeared in print, many people have offered their analyses, both theoretical and experimental, of this reverse sprinkler problem.⁵ The solutions presented often have been contradictory and the theoretical treatments, even when they have been correct, have introduced unnecessary conceptual complications that have obscured the basic physics involved.

All physicists will probably know the frustration of being confronted by an elementary question to which they cannot give a ready answer in spite of all the time dedicated to the study of the subject, often at a much higher level of sophistication than what the problem at hand would seem to require. Our intention is to offer an elementary treatment of this problem which should be accessible to a bright secondary school student who has learned basic mechanics and fluid dynamics. We believe that our answer is about as simple as it can be made, and we discuss it in light of published theoretical and experimental treatments.

II. PRESSURE DIFFERENCE AND MOMENTUM TRANSFER

Feynman speaks in his memoirs of "an S-shaped lawn sprinkler." It should not be difficult, however, to convince yourself that the problem does not depend on the exact shape of the sprinkler, and for simplicity we shall refer in our argument to an L-shaped structure. In Fig. 1 the sprinkler is closed: water cannot flow into it or out of it. Because the water pressure is equal on opposite sides of the sprinkler, it will not turn: there is no net torque around the sprinkler pivot.

Let us imagine that we then remove part of the wall on the right, as pictured in Fig. 2, opening the sprinkler to the flow of water. If water is flowing in, then the pressure marked P_2 must be lower than the pressure P_1 , because water flows from higher to lower pressure. In both Fig. 1 and Fig. 2, the pressure P_1 acts on the left. But because a piece of the sprinkler wall is missing in

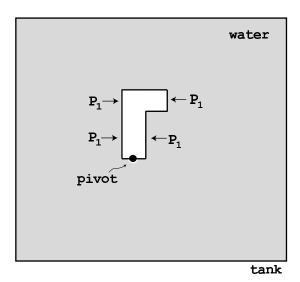


FIG. 1: A sprinkler submerged in a tank of water as seen from above. The L-shaped sprinkler is closed, and the forces and torques exerted by the water pressure balance each other.

Fig. 2, the relevant pressure on the upper right part of the open sprinkler will be P_2 . It would seem then that the reverse sprinkler should turn toward the water, because if P_2 is less than P_1 , there would be a net force to the right in the upper part of the sprinkler, and the resulting torque would make the sprinkler turn clockwise. If A is the cross section of the sprinkler intake pipe, this torque-inducing force is $A(P_1 - P_2)$.

But we have not taken into account that even though the water hitting the inside wall of the sprinkler in Fig. 2 has lower pressure, it also has left-pointing momentum. The incoming water transfers that momentum to the sprinkler as it hits the inner wall. This momentum transfer would tend to make the sprinkler turn counterclockwise. One of the reasons why the reverse sprinkler is a confusing problem is that there are two effects in play, each of which, acting on its own, would make the sprinkler turn in opposite directions. The problem is to figure out the net result of these two effects.

How much momentum is being transferred by the incoming water to the inner sprinkler wall in Fig. 2? If water is moving across a pressure gradient, then over a differential time dt, a given "chunk" of water will pass from an area of pressure P to an area of pressure P-dP as illustrated in Fig. 3. If the water travels down a pipe of cross-section A, its momentum gain per unit time is A dP. Therefore, over the entire length of the pipe, the water picks up momentum at a rate $A(P_1 - P_2)$, where P_1 and P_2 are the values of the pressure at the endpoints of the pipe. (In the language of calculus, $A(P_1 - P_2)$ is the total force that the pressure gradient across the pipe exerts on the water. We obtain it by integrating over the differential force A dP.)

The rate $A(P_1 - P_2)$ is the same rate at which the water transfers momentum to the sprinkler wall in Fig. 2,

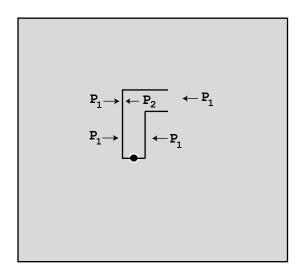


FIG. 2: The sprinkler is now open. If water is flowing into it, then the pressures marked P_1 and P_2 must satisfy $P_1 > P_2$.

because whatever left-pointing momentum the incoming water picks up, it will have to transfer to the inner left wall upon hitting it. Therefore $A(P_1 - P_2)$ is the force that the incoming water exerts on the inner sprinkler wall in Fig. 2 by virtue of the momentum it has gained in traveling down the intake pipe.

