Reply to: All magnetic phenomena are NOT due to electric charges in motion [Am. J. Phys. 90, 7-8 (2022)]

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Fahy and O'Sullivan[1] raise two different issues: (1) is the magnetic dipole moment of the electron (say) due to a current loop (Ampère) or to magnetic monopoles (Gilbert)? and (2) is it intrinsic (localized at a point, and fixed in magnitude), as opposed to the point limit of an extended distribution (of whichever type)? As I understand it, the answer to (1) is that most experiments seem to favor Ampère, but there is some ambiguity in their interpretation. The answer to (2) is unequivocal: It is intrinsic, and that being the case, (1) is perhaps not even a meaningful question.

In ordinary Newtonian mechanics, there is no such thing as intrinsic spin, and in Maxwellian electrodynamics, there are no intrinsic magnetic moments (and no magnetic monopoles). Angular momentum is due to mass in motion, and magnetic moments are due to electric charge in motion; their values can be changed continuously by the application of torques. Do these classical theories explain everything? Of course not. There is no photon in classical electrodynamics, no proper explanation for the Stern-Gerlach experiment, and no adequate account of the behavior of magnetic materials. Intrinsic spin and its associated magnetic moment lie "outside the remit of classical" theories, and it is no accident that their allowed values carry the quintessentially quantum fingerprint: Planck's constant.

Could the classical theories be *extended* to include point particles with intrinsic spin and permanent magnetic moments? Interesting question! Semi-classical theories of spin were introduced in the 1940s (and perhaps earlier) and are under active consideration to the present day.[2] They tend to be awkward and esoteric, but never mind—they are certainly worth exploring.

This leaves teachers with a delicate pedagogical problem: How should one treat familiar electromagnetic phenomena such as ferromagnetism, knowing that any classical account is flawed (and perhaps even "misleading, to say, the least")? Most authors resort to an uncomfortable compromise: Plausible qualitative explanations that endeavor to convey the essence of the mechanism, coupled with a frank admission of their limitations.[3] It's not perfect, but I do think it is preferable to pretending that intrinsic spin fits unproblematically into the classical theory.

That being said, Fahy and O'Sullivan make a valid and important point. The bald assertion that "all magnetic phenomena are due to electric charges in motion" should always be prefaced by "in classical electrodynamics," and (where relevant) accompanied by a clear acknowledgment that the quantum story is quite different, incorporating intrinsic spin (for which the naive classical picture of a tiny rotating sphere is fundamentally defective). I thank Fahy and O'Sullivan for this reminder (the next edition of my textbook will be revised accordingly).

[1]Stephen Fahy and Colm O'Sullivan, "All magnetic phenomena are not due to electric charges in motion," Am. J. Phys. **90**, 7–8 (2022).

[2]See, for instance, J. Barandes, "On magnetic forces and work," Found. Phys. **51**, 79–96 (2021).

[3]In his *Lectures on Physics* (Vol. II, last two paragraphs of Sec. 34-2), Richard Feynman addresses this issue with his characteristic irreverent wit. I thank Kirk McDonald for calling this passage to my attention.

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