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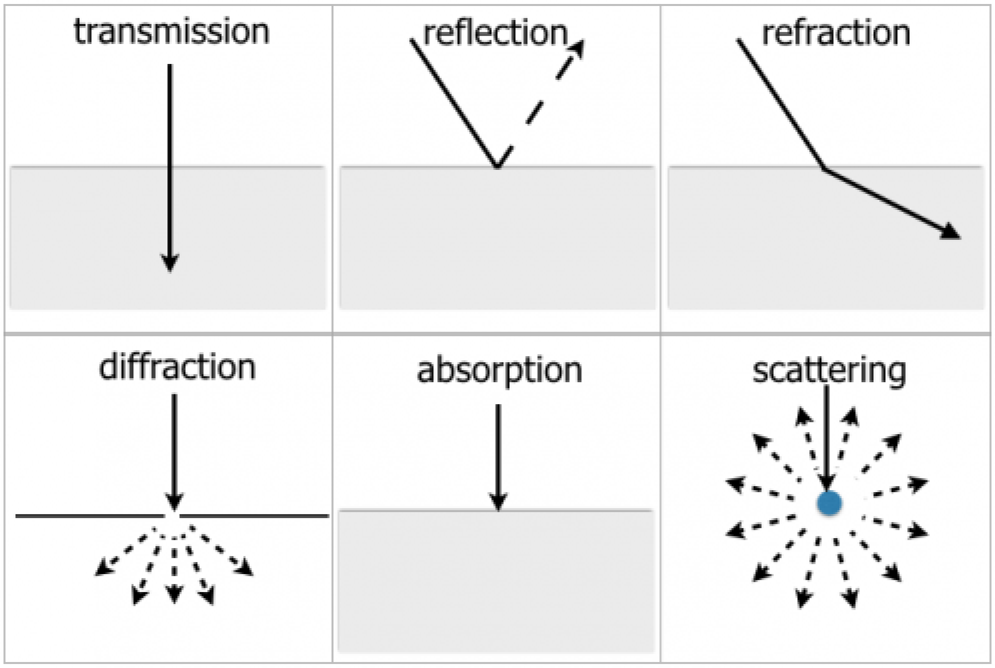
Wave Interaction

When an electromagnetic wave (radio, light, etc) hits a surface, it can do one or a mix of six things[1]:

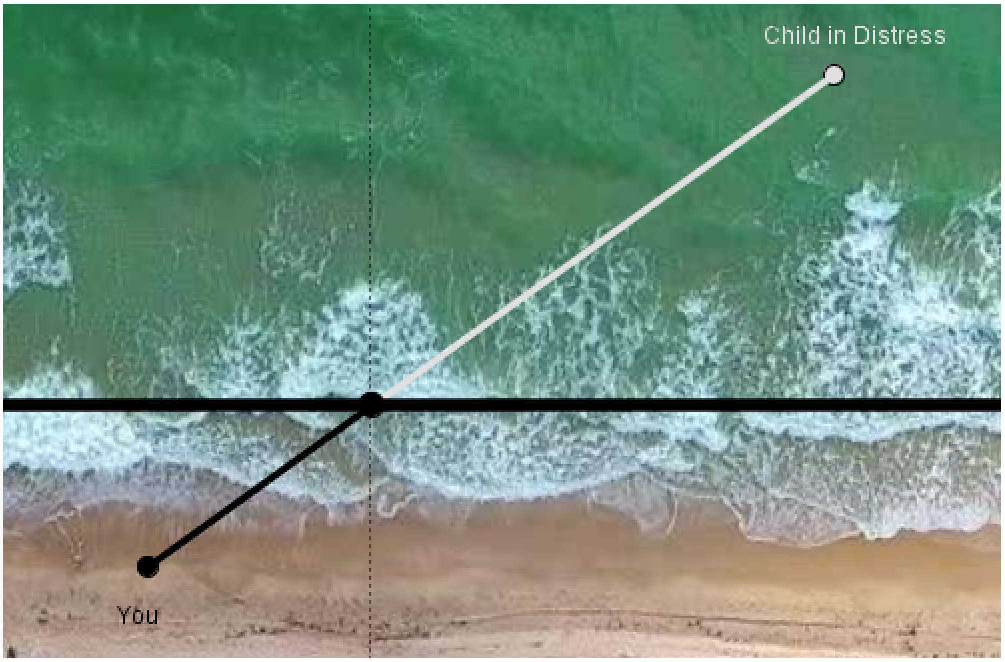


Let's start with refraction and reflection.

