Light, the appearance of objects, and Relativity
An essay for non-physicists

Wagner L. Truppel

March 23, 2014

Introduction

Light is some strange stuff. It sometimes behaves as a wave, sometimes as a particle. It has no mass, but carries energy and exerts pressure. It can be polarized. It makes lasers. It travels in vacuum at great speed, and that speed depends neither on the motion of its source nor on the motion of its detector. It is also fundamentally connected to Quantum Mechanics and to both the Special and the General Theories of Relativity.

In this essay, we'll discuss some implications of just two of the properties of light: the fact that its speed is *finite*, and the fact that its speed is independent of the state of motion of both sources and detectors.

More specifically, we'll look at how the finiteness of the speed of light affects the appearance of objects, both at rest as well as moving, with some bizarre results, only a few of which have anything to do with Relativity. We'll then explore the fact that the speed of light is independent of the state of motion of both sources and detectors and, in the process, you'll also learn and understand some of the fundamental ideas behind Einstein's Special Theory of Relativity.

We will *not* talk about any quantum mechanical properties of light in this essay, nor about General Relativity. Trust me, there's plenty to talk about already.

How fast does light really move?

Light moves in vacuum with a very large speed, approximately 300 thousand kilometers per second. To put this value into perspective, note that it takes light only about 8 *minutes* to cover the distance from the Sun to the Earth, 1.3 *seconds* to go from the Earth to the Moon, and it travels the equivalent of about seven and a half times the Earth's circumference in just one second.

It's no surprise, then, that for a long time light was thought to travel infinitely fast. Galileo, who lived in the 16th century, attempted to measure its speed but was unsuccessful. It was only about a century later, in 1676, that the first successful measurement of the speed of light was made, by the Danish astronomer Ole Rømer.

Rømer succeeded where others had failed by making careful observations of one of Jupiter's moons, Io. We won't get into the details of his observations here. You can read a very nice and easy to understand description here.[1]

Suffice it to say here that Rømer's value for the speed of light was in the right ballpark, about 220 thousand kilometers per second. The importance of his observations, though, is not so much that he found this particular value but that he proved once and for all that light moves at a *finite* speed.

What if light moved really slowly?

For our purposes here, however, light moves much too fast. It's far easier to understand the consequences of its finite speed if we pretend that light moves much much slower. This isn't an original idea; other authors have used the same device in the same manner. One particularly praised popular exposition of the peculiarities of physical phenomena, using this idea of changing the values of physical constants, is the lovely book Mr. Tompkins in Wonderland,[2] written and illustrated by one of the fathers of the Big Bang model, the late physicist George Gamow. It should be noted that early editions contain some errors, which I believe have been corrected in more recent editions.

So, in this essay, we will pretend that light moves at a much slower pace, say, 10 meters per second. If you're familiar with yards rather than meters, that's ok. A yard is just shy of a meter so you can safely read *yard* every time I write *meter*.

It's important to emphasize that pretending that light moves at a much slower pace does not add to, nor take away from, the strange phenomena we'll be discussing here. They still happen in the real world, with the actual speed of light. It's just that it's much more difficult to observe those phenomena in real life.

Looking into the past

The first consequence of the fact that light moves at a finite speed is that every time we see something, we're actually looking at its past. More accurately, we're looking at events or objects as they appeared some time prior to our detecting the light coming from them.

[1] http://www.colorado.edu/physics/2000/waves_particles/lightspeed_evidence.html
[2] http://www.amazon.com/exec/obidos/ASIN/0521447712

When you look at the night sky, for instance, you see stars not as they are *now* but as they were some time ago. Likewise, when you look at the Sun, you're seeing it as it was nearly 8 minutes prior to the moment when you saw it. This observation may seem obvious but it still has some bizarre consequences, which we shall now explore.

