Physics 162: Answers to End-of-Class Questions

January 15 and 16, 2015

Can we move push the tables further back, to get a better view of the board?

Yes, by all means, please move the tables so that you have a clear view of the front of the room. I would have encouraged you to do this earlier if you had mentioned it.

How do LCD screens work?

There are numerous websites that mention this, e.g.,

`http://electronics.howstuffworks.com/lcd.htm`

The principle is utterly different than using an electron beam to excite a phosphor in a cathode ray tube (CRT).

Liquid crystal displays are based on the fact that light can be polarized (its electric field forced to oscillate along a particular line perpendicular to the direction of motion of the light, as you will learn later this semester) by passing the light through a liquid crystal, and whether the liquid crystal polarizes the light or not can in turn be controlled by varying the strength of an electric field across a thin layer of the liquid crystal.

LCDs have the advantage of being thin and light weight (there is no way you could wear a cathode ray tube display on your wrist or use one in a cellphone) and they use small amounts of power. They have the drawback that they are slow compared to CRTs (one can move an electron beam much more rapidly than one can align the molecules in a liquid crystal by an electric field), and have low spatial resolution (electron beams can draw images smaller than the wavelength of light, it is hard to make LCDs with pixels smaller than about 300 pixels per inch).

Is there a value/direction for the electric field exactly at the position of the charge producing the electric field?

The answer is not known experimentally because we do not have the technology to probe the exact center of particles like an electron, which seem to be a point to our best current experiments. There is also the problem that the electric field becomes extremely strong as one gets closer and closer to the center of an electron (via the inverse square law) and strange quantum mechanical things happen as the electric field becomes larger and larger, e.g., so-called virtual particles start to affect the properties of space and it becomes ambiguous what one means by the center of an electron.

From a mathematical point of view, if the electric field is spherically symmetric and everywhere pointing away from the center of an electron, we would expect no vector to exist at the center of the electron, the electric field should either be zero or infinity. But you are asking (I believe) about actual physical electric fields generated by real physical particles, and then the answer is not known.

But here is another puzzle: we know from experiments that electrons not only generate an electric field, they generate a magnetic field, as if they consisted of an electrically charged bar magnet. But how do you associate a bar magnet with an object that is a pure point?

And the laws of physics further allow for an electron, despite being a point particle, to have an electric dipole, i.e., an electron could be like a little rigid rod with opposite charges at both ends (a dipole) but the rod itself has a net charge (the charge of an electron). It turns out that whether an electron has an electric dipole and how strong that dipole is is a very hot and important question in particle physics. Professor Haiyan Gao in our Physics Department is one of several physicists studying this question, and it is very hard because the dipole, if it exists, is very weak so its influence is hidden by the much stronger electrical charge of the electron. If Prof. Gao discovers the electron's electric dipole, she will get a free trip to Stockholm and become quite famous.

Roughly how many electrons are emitted by a cathode ray tube?

There is not a unique answer to your question because one can dial up and down the rate of electrons being emitted by increasing and decreasing the electric field that accelerates the electrons from the electron gun. In searching the Internet (since I didn't know the answer off hand), I saw values of about 100 microampere ($100\,\mu$A) which means 100 millionth of a coulomb flowing per second, which corresponds (to the nearest power of ten) to about 10^{15} electrons moving per second past any point in the beam.

You will be able to appreciate this number in a few weeks when we discuss electrical currents in wires. Typical house-hold devices and laboratory devices use currents of order 0.1-1 A so the cathode ray tube carries a much smaller current than typical daily devices.

What other commercial applications of electric fields are there?

I will mention a few more at the beginning of Wednesday's class on Jan 21, but can say that all of electronics, which involves computers, cellphones, radio, television, the Internet, and the machinery to make these devices (e.g., that create integrated circuits) depend critically on electric fields so the number of commercial applications is huge. Muscles (including hearts) and brains operate by generating and controlling electrical fields that modify the behavior of charged biomolecules and so a huge part of biology, including our ability to think, depends on understanding and (in medicine) controlling electric fields.

This is one reason why the courses Physics 142/152/162 are arguably more widely applicable and important than 141/151/161, the range of applications is substantially greater than problems involving mechanics.

To put it another way, the first semester of intro physics courses discusses the physics of the industrial age, how to convert energy of various kinds to work and so replace animals and people with mechanical machines (cars, airplanes, trains, motors, pumps, washing machines, etc). The second semester courses deal with the physics of the communication and information ages, which encompass a broader variety of applications.

You mentioned that information about an electric field propagates no faster than the speed of light. Why? What does the electric field consist of that travels at the speed of light? Is it energy?

In a vacuum (empty space), changes in electric and magnetic fields (e.g., caused by shaking a charged object back and forth) move at the speed of light because, as you will learn in some detail towards the end of the semester, light consists of oscillating electric and magnetic fields. And it is an experimental observation that nothing in vacuum has been observed to move faster than the speed of light.