Principle of Least Time

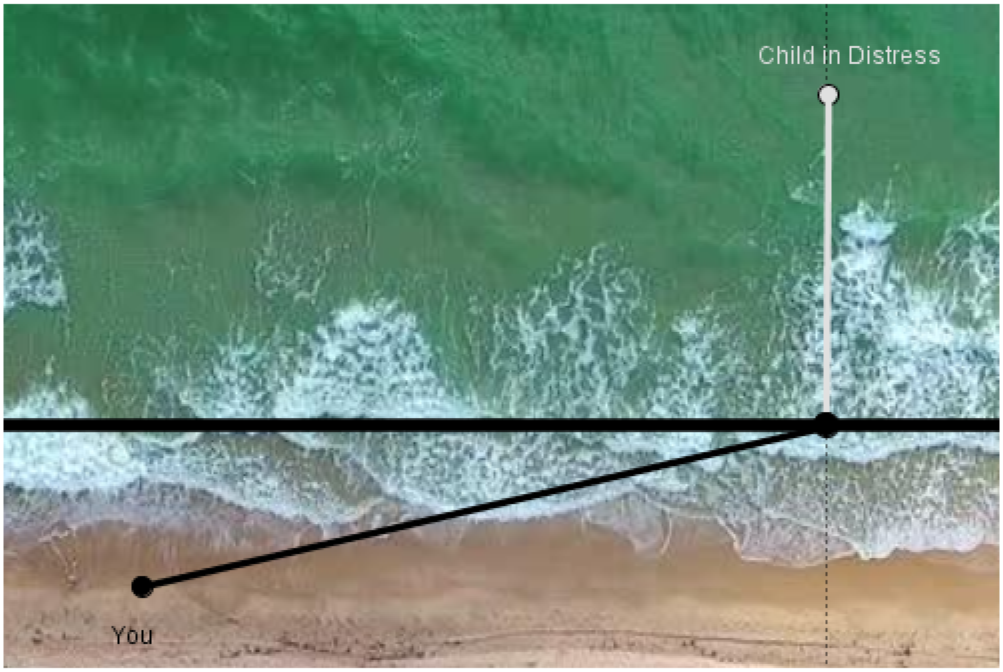
Imagine you're on the beach when you suddenly notice a child in distress in the water. You're a good swimmer but let's say you can run twice as fast as you can swim. What do you do?

Option 1: You make a B-line for the child because the shortest distance between two points is a straight line.



While it's true that this straight line is the *shortest* distance, it's not necessarily the *fastest* path. The problem here is that the water slows you down too much. It's better to cover more ground where you're faster and less where you're slower.

Option 2: You run until you're as close to the child as possible before jumping in the water to swim as little as possible.



That path might be faster than the previous one, but it's not the fastest. Here's a thought experiment:

- Imagine that you could swim as fast as you can run, then Option 1 would be the fastest path because there would be no difference between running or swimming so the shortest path would also be the quickest.
- Now imagine that you could run only *slightly* faster than you can swim. Does that mean you should go all out and run all that distance to spend as little time in the water as possible? If so, how would running yet faster change the path?

Option 2 would be the path to take if you could instantly teleport on the beach (but not in the water). In this case, you'd want to teleport as close to the child as possible, then swim the rest of the way. This path is when you can run infinitely fast.

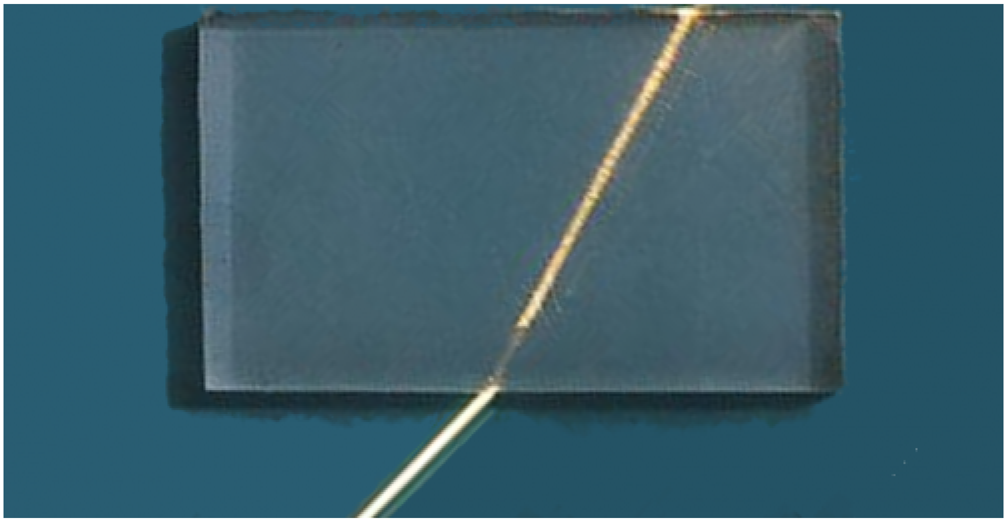
Option 3: For regular running speeds, the quickest path is to enter the water somewhere in between.

