A curious observer's guide to quantum mechanics, pt. 3: Rose colored glasses

"How big is a particle?" Well, that's a subtle (and, unsurprisingly, complex) question.

Miguel F. Morales - Jan 24, 2021 2:00 pm UTC

Enlarge

Getty Images / Aurich Lawson

> ***One of the quietest revolutions*** *of our current century has been the entry of quantum mechanics into our everyday technology. It used to be that quantum effects were confined to physics laboratories and delicate experiments. But modern technology increasingly relies on quantum mechanics for its basic operation, and the importance of quantum effects will only grow in the decades to come. As such, physicist Miguel F. Morales has taken on the herculean task of explaining quantum mechanics to the rest of us laymen in this seven-part series (no math, we promise). Below is the third story in the series, but you can always find the starting story plus a landing page for the entire series thus far on site.*

So far, we've seen particles move as waves and learned that a single particle can take multiple, widely separated paths. There are a number of questions that naturally arises from this behavior—one of them being, "How big is a particle?" The answer is remarkably subtle, and over the next two weeks (and articles) we'll explore different aspects of this question.

Today, we'll start with a seemingly simple question: "How *long* is a particle?"

Go long

To answer that, we need to think about a new experiment. Earlier, we sent a photon on two very different paths. While the paths were widely separated in that experiment, their lengths were identical: each went around two sides of a rectangle. We can improve this setup by adding a couple of mirrors, allowing us to gradually change the length of one of the paths.

EXPLORING THE QUANTUM WORLD

A curious observer's guide to quantum mechanics, pt. 3: Rose colored glasses

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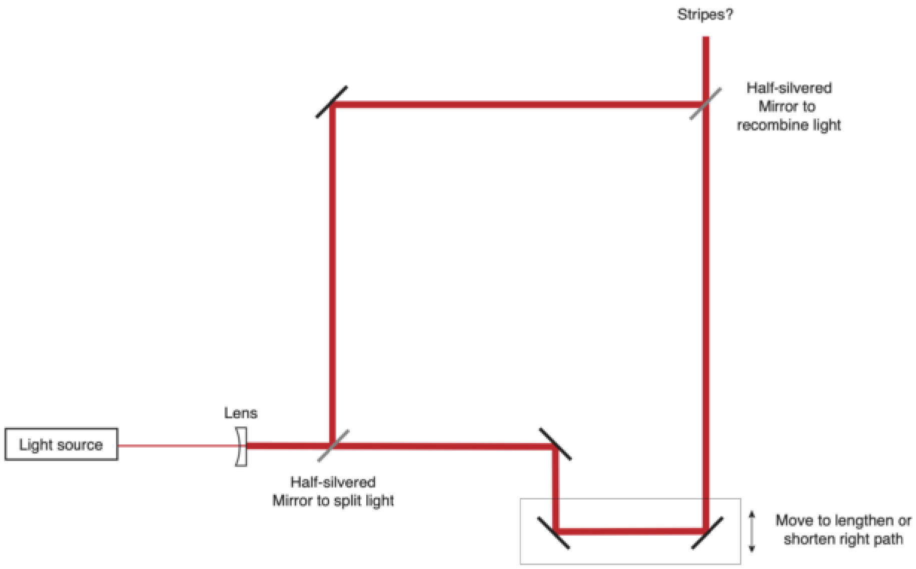


Enlarge / An improved two-path experiment where we can adjust the length of one of the paths.

Miguel Morales

When the paths are the same length, we see stripes just as we did in the first article. But as we make one of the paths longer or shorter, the stripes slowly fade. This is the first time we've seen stripes slowly disappear; in our previous examples, the stripes were either there or not.

We can tentatively associate this fading of the stripes as we change the path length with the *length* of the photon traveling down the path. The stripes only appear if a photon's waves overlap when recombined.

But if particles travel as waves, what do we even mean by a length? A useful mental image may be dropping a pebble into a smooth pool of water. The resulting ripples spread out in all directions as a set of rings. If you draw a line from where the rock fell through the rings, you'll find there are five to 10 of them. In other words, there is a thickness to the ring of waves.

Another way to look at it is as if we were a cork on the water; we would sense no waves, a period of waves, then smooth water again after the ripple had passed. We'd say the 'length' of the ripple is the distance/time over which we experienced waves.

Enlarge / Ripples on a pond. Note the thickness of the ring of waves.

Roberto Machado Noa / Getty Images

Similarly we can think of a traveling photon as being a set of ripples, a lump of waves entering our experiment. The waves naturally split and take both paths, but they can only recombine if the two path lengths are close enough for the ripples to interact when they are brought back together. If the paths are too different, one set of ripples will have already gone past before the other arrives.

