Aluminium rod rolls in non-uniform magnetic field
A demonstration using a simple apparatus that is easily found in laboratories is of great value, especially in understanding abstract concepts. One excellent example is the work of Lyna and Leong [1]. In their demonstration of motional electromotive force, a horseshoe magnet, an aluminium rod, a U-shaped copper rod and an insulating plane are needed. As shown in figure 1, the U-shaped copper rod lies on the inclined plane and the aluminium rod is initially placed on top of the copper rod at the top of the slope. When the aluminium rod is released it accelerates, rolling downwards under the effect of gravitational force until, after reaching the area where the magnetic field is strong, downward acceleration vanishes for a while. If the angle of slope is set appropriately, the retarding magnetic force acting on the aluminium rod can be clearly recognized. Lyna and Leong attributed the magnetic force acting on the aluminium rod to the reduction of the magnetic flux through the area enclosed by the U-shaped copper rod and the aluminium rod, and accordingly to the induced current flowing through the aluminium rod.

After reading Lyna and Leong’s paper and considering the usefulness of their demonstration, we decided to set it up by designing an in-class activity to provide our students with an understanding of the underlying phenomenon. One consideration was to extend the demonstration by replacing the aluminium rod with a wooden rod and to emphasize the role of the induced current flowing through the aluminium rod. Because the wooden rod is an insulator, there was no interaction observed between the wooden rod and the magnetic field; the rod rolled down the inclined plane without any observable change in its acceleration. Another consideration was to prove that there must also be an induced current flowing through the U-shaped copper rod. To demonstrate this, we cut the copper rod into two symmetrical, L-shaped parts and put them back in their original places, keeping the cut ends slightly apart from each other. Subsequently, the aluminium rod was released from the top of the slope and, unexpectedly, the acceleration of the rod vanished for a while in the region of the strong magnetic field, just as in the case with the undivided U-shaped copper rod. No recognizable difference was present between the two cases. Consequently, we realized that to observe the same effect we did not need the copper rod at all. Replicating the experiment in the absence of a U-shaped copper rod gave the same impression as the original one.

The mechanism behind the scene

Eddy currents (also called Foucault currents) are circulating currents induced in solid pieces of metal due to a changing magnetic flux. Figure 2 illustrates a metal sheet leaving a region of constant magnetic field directed into the page, perpendicular to the plane of the sheet. An external mechanical force is applied to keep its velocity constant. As the sheet leaves the region of the field, the changing magnetic flux induces an electromotive force in the sheet, which causes free electrons in the metal to swirl. In accordance with Lenz’s law, the direction of a circulating current must oppose the change causing it, implying a clockwise current flow opposing the decrease of the magnetic flux through the sheet. Here it can easily be shown that eddy currents cause a magnetic force acting on the sheet opposing its motion. Similarly, if the sheet were to enter the region of a constant magnetic field, a magnetic force acting on it and opposing its motion would again be present. Returning to the demonstration and keeping in mind that the aluminium rod has dimensions, any change in the external magnetic field to which the rod is exposed or the relative motion of the horseshoe magnet and the rod can cause an induction of eddy currents. The induction of these currents seems to be the
dominant factor behind the retarded motion of the rod in the original demonstration.

The extent to which eddy currents can cause retarded motion is simple to demonstrate. The apparatus needed for a slightly different version of a well known demonstration, comparable to that suggested by Ivanov [2], are an aluminium plate with minimum dimensions of $30 \times 25 \times 0.1 \text{ cm}$ and a neodymium-disc magnet with dimensions of about $2.0 \text{ cm}$ in diameter and $0.2 \text{ cm}$ in thickness (figure 3). Initially, the aluminium plate is held horizontally and the magnet is placed near one edge of the plate. Then the plate is rotated quickly by about $85^\circ$ around an axis parallel to its edge near which the magnet has been placed. The magnet slides down much more slowly than it would if there were no magnetic interaction between the plate and the magnet. The retarding effect of the magnetic forces can be clearly observed (see video 1, available online at stacks.iop.org/physed/47/XXX/mmedia). Magnetic forces opposing the motion of the magnet originate from the change in magnetic flux through regions of the plate near the magnet, caused by the motion of the magnet itself. This demonstration surprises students who are unfamiliar with eddy currents and it can easily be carried out in any classroom environment.

**Conclusion**

Replicating the demonstration in the absence of a U-shaped copper rod, the retarding force on the aluminium rod cannot be explained without mentioning eddy currents. When designing a demonstration or preparing a question involving a 3D conductor with a non-negligible size, the possible existence of eddy currents should be considered.

**References**
