What are the differences between permittivity and permeability?

Jeremiah Johnson · Updated April 30
Physics Theorist

Two of the most complex and least understood constants in Physics are the Permittivity and Permeability constants. It's always fun watching people try to explain these two. Just what are these constants? How do they affect the bigger picture?

Let's stop that line of thought for a minute. We're going to diverge to a physics topic that may seem to be off course(or is it?). Going back to elementary Physics, the Newton-Laplace equation.

Speed of Sound

$$c = \sqrt{\frac{p}{\rho}}$$

c is the speed of sound
p is pressure
ρ is density

This is the way to calculate how fast sound waves move through a medium. I'm sure you've seen it before. As you increase pressure or decrease density, the speed of sound increases. This can also be changed to be based on temperature since:

$$TR = \frac{p}{\rho}$$

T is temperature
R is a gas constant which just allows us to convert this between different mediums since the molecules are different sizes and/or have varying degrees of freedom.

So basically this is saying temperature increases as pressure increases or density decreases. Good to know!

If we set R to 1, by setting our units to natural units[1] for the given medium, our above speed of sound equation could be written:

$$c = \sqrt{T}$$

Okay, now let's leave this sit a moment and we'll return to our original question.

Speed of Light in the Vacuum

We'll start with an equation that looks oddly similar to our speed of sound equation above:

$$c = \sqrt{\frac{1}{\varepsilon_0 \mu_0}}$$

c is the speed of light
ε_0 is the vacuum permittivity and spoken epsilon naught
μ_0 is the vacuum permeability and spoken mu naught

So now that you've started down the rabbit hole, let's talk a little bit about history. Human history is full of examples of people over complicating very simple things. Ever find the US Tax Code of Federal Regulations and Administrative Rules in a library? Takes up an entire section. Or go to a remote village in the Laotian rainforests to hear their elaborate stories to explain everything from the Sun to why women have babies. We constantly are making up more of things then what there really is.

And that brings us back to the permittivity and permeability of free space.

We're not going to discuss the history of these or how we found them. You can read all about that on Wikipedia. We are only going to simplify them to what they truly represent.

$\varepsilon_0 = 8.85418782 * 10^{-26} \frac{s^4 A^2}{m^3 kg}$

s are seconds
A are Amperes
m are meters
kg are kilograms

But what's an Ampere?

There are actually two components of the Ampere that are at a right angle to each other. One component is the amount of current moving through two wires a meter apart. The other component is the force *between* the two wires, which is perpendicular to the current. Each wire has 1 Ampere going through them. We're going to do something a little unconventional and use the force component between the two wires(but the results will be pleasantly surprising):

$A = 2 * 10^{-7} N/m$

But we will need to divide this by two because 1 Ampere is going through each wire.

N are Newtons

So what's a Newton?

$N = 1 \frac{kgm}{s^2}$

So this whole time, we could have just used kilograms, meters, and seconds. Let's try this again but with just these 3 units:

$\varepsilon_0 = 8.85418782 * 10^{-26} \frac{s^4 kg^2 m^2}{m^3 kg m^2 s^4}$

Now simplify:

$\varepsilon_0 = 8.85418782 * 10^{-26} \frac{kg}{m^3}$

So this is just kilograms divided by meters cubed. That happens to be...(drum roll please)... density(m/V)! Well, why didn't we just call it density to begin with? Good grief! Density of what? It's the density of the vacuum, the medium which carries light waves, which implies space has a tiny bit of mass. Let's change this to:

$\rho_s = 8.85418782 * 10^{-26} \frac{kg}{m^3}$

Onto permeability now:

$\mu_0 = 1.25663706 * 10^{-6} \frac{mkg}{s^2 A^2}$

And using the orthogonal value of the Ampere:

$\mu_0 = 125663706 \frac{mkgm^2 s^4}{s^2 kg^2 m^2}$

$\mu_0 = 125663706 \frac{ms^2}{kg}$

This is just another way to write pressure https://en.m.wikipedia.org/wiki/Pressure but it is inversed. When we measure pressure, we are measuring force divided by an area.

$p = F/Area = N/m^2 = \frac{kg}{ms^2} = \frac{kgm}{m^2 s^2}$

As you can see above, the only difference between pressure and our inversed permeability is that pressure has another unit of length in both the top and bottom. In other words, it is the exact same as pressure. But if we multiply back in another meter unit to the top and bottom, we get Energy density:

$p = \frac{kgm^2}{s^2} \div m^3 = \frac{J}{m^3}$

That is just the quantity of kinetic energy per cubic meter. Which makes sense. The more energetic a gas is, the more pressure there is.

