The Actio-Reactio Apparatus

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Virtually all students that we encounter in our introductory physics courses are able to recite that "for every action there is an equal and opposite reaction." But once confronted with real-life situations such as a truck colliding with a subcompact, or a small car pushing a truck, students often resort to their gut feeling and respond with answers revealing common misconceptions. One reason for the persistence of these misconceptions is the fact that in most cases we cannot directly see the forces[1] that two objects exert on each other. Visualizing these interaction forces would definitely aid in the eradication of student misconceptions. The Actio-Reactio apparatus we present here is a very simple tool that visualizes Newton's third law interaction forces.

The Apparatus

The apparatus, shown in Fig. 1a, consists of two compression springs with a spring constant of approximately 2 kN/m, two handles, and a central cylindrical section mounted in the middle of a 1/4-in ground and polished shaft (cf. Fig. 1b). The axial sections of both handles have a bore of 0.205 in and a slit about 1/8 in wide by 2 in long. Both springs float freely on the 1/4-in polished shaft. Similarly, the handle sections move freely on the shaft. Two roll pins about 1 in from either end of the shaft protrude into the 1/8-in wide slit and prevent the handles from falling off. Small pointers, attached to the end of each pin, serve as force indicators. However, students can judge the compression force by the length reduction of the compression springs from some distance away from the apparatus.

Fig. 1a. Photograph of the Actio-Reactio apparatus.

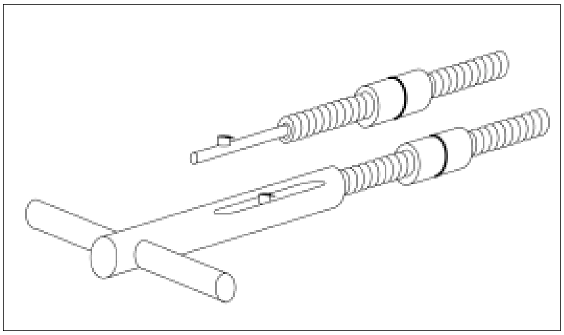

Fig. 1b. Schematic drawing of apparatus details.

The Experiments

In the following sections we will outline a few of the many possible experiments that employ the Actio-Reactio apparatus to visualize the equality of the action and reaction force while two objects interact. To keep the attention of the students during the classes devoted to Newton's third law, we do not ask our students to "verify" Newton's third law for a number of scenarios but instead suggest the possibility of cases where the third law might not hold. We challenge our students to find all those situations where Newton's third law holds and to identify all those cases where they think that it does not hold. (Typically, it does not take too long until students discover that cases in violation of the law cannot be found.) For the sake of a more systematic approach, we suggest to our students that we will proceed in order of increasing complexity. That is, we will first start to explore **static scenarios**, continue with situations where the two objects involved move at **constant speed**, then investigate situations characterized by **constant acceleration**, and finally look at scenarios where the **accelerations are "horrible,"** e.g., during collisions and explosions.

Experiment A (static scenario) — *"The Smart Wall"*

A strong student flexes his muscles and pushes against the wall (Fig. 2). Does the wall push back? A common misconception does not ascribe forces to inanimate objects. However, the Actio-Reactio apparatus readily reveals that the wall in return exerts a force on the student. Moreover, the apparatus shows that the wall exerts a force on the student that is equal in magnitude to the force the student is exerting on the wall. If he exerts twice the force on the wall, the wall pushes back with twice the force. If he pushes against the wall with a force of 22.34 N, the wall pushes back with exactly that force. It appears that the wall is quite smart! How does the wall know to push back with exactly 22.34 N? The students may ponder this question until the next class meeting.

Experiment B_1 (moving at constant speed) — *"Small Car Pushing Truck"*

Imagine a truck broken down with transmission problems. A Volkswagen pushes the truck with a constant velocity of, let's say, 10 km/h to the nearest garage. Does the Volkswagen exert a larger force on the truck since it is moving the truck in the forward direction, or does the truck exert a larger force on the Volkswagen since it is so much more massive? To explore this situation, we place two or three students on the larger of the two Kinesthetics Carts,[2] representing the truck, and a lighter student on the smaller Kinesthetics Cart, in lieu of the Volkswagen (see top photo on cover). The rear bumper of the truck and the front bumper of the Volkswagen are replaced by the Actio-Reactio apparatus, allowing the students to visualize the forces between the two vehicles.

Fig. 2. Newton's third law examined in a $v = 0$ scenario. This "smart" wall pushes back with an equal and opposite force.

While some students predict that the Volkswagen would have to exert a larger force on the truck since both truck and Volkswagen move in the forward direction, other students argue that the truck exerts a larger force on the Volkswagen due to its larger mass. The Actio-Reactio apparatus clearly shows that the truck exerts the same force on the Volkswagen as the Volkswagen exerts on the truck.

