The Can Crusher

(1) Capacitors are discharged generating a large, rapidly changing current through the coil surrounding the can. Let's call this current i_c ("c" stands for coil).

In the following discussion, let's just consider the period when i_c is *increasing*.

(2) The current i_c generates a magnetic field, $\mathbf{B_c}$. If the current is oriented as shown in Fig. 2, $\mathbf{B_c}$ points downwards.

(3) Now, $\mathbf{B_c}$ is increasing so there is an increasing flux downwards through the can. By Faraday's Law, this will induce a current, i_{ind}, circulating in the can itself. Lenz's Law gives the direction of this current, which is shown in Fig. 3.

(Make sure you keep the pictures straight. The current in the coil, i_c, is flowing through the coil which is wrapped *outside* the can. The induced current, i_{ind}, is flowing within the aluminum walls of the can.)

(4) The coil field, $\mathbf{B_c}$, will exert a force on the induced current, i_{ind}, and hence on the can itself. This is the first thing we learned about magnetic fields - they exert forces on currents.

At this point, many students are confused about the various possibilities and why I'm focusing on the force that $\mathbf{B_c}$ exerts on i_{ind}. So, what about …

- … $\mathbf{B_c}$ exerting a force on the coil carrying i_c? There is a force on the coil from $\mathbf{B_c}$, so the coil needs to be strong enough that it doesn't get crushed. I don't need to consider this force, however, because it doesn't act on the can.

- … $\mathbf{B_{ind}}$ exerting a force on i_{ind}, and hence on the can itself. This is a little tricky. The idea here is that the induced current, i_{ind}, will generate a magnetic field which, in class, we've called, $\mathbf{B_{ind}}$. (In fact, we usually start with $\mathbf{B_{ind}}$ to help us apply Lenz's law and figure out the direction of the current.)

  Well, a magnetic field is a magnetic field, no matter which current generates it, so $\mathbf{B_{ind}}$ should exert a force on i_{ind} just as $\mathbf{B_c}$ does. Don't we have to consider it? Technically, we do. Remember, however, the current i_{ind} will flow in the direction that generates a $\mathbf{B_{ind}}$ that opposes the change in flux, but it is generally not successful in completely opposing the change. In fact, $\mathbf{B_{ind}}$ is much smaller than $\mathbf{B_c}$, so we can get away with just focusing on the force from $\mathbf{B_c}$.
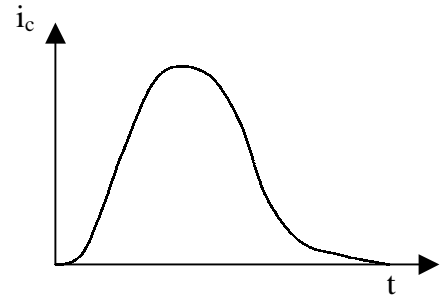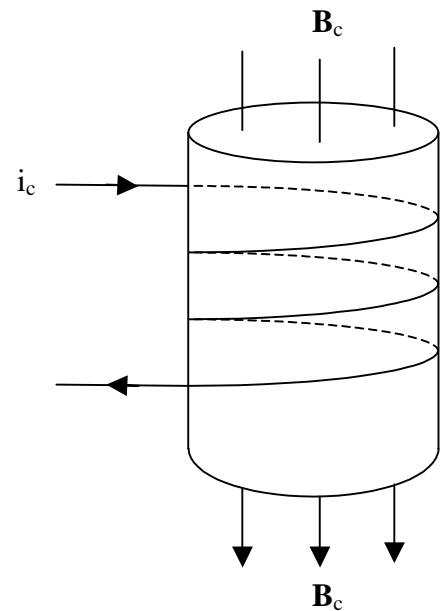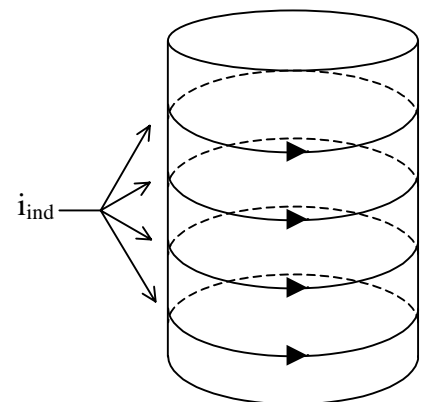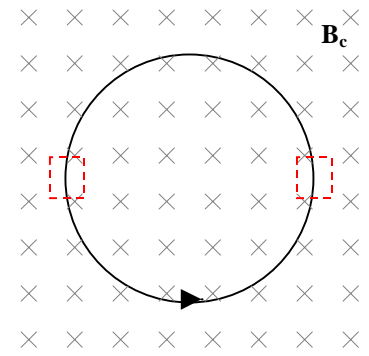