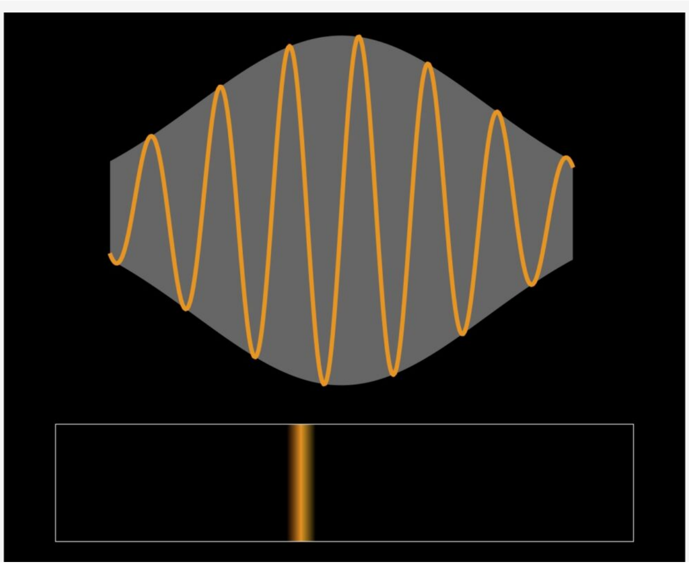
This picture nicely explains why the stripes slowly disappear: they are strong when there's perfect overlap, but fade as the overlap decreases. By measuring how far until the stripes disappear, we have measured the length of the particle's wave ripples.

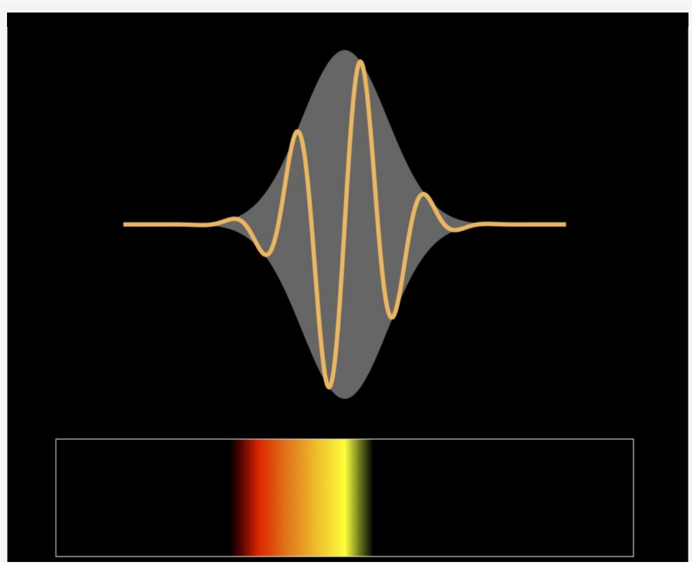
Digging through the light bulb drawer

We can go through our usual experiments and see the same features we saw before: turning the photon rate way down (which produces a paintball pointillism of stripes), changing the color (bluer colors mean closer spacing), etc. But now we can also measure how the stripes behave as we adjust the path length.

While we often use lasers to generate particles of light (they are great photon pea shooters), any kind of light will do: an incandescent light bulb, an LED room light, a neon lamp, sodium streetlights, starlight, light passed through colored filters. Whatever kind of light we send through creates stripes when the path lengths match. But the stripes fade away at distances that range from microns for white light to *hundreds of kilometers* for the highest quality lasers.

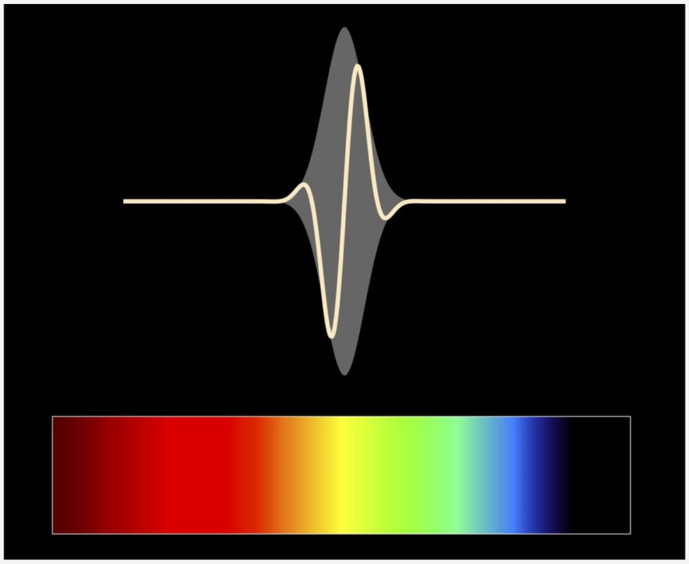
Light sources with distinct colors tend to have the longest ripples. We can investigate the color properties of our light sources by sending their light through a prism. Some of the light sources have a very narrow range of colors (the laser light, the neon lamp, the sodium streetlight); some have a wide rainbow of colors (the incandescent bulb, LED room light, starlight); while others such as sunlight sent through a colored filter are intermediate in the range of composite colors.