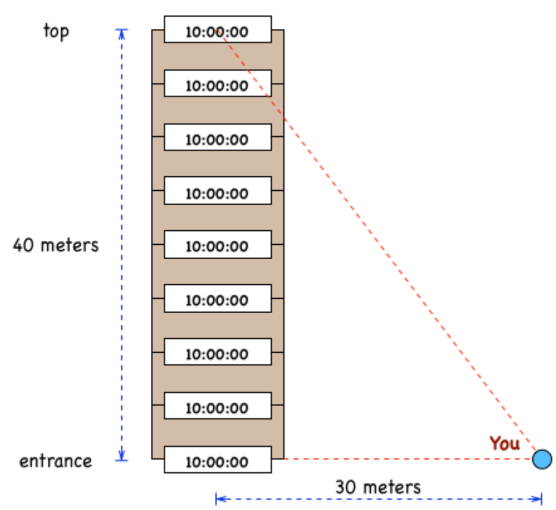
A building full of clocks

Suppose that you are standing in front of a 40-meter-tall building, a distance of 30 meters from it, and let's ignore the fact that your eyes stand at some height above the ground.

The light that comes from the building's entrance on the ground takes, then, 3 seconds to reach you, according to our speed of light of 10 meters per second. On the other hand, the light that comes from the top of the building — having to travel the hypotenuse of a right triangle of sides 30 and 40, that is, having to travel 50 meters — takes 5 seconds to reach you.

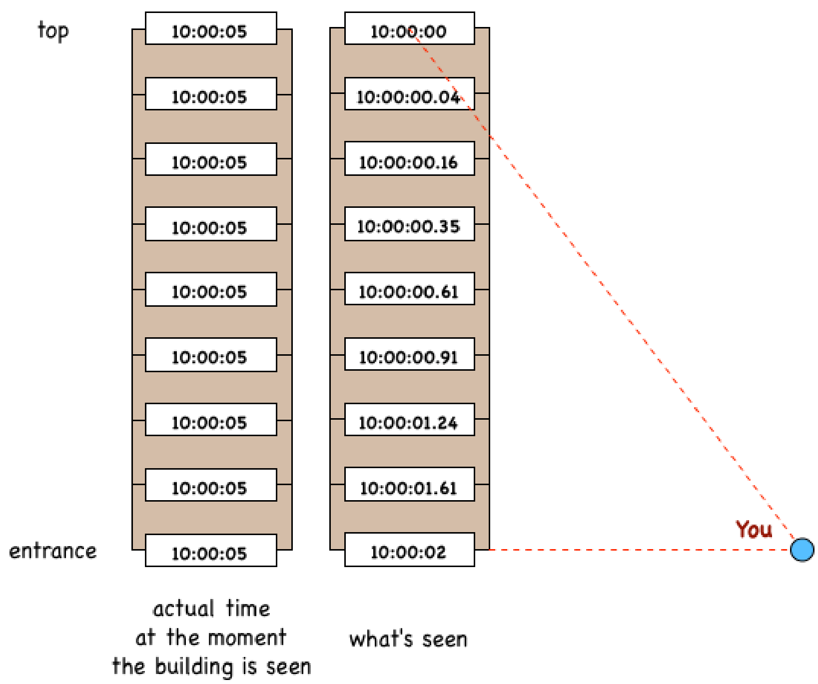
So when you see the entire building at once, that is, when an image of the entire building forms on your eyes' retinas, you are not only seeing the building as it was in the past, but you're seeing a "mosaic in time" so to speak, where each part of the building is seen at a different time in the past. For example, you see the entrance as it was 3 seconds ago but you see the top of the building as it was 5 seconds ago.

To make this more obvious, imagine that the building has digital clocks on its windows, visible from the street, say, one clock every 5 meters, for a total of 9 clocks. Moreover, imagine that all clocks are synchronized so they all show the same time, all the time. Incidentally, we'll be talking more about synchronization and simultaneity in later sections.



What do you see, standing 30 meters away from the entrance? As explained above, the image of the clock at the entrance takes 3 seconds to reach you while the image of the clock at the top of the building takes 5 seconds to reach you. Therefore, when you *see* the top clock showing, say, 10:00:00, what do you *see* the other clocks showing, and what is the *actual* time they're physically displaying at that moment?