It turns out that, people have a pretty good intuition of where that "somewhere" is. But using Calculus, it's possible to find exactly where to enter the water to get to the child as quickly as possible.

Refraction

In science classes, we learn that the speed of light is roughly 300,000,000 meters per second.[2] But that's the speed of light in empty space. In air, glass, or water, light slows down. And since light has different speeds in different media, it means that, even for light, the quickest way to get from point A to point B is **not** necessarily a straight line.

If you shine a beam of light through a piece of glass, it will bend so as to get to the other side as quickly as possible.[3]

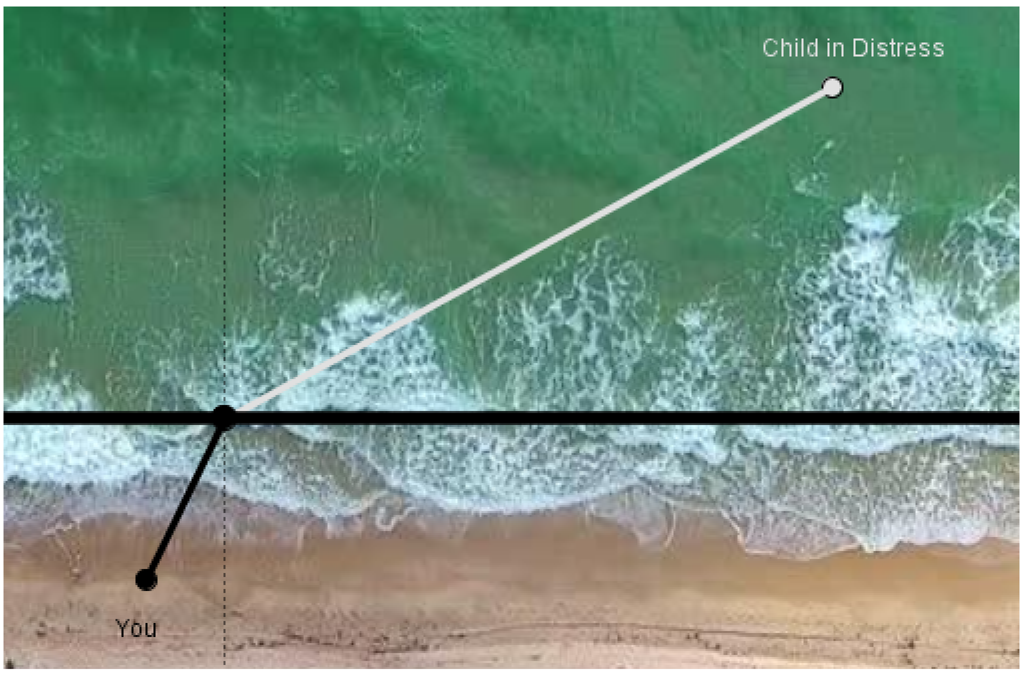


This principle is called Fermat's Principle of Least Time and in first year Calculus, students use this principle to derive Snell's Law of Refraction, taught in high school physics, which relates the angles of incidence and refraction to the refractive indices.

Qualitatively: If light enters a medium where it travels slower, it'll bend "inward" so as to spend less time in that medium (like the picture above).

But what if light goes into a medium where it can travel faster? Then this happens:

If this last one feels weird to you, imagine this: suppose you're a turtle who can swim twice as fast as you can walk. It makes sense that you'd want to spend more time in the water and less on the beach:

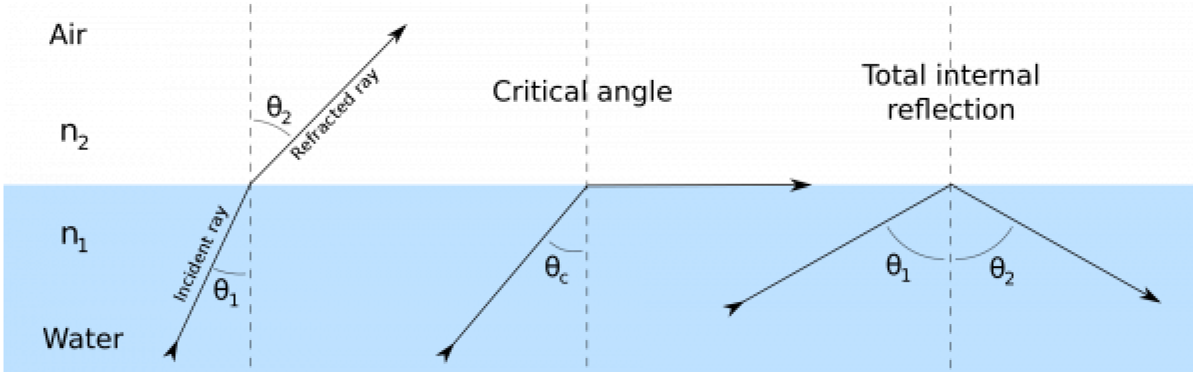


To recap:

- When going from a "quick" medium to a "slow" medium, light bends away from the surface to spend less time in the slow medium.
- When going from a "slow" medium to a "quick" medium, light does the opposite and bends towards the surface.

Total Internal Reflection

This second case (going from a "slow" medium to a "fast" medium) is really interesting because at some point, the light beam bends so much that it "exits" parallel to the surface, and then reflects like a mirror:[4]



This behaviour is a bit hard to explain without going into the math, but here's an animation that allows you to explore it:

- You can move four points around to see how the refracted ray changes: "n_1", "n_2", "Laser", and "Entry point".
- Note though that this particular animation only works if the laser is below the horizontal line.

n_1 and n_2 are the Refractive Indices of the media. They are defined as the ratio of the speed of light in vacuum to the speed of light in the media $\left(n = \frac{c}{v}\right)$. For example, if $n = 2$, then the speed of light is twice as *slow* in the medium as it is in vacuum. The bigger n is, the slower the speed. n=1 means that the speed is the same as the speed of light in a vacuum.

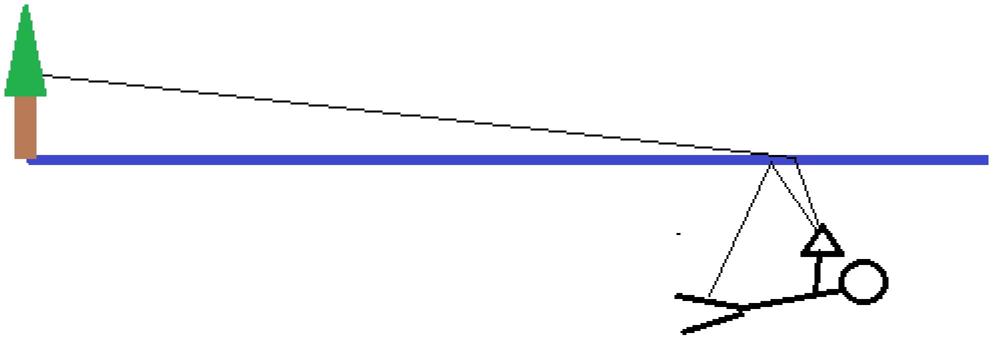
A few things to try:

- Set n_1 = 1 and Set n_2 = 2 and move the Laser and the Entry Point around. These are the paths when you can run twice as fast as you can swim. Notice that if you set n_1 = 2 and n_2 = 4, or n_1 = 2.5 and n_2 = 5, it shouldn't matter. What really matters is the relative speeds between the two media.
- Now move the laser in a straight line so that the angle θ_1 doesn't change. The refracted ray shouldn't change either. So it doesn't matter how far the laser is from the surface. What matters is the angle at which the beam hits the surface.
- Now move the laser back and forth in a semi circle around the Entry Point. Although the laser is the same distance away from the Entry Point, the angle of incidence changes so the refracted ray changes.
- Now set n_1 = 1.5 and Set n_2 = 1 and play with the laser to change its angle of incidence (important). At what angle do you notice that the refracted ray goes parallel to the surface? This is called the critical angle. Passed that angle, the ray can't go through and gets reflected instead.

