General Physics - E&M (PHY 1308) Lecture Notes

Lecture 020: Magnetism

SteveSekula, 18 October 2010 (created 11 October 2010)

no tags

Goals of this lecture

- Introduce magnetism and motivate its connection to the motion of electric charge
- Introduce the mathematical language needed to describe these phenomena

Demonstrations

- Permanent Magnets ("normal" and "strong")
- http://phet.colorado.edu/en/simulation/magnets-and-electromagnets
- Response of electric charge to magnetic field (try to setup cathode-ray tube and permanent magnet)

Qualitative discussion of magnetism

We will seemingly take a left turn today in the course and stop talking about electric fields for a short time. We will discuss magnetism. However, you cannot understand magnetism without understanding electric charge. You will quickly see this. We will briefly discuss the qualitative properties of magnetism and then develop the mathematics needed to describe it. We will see that something beautiful emerges: a deep symmetry between the laws that govern electric force and field and the laws that govern magnetic force and field.

- Demonstrate the existence of two "magnetic charges" - "north" and "south" - and how they are similar in behavior to electric charge (like poles repel, unlike pole attract)

- Demonstrate the change in magnetic force as a function of distance using permanent magnets and class participation.
- Demonstrate the response of electric charge to a magnetic field using a cathode-ray tube, if possible

The units of the magnetic field, denoted by $\vec{B}$ (with magnitude $|B|$), are the Tesla (T). 1T is a large magnetic field. It's more typical to deal with fields in units of Gauss, where $1\mathrm{G} = 10^{-4}\mathrm{T}$. The earth's magnetic field has a strength of about 1G, while refrigerator magnets have strengths of $100\mathrm{G}$. MRI machines have large strengths, often several Tesla. There are stars in the universe which have collapsed, under their own gravitational pull, to compact, fast-spinning bodies called *magnetars*; the fields of a typical magnetar are about $10^{11}\mathrm{T}$.

The magnetic force on a charged particle

We have seen that a charged particle responds to a magnetic field, but not in the same way it responds to an electric field. Electric charges experience an electric force that is either parallel or anti-parallel to the electric field (depending on the charge of the particle). However, electric charges experience a magnetic force that is PERPENDICULAR to the direction of the magnetic field and to the motion of the charge. The magnetic force on an electric charge then has the following features:

- Its magnitude is proportional to the strength of the field (more field = more force), the speed of the particle (no speed = no force), and the charge of the particle (more charge = more force)
- Its direction is perpendicular to that of the motion and the field

To describe this force, we need the *cross product*. The *dot product* is a measure of how parallel two vectors are, but we need something that is a measure of how *perpendicular* two vectors are. The cross-product does this, AND has the benefit of returning a *vector* in the direction perpendicular to the original two vectors. The force law has been determined from experiment to be:

$$\vec{F} = q\vec{v} \times \vec{B}$$

Let's review some properties of the cross-product:

- You can obtain the magnitude of the cross-product using

$$|F| = |q||v||B| \sin\theta$$

  where θ is the angle between the velocity and the field.
- The direction of the cross-product is perpendicular to BOTH the velocity and the field. You can estimate the direction using the right-hand rule: point your fingers of your right hand in the direction of the velocity, curl your fingers in the direction of the field, and your thumb points in the direction a *positive* charge will be pushed. Flip your thumb over to get the direction a *negative* charge will be pushed. Use this to check your math.
- See updated cross-product video: http://www.youtube.com/watch?v=tqds10BFrQk (fixed an inherent math mistake in the original trick)

The full-on components of the cross-product are:

$$F_x = q(v_y B_z - v_z B_y)$$

$$F_y = q(v_z B_x - v_x B_z)$$

$$F_z = q(v_x B_y - v_y B_x)$$

Note that if the charge is negative and not positive, all components of the force reverse sign.

The total force on a charged particle: electric and magnetic force

Magnetic fields influence the motion of electrically charged particles. That suggests there is some deep connection between electricity and magnetism. That said, both electric fields and magnetic fields can be present in a region of space. In that case, the total *electromagnetic force* is given by:

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

You just add the vectors to get the total force vector on a charged particle. This property is useful; you can select particles of a specific velocity if you select the electric and magnetic fields so that only particles of that velocity can survive traveling through the fields.