In order to see the top clock showing 10:00:00, the image of that clock at that moment is formed by light that must have left the top clock 5 seconds earlier. So the actual time *now*, when you see the top clock showing 10:00:00, is 10:00:05. However, during those 5 seconds, the light from the entrance clock showing 10:00:00 came and passed by you, because it only takes 3 seconds to reach you. That means that you see the entrance clock showing 10:00:02 when you see the top clock showing 10:00:00.



Yes, this is a bit confusing and counterintuitive. Think of it this way. At 10:00:00, light signals leave both the entrance and the top clocks, toward you. You will see the image of the entrance clock showing 10:00:00 3 seconds later but the light from the top clock (also showing 10:00:00) hasn't reached you yet, and won't do so for another 2 seconds. It's only the image of the entrance clock at 10:00:02 that will reach you at the same time as the image of the top clock at 10:00:00, so that's why you see 10:00:02 at the entrance, 10:00:00 at the top, but it's actually physically 10:00:05 at that moment. Naturally, intermediate clocks, from top to entrance, will show values between 10:00:00 and 10:00:02.

Seeing double isn't always an eye problem

Now suppose that your friend Clark Kent is standing at the top of the building (perhaps it's the Daily Planet) and waves at you. It will take 5 seconds before you see the image of him waving, during which time Clark might come down to the ground level and wave at you again, from the entrance. You'd then see *that* image 3 seconds after he waves for the second time.

So, if Clark were capable of traversing the height of the building in 2 seconds, then he'd reach the entrance and wave at you just at the right moment for *that* image to reach you at the same time you see him waving at you from the top of the building. In other words, you'd see Clark waving at you from two different locations, at the same time! Of course, he was *never* actually in two places at once but you'd see two images of him, from different places, at the same time.

How fast would Clark have to move to accomplish that feat? Well, he'd have to cover the height of the building — 40 meters — in 2 seconds, so he'd have to move at 20 meters per second, which is to say, at *twice* our pretended speed of light.

Now, if you're thinking that preventing this kind of situation is the reason why no object can move faster than light, you'd be mistaken. There is nothing intrinsically wrong or inconsistent with moving faster than a signal that carries information. For example, if we were talking about sound instead of light, it wouldn't be groundbreaking to learn that it's possible to *hear* the same signal from two different places at the same time. All that would be required is for the source of the signal to move faster than the speed of sound, and that's perfectly possible (albeit by no means easy).

Yet, it *is* true that objects with mass cannot move at or above the speed of light and, therefore, Clark would most definitely not be able to appear waving from two different places at the same time. We will return to this issue of a speed limit in a later section.

Lightly rotten apples

The fun doesn't stop there, however. Since the light that comes from the top of the building must have left earlier than the light that comes from the entrance — in order for you to see the entire building at once — you see the top of the building earlier in the day than you see the entrance (by 2 seconds, in fact).

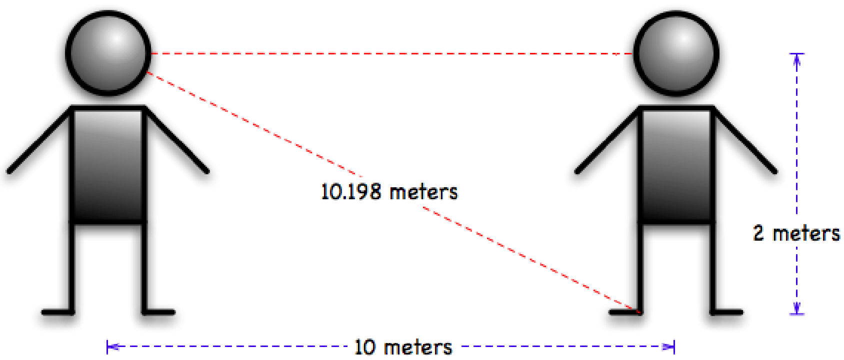
In other words, if light moved really really slowly, so that the difference in the times involved were not seconds but, say, a couple of hours, you might see the top of the building still lit by daylight while the entrance is already in the dark of night.

