Light Is a Wave

This handout attempts to survey the situation and understanding that reigned from approximately 1860-1900.

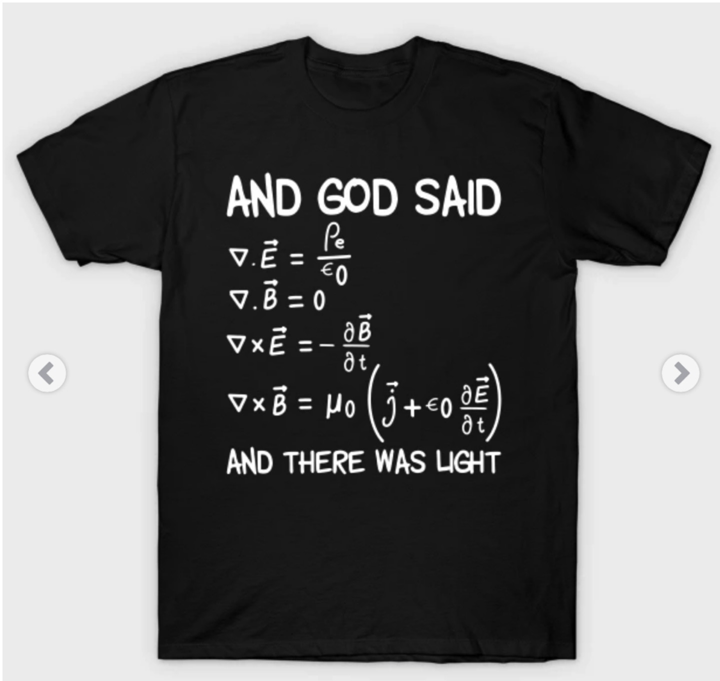
To appreciate what is being unveiled in Q4.2, you have to be steeped in the first two paragraphs of Q4.1 and being steeped in those paragraphs actually requires a semester of study of electromagnetism. The upshot is that in the late 1800s, light was beautifully and, it was thought, completely, described by Maxwell's Equations, which explained light as an electromagnetic wave.

The debate as to whether light was a wave or a particle actually went all the way back to Newton vs. Huygens, with Newton on the side of "corpuscles" and Huygens on the side of waves.

Left, Newton in his 40s, painting from the collection of the Earl of Cantor. Right Huygens in 1671, painting from the Haags Historisch Museum.

Maxwell's Equations — 1865

You may have seen Maxwell's Equations emblazoned on T-shirts, along with some phrases like, "Let there be light,"



“and there was light.” The equations on the T-shirt are Maxwell’s equations.

Solving Maxwell’s Equations

I can tell you something about the symbols in Maxwell’s Equations, and how they are manipulated, but the only important thing to know is that that Maxwell’s equations can be rearranged to give this equation:

$$\frac{1}{c^2}\frac{\partial^2 \mathbf{E}}{\partial t^2} - \nabla^2 \mathbf{E} = -\left(\frac{1}{\varepsilon_0}\nabla\rho + \mu_0\frac{\partial \mathbf{J}}{\partial t}\right)$$

In vacuum, there is no electric charge density ρ, and no electric current density $\boldsymbol{J}$. So in vacuum the right-hand side of the equation is 0.

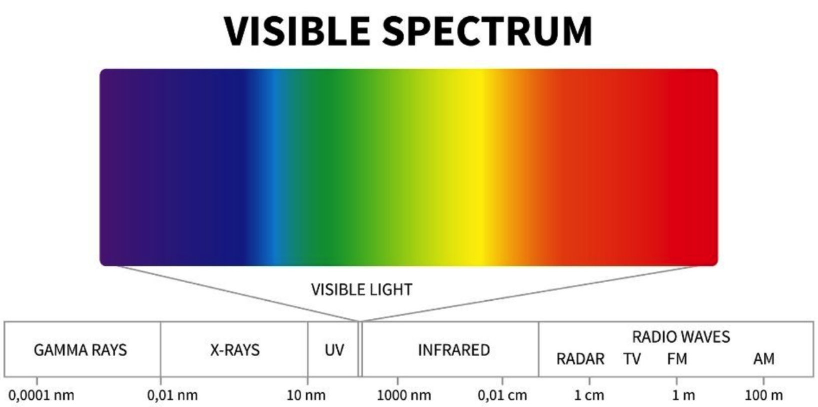
The other thing you need to know is that, ∇^2, “the Laplacian,” is just vector calculus shorthand for $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$. Once you know that, then you can see that this is a familiar wave equation, except in 3D.

How strange that a wave can travel through the vacuum!! Usually we expect that there is a medium, like water (for water waves), or a string (for transverse waves), or rock (for both longitudinal and transverse earthquake waves), or air (for sound waves), and the idea that waves could travel though empty space was so troubling that for a long time people searched for “the ether” which was presumed to be some hard-to-detect substance through which the electromagnetic waves. There was no evidence for the ether in the late 1800s and evidence started accumulating against it.

The Electromagnetic Spectrum

If you accept that ***E*** in vacuum is following a fairly standard wave equation, of the type you have been studying for waves on a string, torsion waves, and compression waves, then you readily believe that the solutions of Maxwell's equations have $\sin(kx - \omega t)$ in them or $\cos(kx - \omega t)$. The only restriction on these solutions is that $\frac{\omega}{k} = c$. Here and above, c is the speed of light and it comes directly from solving Maxwell's equations. NB: it is not a third independent constant. The formula you get for the speed of light when you solve Maxwell's equations is: $\epsilon_0 \mu_0 = \frac{1}{c^2}$, and that is one of the triumphant predictions of Maxwell's theory.

Let us say again, the electromagnetic wave can have any wavelength and any frequency provided that $\frac{\omega}{k} = c$. Our eyes are only sensitive to a teeny bit of the electromagnetic spectrum. Here is the full spectrum in its grandeur, as explained by Maxwell, and as exploited in many areas of technology, beginning with radio:



Across the bottom is an enormous scale going from picometers to kilometers, and the scale is so large it must be presented logarithmically, and in principle it goes off to infinity in either direction. The infinite range is called “the electromagnetic spectrum.”

Color Perception

In the very small range near the middle of the electromagnetic spectrum diagrammed above is 400 to 700nm. This is the only part of the electromagnetic wave we can see, and that little range is called “the visible spectrum.”

Our eyes have three types of “cones” for wavelength ranges that we call red, green, and blue. People who are “red-green colorblind” only have two types of cones.

A very few people are “tetrachromats” and have four types of cones. Concetta Antico is an artist who tries to share her experience of tetrachromacy with the rest of us:

One effect is that she perceives many different colors in mixtures that we regular folks would just describe as white.

Returning to regular folks with three types of cones, out of the three intensity readings that the cones give us of any given object, our minds infer where light is on the spectrum. It is actually easy to make mixtures that fool us, and color printers and color monitors exploit that fact.

Perhaps it is somewhat bizarre, even though we are all used to it, that we interpret all three sensors being approximately equally lit up as sort as white. White light is most definitely a mixture, and coming back full circle to Newton, one of his experiments was to convincingly demonstrate that. He named the seven colors he found in white light red, orange, yellow, green, blue, indigo, and violet, and people still memorize the acronym, ROY G BIV.

Conclusion

So as you wade into Q4.2, please try to appreciate how deeply wedded physicists were to the wave theory of light, because it came from Maxwell’s equations which took much of the 19th century to perfect and explained so many disparate phenomena. If you first appreciate the enormous success of the wave theory, then the results described in Q4.2 can be seen as the shock which they were. Q4.2 describes new experiments involving light.