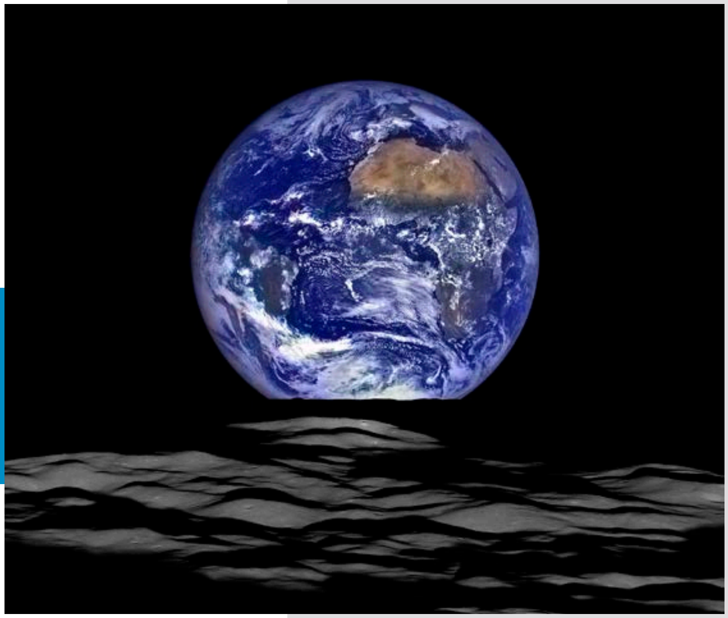
True Blue



NASA's Lunar Reconnaissance Orbiter captured a unique view of a vivid blue "Earthrise" from the spacecraft's vantage point in orbit around the moon in December 2015.

Credit: NASA

We call Earth the Blue Planet because it's covered in water—but what makes water blue? And why is it not blue in your glass or your ice cubes?

Water has many rare properties, some of which we've covered on previous episodes.

But this property, its blueness, is unique to water and goes right to its core. It's the only molecule in the universe that *vibrates* a color.

How is that?

The water molecule is made up of two atoms of hydrogen and one of oxygen.

The hydrogen atoms are very lightweight, but their bonds are very strong. Imagine ping pong balls connected by metal springs. It doesn't take much to start water molecules vibrating.

In basic terms, light itself is vibrating electromagnetic energy. Different colors have different vibrational frequencies.

Water molecules vibrate fast enough to reach the lower frequencies of visible light, where they absorb red light, so we see the blue light that remains.

This effect is too faint to notice in your glass of water. But it's already visible in a bathtub or swimming pool, and gets more pronounced when the effect is amplified, as light passes through more and deeper water.

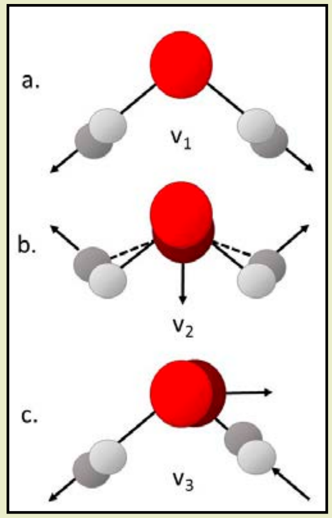
Scuba divers know this well. Past a certain depth, blue becomes the *only* color—till they turn on a flashlight, which reintroduces full-spectrum white light, and all the colors appear again.

There are other molecules that vibrate, but none that can reach into the visible light spectrum. Only water is true blue.

Background: True Blue

Synopsis: A glass of water appears colorless, but large bodies of water appear blue. Ice cubes are clear, but glacial ice looks blue. While interactions between photons of light and electrons orchestrate the colors of most materials, water gets its intrinsic color from unique molecular vibrations that play out within the spectrum of light visible to humans.

- In a previous *EarthDate*, we learned that the sky looks blue for a couple of reasons:
  - Higher-frequency blue and violet light are more energetic (shorter wavelengths) than other colors, so they are scattered more effectively by molecules of air that reflect them toward our eyes.
  - Since violet is higher frequency than blue, why doesn't the sky look more violet? Most humans have trichromatic vision with red, green and blue cones in our retinas, but the color range for the blue cone (380–450 nm) drops off dramatically in the violet range, so we don't see violet light as well.
  - So, when it is clear outside, the scattering of light in air and the limitations of human color vision cause the sky to appear blue.
- Most materials get their color as light photons are absorbed, emitted, or reflected by their electrons. But water is different: It appears blue because of molecular vibrations.
  - Water is the only natural substance that has an intrinsic hue caused by molecular vibrations, and that is because hydrogen is light and hydrogen bonds are strong, with a bent configuration that enables them to vibrate. It only takes a small volume of water to amplify the faint blue color generated by these vibrations to the point that we can see it.
- Water is a special molecule with all kinds of special properties.
  - Water molecules are bonded by hydrogen bonds that create a bent molecule with polarity; one end is positive while the other is negative. This polarity makes it the "universal solvent," critical to life and Earth processes.



The bent water molecule H_2O can vibrate in three different ways. It is helpful to think of metal spheres attached to strong springs when visualizing these vibrations. The three normal vibrations are: (a) the symmetrical stretch, (b) the symmetrical bend, and (c) the asymmetrical bend.