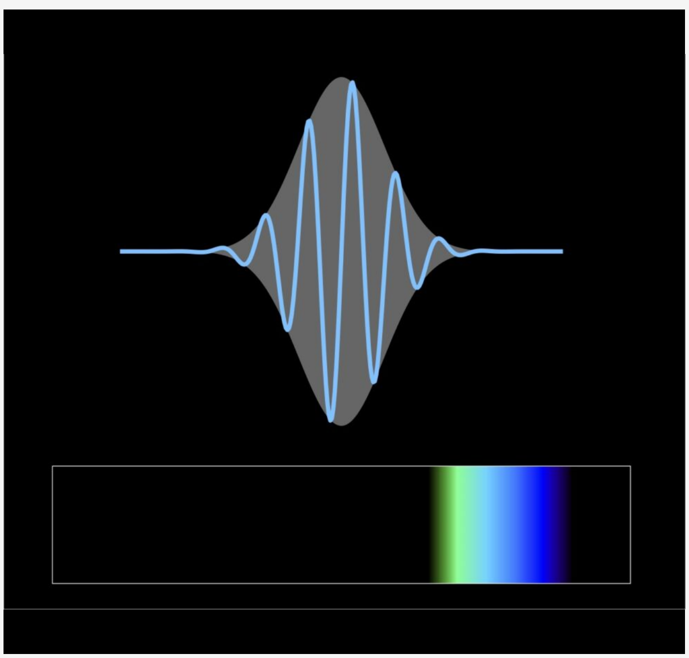
We can measure the length of a ripple by seeing how far we can lengthen one arm of the experiment before the stripes disappear. A long ripple has a narrow range of colors [credit: Miguel Morales]

A medium length ripple has a wider range of component colors. [credit: Miguel Morales]

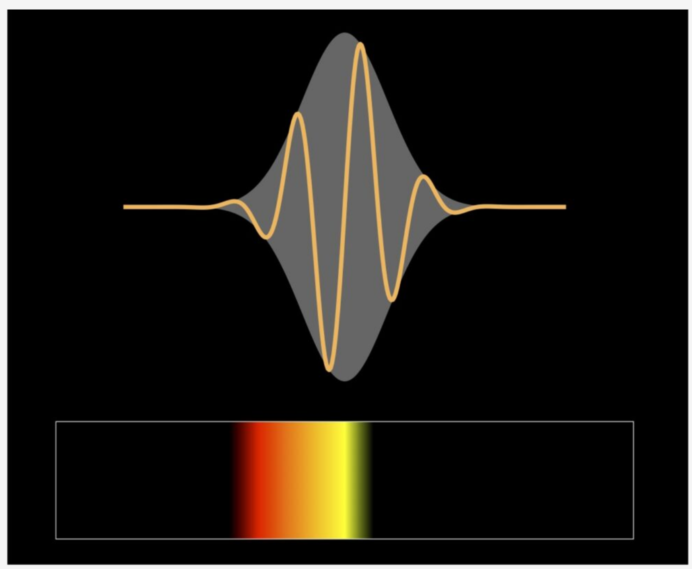


A very short pulse of light necessarily includes a wide range of colors, becoming white. [credit: Miguel Morales]

What we notice is that there is a correlation: the narrower the color range of the light source, the longer the path difference can be before the stripes disappear. The color itself does not matter. If I choose a red filter and a blue filter that allow the same width of colors through, they will have their stripes disappear at the same path difference. It is the *range* of color that matters, not the average color.



A medium length ripple of blue light and its component colors. [credit: Miguel Morales]

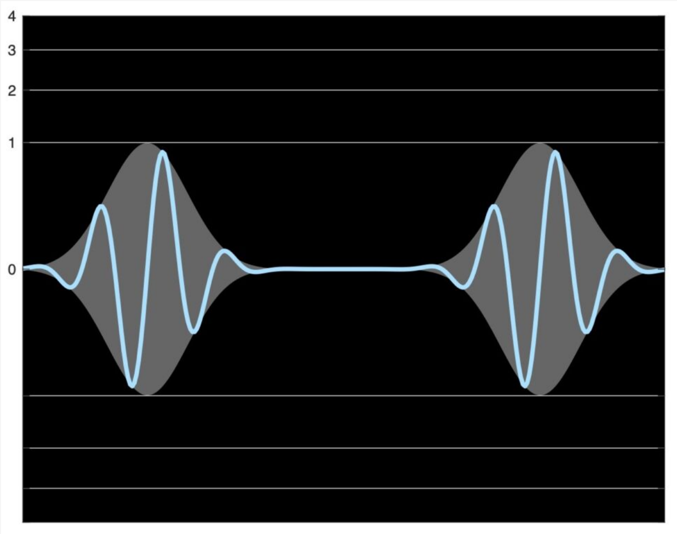


A medium length ripple of orange light. Note that while the orange wave is longer than the blue wave (shown by colored line), the length of the ripple is the same (shown by grey region). The length of the ripple depends on the range of color, not the central color. [credit: Miguel Morales]