Because the pressure difference and the momentum transfer effects cancel each other, it would seem that the reverse sprinkler would not move at all. Notice, however, that we considered the reverse sprinkler only after water was already flowing continuously into it. In fact, the sprinkler will turn toward the water initially, because the forces will balance only after water has begun to hit the inner wall of the sprinkler, and by then the sprinkler will have begun to turn toward the incoming water. That is, initially only the pressure difference effect and not the momentum transfer effect is relevant. (As the water flow stops, there will be a brief period during which only the momentum transfer and not the pressure difference will be acting on the sprinkler, thus producing a momentary torque opposite to the one that acted when the water flow was being established.)

Why can't we similarly "prove" the patently false statement that a non-sucking sprinkler submerged in water will not turn as water flows steadily out of it? In that case the water is going out and hitting the upper inner wall, not the left inner wall. It exerts a force, but that force produces no torque around the pivot. The pressure difference, on the other hand, does exert a torque. The pressure in this case has to be higher inside the sprinkler than outside it, so the sprinkler turns counterclockwise, as we expect from experience.

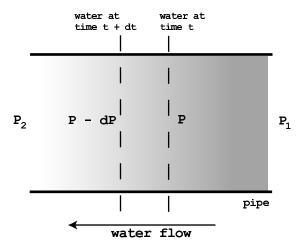


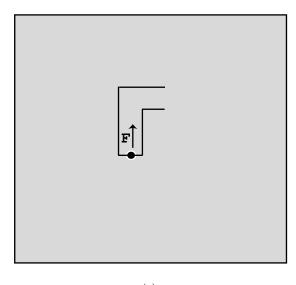
FIG. 3: As water flows down a tube with a pressure gradient, it picks up momentum.

III. CONSERVATION OF ANGULAR MOMENTUM

We have argued that, if we ignore the transient effects from the switching on and switching off of the fluid flow, we do not expect the reverse sprinkler to turn at all. A pertinent question is why, for the case of the regular sprinkler, the sprinkler-water system clearly exhibits no net angular momentum around the pivot (with the angular momentum of the outgoing water cancelling the angular momentum of the rotating sprinkler), while for the reverse sprinkler the system would appear to have a net angular momentum given by the incoming water. The answer lies in the simple observation that if the water in a tank is flowing, then something must be pushing it. In the regular sprinkler, there is a high pressure zone near the sprinkler wall next to the pivot, so it is this lower inner wall that is doing the original pushing, as shown in Fig. 4(a).

For the reverse sprinkler, the highest pressure is outside the sprinkler, so the pushing originally comes from the right wall of the tank in which the whole system sits, as shown in Fig. 4(b). The force on the regular sprinkler clearly causes no torque around the pivot, while the force on the reverse sprinkler does. That the water should acquire a net angular momentum around the sprinkler pivot in the absence of an external torque might seem a violation of Newton's laws, but only because we are neglecting the movement of the tank itself. Consider a water tank with a hole in its side, such as the one pictured in Fig. 5. The water acquires a net angular momentum with respect to any point on the tank's bottom, but this angular momentum violates no physical laws because the tank is not inertial: it recoils as water flows out of it.⁶

But there is one further complication: in the reverse sprinkler shown in Fig. 4, the water that has acquired left-pointing momentum from the pushing of the tank wall will transfer that momentum back to the tank when



(a)

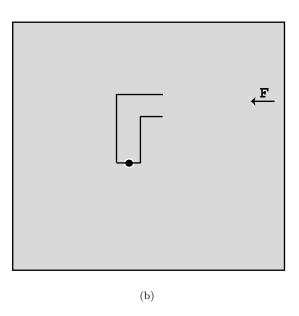


FIG. 4: The force that pushes the water must originally come from a solid wall. The force that causes the water flow is shown for both the regular and the reverse sprinklers when submerged in a tank of water.

it hits the inner sprinkler wall, so that once water is flowing steadily into the reverse sprinkler, the tank will stop experiencing a recoil force. The situation is analogous to that of a ship inside of which a machine gun is fired, as shown in Fig. 6. As the bullet is fired, the ship recoils, but when the bullet hits the ship wall and becomes embedded in it, the bullet's momentum is transferred to the ship. (We assume that the collision of the bullets with the wall is completely inelastic.)