Figure 1

Figure 2

Figure 3

(5) As the final step, let's analyze the force on the can. To do this, let me switch to a point of view looking down on the top of the can. This is shown in Fig. 4. As you can see by looking at Fig. 2, $\mathbf{B_c}$ is going into the top of the can, so it's shown going into the page in Fig. 4. Likewise, i_{ind} is going counter-clockwise.


Figure 4

Let look at the force on the two small pieces of the current outlined by the small dashed rectangles in Fig. 4.

- Left piece: the current is going downward and the field is into the page so, by the right-hand-rule, the force is to the right - towards the center of the loop.

- Right piece: now the current is going upward, but the field is still into the page, so the force is to the left - again, towards the center of the loop.

If we would continue to look at pieces at the top and bottom and everywhere else, the answer would always be the same: the force is towards the center. This is shown in Fig. 5.
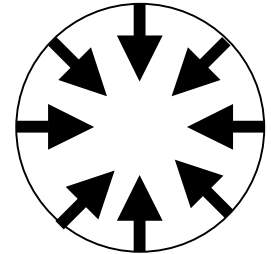
We see that the net force on the can is zero, as is always the case for a flat loop in a uniform field. There can, in general, be a torque, but we don't even have that in this case. There is an inward *pressure* on the can, however, and that's what crushes the can!

Figure 5

Force vectors on different pieces of the loop.

A Little More …

- In step (2), I told you that $\mathbf{B_c}$ pointed downwards. Make sure you understand this.

- In step (3), I indicated the direction of the induced current. Make sure you can get this as well. There are a number of ways to approach this. Although not the fastest, the approach that is most reliable and works for all the various kinds of problems we've looked at asks these questions:

  ➢ How is the flux changing? (Ans: increasing downwards.)

  ➢ Which way should $\mathbf{B_{ind}}$ be oriented to oppose this change? (Ans: upwards.)

  ➢ Which way should i_{ind} flow to give you this $\mathbf{B_{ind}}$? (Ans: the direction shown in Fig. 3.)

- This entire discussion focused on the period during which i_c is increasing. What happens when i_c starts to decrease? Do the forces act to further crush the can or to inflate it?

- How does the changing flux actually generate the induced current, i_{ind}? Magic? As introduced in the beginning of class, Faraday's Law is $\xi = -N\dfrac{d\Phi}{dt}$. This tells you that there is an induced EMF and hence an induced current, but not why. What is actually happening is that the changing flux generates, or induces, an electric field and that is what shows up as the induced EMF. The induced electric field has field lines that go in circles, like the current in this case, and *in the same direction as the current.* Even if the can wasn't there to carry a current, the electric field would still be there.

Well, then how does the changing flux create the electric field? Magic? Uh, yes, in a way. For purposes of this class, this is just how nature works. This is what we are given. (Physicists generally choose to explain these effects in terms of still other things, but that's another story.)

The Ring Toss

The explanation behind the Ring Toss is similar to that of the Can Crusher. The difference is that a nonuniform magnetic field is needed for the Ring Toss, whereas a uniform field works best for the Can Crusher.

(**1**) We start with a ring sitting on *top* of a coil (instead of having a can in the *middle* of the coil), as shown in Fig. 1. The ring toss would probably work better if we used discharging capacitors to drive current through the coil, since we could get a larger peak current, but for reasons of convenience we simply plug it into the wall. The voltage from a wall outlet oscillates sinusoidally, so the current through the coil does so as well, as shown in Fig. 2.