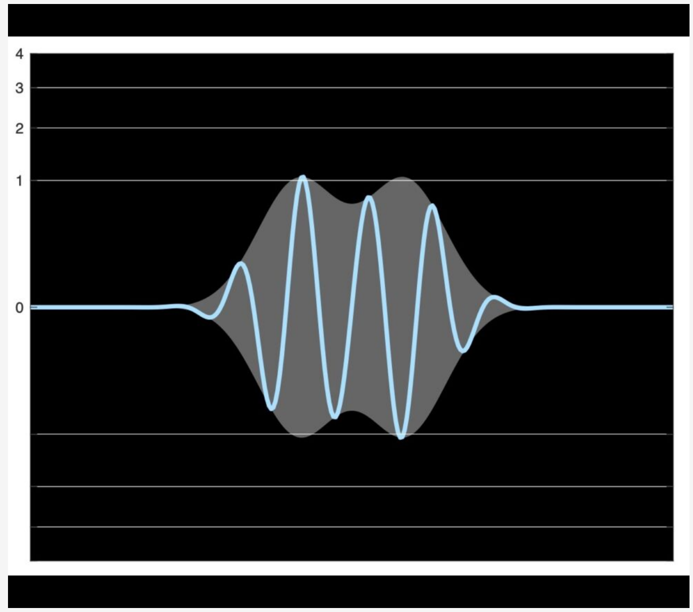
Which brings us to a rather startling result: the length of a particle wave is given by the range of colors (and thus energies) it has. The length is not a set value for a particular kind of particle. Just by digging through our drawer of light sources, we made photons with lengths ranging from microns (white light) to a few cm (a laser pointer).

Friendly photons

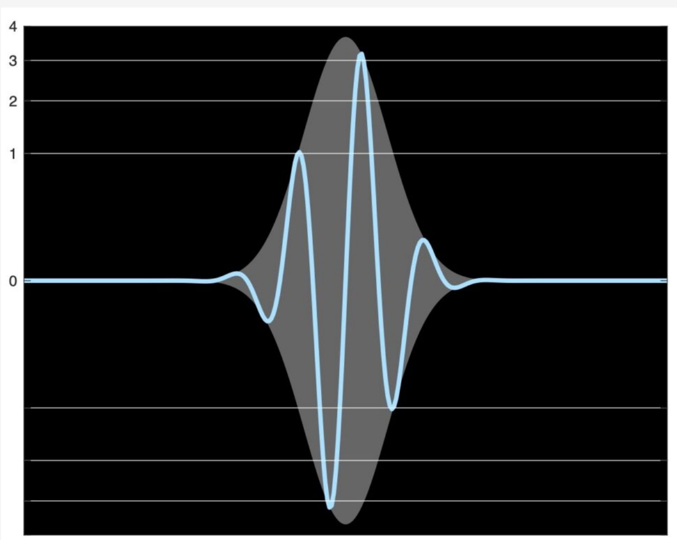
We saw in the second article that two independent particles can interact and mix, so what does the mixing of two sets of ripples look like?



Two well separated ripples of light. The horizontal lines are associated with the probability of seeing a photon. [credit: Miguel Morales]



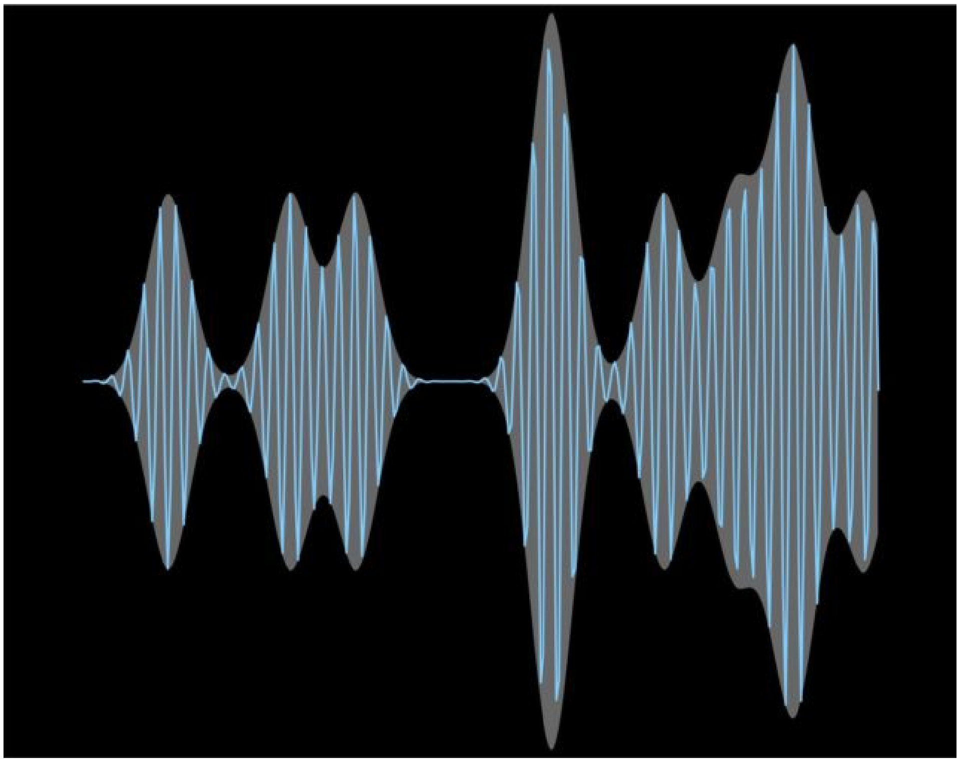
Two ripples partially overlapping. [credit: Miguel Morales]