To appreciate what this really means, consider a truly gigantic apple. You'll see the stem at the top, and the front of the apple, but the front of the apple will appear older than the stem, because the stem is farther away. So, again, if light moved really really slowly, you might see the front of the apple rotting, or already rotten, while the top looks fresh. This does not mean that the apple is actually rotting at different rates. Not at all. The apple is still rotting at the same rate everywhere. It's just that what you *see* is affected by the finiteness of the speed of light and the distances involved.

Funny-looking people

Before we move on to examine what objects look like when they're moving, let's go through one more example of the bizarre consequences of the finiteness of the speed of light. However, let's now pretend that light moves really really really slowly, so that we can amplify the effects to an even greater degree than we have done so far. Let's say that light moves at a crawling 1 millimeter per second. That's a thousandth of a meter, per second.

So, suppose that Albert and his friend Bob are looking at each other, from a distance of, say, 10 meters. Also, let's say that their eyes are at an even 2 meters above the ground. Neither one is moving. What do they look like, to one another?



Just as in the case of the building, light from farther away regions has to leave earlier to arrive at the eyes at the same time as light from nearer regions. In this particular example, with light moving at 1 millimeter per second, the light reflected by one's eyes takes 10,000 seconds — or nearly 2 hours, 46 minutes, and 40 seconds — to arrive at the other person's eyes. The light from the feet takes 198 seconds (3 minutes and 18 seconds) longer, for a total of 2 hours, 49 minutes, and 58 seconds. What does that mean? For starters, it means that Albert sees Bob's head arriving some 3 minutes *before* Albert sees Bob's feet. In other words, Bob looks like a head floating in space and the rest of his body appears gradually, top to bottom, over the period of 3 minutes and 18 seconds. Moreover, by the time Albert *sees* Bob in his entirety:

- Bob is actually nearly 3 hours older and may have already left the scene;
- The image of Bob's head is older than the image of Bob's feet by over 3 minutes. If light moved even slower and the distances were larger, it would be possible for Albert to see an old man's face at the same time he sees the feet of a baby, with corresponding intermediate aging for other body parts;
- The image of Bob's feet is more illuminated than the image of Bob's head, if they met near the time the Sun sets.

Now, if you think that's strange, wait until you learn what things look like when they're *moving*. By the way, once again, all these bizarre consequences are happening right now in the real world, with the actual speed of light. It's just that the time delays are so incredibly tiny that no one is capable of experiencing them, and we never will.

Also, it bears repeating that nothing that's been described so far has anything to do with the Theory of Relativity. Everything discussed so far is merely a consequence of the fact that light moves at a finite speed. It's when we require the speed of light to be a universal speed limit that Relativity comes into play. We'll come back to this later.

Causality and simultaneity, or the lack thereof

Speaking of the Theory of Relativity, one celebrated result that is often attributed to it is the lack of simultaneity, that is, the idea that events that appear simultaneous to one observer may not appear so to other observers. As it happens, however, this lack of simultaneity has *nothing* to do with Relativity and is merely a consequence of the finiteness of the speed of light.

We've already seen that in the example of the building full of clocks. Two light signals that leave the building at, say, 10 o'clock, one from the bottom and the other from the top, do not arrive at the same time at our eyes when we're on the ground 30 meters away. To us on the ground, those two light signals are not simultaneous.

***** a figure with 2 observers, one equidistant from the top and bottom of the building, the other on the ground; discuss how the lack of simultaneity is due to different optical path lengths (so long as light is traveling at the same speed through both paths). *****

***** use the superman example to discuss causality; how the time-ordering of causal events cannot be reversed if the speed of light is a limit to how fast objects can move. Likewise, how the time-ordering of events that are not causally connected can be reversed even if moving slower than the speed limit. *****

Let's get moving

So far, we've explored the effects of the finite speed of light on the appearance of objects, but only when those objects are *not moving*. It's time we looked at the case when objects move with respect to one another.

Motion is a relative concept, meaning that it doesn't make sense to say that something is moving, without specifying who or what it's moving relative to. This is more easily understood if you consider the fact that you're not moving with respect to your car when you're driving, yet you are moving with respect to other cars on the road, and with respect to the road itself. Thus, when you say that you're moving at, for example, 50 kilometers per hour, you must always specify with respect to what you're measuring that speed.