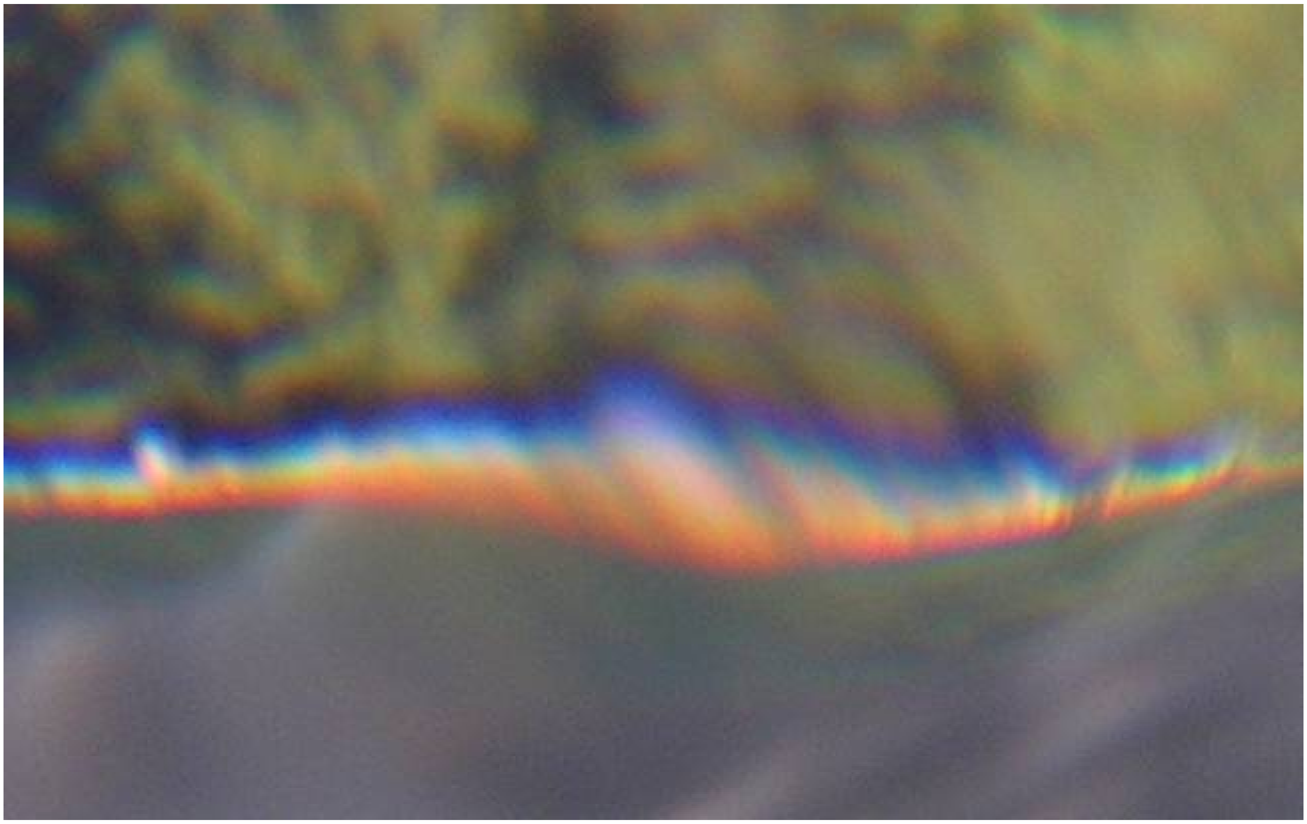
Example

Here's an underwater picture VE7HZF took in a lake with a waterproof camera. The camera is completely submerged under water looking up toward the surface. Above a certain angle, it's possible to see the beach, trees, and the sky. But below a certain angle, we see the reflection of his wetsuit.

Here's a sketch of the setup:

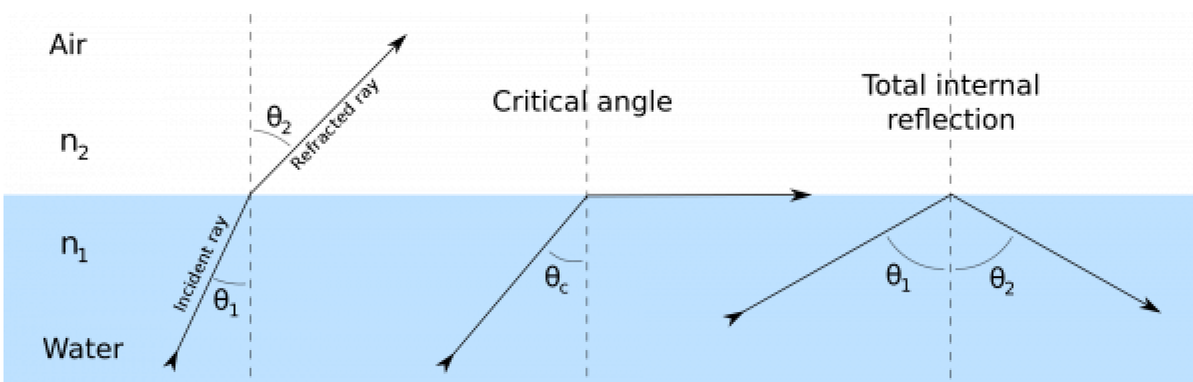


The other cool thing about that picture is that if you zoom in on the beach, you'll see the colours separate (as if through a prism). This indicates that the index of refraction, *n*, depends on the frequency.This will be important when we relate all of this back to radio waves.