Two ripples mostly overlapping. When ripples overlap the probability of seeing photons close together increases dramatically—photons like to bunch together and hold hands. [credit: Miguel Morales]

In the sequence above, you can see how photon ripples add as they overlap. As the height of the waves increases, the probability of seeing photons increases dramatically.

Let's start with some photons emitted randomly in time—sunlight or starlight is perfect for this. Huge numbers of atoms are emitting photons of light across the surface of a star, each independently of the others, so the emission of the photons is perfectly random in time. But if we take those photons and squeeze them onto an optical fiber, some of the ripples from separate photons will overlap.



Enlarge / A few photon ripples, randomly inserted into a fiber. Where the ripples overlap the photons bunch.
Miguel Morales

Because we have an enhanced probability of seeing photons when their ripples overlap, if we watch for the photons coming out at the end of the fiber, their appearance is no longer random—photons like to bunch. We see more photons exiting the fiber very close together in time, and this enhancement happens at the size of the ripple we measured at the start of this article. This bunching is a beautiful quantum mechanical effect—photons like to hold hands when they overlap.

This also leads us to a subtle question. Starlight or sunlight is a mixture of all colors, so the ripples are very short and we see this in the bunching which appears only if we look at very short intervals. But if we associate one ripple with one photon, what is the color of the photon? Was it a red photon or a green photon or a blue photon? Intriguingly, the most natural answer is the photon was white—each photon ripple is a mixture of all colors. If we force each photon to have a defined color, then the ripples are very broad, and we would see that in the bunching length.

So a photon in flight has a mixture of colors. Just as asking which path the photon takes makes no sense, asking what color a white photon has while in motion turns out to make no sense.

Particle Introverts and Extroverts

All of our previous experiments have shown that all particles behave the same way, whether we use photons or neutrons or Bucky Balls. So, being careful observers, we'll want to repeat our last experiments with neutrons. We measure the length of the neutron ripples with our variable path length experiment, and the fringes slowly fade in the same way. But if we take randomly emitted neutrons and allow the ripples to overlap, we find that neutrons avoid each other. Instead of bunching up like photons, neutrons push each other away, or anti-bunch.

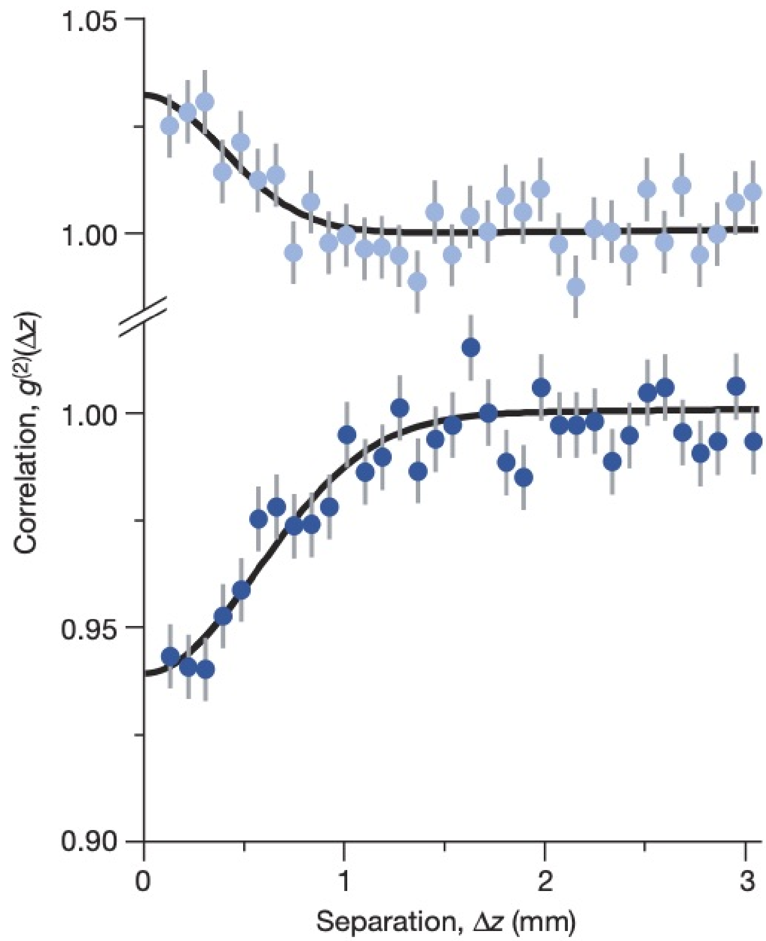
This is still a very quantum mechanical effect; classically we'd expect randomly emitted neutrons to arrive, well, *randomly*. But instead of bunching up and holding hands like photons, neutrons avoid each other.

