Ph.D. Quals Question
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The "Shake" Flashlight

The students enter the examiner's office find the device pictured below sitting on the table in front of them. They are asked what they think it is and what is does. How does it work? They are reminded that the subject of the quals exam is electromagnetism.

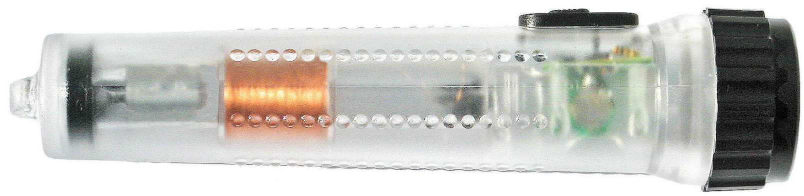

Figure 1. Picture of the "Shake" Flashlight used in this quals exam. It was chosen because it was transparent and its internal parts could be seen reasonably clearly.

On first inspection the item is clearly a flashlight, and when (most) students press the switch they find an LED light comes on – with the beam emerging from the right side of the flashlight as pictured above. Also, most students find that the silver-colored cylindrical item toward the rear of the flashlight's tube (in the picture) has a disconcerting habit of sliding backwards and forwards through the hollow orange-colored unit, which is quite obviously a coil of fine copper wire. There are black rubber bumpers at both ends of the tube containing the sliding silver cylinder and the coil, which suggests the the backwards and forwards motion of the cylinder is a design feature. There are no obvious batteries and when this lack of batteries is noticed, or if queried, the examiner tells them that the flashlight is advertised as needing no batteries. Needless to say, a developing electrical engineer would be expected to notice that there is no provision for batteries to be inserted!

At this stage the students are expected to deduce that the silver unit is a magnet (a small iron nail will stick to the flashlight next to the sliding unit) and that its function is to produce a time-varying magnetic field through the coil, which produces an EMF in the coil, that (1) powers a current that (2) is fed into the circuitry that can be seen at the front of the flashlight (right under the switch). A careful inspection reveals two thin wires leaving the coil and entering the circuitry.

When these conclusions are passed on to the examiner he asks what is the electrical engineering behind the induced current and this should lead to a discussion of Faraday's Law:

$$\xi = -\frac{d\Phi}{dt}$$

where we are considering the EMF ξ induced in a closed circuit threaded by a time-varying magnetic flux Φ. It was expected that this discussion would include a brief explanation of the negative sign (the examiner asks "why is it not a positive sign?"), a mention of Lenz's Law, and how conservation of energy is involved. In addition, because the coil in the flashlight pictured above obviously contains a large number of turns, it was expected that mention would also be made of how the number of these turns, N, would appear in Faraday's Law:

$$\xi = -N\frac{d\Phi}{dt}$$

where the magnetic flux Φ is the flux passing through just one of the coil's turns. Obviously increasing N is a good way to increase the EMF being generated in the coil and thus increasing the efficiency of the generation process.

Some students started the above discussion with the Maxwell equation derived from Faraday's Law : $\nabla \times \mathbf{E} = -\partial B/\partial t$. However, although there is nothing wrong with the equation, it is not particularly useful in discussing how the flashlight works.

The question now arises: The sliding magnet does not generate a steady EMF as it slides back and forth. Fairly obviously it must be an oscillating EMF producing an oscillating current into the circuit part of the flashlight. How do we account for the steady flashlight beam produced?

At this stage most students look really hard at the small electronics section of the flashlight. Apart from the switch there is a small resistor in series with the LED, four small black items into which the wires from the coil disappear, and what looks like a moderately large capacitor. That's all. The correct response here, which a surprisingly large number of the students gave, was to identify the four black items as diodes and to identify their role as components of a full wave rectifier. After some discussion the electrical diagram for the flashlight was derived as shown here:

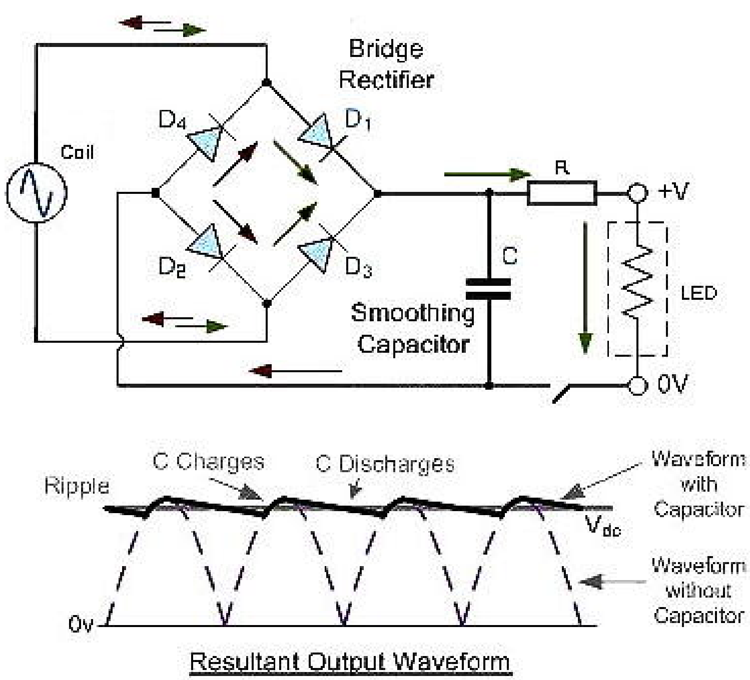

Figure 2. Circuit diagram for the "Shake" Flashlight used in this quals exam (modified from an internet version). The four diodes are denoted by D_1, D_2, D_3, and D_4. The switch is shown open here in the circuit but is closed when the flashlight is being operated.

Note 1: In the flashlight used in the quals, what appeared to be a capacitor was in fact a small nickel metal hydride battery (located in exactly the same place in the circuit as the capacitor shown above). Its function in the circuit differed little from a capacitor, with the charging current simply recharging the battery instead of charging a capacitor. However, your examiner has another "shake" flashlight with capacitor instead of a battery and he greatly prefers the version with the small battery. The capacitor version must be shaken for around 30 seconds to generate 3–4 minutes of light. The shaking required to keep its light going soon becomes VERY tedious.

Note 2: In his best selling 2013 novel *Inferno*, author Dan Brown introduces a "Faraday pointer" as an important plot element. It is nothing but a small "shake" flashlight with a transparent image on the lens that gets projected onto a viewing surface.