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Question 1: Throwing Out Energy; Question 2: Blood Pressure

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are other constraint forces acting on the charges because they are inside a physical loop of wire. Ultimately, the work is done by the constraint forces. In the frame in which the loop is moving, the force due to the magnetic field is perpendicular to the velocity. This is a centripetal force: a charge inside the loop "wants" to move in a circle, but not the circle of the wire loop. Instead, if the charge were free, it would move in a circle in which the axis is horizontal. Because the loop is moving upward at constant velocity, there must be another force that keeps the charge inside the loop of wire. This constraint force, whatever it is, is the force that does work on the charge.

In the other reference frame, in which the loop is unmoving, we attribute the work to the electric field circulating around the loop. However, if a charge in the loop were free to move on its own, it would again not circulate around the wire loop. Instead, it would move off on a trajectory determined by the electric field and the charge's mass. We again must assume that there are external constraint forces acting on the charge to keep it inside the wire, which must be the ones doing the work on the charge.

Conclusions

I wrote this article because I wasn't satisfied with typical textbook discussions of EMF. Most textbooks simply state that the EMF is due to the changing flux and don't address the issues involved in examining it in different reference frames. This is regrettable, as the example given above shows, and there are some subtleties about it that aren't immediately apparent.

Relativity says that the EMF in one frame must be equal to that in another, no matter its cause in either frame; what surprised me was that in this problem, the equivalence is enforced by the divergence-free nature of the magnetic field. In one frame the EMF is due to the time-changing flux threading the loop because of the z-component of the field; in the other, it comes from the forces due to components of the field *perpendicular* to the z-axis, which are constant in time. This is not a trivial statement, as it underscores the relation between $\boldsymbol{E}$ and $\boldsymbol{B}$ fields in different reference frames.

The moral is that it is always important to remember that what we label an electric or magnetic field in one reference frame will often be different in another one, that, in fact, neither field is independent of the other, and both are different aspects of one electromagnetic field.

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References

1. David Griffiths, *Introduction to Electrodynamics*, 4th ed. (Pearson, Boston, 2013), pp. 312–314. Equation (1) of this paper is Eq. 7.17 of the textbook.
2. For example: C. J. Foot, *Atomic Physics* (Oxford University Press, Oxford, 2005), pp. 190–194.
3. Ref. 1, p. 315.
4. For example, see: H. F. Meiners (ed.), *Physics Demonstration Experiments*, Vol. II (The Ronald Press Co., New York, 1970), pp. 932–951. This is a long out-of-print book with a number of very nice demos.

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Fermi Questions

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Question 1: Throwing out energy

How much energy do Americans waste each year by throwing out the unused ice in their drinks? *(Thanks to John Klinck of Old Dominion University for suggesting the question.)*

Question 2: Blood pressure

Why is blood pressure measured on the upper arm? Does it really matter?

Look for the answers online at *tpt.aapt.org*

Question suggestions are always welcome!

For more Fermi questions and answers, see *Guesstimation 2.0: Solving Today's Problems on the Back of a Napkin,* by Lawrence Weinstein (Princeton University Press, 2012).

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