We can repeat this experiment with all the particles we know, and they divide into two distinct camps: the extroverts that like to join up (bosons), and the introverts that avoid one another (fermions). There is no kind of particle that will arrive randomly—they are all either introverts or extroverts. Quarks, electrons, protons, and neutrons all belong to the introvert fermion camp; photons, gluons, and pions are all extrovert bosons.

Fermions have one additional trick up their sleeve: two fermions can be packed together so that they behave like a boson. All quarks are introvert fermions, yet pions are made up of 2 quarks and act like extrovert bosons. Protons and neutrons, which are made up of 3 quarks, act like fermions. So it is possible to make composite particles out of fermions that are bosons, as long as an even number of fermions are used. Given a wingman, fermions are much friendlier. (Interestingly you cannot pack bosons to act like fermions.)

This leads us to one of my favorite quantum demonstrations of all time. Jeltes and colleagues started out by cooling some Helium atoms to less than a millionth of a degree above absolute zero. This cooling decreases the range of energy, or colors, which increases the ripple length of the Helium atoms to about half a millimeter—the size of typical sand grains.

They then dropped the helium onto a detector and looked for the bunching or anti-bunching in the arrival time. When they use Helium-4, which has 2 protons, 2 neutrons, and 2 electrons (total of 6 fermions), they clearly see the bunching of an extrovert boson. But when they use Helium-3 instead (2 protons, 1 neutron, 2 electrons for a total of 5 fermions) they see the anti-bunching of an introverted fermion.



Samples of 4He atoms (bosons, upper line) and 3He atoms (fermions, lower line) are cooled to half a millionth of a degree above absolute zero, dropped onto a detector, and the separations between atoms is recorded. 1.00 means the atoms arrived randomly. At close distances the particle ripples overlap and the extrovert 4He* atoms show up more often than random (bunch) while the introvert ^{3}He atoms show up less often than random (avoid each other). Because 3He weighs slightly less than 4He its ripple length is a little longer (0.75 mm vs. 0.56 mm).
Jeltes et. al.

This is just a stunning experiment. It shows that the length of a particle in motion is related to the range of energies (colors) involved; it uses a composite particle; and it clearly shows the bunching and anti-bunching of bosons and fermions with the same apparatus just by changing the isotope of helium. It's an experimentalist mic drop.

Uncertainty

In our light experiment, a short packet of ripples was associated with a wide range of colors (energy), while a narrow range of colors indicated a long packet of ripples. We saw this again in the Jeltes experiment: by cooling the atoms to less than a millionth of a Kelvin, they were able to narrow their energy range and thus increase the length of the Helium ripple to half a millimeter.

An implicit consequence of this behavior is that it is impossible to have both a short particle wave and a small color range. If you limit the color range, the particle's length increases; if you shorten the ripple length, the color range necessarily increases.