Well, not always, actually. There is one exception to that rule, and that's the speed of light. For reasons that we'll get to in a later section, and which form the basis of Einstein's Special Theory of Relativity, light is different in that its speed is the same for everyone and everything, regardless of their state of motion. If another car on the road turns its lights on, it matters not how fast that car, or your car, is moving: you'll measure the speed of that light beam to have the same value in every case.

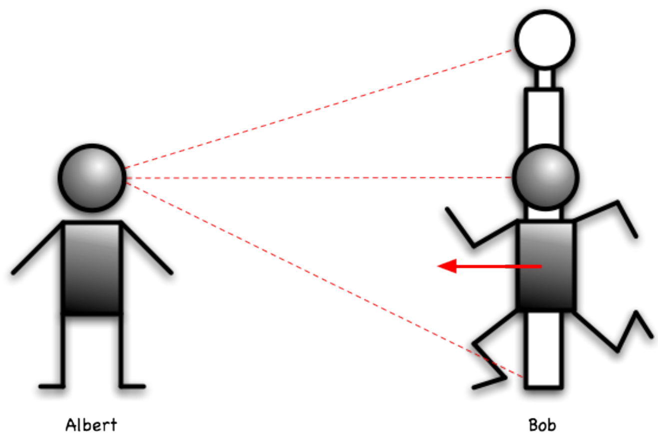
That is a seemingly mind-boggling property of light and it has many strange consequences, but we'll defer an examination of them to a later section. For now, just remember that the speed of light has the same value no matter the state of motion of its source or of any detector.

Slanted running

Suppose that our old friend Albert is having a good time eating an ice cream when his friend Bob sees him and decides to run directly towards Albert. What does Albert *see* when Bob passes by a lamp post on the sidewalk?

Since light reflected from Bob and from the lamp move at a finite speed,[3] it follows that Albert will see Bob passing the lamp when Bob has, in fact, *already* passed it. In other words, Bob is physically *closer* to Albert than he appears to be. This is because in the time taken by light to travel to Albert, Bob has also moved closer to Albert. In fact, if Bob

[3]Which speed, though? Because of the Theory of Relativity, that speed is the same as always, and in every direction. However, if we didn't know that the speed of light must be the same regardless of the motion of its source and detectors, the analysis would be far more complicated because when running *towards* Albert, the light reflected from Bob's head would travel towards Albert's eyes at the speed $(c+v)$, where c is the usual speed of light and v is Bob's running speed with respect to Albert. However, the light reflected off Bob's feet would travel towards Albert's eyes at a different speed because it's traveling in a different direction. In the analysis above, I'm implicitly using the fact that light moves at the same speed in every direction and regardless of the motion of its sources and detectors.



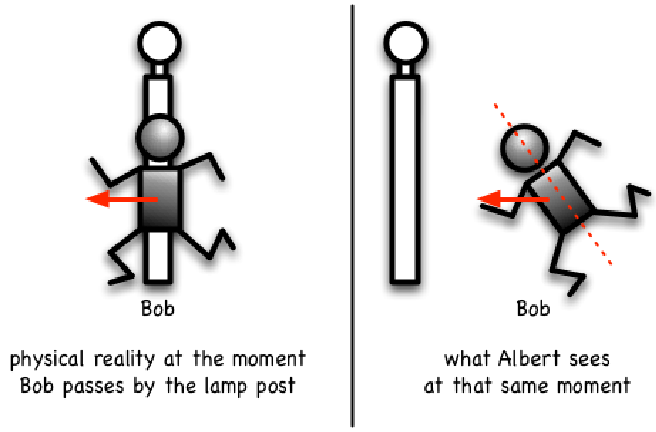
could move faster than light then he'd arrive at Albert *before* Albert sees Bob passing the lamp post. So, when Bob is just passing by the lamp post, Albert will see him as he was some time *before* he passed by it.