Snell's Law (Optional)

Snell's law gives the relationship between the angle of incidence and refraction depending on the refraction indices: $$ n_1 \sin(\theta_1) = n_2 \sin(\theta_2) $$



There are four interesting cases here:

- If $n_1 < n_2$ (high speed to low speed), then the left hand side of the equation is in danger of being less than the right hand side. To maintain the equality, $\theta_1 > \theta_2$, which means that the path curves away from the surface.
- If $n_1 > n_2$ (low speed to high speed), then the right hand side of the equation is in danger of being less than the left hand side. To maintain the equality, $\theta_1 < \theta_2$, which means that the path curves away from the surface.
- If we keep increasing n_1 compared to n_2, then θ_2 can increase to the point where it's going parallel to the surface ($\theta_2 = 90^\circ$), which means that: $\frac{n_1}{n_2} \sin(\theta_1) = 1 $. At

this point, we call θ_1 the critical angle.

- If we keep increasing n_1 even further, then $\frac{n_1}{n_2} \sin(\theta_1) >1 $, which means that it's impossible for θ_2 to keep up since $\sin(\theta_2) \leq 1$. This is when Total Internal Reflection occurs, which is what we use to “bounce” radio waves off the ionosphere (more on that next).

Polarization

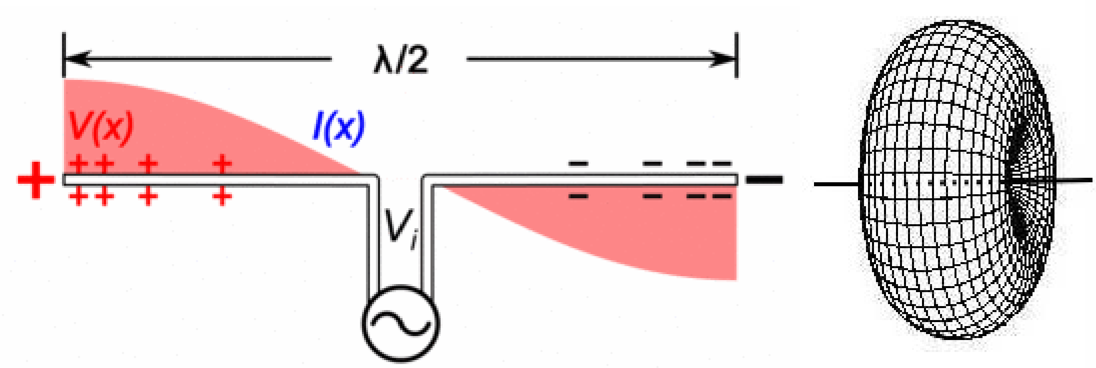
How To Make A Radio Wave

Back on the Intro Page, we introduced to the idea of frequency and saw that

> A Hertz (Hz) is a measure of how fast something vibrates […]
>
> Just seeing “Hz” doesn't tell you anything about what it is that's oscillating in the same way that seeing “°C” doesn't tell you anything about what it is that has temperature. “Hz” is a unit of measure, not a thing itself.
>
> Without going into too much detail (yet), radio waves are created by oscillating electric currents. How many times this current oscillates per second is called the frequency, which is measured in Hz (or kHz, MHz, GHz).

It's now time to add a few more details. Here is a basic recipe for making a radio wave:

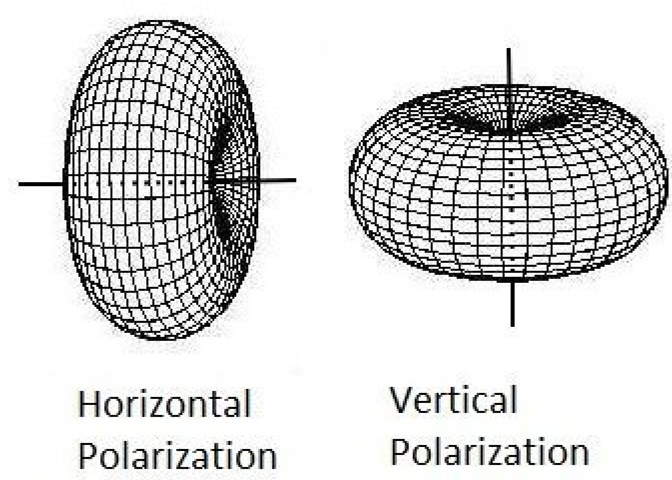
1. Get a length of conducting wire and lay it in a straight line.
2. Cut it in half right in the middle and bend both ends at right angle.
3. Connect the two middle ends to each side of an alternating current generator.