  - The hydrogen bonds in the bent molecule can vibrate in three different ways: stretching, bending symmetrically, or bending asymmetrically.
  - Like changes of pitch in music, these vibrations can combine or create harmonics (overtones), which shift their frequencies higher to more energetic states.
  - This happens in other polar molecules, but water is the only molecule with a frequency shift that we can see because the shift occurs within the visible spectrum.
  - These vibrations are just high enough frequency to make it into the visible part of the electromagnetic spectrum (soaking up the red end), so we can see the complementary blue color in the human visible range (similar to a high audible pitch just barely making it into the audible range for humans).

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References: True Blue

Why Is the Ocean Blue? Colors from Vibrations | Webexhibits.org
Why Is Water Blue? | Dartmouth
Ocean Color | NASA Science
Why Are Some Glaciers Blue? | LiveScience
Why Is Glacier Ice Blue? | Alaska Satellite Facility

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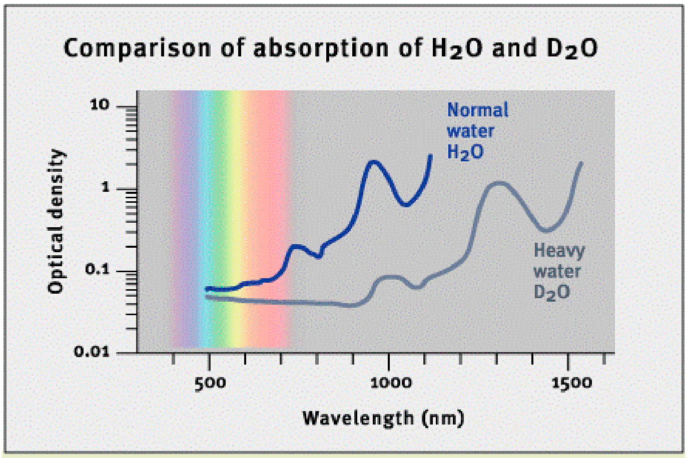
- On the other hand, "heavy" water (D_2O), which has a higher molecular weight than regular water (H_2O), appears colorless.
    - Deuterium (D) is a stable isotope of hydrogen. Most hydrogen on Earth is protium, with a nucleus consisting of a single proton, but deuterium's nucleus contains both a neutron and a proton, increasing its molecular weight by 10%.
    - Adding just 10% more weight of deuterium pushes the vibrational frequency out of our visible range.
    - D_2O is always colorless to the human eye because the cones in our eyes dictate our visible range.
    - Other molecules absorb at even longer wavelengths (lower frequencies) than water or heavy water, falling even further outside of the visible spectrum.



These graphs of their visible and near infrared spectrums show why water (H_2O) is blue, while "heavy" water (D_2O) is colorless. Normal water selectively absorbs light in the red part of the visible spectrum, so we see the complementary color, blue. Heavy water absorbs light outside of the visible spectrum, so it is colorless. Frequency = 1/wavelength, so higher frequencies like blue have shorter wavelengths than lower frequencies like red.

- We can see the color better with a larger volume of water because the color amplifies through the volume of water molecules, just like turning up the volume for audio amplification makes it easier to hear sound. So, all pure water looks colorless in small volumes, like a drinking glass, but blue in larger volumes, like a bathtub, lake or ocean.
    - Large bodies of water are not blue because they reflect the blue of the sky. In fact, they remain blue even under gray skies (unless sediments are stirred up).
    - Scuba divers know that as you go deeper under water, red light is progressively absorbed until all we can see are shades of blue. If you turn on a white flashlight, adding back the longer red wavelengths, you can see that all the colors do exist at these depths.
    - And it's not just lakes and oceans: if you do an experiment looking through a long tube filled with water, you will see a blue color due to the increased volume (amplification).
    - You can even see this blue effect if you fill a white bathtub with tap water.

You can see how the blue color of water amplifies with volume in this photo of a bucket floating in a swimming pool. The bucket has a small volume of water, which appears a very faint blue, while the pool is much deeper and therefore appears an intense blue.

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- Another mystery: snow is white, ice cubes look clear, but glacial ice is a beautiful turquoise blue.
  - When snow falls, it appears white because snowflakes reflect the light that hits them.
  - As snow is layered it is gradually compressed into glacial ice, entrapping air bubbles that contain fossil air (which help us understand long-term changes in the atmosphere). If there are a lot of bubbles, the ice looks whitish because the air bubbles reflect the entire visible spectrum of light.
  - As glacial ice is buried under more layers, it becomes more compressed, growing denser and expelling air bubbles. With fewer air bubbles to reflect light, the ice turns bluer and bluer for the same reasons water looks blue: vibrational transitions in water molecules absorb light at the red end of the spectrum, transmitting a beautiful blue.
  - Glacial lakes and rivers, however, appear to be bright turquoise shades due to the added effect of sunlight reflecting off glacial sediment in the water (which is blue because of molecular vibrations).
  - In Antarctica, huge stretches of deep blue ice are polished by the wind. Some Antarctic ice is more than 2 million years old.
- If you think about molecules behaving like vibrating strings, the lightest molecules with the strongest bonds are H_2O, so they create the highest "pitch," which happens to be a high enough frequency to just barely land in the visible spectrum—rendering water, ice, and Planet Earth blue.

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