If the firing rate is very low, the ship periodically acquires a velocity in a direction opposite to that of the

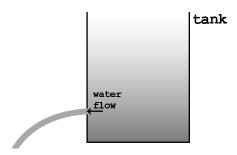


FIG. 5: A tank with an opening on its side will exhibit a flow such that the water will have an angular momentum with respect to the tank's bottom, even though there is no external source of torque corresponding to the angular momentum. The apparent paradox is resolved by noting that the tank bottom offers no inertial point of reference, because the tank is recoiling due to the motion of the water.

fired bullet, only to stop when that bullet hits the wall. Thus the ship moves by small steps in a direction opposite that of the bullets' flight. As the firing rate is increased, eventually one reaches a rate such that the interval between successive bullets being fired is equal to the time it takes for a bullet to travel the length of the ship. If the machine gun is set for this exact rate from the beginning, then the ship will move back with a constant velocity from the moment that the first bullet is fired (when the ship picks up momentum from the recoil) to the moment the last bullet hits the wall (when the ship comes to a stop). In between those two events the ship's velocity will not change because every firing is simultaneous to the previous bullet hitting the ship wall.

As the firing rate is made still higher, the ship will again move in steps, because at the time that a bullet is

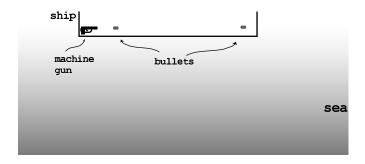


FIG. 6: In this thought experiment, a ship floats in the ocean while a machine gun with variable firing rate is placed at one end. Bullets fired from the gun will travel the length of the ship and hit the wall on the other side, where they stop.

being fired, the previous bullet will not have quite made it to the ship wall. Eventually, when the rate of firing is twice the inverse of the time it takes for a bullet to travel the length of the ship, the motion of the ship will be such that it picks up speed upon the first two shots, then moves uniformly until the penultimate bullet hits the wall, whereupon the ship looses half its velocity. The ship will finally come to a stop when the last bullet has hit the wall. At this point it should be clear how the ship's motion will change as we continue to increase the firing rate of the gun.⁸

For the case of continuous flow of water in a tank (rather than a discrete flow of machine gun bullets in a ship), there clearly will be no intermediate steps, regardless of the rate of flow. Figure 7 shows a water tank connected to a shower head. Water flows (with a consequent linear and angular momentum) between the points marked A and B, before exiting via the shower head. When the faucet valve is opened, the tank will experience a recoil from the outgoing water, until the water reaches B and begins exiting through the shower head, at which point the forces on the tank will balance. By then the tank will have acquired a left-pointing momentum. It will lose that momentum as the valve is closed or the water tank becomes empty, when there is no longer water flowing away from A but a flow is still impinging on B.

A. K. Schultz⁹ argues that, at each instant, the water flowing into the reverse sprinkler's intake carries a constant angular momentum around the sprinkler pivot, and if the sprinkler could turn without any resistance (either from the friction of the pivot or the viscosity of the fluid) this angular momentum would be counterbalanced by the angular momentum that the sprinkler picked up as the water flow was being switched on. As the fluid flow is switched off, such an ideal sprinkler would then lose its angular momentum and come to a halt. At every instant, the angular momentum of the sprinkler plus the incoming water would be zero.

Schultz's discussion is correct: in the absence of any resistance, the sprinkler arm itself moves so as to cancel the momentum of the incoming water, in the same way that the ship in Fig. 6 moves to cancel the momentum of the flying bullets. Resistance, on the other hand, would imply that some of that momentum is picked up not just by the sprinkler, but by the tank as a whole. If we cement the pivot to prevent the sprinkler from turning at all, then the tank will pick up all of the momentum that cancels that of the incoming water.