Voila! Assuming that the length of the antenna (the two pieces of wires) match the frequency of the current generator (more of this later), and that the antenna is high enough above the ground, you've created a radio wave.[5] As electrons move up and down the length of the wires, they create varying electric and magnetic fields that couple together according to Maxwell's Equations and propagate outward in a doughnut shape.[6]

Horizontal vs Vertical Polarization

Here's the critical part though: In the same way that an alternating current through an antenna creates a radio wave, a radio wave hitting an antenna induces an alternating current through it **if the radio wave hitting the antenna is in the same “direction” as the antenna**.



This “direction” is called polarization.

Effect on Communication

In practice, polarization is more important for VHF and UHF communication because signals go directly from the transmitting station to the receiving one. For skywave HF communications, the ionosphere can change the polarization of the signal from moment to moment as the radio wave refracts, reflects, or goes through magnetic fields in the atmosphere. As such polarization of the antennas on HF frequency doesn't matter much.

Scattering

Scattering occurs when an EM wave hits a bunch of “small particles”[7] that in turn re-radiate the wave in all direction. Here are a few examples[8] in the visible light spectrum:

The first picture shows a laser beam shinning at the wall. In the second picture, water is sprayed into the path of the laser beam.

The reason the beam is invisible in the first picture is that all the light from the laser travels toward the wall (an none toward the camera). But in the second picture, the water vapour scatters some of that light in random directions, allowing some of it to reach the camera. There's a subtle point here: light for a regular light bulb also does this to some extent. What I mean is this:

- Look at the light bulb in the room you're in.
- Now look at an object that the light bulb illuminates.
- Now imagine a straight line between the light bulb and that object.

Just as with the laser in the first picture, you don't see any light along *that* line. If you did, the entire room would be glowing white from all the different light rays that the light bulb emits. In fact, you can see this on a foggy day when it's also sunny. Or on a foggy evening when you're driving with the high beam on.

Effect on Communications

We'll talk about the effects of scattering on communications in more detail later because we need to see a few more basics first. But for now, it's easy to imagine that a radio signal received through scattering will generally be weak, and suffer from rapid flutter or hollow sounding distortion.

It'll be weak because only a small portion of the energy reaches you (think of how much weaker the scattered light from the laser is compared to the what's reaches the wall directly). And it'll be distorted because your antenna will be receiving the signal from multiple directions (radio wave-paths) at once (think of how you can see the green laser scattered by the mist as an extended line, instead of a single point). As we'll see later, when a signal splits and takes different path (of different lengths), they recombined with an “echo” which cans cause distortion.

More on all of this later.

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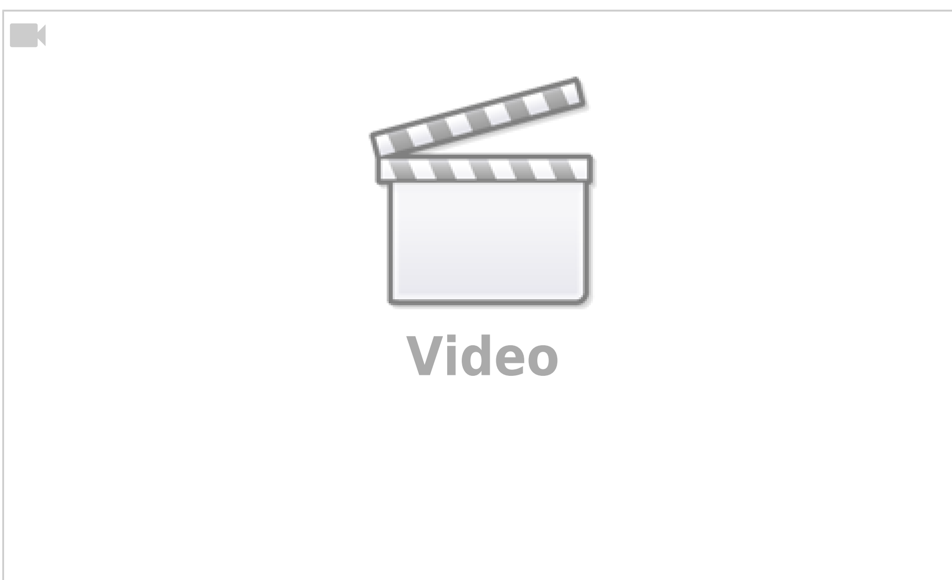
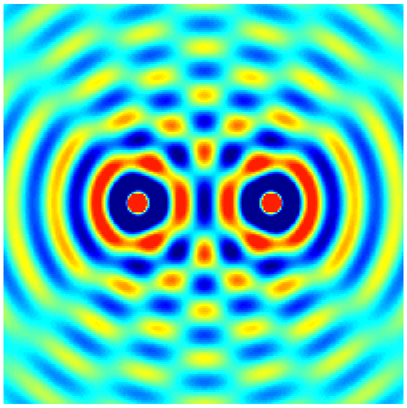
Interference