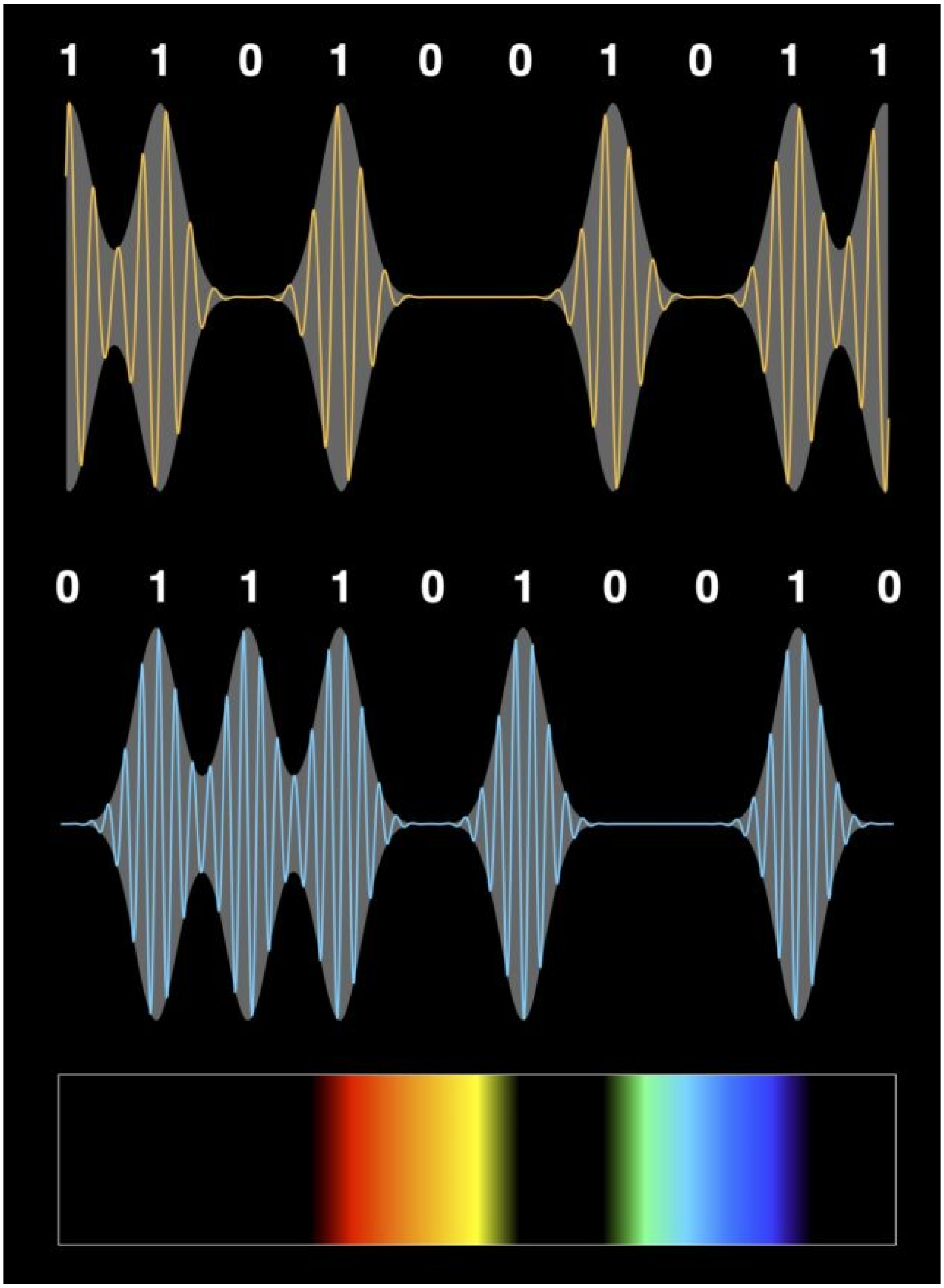
We see this experimentally in pulsed lasers. A nanosecond laser pulse will have a color—it will look red or blue. If we send this pulse through a prism, we will see that there is a range of color, but the range only includes different shades of the same color. But as the laser pulse gets shorter, the color content necessarily becomes broader. A femto-second laser is *white*.

This is not an accident of technology. If you send a femto-second laser pulse through a colored filter, the pulse gets longer because there are no longer enough colors to make a short pulse.

This interplay of the length of a traveling particle and the range of colors is a *very* deep feature of quantum mechanics—it is commonly known as the Heisenberg uncertainty principle. The location and energy (momentum) cannot be both well defined. A sharp position necessitates a wide range of energy, and a sharp energy (narrow color range) necessitates a long particle ripple.

Back at the Visitor's Center

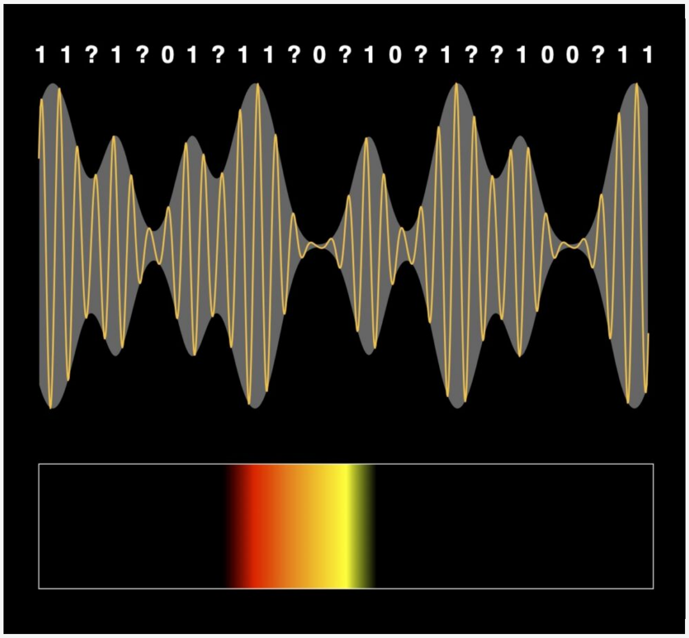
So how does this relationship between the range of color and the length of a particle ripple affect our everyday world? Sending light pulses down an optical fiber naturally brings to mind computer internet connections and fiber optic network connections.