Experiment B_2 (constant speed) — *"Small Car Pushing Truck Uphill"*

In this situation a Volkswagen (cart with one student) places its front bumper against the rear bumper of a truck (cart with three students) and proceeds to push the truck uphill (see bottom photo on cover). Although this experiment seems to be only a slight modification of Experiment B_1, student predictions with regard to the forces between the two vehicles differ from their previous responses. "Now the Volkswagen definitely has to exert more force on the truck since we have to overcome the additional downhill force," and conversely, "Now the truck exerts the larger force on the Volkswagen because of its inertia and the additional downhill force." But again the Actio-Reactio apparatus indicates that the force on the truck due to the Volkswagen, F_{TV}, is equal and opposite to the force on the Volkswagen due to the truck, F_{VT}.

Experiment B_3 (constant speed) — *"Car with Trailer Going Downhill"*

To check the students' understanding of Newton's third law in the "constant speed" situations, we add other scenarios such as the following. A sport-utility vehicle (SUV) with a heavy trailer is slowly driving down a steep incline. Is the trailer exerting a larger force on the SUV since it would like to roll down the incline faster than the slow-moving SUV, or is the SUV exerting a larger force on the trailer since it needs to keep the trailer behind itself and indeed succeeds in doing so? The answer can be obtained effectively and convincingly with two Kinesthetics Carts and the Actio-Reactio apparatus, requiring virtually no setup time. The larger of the two Kinesthetics Carts is in the front and carries two students. The first student, the "driver," faces forward and puts both feet on the ground letting them act as the SUV's brakes. The second student faces rearward and holds one end of the Actio-Reactio apparatus. A third student, sitting on the smaller Kinesthetics Cart with her legs crossed, faces forward and holds the other end of the Actio-Reactio apparatus. While the SUV with its trailer is "parked" on the incline, the Actio-Reactio apparatus clearly indicates equal and opposite forces between SUV and trailer. And while the "driver" allows the SUV to slowly coast down the incline, the students again see that the forces between the SUV and its trailer are equal and opposite. *Note:* We typically use the handicap access ramp in our building for an inclined plane. A slightly inclined parking lot would be equally suitable.

Experiment C (constant acceleration) — *"Small Car Pushing Truck"*

We now return to the story of Experiment B_1, involving the Volkswagen and the truck on a level road. However, this time the Volkswagen is accelerating the truck. After all, the Volkswagen starts to push the truck from rest and somehow needs to get up to the constant velocity (we called it v = 10 km/h). Let's assume that the Volkswagen accelerates the truck with a constant acceleration a. The number of students who strongly argue in favor of a larger force acting on the truck is now significantly increased in this "Scenario III" situation involving a constant acceleration a. The most prominent argument goes along the line "Since the truck now has a positive acceleration a in the forward direction, there must be a net force on the truck in the forward direction; consequently, the Volkswagen must exert a larger force on the truck!" However, a quick experiment with the Actio-Reactio apparatus reveals once again that the forces are equal and opposite.

Experiment D (nonuniform acceleration) — *"Gentle Collision with a Truck"*

A Mack truck collides head-on with a Volkswagen, both moving at, let's say, 50 km/h. During the collision, which of the two vehicles exerts the larger force on the other? Here we have a scenario that involves a highly nonuniform acceleration. The great majority of students now argue strongly in favor of the truck. Undoubtedly, this close encounter leaves the Volkswagen "ready for recycling," while the Mack truck escapes with "minor dents." Some students have argued that "Newton never saw a Mack truck and therefore Newton's third law is most likely not applicable in this situation!"

Obviously, we do not want to replicate the collision with a real Mack truck, but we simulate the event with a very gentle collision using again the Kinesthetics Carts. Two or three students are sitting on one cart facing forward, i.e., facing the site of the impending collision. One student sits on another cart, also facing forward, i.e., toward the collision site. Either the first student on the "truck" or the student representing the Volkswagen holds the Actio-Reactio apparatus in such a way that the opposite handle will meet the outstretched hands of the student on the other cart. Now the cars are slowly moved toward each other simulating the collision. The Actio-Reactio apparatus inserted between the hands of the "Volkswagen driver" and the "Mack truck driver" shows that both springs start to compress equally, followed by equal maximal compression, then again smaller but equal compression. Students can readily see that even in this "Scenario IV" situation involving a highly nonuniform acceleration, the interaction forces are once again equal and opposite.

Conclusion

We presented here an extremely simply apparatus that can aid students significantly in the conceptual understanding of Newton's third law. The selection of experiments presented here allows students to actually "see" that the interaction forces between two objects are equal, regardless of the complexity of the situation.