An important property of waves (radio, sound, water, quantum mechanical!, or otherwise) is that they can interfere with one another. Here's a *Veritasium* video showing how light going through two slits can interfere: In some places, the waves add up, in other places, they cancel out. Although not directly about radio waves, we saw in the intro that light and radio waves are in fact on the same electromagnetic spectrum.



Here's a computer animation from Wikipedia showing the same principle:



In terms of radio signals, every time you have more than one source (either because of reflection or because of another radio or antenna), you'll have regions where the signal fades and regions where it increases. Here's why...

Wave Addition

Two waves add up together at every point. Here, the blue and green waves are generated and add up together to form the red wave. You can move the blue and green waves and see the result. To convince yourself that the red wave is really the sum of the blue and green waves, look at points A, B, and C. You can move the blue or green waves by sliding their phase (φ and Φ) around. You'll see that point C is always the sum of A and B.

Where do the blue and green waves need to be so that...

- the red wave is the biggest?
- the red wave is cancelled out?[9)]

If you press the play button on the bottom left corner, you'll see the blue wave travel to the right and the green wave travel to the left. The red wave oscillates up and down but doesn't travel anywhere. This is called a *standing wave*, which we'll see again later when we discuss SWR.

Wave Reflection and Multipath

More commonly, radio waves often suffer from *multipath* interference caused by some sort of reflection (from mountains, the ground, buildings, the ionosphere, ...) This leads to fading (*QSB*) as either the transmitter, the receiver, or the reflective surface moves.

This next animation shows the direct wave going from the transmitter to the receiver, as well as a wave reflected by the horizontal axis.

The first thing to notice is that when a wave reflects off a surface, it suffers a half-wavelength phase shift. This means that if the receiver is right next to the “mirror”, the signal will cancel out.

If the receiver then moves away from the “mirror”, the reflected signal has to travel over a longer distance than the direct signal before reaching the receiver. This means that phase between the two waves will change, sometimes cancelling each other, sometimes reinforcing each other. When the path difference (Δ) between the reflected and direct waves is a whole number of the wave length, the two waves cancel each other because of the half-wavelength difference from the reflection. But when the difference is a multiple of a half wavelength, the two waves add up constructively and the resulting signal is stronger.

In this example, if the receiver moves straight up, the signals will interfere destructively every 5 wavelength-units or so. This means that on the 2m band, the signal will fade every 10 meters or so. This is why the signal strength of a mobile station sometimes goes up and down rapidly as the car moves, which we call picket fencing.

For more details, see the Fresnel Zone Wikipedia article.

Questions

- B-007-004-003 → B-007-004-007
- B-007-004-008 → B-007-004-011
- B-007-008-002 → B-007-008-005

[1] Picture from http://www.mrwaynesclass.com/lightOptics/reading/index02.html

[2] It takes light roughly 8 minutes to travel from the Sun to the Earth

[3] Picture modified from Wikipedia: Refractive Index

[4] Picture from Wikipedia: Total Internal Reflection

[5] GIF from Wikipedia Dipole Antenna

[6] Picture modified from Wikipedia Dipole Antenna

[7] The “small particles” can be single atoms, molecules, dust, or pockets of gas with a different index of refraction. They can also be bigger objects like meteors or small planes! The size of the “particle” is always relative to the wavelength of the EM wave. To a 160m radio wave, a meteor is small, but to a laser beam (≈500nm), a dust particle is very big.

[8] The laser pictures were taken by Patrick, VE7HZF with help from Justine. The picture of the forest is from: https://www.souvenirpixels.com/Photo-blog/i-cZgCHvZ

[9] Fun fact: This is how noise cancelling headphones work. The headset has a microphone that picks up the noise, inverts the waves, and plays them back in the ear piece. The combination of the real life noise and the inverted noise being played in the speaker cancel out (somewhat).