How does non-ideal fluid behavior affect this analysis? Viscosity, turbulence, and other such phenomena all dissipate mechanical energy. Therefore, a non-ideal fluid rushing into the reverse sprinkler would acquire less momentum with respect to the pivot, for a given pressure difference, than predicted by the analysis we carried out in Sec. II. Thus the pressure difference effect would outweigh the momentum transfer effect even in the steady state, leading to a small torque on the sprinkler even

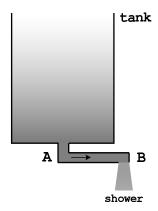


FIG. 7: A water tank is connected to a shower head, so that water flows out. Water in the pipe that connects the points marked A and B has a right-pointing momentum, but as long as that pipe is completely filled with water there is no net horizontal force on the tank.

after the fluid has begun to hit the inside wall of the sprinkler. Total angular momentum is conserved because the "missing" momentum of the incoming fluid is being transmitted to the surrounding fluid, and finally to the tank.

IV. HISTORY OF THE REVERSE SPRINKLER PROBLEM

The literature on the subject of the reverse sprinkler is abundant and confusing. Ernst Mach speaks of "reaction wheels" blowing or sucking air where we have spoken of regular or reverse sprinklers respectively:¹⁰

It might be supposed that sucking on the reaction wheels would produce the opposite motion to that resulting from blowing. Yet this does not usually take place, and the reason is obvious ... Generally, no perceptible rotation takes place on the sucking in of the air ... If ... an elastic ball, which has one escapetube, be attached to the reaction-wheel, in the manner represented in [Fig. 8(a)], and be alternately squeezed so that the same quantity of air is by turns blown out and sucked in, the wheel will continue to revolve rapidly in the same direction as it did in the case in which we blew into it. This is partly due to the fact that the air sucked into the spokes must participate in the motion of the latter and therefore can produce no reactional rotation, but it also results partly from the difference of the motion which the air outside the



(a)



FIG. 8: Illustrations from Ernst Mach's *Mechanik*¹⁰: (a). Figure 153 a in the original. (b). Figure 154 in the original. (Images in the public domain, copied from the English edition of 1893.)

tube assumes in the two cases. In blowing, the air flows out in jets, and performs rotations. In sucking, the air comes in from all sides, and has no distinct rotation...

Mach appears to base his treatment on the observation that a "reaction wheel" is not seen to turn when sucked on. He then sought a theoretical rationale for this observation without arriving at one that satisfied him. Thus the bluster about the explanation being "obvious," accompanied by the tentative language about how "generally, no perceptible rotation takes place" and by the equivocation about how the lack of turning is "partly due" to the air "participating in the motion" of the wheel and partly to the air sucked "coming in from all sides."

Mach goes on to say that¹¹

if we perforate the bottom of a hollow cylinder ... and place the cylinder on [a pivot], after the side has been slit and bent in the manner indicated in [Fig. 8(b)], the [cylinder]

will turn in the direction of the long arrow when blown into and in the direction of the short arrow when sucked on. The air, here, on entering the cylinder can continue its rotation *unimpeded*, and this motion is accordingly compensated for by a rotation in the opposite direction.

This observation is correct and interesting: it shows that if the incoming water did not give up all its angular momentum upon hitting the inner wall of the reverse sprinkler, then the device would turn toward the incoming water, as we discussed at the beginning of Sec. III. 12

In his introduction to Mach's Mechanik, mathematician Karl Menger describes it as "one of the great scientific achievements of the [nineteenth] century," ¹³ but it seems that the passage we have quoted was not well known to the twentieth century scientists who commented publicly on the reverse sprinkler. Feynman¹ gave no answer to the problem and wrote as if he expected and observed rotation (though, as some have pointed out, the fact that he cranked up the pressure until the bottle exploded suggests another explanation: he expected rotation and didn't see it). In Refs. 14 and 15 the authors discuss the problem and claim that no rotation is observed, but they pursue the matter no further. In Ref. 16, it is suggested that students demonstrate as an exercise that "the direction of rotation is the same whether the flow is supplied through the hub [of a submerged sprinkler] or withdrawn from the hub," a result which is discounted by almost all the rest of the literature.

