

14: Fields in Matter

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14.1 Dielectrics

We very briefly talked about dielectric materials when we studied capacitors. We learned that when a dielectric is used to fill a capacitor instead of the vacuum, its capacitance and other properties change by a factor of K , the dielectric constant.

$$C = KC_0$$

We did not discuss in any detail, however, what causes this or what any other implications might be.

More in general, in a dielectric we can replace all ϵ_0 with $\epsilon = K\epsilon_0$

14.1.1 Polar Molecules

Most molecules are to some degree *polar*, which means they have an electric dipole moment. When placed freely in an electric field, a dipole will feel a torque and rotate around until it aligns itself with that applied field. The negative side of the dipole will spin around so as to become an endpoint for incoming electrical field lines. Assuming the molecule is rigid, the positive side will then be facing the other way and act as the origin for an equal number of field lines as terminate on the negative side.

This picture assumes, however, that the molecules are free to rotate. In practice, a solid material will have some structure into which its molecules are locked. How strongly locked varies widely from material to material, but there are generally some forces holding those molecules in place where they are. If nothing else, the mutual repulsion between like charges can discourage neighboring dipoles from pointing the same direction. This depends on the arrangement, however, and is different for each material. Consider

two possible simple arrangements. In the first, our dipoles are arranged in a rectangular grid. The lowest energy configuration for this, or alternatively the configuration which minimizes the repulsive forces and maximizes the attractive forces, is for each molecule to be oriented opposite to that of its neighbors. If you remember the applet in our first workshop, we watched this exact thing happening.

In the similar case where each row of dipoles has been shifted by a half position, however, we find that the lowest energy configuration is for rows of dipoles to all be aligned. Our applet won't spontaneously produce this because for free particles the first configuration is still more favorable, but if the material structure demands this grid, the dipoles are at their lowest energy with this orientation.

Neither material will, in a real circumstances, form a perfect grid of the lowest energy variety. There are lots of reasons for this but thermal energy is the easiest to understand. At any non-zero temperature, these molecules will be vibrating and jostling one another. That jostling will inevitably knock some dipoles around and dis-align them. The hotter the material, the more this is going to happen. Also, on average different regions of the material will settle into different orientations. So for instance in the offset grid case there may be a large region with predominantly positive charges on the left and negative on the right. But nearby will be a few regions with the opposite arrangement. On average, these will all tend to average out such that there is no overall charge separation.

These two materials, despite a similar apparent lack of large scale electric fields, will respond much differently to an applied external electric field. The first will fight against its dipoles being flipped into agreement, because this will force more internally repulsive forces. Meanwhile the second material will happily flip all of its dipoles into agreement. Disparate regions with opposing orientations will fall into line with minimal coaxing by the external field. They *want* to line up, there just wasn't anything around to tell them which way to go! This difference in response is one thing that causes different

materials to have different dielectric constants. The first region will have $K_1 \gtrsim 1$ (slightly greater than 1) while for the second region $K_2 \gg 1$.

14.1.2 Dielectrophoresis

In addition to different materials having a different eventual response to an applied electric field, they will also respond at different speeds. Imagine that I apply a strong alternating electric field to a dielectric material. If the alternation is slow enough, the molecules will all flip (or at least as much as they ever would depending on K) and settle down before the field alternates, at which point they'll turn around again. However, if we keep flipping back and forth too quickly, there won't develop any kind of response because the field will essentially be fighting with itself, always undoing whatever alignment it accomplished on the previous cycle.

We can take advantage of this fact in a practical fashion to separate out materials (especially in liquids or solution). By applying 2 electric fields to a sample, it is possible to pull out all of a particular constituent while leaving the rest behind. The first, stronger field, will be set up to alternate at the precise resonant frequency of the material we want to extract. By careful timing this field, we can maximally orient the dipoles of that particular type, while leaving any others to remain randomly distributed. The second electric field is constantly varying. A free dipole in a uniformly varying field will find the forces on each pole to be slightly out of balance, such that there is an overall net force on the molecule. For the randomly oriented materials this will have no significant effect, but it will apply a constant force to one side on the aligned substance. Over time, this will concentrate our desired sample on one electrode or the other. This technique is called Dielectrophoresis and can be used on anything from simple molecules to huge proteins or even entire cells

14.2 Ferromagnetism

Ferromagnetism is in some superficial sense similar to the dielectric behavior of the shifted material I discuss above. However, the physics behind the magnetic dipoles in a ferromagnet wanting to line up is rooted in quantum mechanics and is considered an advanced topic even in that context. So, we aren't going to get into the details of how it works with that kind of detail. The important features on a large scale, luckily, are easily understood without this microscopic understanding.

A ferromagnetic material is one in which neighboring magnetic dipoles (Pretend they come from electrons orbiting a nucleus. Its mostly wrong, but close enough to the real thing not to do us any harm.) want to be aligned. This property is fairly rare, and its no surprise given how much two bar magnets will fight against being lined up together side to side. Where this property *is* present, however, it results in large regions of our object having lined up magnetic dipoles. Different regions, as I mentioned for the dielectric above, will still have different preferred directions. As a result, the overall magnetic field tends to cancel out.

However, an applied magnetic field can encourage the disparate regions to come into greater agreement. A little encouragement tells them which direction to prefer and once they flip and line up, the net effect is to greatly enhance the applied field. By telling the already present magnets which way to point, we can harness a latent magnetism that was previously hiding behind the averaging process.

14.3 Paramagnetic and Diamagnetic Materials

Para- and diamagnetic materials have much weaker responses than ferromagnets, and behave more akin to dielectrics. In analogy with dielectrics, we can describe these by taking μ_0 and replacing it with some other value μ within the material. Diamagnetics have $\mu < \mu_0$ while paramagnetics have $\mu > \mu_0$.