I say in a vacuum, because in a medium like air or water or metal, light travels slower than the speed c of light in vacuum, the speed in a medium is c/n where $n \geq 1$ is a number called the "index of refraction" of the medium. For many familiar transparent media, n varies from 1.3 (water) to about 2 (diamond), but there are some exotic quantum mechanical media (Bose-Einstein condensates) for which $n \approx 10^8$ and light slows down so much in these media that you can walk faster than the speed of light in that medium.

(As an aside, it is possible for particles like protons or neutrons to move so fast in glass or water that they are moving faster than the speed of light in the medium but slower than the speed of light in vacuum, so the particle speed v satisfies $c/n < v < c$. When this situation occurs, the light equivalent of a sonic shock wave occurs and the particle generates a new kind of light called Cerenkov radiation, which is easily observed and that gives valuable information about the speed of the particle. I will talk about Cerenkov radiation and show you pictures of this later this semester.)

But what "is" an electric field and why can't these things move faster than the speed of light? From our 21st-century perspective, based in turn on our knowledge of quantum mechanics and quantum field theory, electric fields consist of quantized particles called photons that propagate through space (like massless bullets) at the speed of light in vacuum. It is the quantum mechanical scattering of these photons off of electrons and protons that lead to the effect of electric fields and magnetic fields. But this line of thinking is too hard and advanced at the 162 level, you need to learn some quantum mechanics and then some quantum field theory to understand these ideas. (All of you can learn this, but it takes time and training.)

A final observation is why is there a maximum speed of transmission of information or of physical effects? In the end, this is an experimental fact and there is no current theoretical reason for why it has to be the case. One can think of two logical possibilities: that as things move about, there is no maximum speed (the maximum speed is infinity), or there is a finite maximum speed. It was through some brilliant reasoning that Einstein realized that, if there was a maximum speed, it had to be the same speed in all inertial frames of reference, and this further implied strange effects like time dilation, length contraction, and that the passage of time is not the same for everyone, all of which have been verified experimentally to great accuracy. Einstein's theory allows for massless objects to exist (and such objects do exist in the form of photons and gravitons) and his theory then predicts that such massless objects have no choice but to move at the speed of light in vacuum. Since electric and magnetic affects are associated with collisions of massless photons, this implies that electric and magnetic influences can not travel any faster than the speed of light in vacuum.

Why are we allowed to call electrons "point particles"? Is there no way to define their size?

For many decades, particle experimentalists have collided electrons with each other and have collided photons (quantized light particles) with electrons, with ever higher energies which means at ever small length scales. All the data so far are completely consistent with scattering off of a point object.

In contrast, when scientists started scattering high energy electrons and photons off of protons, they discovered that the proton did not act like a point object, it acted like a finite-size bag (of dimensions about 10^{-15} m) that contained point-like objects inside that we now interpret as quarks and gluons. So protons and neutrons act like they have three quarks and a variety of gluons inside, they are not point-like objects.

How do charges alter the space around them to create an electric field? In other words, through what medium are charges acting to create these fields?

Up until the early to mid 20th century, the answer to this was not known. Scientists, including James Maxwell whose equations unified all electric and magnetic phenomena, did not know what an electric field or magnetic field was made of, they just knew how to give a highly useful description of their properties. (Newton's law of gravity was the same, Newton did not explain what "is" gravity, he just found a concise valuable way to describe gravity.)

These scientists believed that empty space could not exist, that it had to be filled with some unknown medium analogous to water or air that was called "the ether". (It was something like our current problem with dark matter, we know it exists but we don't know what it is.) Maxwell and others then believed that electric and magnetic influences, including light itself, involved mechanical disturbances of the ether, just as sound and water waves represent mechanical disturbances of air and water.

But Maxwell and others knew that the ether had to be a very strange substance. He and others knew that visible light vibrated with crazy high frequencies, 10^{14} oscillations a second, and no known substance on Earth could vibrate so rapidly mechanically, it would have to be very stiff to oscillate so fast. But then the planets orbiting around the Sun would have to push their way through this stiff ether, which should then act like a thick viscous fluid that would slow them down and cause them to fall into the Sun, so this didn't make any sense.

And finally, Michelson and Morley in 1887 carried out a brilliant experiment in which they tried to measure the speed of the ether as it flowed past the Earth and found, to their utter confusion, that the ether didn't seem to exist, which meant that there was no medium for light to move through, and that made no sense since Maxwell's equations had many correct predictions about light being a wave. It took some brilliant thinking by Einstein, as he developed his theory of relativity and proposed that light consisted of particles (called photons by someone else), that he was able to explain the physics of the Michelson-Morley experiment.