We would like to conclude this paper with a graph illustrating the learning gains. Since the inception of Workshop Physics in the mid-1980s, all of our students have consistently filled out pre- and post-instruction conceptual exams. Some of the results are reported in Refs. 3 and 4. For the graph shown here (cf. Fig. 3), we have extracted the answers to those questions on the

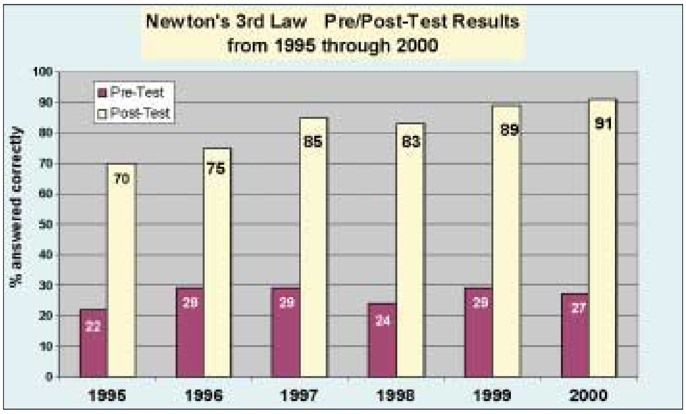

Fig. 3. Pre- and post-test results of Dickinson students on Newton's third law conceptual questions of the FMCE from 1995 to fall 2000. The pre-test scores consistently fall between 22% and 29%. Post-test scores increase from 70% in 1995 to 91% in 2000. The Actio-Reactio apparatus was first used in 1997 and is most likely responsible for the significant increase in post-test scores between the fall of '96 and the fall semester 2000. Additional experiments involving the Actio-Reactio apparatus were added in 1999.

Force and Motion Conceptual Evaluation (FMCE)[5] that pertain directly to Newton's third law. The graph shows pre- and post-test results from fall 1995 through fall 2000. Note that the pre-test scores are fairly stable over the six-year period displayed in Fig. 3.

A Few Hints

(1) The PASCO Kinesthetics Cart set consists of an upper cart and a lower cart, designed such that one cart can ride piggyback on the other. The experiments described here can be performed with one set of Kinesthetics Carts. However, if an upper and lower cart are used, there is a risk that the lower cart might slide underneath the upper cart, possibly injuring the foot of the rider on the lower cart. We therefore strongly recommend the use of two upper carts or two lower carts. Other carts with low-friction bearings might work equally well.

(2) The slope of the incline should be on the order of 3–7%. Typically, we use our Terrazzo handicap access ramp (7% slope and 2.2 m wide) for this experiment.

(3) In Experiment C, the collision between the Mack truck and the Volkswagen, we recommend that you capture the compression of the springs with a high-speed digital video camera and play back the relevant frames in single-frame mode.

Acknowledgments

I would like to thank Rick Lindsey for manufacturing the new, improved Actio-Reactio apparatus, and Gail Oliver for compiling the results from the FMCE questions pertaining to Newton's third law.

References

1. We cannot "see" the force, but we can see the effect of the force. In some cases this effect can be seen quite clearly, e.g., when a finger pushes against a beach ball and produces a small indentation. In other cases this effect cannot be seen, e.g., when the bumper of a Volkswagen pushes against the bumper of a truck.
2. Hans Pfister and Priscilla Laws, "Kinesthesia-1: Apparatus to experience 1-D motion," *Phys. Teach*. **33**, 214 (April 1995). Kinesthetics Carts are available from PASCO scientific; http://www.pasco.com.
3. Edward F. Reddish and Richard N. Steinberg, "Teaching physics: Figuring out what works," *Phys. Today* **52**, 24 (1999).
4. Eric Stokstad, "Reintroducing the intro course," *Science* **293**, 1608 (2001).
5. Ron Thornton and David Sokoloff, Center for Science and Mathematics Teaching, Tufts University, "Force and Motion Conceptual Evaluation" (FMCE).

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Dueling Scientists

etcetera... Editor:
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"Around the end of the 18th century, a decades-long dispute, which outlived both the protagonists, raged between Luigi Galvani[1] and Allessandro Volta[2] over whether electricity was generated mechanically or by living systems. Their vitriolic exchanges through lectures, scientific publications, and other media laid the groundwork for the development of electromagnetic theory and for the discovery of how the nervous system functions. Each used all his resources to prove the other was wrong, when in reality *both were right*."[3]

1. Luigi Galvani, Italian scientist (1737–1798).
2. Allessandro Volta, Italian physicist (1745–1827).
3. Thomas Isenhour, "Dueling docs," *Am. Sci.* **89**, 374–375 (July–Aug. 2001).