Shortly after Feynman's memoirs appeared, A. T. Forrester published a paper in which he concluded that if water is sucked out of a tank by a vacuum attached to a sprinkler then the sprinkler will not rotate.¹⁷ But he also made the bizarre claim that Feynman's original experiment at the Princeton cyclotron, in which he had high air pressure in the bottle push the water out, would actually cause the sprinkler to rotate in the direction of the incoming water.¹⁷ An exchange on the issue of conservation of angular momentum between A. K. Shultz and Forrester appeared shortly thereafter.^{9,18} The following year L. Hsu, a high school student, published an experimental analysis which found no rotation of the reverse sprinkler and questioned (quite sensibly) Forrester's claim that pushing the water out of the bottle was not equivalent to sucking it out. 19 E. R. Lindgren also published an experimental result that supported the claim that the reverse sprinkler did not turn.²⁰

After Feynman's death, his graduate research advisor, J. A. Wheeler, published some reminiscences of Feynman's Princeton days from which it would appear that Feynman observed no motion in the sprinkler before the bottle exploded ("a little tremor as the pressure was first applied ... but as the flow continued there was no reaction").²¹ In 1992 the journalist James Gleick published a biography of Feynman in which he states that both Feynman and Wheeler "were scrupulous about never revealing the answer to the original question" and

then claims that Feynman's answer all along was that the sprinkler would not turn.²² The physical justification that Gleick offers for this answer is unenlightening and wrong. (Gleick echoes one of Mach's comments¹⁰ that the water entering the reverse sprinkler comes in from many directions, unlike the water leaving a regular sprinkler, which forms a narrow jet. Although this observation is correct, it is not particularly relevant to the question at hand.)

The most detailed and pertinent work on the subject, both theoretical and experimental, was published by Berg, Collier, and Ferrell, who claimed that the reverse sprinkler turns toward the incoming water. ^{24,25} Guided by Schultz's arguments about conservation of angular momentum, ⁹ the authors offered a somewhat convoluted statement of the correct observation that the sprinkler picks up a bit of angular momentum before reaching a steady state of zero torque once the water is flowing steadily into the sprinkler. When the water stops flowing, the sprinkler comes to a halt. ³¹

The air-sucking reverse sprinkler at the Edgerton Center at MIT shows no movement at all.²⁷ As in the setups used by Feynman and others, this sprinkler arm is not mounted on a true pivot, but rather turns by twisting or bending a flexible tube. Any transient torque will therefore cause, at most, a brief shaking of such a device. The University of Maryland's Physics Lecture Demonstration Facility offers video evidence of a reverse sprinkler, mounted on a true pivot of very low friction, turning slowly toward the incoming water. 26 According to R. E. Berg, in this particular setup "while the water is flowing the nozzle rotates at a constant angular speed. This would be consistent with conservation of angular momentum except for one thing: while the water is flowing into the nozzle, if you reach and stop the nozzle rotation it should remain still after you release it. [But, in practice,] after [the nozzle] is released it starts to rotate again." ³⁷

This behavior is consistent with non-zero dissipation of kinetic energy in the fluid flow, as we have discussed. Angular momentum is conserved, but only after the motion of the tank is taken into account.³⁸

V. CONCLUSIONS

We have offered an elementary theoretical treatment of the behavior of a reverse sprinkler, and concluded that, under idealized conditions, it should experience no torque while fluid flows steadily into it, but as the flow commences, it will pick up an angular momentum opposite to that of the incoming fluid, which it will give up as the flow ends. However, in the presence of viscosity or turbulence, the reverse sprinkler will experience a small torque even in steady state, which would cause it to accelerate toward the incoming water. This torque is balanced by an opposite torque acting on the surrounding fluid and finally on the tank itself.

Throughout our discussion, our foremost concern was

to emphasize physical intuition and to make our treatment as simple as it could be made (but not simpler). Surely a question about what L. A. Delsasso called, according to Feynman's recollection, "a freshman experiment" deserves an answer presented in a language at the corresponding level of complication. More important is the principle, famously put forward by Feynman himself when discussing the spin statistics theorem, that if we can't "reduce it to the freshman level," we don't really understand it.³⁹

We also have commented on the perplexing history of the reverse sprinkler problem, a history which is interesting not only because physicists of the stature of Mach, Wheeler, and Feynman enter into it, but also because it offers a startling illustration of the fallibility of great scientists faced with a question about "a freshman experiment."