With our "modern" understanding, we now realize that there is no ether and that there really can be a vacuum with no physical medium present. (I am afraid this isn't really true, you can look up the Lamb shift and the Casimir effect, which are experiments that show that, in accord with quantum field theory, over very short times, particles can burst into existence and then disappear in the vacuum, and cause physical effects like shifts in the levels of hydrogen atoms (the Lamb effect) and cause attractive forces to appear on two parallel metal plates in complete vacuum (the Casimir effect). Light can move through a complete vacuum because it consists of particles that move through vacuum, just like the Earth moves through a vacuum about the Sun. Einstein did not understand how photons led to electric and magnetic fields, that came later as other scientists unified quantum mechanics with electromagnetism via quantum electrodynamics (QED).

So our modern view is that electrons establish their electric fields and currents establish their magnetic fields by shooting photons off into space (much like the campfire analogy I mentioned for explaining an inverse square law), and the collisions of these photons with other charged particles lead to Coulomb's law and to the full Maxwell equations.

If the electrical force is so large, how does a nucleus stay together in the center, with such strong repulsive forces?

Your question is the very question that key scientists in the early 1920s asked once they knew about electrons and protons: how can a gold nucleus with 79 protons not blow itself to pieces given the huge electrical repulsion? A variety of experiments led to the conclusion that there had to be some new ways that particles interact besides gravity and electric fields, and these new ways were eventually called the strong and weak interactions. The strong interaction, which exists between protons and between protons and neutrons, was found experimentally to be about 100 times stronger than electrical interactions, and it is this interaction that holds a nucleus together against the enormous electrical repulsion.

But here is an interesting twist: the strong interaction is very short ranged, it decays to zero influence over distances about the size of a proton. So only protons and neutrons that are actually touching each other are attracted by the strong interaction. In contrast, each proton in nucleus feels a repulsion from all of the other protons since the Coulombic repulsion is long-range, falling off as $1/d^2$. The result is that, as you make a nucleus bigger and bigger, the electrical repulsion grows faster than the nuclear attraction and eventually the nucleus will self-destruct. This basically explains why the periodic table of elements comes to an end and you can't find stable (non-radioactive) elements with more protons than about 82, the electrical repulsion becomes so strong that no number of protons and neutrons can hold the nucleus together.

So where does the ratio of 10^{40} of the electric attraction to gravitational attraction of proton and electron come from?

The answer is not known.

A leading guess, without any experimental support, is associated with research done by Lisa Randall and collaborators at Harvard. As a theoretical physicist, she proposed that there must be more spatial dimensions than the three we observe directly and for reasons that I don't understand myself, but having to do with gravity being a "geometric" disturbance of space-time, gravitational forces, but not electrical can "leak' out into the extra spatial dimensions that then make gravity much weaker than electrical forces.

Another guess is related to the idea of the multiverse. One of the crazier, but logically reasonable, predictions of quantum field theory is that, if a "Big Bang" occurs, more than one universe can arise from quantum fluctuations. Further calculations suggest that the laws of nature and particle properties do not have to be the same in these different universes, e.g., the charge of an electron could be different or charged objects might interact by a law that is not Coulomb's law. So theorists have proposed that there may in fact be many different universes, each with different properties. And then the 10^{40} arises purely by accident, we are in one of the many universes for which this ratio has a big value because of some random but boring event associated with the quantum mechanics of the Big Bang. So then the question of where the 10^{40} comes from is a "wrong" question, there is no useful answer since other universes would have different values for this ratio.

There seems to be no way to test the multiverse idea in the foreseeable future so physicists are touchy about this as a theoretical prediction. But the possibility of a multiverse is allowed by our current laws of physics and so needs to be taken seriously. Hopefully, at some point in the future, an experiment will be devised (perhaps by your future research group?) and the idea confirmed or falsified.

How do we know the mass of a proton or electron?

You will learn the trick this semester, and actually saw the trick the first class of this semester, when I showed you a demo of bending an electron beam into a circle using a surrounding magnetic field.

Briefly, by a difficult experiment carried out by Robert Millikan around 1909 (see the Wikipedia entry "Oil drop experiment"), Millikan was able to measure directly the charge $e \approx 1.6 \times 10^{-19}\,\mathrm{C}$ on an electron. It then turns out that, if you shoot a charged particle like an electron or proton into a uniform magnetic field, it follows a circular path (just like the electron beam in the first class). By measuring the radius R of the circular path and by knowing the magnetic field strength B, one can calculate the ratio e/m of the ratio of charge to mass of the particle. Since e is known independently, one deduces the mass m of the particle.

Modern versions of this idea allow the mass of quite complicated molecules to be measured to high accuracy (tiny fraction of a proton mass) using a device called a "mass spectrometer". (You can look up the Wikipedia article "Mass spectroscopy" to learn more.) Biologists, chemists, and physicists have collaborated to produce special mass spectroscopes that can measure the masses of many large proteins rapidly, which is providing a lot of valuable data about the so-called "proteome" of a cell (see yet a third Wikipedia article by that name), namely all the different kinds of proteins that a living cell has at some given moment. These data are having a revolutionary effect on biology since, until recently, no one had ever identified all the proteins in a living cell.