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May the Forces Be With You!

Christopher Sirola
University of Southern Mississippi, Christopher.Sirola@usm.edu

Joe Heafner, Column Editor, Science Department
Catawba Valley Community College, Hickory, NC 28602; heafnerj@gmail.com

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Christopher Sirola, Associate Professor, Department of Physics & Astronomy, University of Southern Mississippi, Hattiesburg, MS 39406; Christopher.Sirola@usm.edu

In everyday life, we usually directly note two basic forces: gravity and electromagnetism. Gravity—as in the acceleration due to Earth's gravity—tends to be a background force of sorts, something that is always present and always the same. We don't always see electricity and/or magnetism as such, but their subsidiaries are all around us—friction, normal force, tension, springs, and the like.

Physicists, however, currently recognize two other "fundamental" forces of nature—the strong nuclear force and the weak nuclear force.[1] Because these forces act at such small scales—the nuclei of atoms—we aren't typically aware of them. But without either, the Sun doesn't shine and Earth isn't inhabitable.

By and large, if a teacher gets to address the strong and weak forces, it's almost always in passing. The mathematics of either are far above the norm for most introductory undergraduate physics courses,[2] and even for physics majors are usually approached with all due caution. Yet, wouldn't it be a good idea to teach these, if at all possible?

Several years ago, I worked with one of our PhD candidates in physics education in order to address this issue. One of the results was the creation of a relatively simple classroom activity, whose purpose is to get across the basic concepts lying behind both nuclear forces. Furthermore, the activity does not require much in the way of equipment, with one important exception.

Below is a short list (Table I) of some of the key aspects of the fundamental forces, including gravity and electromagnetism for good measure.

Table I. Basic properties of the fundamental forces.[4]

	Gravity	Electro-magnetism	Strong Nuclear	Weak Nuclear
Range	Infinite	Infinite	~ 10^{-15} m	~ 10^{-7} m
Relative Strength	~ 10^{-39}	~ 10^{-2}	1	~ 10^{-7}
Attractive or Repulsive?	attractive only	attractive or repulsive	attractive only	N/A

In essence, the strong nuclear force is the strongest of all the forces, is only attractive, and only works at distances smaller than atomic nuclei. The weak force is much weaker than the strong force (hence its name) and also only acts at extremely short ranges.[3] Both gravity and electromagnetism, in contrast, have unlimited ranges.

Since you're unlikely to have a particle accelerator available for your students, we aren't going to measure strong and/or weak interactions. But we can simulate them. To do so, you'll need duct tape, some coins and/or playing dice, weights, carts (or something else one can smash together), and magnets. We also possess tracks with grooves for the cart wheels to fit inside, ensuring one-dimensional motion.

The carts are the one set of items where we need some specialization. In this case, you want carts that have (a) magnets embedded in one end, (b) Velcro strips glued to the other end, and (c) an extending arm that projects outward at the push of a button. Each student group will need two carts. One can procure carts from any of a number of companies that market science products to high school and/or college classrooms.

Simulating the weak nuclear force

The weak nuclear force is responsible for certain forms of radioactive decay. Radioactive decay randomly splits apart atomic nuclei into smaller pieces (neutron decay is a famous example). So we need a way to both simulate breaking apart large objects into smaller ones and to do so randomly.

Place two carts on the track so that their Velcro strips hold them together (Fig. 1). We also find it helpful to place weights on each cart—more weight on one cart than the other. Have students flip a coin (playing dice may also be used). If the coin comes up "tails," they do nothing and flip again. If the coin comes up "heads," they push a button (on top of either cart) that extends its arm (Fig. 2). The arm is on a spring and extends rather quickly, so the carts will be pushed apart rather quickly. The weights slow down the reaction, so the students can appreciate the reaction better.

This quick exercise shows off the basic properties of the weak nuclear force: its random nature, the particles split apart, and that it is short range (the arm won't push the carts apart unless the carts are close enough together). We can even use this to discuss how the radioactive products can be different masses by placing different weights on top of the carts.

Simulating the strong nuclear force

The strong nuclear force is responsible for holding nuclear particles together (protons, neutrons, and the like), and thus is also responsible for nuclear fusion. But nuclear fusion is difficult. The Sun's primary process, the proton-proton chain, begins by smashing two protons together. Since protons possess positive electric charges, they otherwise repel each other. The strong force is stronger than this, but is also extremely short range. So we need a way to simulate all these features.