$\mu_0 = \frac{1}{p_s}$

It's just inverse pressure. Let's change this to:

$p_s = 7.957747163687 * 10^{-9} \frac{kg}{ms^2}$

Which is the same as $1/\mu_0$. So the permeability of space is just the (inverse)pressure of space, which is the same as the kinetic energy of space per cubic meter(E/V). That sure is a lot more simple to understand, at least for me!

Therefore the speed of light equation becomes:

$c = \sqrt{\frac{p_s}{\rho_s}}$

Does that look familiar to anyone? Of course! The Newton-Laplace equation we started with.

Let's rewrite it like this:

$c = \sqrt{\frac{E/V}{m/V}}$

V is Volume(i.e. m^3)

E is Energy

m is mass

To clarify this, it's referring to space itself as a substance transmitting vibrational waves which we see as light, matter-waves, neutrinos, etc. So the speed of light is equal to the square root of the kinetic energy per volume divided by the mass per volume.

If we want to take *that* a step further, we can cancel the volume on the top and bottom of the fraction which gives us back:

$c = \sqrt{\frac{E}{m}}$

And moving things around, we get:

$c^2 = E/m$

$mc^2 = E$

or

$E = mc^2$

Next article deals with gravity and how it ties into this. If you found this helpful, please upvote so others can find it and thank you for reading! Feel free to post your comments or questions below.

Update: After doing some checking around, I've found the above values for the vacuum energy density and mass density we calculated are actually predicted to be very close to within those ranges at $10^{-9} J/m^3$ and $10^{-26} kg/m^3$ respectively:

Link to University of California Webpage

These are calculated based on the values of the Wilkinson Microscope Anisotropy Probe (WMAP). Great to know the math works!

Update #2: Just wanted to clarify that there is nothing wrong, per se, with the vacuum permeability and permittivity constants in the way they've been traditionally defined. That definition serves a distinct and useful purpose - that is how the energy density and mass density of the vacuum affect magnetism and charge.

Footnotes

[1] Natural units - Wikipedia

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David Thorp
March 25, 2018 · 1 upvote from Jeremiah Johnson

This is great

Reply Upvote · 1

Lee Shipton
August 28, 2018

Since the vacuum has both permittivity and permeability does this imply that the vacuum is indeed the medium that supports an electromagnetic wave. If the permittivity and permeability where to be even less than Epsilon0 and Mu0 then that would imply that the velocity of light could be greater than ... (more)

Reply Upvote

Jeremiah Johnson
Original Author · August 28, 2018

There is no flaw in that reasoning if we are to consider only the frame of the distant observer and what they can measure of c globally. However, keep in mind that we are composed of matter and matter is composed of oscillations of the vacuum. Those oscillations evolve at c(see the Schrodinger or Di ... (more)

Reply Upvote

Lee Shipton
August 31, 2018

Thank you for your comments. Unfortunately my physics is not up to the level required to understand your second paragraph, I wish it were!

Why is it important to state that my understanding depends on the frame of a distant observer. Surely what I am stating is particularly true from within my own fr ... (more)

Reply Upvote

Christian Gingras
August 1, 2018

I was trying to understand the “impedance of free space”, that mysterious 377 ohm which is purely resistive since it don’t depends of the frequency.

This one of a kind answers this and goes around to explain e=mc2, the equation that everybody knows but without even giving the unit of energy (Joule?) ... (more)

Reply Upvote

Jeremiah Johnson
Original Author · August 1, 2018

Something for you to consider:

Planck Impedance is simply mu0/4pi. And as we found in this answer, mu0 relates to the inverse vacuum energy density - that is inverse pressure of the vacuum. So this then simplifies to *c*(p4pi)^-1.

Reply Upvote

Lee Shipton
May 25, 2018

Thank you! That is one of the best answers I have seen on Quora.

Reply Upvote

Jeremiah Johnson
Original Author · May 25, 2018

Thank you!

Reply Upvote

Bob Davis
March 18, 2018

How come matter has a lower temperature? This is related to your gravity explanation.

Reply Upvote

Thank you for your question. This reference to temperature is not in any way related to the temperature you can measure with a thermometer. It is referring purely to the relation of the energy density of space divided by the mass density of space(not the amount of massive particles within the space, ... (more)

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Bob Davis 2 questions: 1 what evidence suggest neutrinos are longitudinal? 2 now if you could only...

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In layman's terms, why is Einstein's famous equation "E = mc^2" and not "E = mc" or "E = mc^3"? In other words, what does the fact that the speed of light is squared reflect upon the nature of reality and how light interacts with mass and energy?
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