Surely, as the Duchess said to Alice during one of her

adventures in Wonderland, "everything's got a moral, if you can only find it." $^{\rm 40}$

Acknowledgments

The historical section of this paper owes a great deal to the list of references on the reverse sprinkler that is given at the Web site for the University of Maryland's Physics Lecture Demonstration Facility. ²⁶ Thanks are due to several readers who commented on this paper after it first appeared in manuscript form, particularly to J. M. Dlugosz, who took it upon himself to clarify the relationship between this discussion and the account of the experimental results at the University of Maryland. The result of his inquiries was a useful exchange with R. E. Berg.

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¹ R. P. Feynman, Surely You're Joking, Mr. Feynman, (Norton, New York, NY, 1985), pp. 63–65.

² R. P. Feynman, *Ibid.*, p. 63.

³ It has not been possible to identify the book to which Feynman was referring. As we shall discuss, the matter is treated in Ernst Mach's *Mechanik*, first published in 1883. ¹⁰ Yet this book is not a "hydrodynamics book" and the reverse sprinkler is presented as an example, not a problem. In Ref. 21, J. A. Wheeler suggests that the problem occurred to them while discussing a different question in the undergraduate mechanics course that Wheeler was teaching and for which Feynman was the grader.

⁴ R. P. Feynman, *Ibid.*, p. 65.

⁵ In the literature it is more usual to see this problem identified as the "Feynman inverse sprinkler." Because the problem did not originate with Feynman and Feynman never published an answer to the problem, we have preferred not to attach his name to the sprinkler. Furthermore, even though it is a pedantic point, a query of the Oxford English Dictionary suggests that "reverse" (opposite or contrary in character, order, or succession) is a more appropriate description than "inverse" (turned up-side down) for a sprinkler that sucks water.

 $^{^{6}}$ This observation might seem trivial, but its consequences can be counterintuitive. The Zapruder film of the 1963 assassination of U.S. president J. F. Kennedy, shows Kennedy's head snapping backward after the fatal shot, even though the official theory of the assassination asserts that the shot was fired from behind Kennedy by gunman L. H. Oswald. For several decades, conspiracy theorists have seized on this element of the Zapruder film as evidence that the fatal shot could not have been fired by Oswald and must have come instead from in front of the president's motorcade. In 1976, L. W. Alvarez published an analysis of the Zapruder film in which he explained that the jet of brain tissue that emerged from president's exit wound might easily have thrown his head in the direction opposite to that of the incoming bullet. Alvarez demonstrated this to his satisfaction both theoretically and experimentally,

the latter by firing at a melon and photographing it as it moved in the direction opposite to what one would naively have expected.⁷

⁷ L. W. Alvarez, "A physicist examines the Kennedy assassination film," Am. J. Phys. 44, 813–827 (1976).

⁸ Two interesting problems for an introductory university-level physics course suggest themselves. One is to show that the center of mass of the bullets-and-ship system will not move in the horizontal direction regardless of the firing rate, as one expects from momentum conservation. Another would be to analyze this problem in the light of Einstein's relativity of simultaneity.

⁹ A. K. Schultz, "Comment on the inverse sprinkler problem," Am. J. Phys. 55, 488 (1987).

E. Mach, Die Mechanik in Ihrer Entwicklung Historisch-Kritisch Dargerstellt (1883). First published in English in 1893 as The Science of Mechanics: A Critical and Historical Account of its Development (Open Court, La Salle, IL, 1960), 6th ed., pp. 388–390.

¹¹ E. Mach, *Ibid.*, p. 390.

¹² In Ref. 23, P. Hewitt proposes a physical setup identical to the one shown in Fig. 8(b), and observes that the device turns in opposite directions depending on whether the fluid pours out of or into it. Hewitt's discussion seems to ignore the important difference between such a setup and the reverse sprinkler.

 $^{^{13}}$ E. Mach, $\mathit{Op.\ cit.},\, \mathrm{p.\ v.}$

¹⁴ P. Kirkpatrick, "A neglected lesson from the Cartesian diver," Am. J. Phys. 10, 160 (1942).

¹⁵ H. S. Belson, "'Empty' hero's engine," Am. J. Phys. **24**, 413–414 (1956).