Place two carts on the track, but here have their magnetized ends facing each other (Fig. 3). With one cart at rest on

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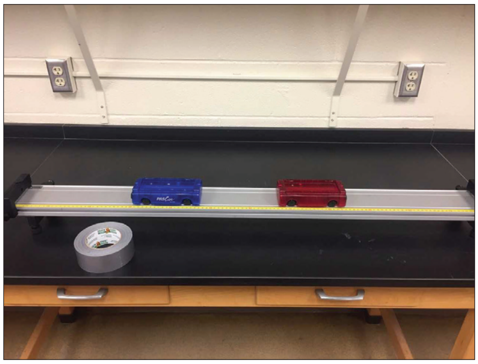

Fig. 1. Two carts on a grooved track.

Fig. 2. Cart with arm extended.

Fig. 3. The circles (disks) embedded in the end of the cart are magnets.

the track, gently push the other cart toward it. The magnets on the carts repel each other, and the carts will push each other apart without even touching. Next, tear a small strip of duct tape and roll it into a cylinder, sticky-side out. Then place the duct tape cylinder on the magnetized end of one cart (Fig. 4). Place this cart back on the track and repeat the above process.

Students will find that, if they push the carts together too slowly (or too quickly!), the carts will still repel each other. But if they push the carts together at just the right speed, they will stick together due to the duct tape. (This is an opportunity for students to experiment on their own. They may find they need to put duct tape on both carts, for example.)

The duct tape's attraction (stickiness) is more powerful than the repulsion of the magnets, simulating the notion of the strong nuclear force being stronger than the electrical repulsion protons actually face. Also, the magnets work at a distance, but the tape only works when touching, simulating the differences in range.

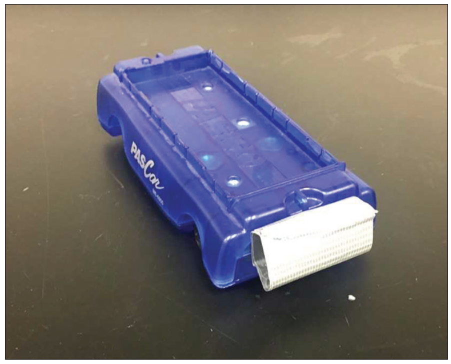

Fig. 4. Duct tape rolled into a cylinder, sticky-side out, attached to the magnetized end of a cart.

Why does it matter? Or, where does this show up?

I use this for both astronomy and physics introductory classes. Radioactive decay and (especially) nuclear fusion show up in astronomy, in places such as the proton-proton chain of reactions powering the Sun and in supernovae. I personally like using this activity when teaching about supernovae, because of the importance of both forces in understanding our observations of these phenomena. Supernovae, in turn, are of importance because most of our heavy elements (for an astronomer, this means any element besides hydrogen or helium) come from them—and, as we like to remind people, people wouldn't exist without them.

Fitting this activity into an introductory physics class is perhaps more problematic. Most courses wait until the very end to cover ideas such as radioactive decay and the structure of the nucleus, if they get to cover them at all. But it is also the case that force, as part of the laws of motion, is introduced rather early in physics classes. We spend much time in physics classes talking about friction and tension; it would be a prime location in one's semester to throw in nuclear forces as well.

I have a sample activity to share for those who are interested.[5] Good luck, and clear skies!

References

1. Physicists tend to group the weak and electromagnetic forces together under the banner "electroweak." For more information, see Don Lincoln, "God's thoughts: Steps toward a theory of everything," *Phys. Teach.* **55**, 204 (April 2017).
2. By this, I mean the equations that govern weak and strong nuclear forces. Undergraduates and high school students are fully capable of grasping the statistics of radioactive decay, for example.
3. The weak force is responsible for changing subatomic particles into other types of particles—for example, neutron decay—and doesn't officially exhibit either a repulsive or attractive force.
4.. The relative strengths cited are from their dimensionless coupling constants; see "Coupling Constants for the Fundamental Forces," HyperPhysics, Georgia State University, http://hyperphysics.phy-astr.gsu.edu/hbase/Forces/couple.html.
5. A sample activity is available for readers at *TPT Online*, http://dx.doi.org/10.1119/1.5021444, under the Supplemental tab.