Just as we did before, we'll just analyze the situation during the initial period where i_c is increasing.

(**2**) Just as in the can crusher, the increasing current gives rise to an increasing magnetic flux downward. This induces a current in the ring as shown in Fig. 1. The vertical component of $\mathbf{B_c}$ will also exert an inward pressure on the ring that will try to collapse it, but the ring is made of thick aluminum and won't crush.

(**3**) However, this time the magnetic field has a significant horizontal component.

- The left field line indicates there is a component of the magnetic field on the *left* side of the ring pointing towards the *right*.

- The right field line indicates there is a component of the magnetic field on the *right* side of the ring pointing towards the *left*.

Figure 3 shows the situation looking down on the ring and showing only the horizontal component of the magnetic field. (The component of the magnetic field going into the page is ignored since it isn't strong enough to crush the ring, and so doesn't have any mechanical effect.)

(**4**) Again, let's consider the force exerted by $\mathbf{B_c}$ (horizontal component) on the two small pieces of the loop indicated by the rectangles in Figure 3.

- Left piece: the current is going downward and the field is to the right, so by the right-hand-rule, the force is out-of-the page. Or, from the point of view taken in Figure 1, upwards!

- Right piece: the current is going upwards and the field is to the left, so by the right-hand-rule, the force is still out-of-the page.

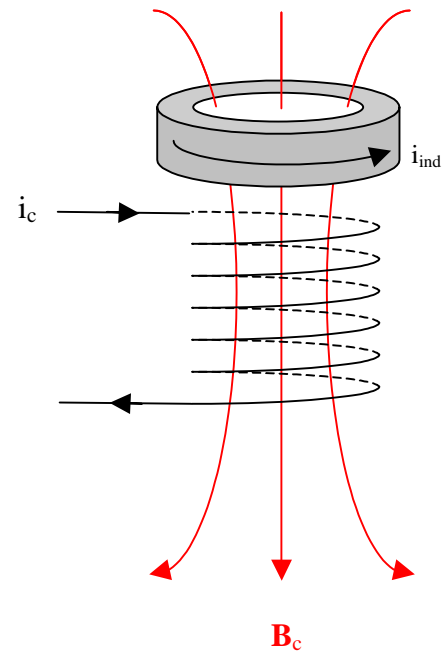The force on every piece of the loop is upwards, so the rings flies up as we saw in class.
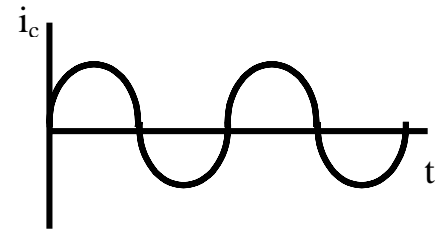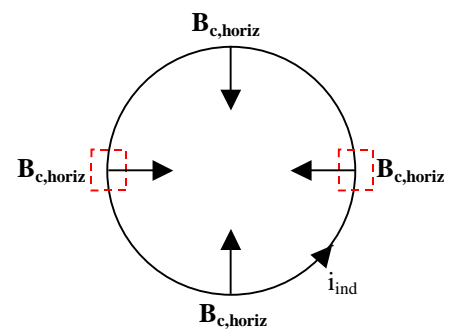

Figure 1

Figure 2

Figure 3

A Little More …

- Now, consider what happens when i_c starts to decrease. Does the force reverse direction, meaning the ring has only a short time in which to shoot above the region where there is a substantial magnetic field? How about when i_c actually changes direction, thus changing the direction of B_c?

- Because the coil used in the Can Crusher demonstration was too short, the can was also in a nonuniform magnetic field. However, because the coil was centered on the can, an upward force exerted on the top of the can by the fringing fields near the top of the coil is balanced by a downward force on the bottom of the can by the fringing fields near the bottom of the coil, so the can won't fly up or get pushed down.