Proceedings of the National Science Foundation Conference on Instruction in Fluid Mechanics, 5–9 September 1960, Exp. 2.2, p. II–20.

¹⁷ A. T. Forrester, "Inverse sprinklers: A lesson in the use of a conservation principle," Am. J. Phys. **54**, 798–799 (1986).

¹⁸ A. T. Forrester, "Comments on a letter by A. K. Schultz," Am. J. Phys. **55**, 488–489 (1987).

¹⁹ L. Hsu, "Two simple experiments and the resolution of the Feynman-Forrester conflict," Am. J. Phys. **56**, 307–

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- E. R. Lindgren, "The transport of momentum theorem," Am. J. Phys. 58, 352–357 (1990).
- ²¹ J. A. Wheeler, "The young Feynman," Phys. Today **42** (2), 24–28 (1989).
- ²² J. Gleick, Genius: The Life and Science of Richard Feynman (Pantheon, New York, NY, 1992), pp. 106–108.
- ²³ P. Hewitt, "Figuring physics," Phys. Teach. **40**, 390, 437 (2002).
- ²⁴ R. E. Berg and M. R. Collier, "The Feynman inverse sprinkler problem: A demonstration and quantitative analysis," Am. J. Phys. **57**, 654–657 (1989).
- ²⁵ R. E. Berg, M. R. Collier, and R. A. Ferrell, "The Feynman inverse sprinkler problem: A detailed kinematic study," Am. J. Phys. **59**, 349–355 (1991).
- ²⁶ R. E. Berg et al., University of Maryland Physics Lecture Demonstration Facility,
- ²⁸ M. Kuzyk, "Letter," Phys. Today **42** (11), 129–130 (1989).
- ²⁹ R. E. Berg and M. R. Collier, "New device lets you unwater your lawn," Phys. Today 43 (7), 13 (1990).
- ³⁰ A. Mironer, "The Feynman sprinkler," Am. J. Phys. **60**, 12 (1992).
- ³¹ There are other references in the literature to the reverse sprinkler. For a rather humorous exchange, see Refs. 28 and 29. Already in 1990 the American Journal of Physics had received so many conflicting analyses of the problem that the editor proposed "a moratorium on publications on Feynman's sprinkler." In one of her 1996 columns for Parade Magazine, Marilyn vos Savant, who bills herself as having the highest recorded IQ, offered an account of Feynman's experiment which, she claimed, settled that the

- reverse sprinkler does not move.³² Vos Savant's column emphasized the confusion of Feynman and others when faced with the problem, leading a reader to respond with a letter to his local newspaper in which he questioned the credibility of physicists who address matters more complicated than lawn sprinklers, such as the origin of the universe.³³
- ³² M. vos Savant, "Ask Marilyn," Parade Magazine, Oct. 6, 1996.
- A. de Gruyter, "Big Bang Theorists Can't Simulated Water Sprinkler Reversal," Houston Chronicle, Oct. 26, 1996, p. A35.
- ³⁴ J. S. Miller, "Physics in a toy boat," Am. J. Phys. **26**, 199 (1958).
- ³⁵ R. S. Mackay, "Boat driven by thermal oscillations," Am. J. Phys. **26**, 583–584 (1958).
- ³⁶ I. Finnie and R. L. Curl, "Physics in a toy boat," Am. J. Phys. **31**, 289–293 (1963).
- >³⁷ R. E. Berg, private communication with J. M. Dlugosz and A. Jenkins (2004).
- ³⁸ In the late 1950's and early 1960's, there was some interest in the related physics problem of the so-called "puttputt" (or "pop-pop") boat, a fascinating toy boat that propels itself by heating (usually with a candle) an inner tank connected to a submerged double exhaust. Steam bubbles cause water to be alternately blown out of and sucked into the tank. ^{34,35,36} The ship moves forward, much like Mach described the "reaction wheel" turning vigorously in one direction as air was alternately blown out and sucked in.
- ³⁹ R. P. Feynman, Six Easy Pieces, (Perseus Books, Cambridge, MA, 1994), p. xxi.
- ⁴⁰ L. Carroll and M. Gardner (ed.), The Annotated Alice: The Definitive Edition, (W. W. Norton, New York, NY, 2000), p. 91.