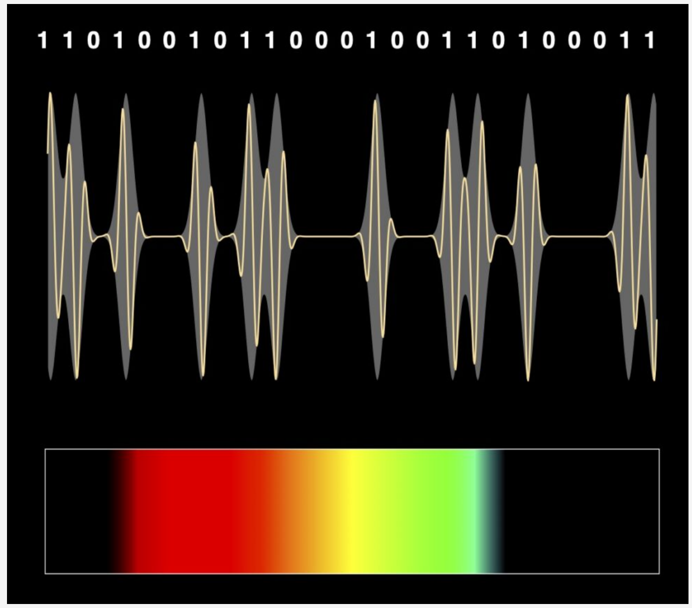
Enlarge / Two digital signals being sent down a fiber, one in orange and the other in blue. At the far end of the fiber the color range associated with the top user (red-yellow) and the lower user (green-indigo) can be separated and each user will receive their data.
Miguel Morales

If we envision a digital data stream where each light pulse represents a 1 and a missing pulse indicates a 0, the speed at which I can send data is directly related to the length of the pulses. The shorter the pulses, the more closely in time they can be packed.

But there is a limit to how closely I can pack photon ripples—if they get too close, they start holding hands. This photon friendliness starts erasing the data I was trying to convey. As I keep increasing the data rate, I need to make the pulses shorter and shorter to keep the ripples from overlapping and erasing the message. But to make a shorter pulse I must use a wider range of colors.



If the data rate become too fast the pulses start overlapping, garbling the message. [credit: Miguel Morales]



The clarity of the fast data can be restored by using narrower pulses, but this in tern requires a wider color range—more bandwidth. [credit: Miguel Morales]

The term bandwidth means the range of color, and this word has crept into everyday language in a technically correct way. The higher the data rate, the more color bandwidth you need.

This gets more interesting if several users are sharing a single fiber. Parallel data streams can come from many users on a fiber-optic backbone or all the TV channels provided by your local cable TV provider. Conceptually, each data stream has its own color range, so one channel is on orange, the next one yellow, another yellow-green, etc. At the end of the fiber, we can use a prism to split the channels and give each user their data stream.

Clearly, the internet provider can make more money by splitting the color allocation ever finer, but there is a limit. Each user needs not just a central color, but a *range* of colors so they can make pulses fast enough. The width of the range of color—the color bandwidth—determines how short they can make pulses and thus how fast they can send or receive data.

While the internet provider can put many different colors onto a fiber, the total bandwidth is conserved. The internet provider can have a 1,000 users, each at a slow, narrow bandwidth, or 10 users each with very fast, high-bandwidth connections. But there is only so much color range to go around.

This naturally applies to radio waves too (radio is just low-frequency light). How we manage and sell the limited range of radio colors is called spectrum management. Here is a link to one of my favorite charts: the radio spectrum allocation for the US (note the logarithmic frequency scale). There are many users, and you can read off the maximum data rate of each user by the width of their allocation. High data rate users like high definition TV and cell phones need wide blocks of radio colors, while low data rate users like FM radio and GPS need only need narrow allocations of color.

Next week's expedition

This week, we explored the 'length' of a particle. This leads to the concept of bandwidth, and the one-to-one correspondence between the length of ripple and the color range. A short ripple necessitates a wide color range.

In next week's hike, let's go big. We'll ask how wide a particle is, and in the process see quantum mechanical effects that span light-years! So keep your binoculars handy and meet me back here next week.

FAQ

But bandwidth can be explained classically without resorting to quantum mechanics! Yes, of course, any wave-like description incorporates the idea of bandwidth. But I find it helpful to keep an eye on the fundamental waviness of particles in motion. I could decide to send my message using a stream of neutrons instead of light, and due to the waviness of particles the same bandwidth arguments would apply. These ideas of particle waviness and bunching will become increasingly important in the next two articles.

Don't all lasers have a narrow color? Interestingly no. To work all lasers require amplification of light (stimulated emission), and early lasers and the inexpensive lasers you may have around the house have a very narrow color range over which they can work. However, there are amplification media that work over a wide range of colors. In the optical/IR titanium doped sapphire is a favorite, and Erbium-doped fiber amplifiers work over a wide range of infra-red colors and are crucial for long distance internet fiber communication. Because of the ubiquity of Erbium-doped fiber amplifiers, there is a good chance that at a wide color laser was involved in getting this webpage to you.

This is basically just magic, isn't it? I found this a very funny question. Then I started wondering how I could *test* whether science is magic? At least in popular culture magic is: arcane knowledge (✓) learned through many years of arduous study (✓) by pouring through old books filled with cryptic runes (✓) apprenticed to temperamental sages (✓) while living on scraps in a tower or dungeon (✓). And one must always be careful when performing major feats of magic/science, as the results are never quite what you hoped (✓). So I guess the answer is, experimentally at least, that yes it's magic.

Miguel F. Morales is a professor of physics at the University of Washington in Seattle.