But that's not all. Since light reflected from Bob's feet, and from the lamp, have to travel a longer distance than the light reflected from Bob's head, it follows that Albert will see Bob's feet near the bottom of the lamp post but will see Bob's head *ahead* of the lamp (closer to Albert than the lamp), as if Bob was slanted forward. Moreover, just as before, Bob's head will appear older than his feet.

This is all because the farther away we look distance-wise, the earlier in time we'll be seeing. Thus, Bob's head, which is closer to Albert than Bob's feet, will create an image in Albert's eyes that is older (more recent in the time line) than the image of Bob's feet. But that means Bob's feet must have been somewhere farther away from Albert than Bob's head (so far as the images in Albert's eyes are concerned) and this is why Bob looks rotated *towards* Albert, even as he (Bob) runs. To summarize, when Bob physically passes by the lamp post, Albert will see him not yet passing the post and will also see him rotated forwards, in addition to the old-head/young-feet phenomenon we discussed previously.

Slanted running... away

What if Bob was running directly *away* from Albert, instead of towards him? It's not difficult to conclude, based on what we've discussed so far, that by the time Albert *sees* Bob passing by the lamp post, Bob is in fact farther away from it. In other words, Bob is actually farther away than he appears to be according to Albert. And since Bob can't move faster than light, it follows that he cannot be farther away than *twice* the distance that Albert thinks he is.



To understand why, let's imagine that Bob could move at the speed of light. Then, by the time the image of Bob passing by the lamp post reaches Albert, Bob will have moved the same distance in the direction away from Albert. Thus, Albert sees Bob passing the lamp post but Bob is twice as far. Since, however, Bob cannot in fact move as fast as light, he will have covered a shorter distance so he cannot be even twice as far away from Albert, let alone farther than that, when Albert sees him passing by the lamp post.

In addition, as before, Bob will appear slanted, only now it's in the direction away from Albert. This is because as light from Bob's feet leaves towards Albert, Bob moves a bit farther away. So Bob's head is ahead of the post when light from it starts its journey towards Albert. That light will reach Albert at the same time as the earlier light from Bob's feet, even though that light has already moved a little as well (towards Albert). To summarize, when Bob physically passes by the lamp post, Albert will see him not yet passing the post and will also see him rotated forwards, *away* from Albert. Also, Bob's head again appears older than his feet.

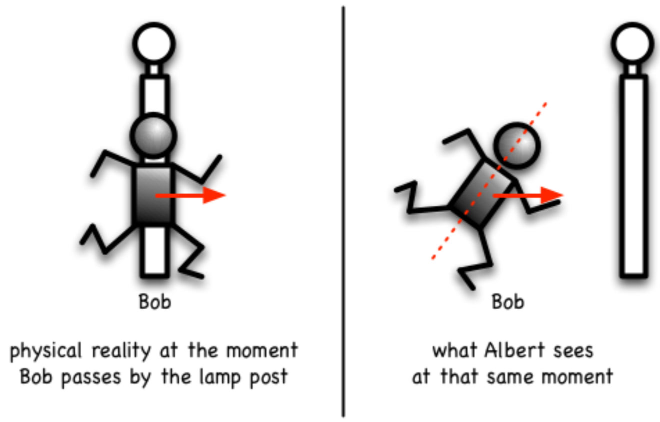
Oh, he's just passing by...

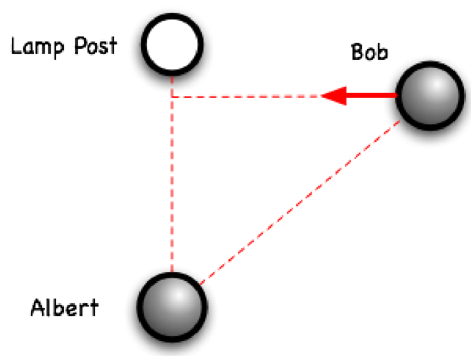
Had enough weirdness? No? Then suppose that Albert is looking at the lamp post when Bob runs by, but neither towards nor away from Albert, as in the picture below, seen from above. What does Albert see now?

To be written...

Enter *Relativity*

To be written...


Bob
physical reality at the moment
Bob passes by the lamp post
Bob
what Albert sees
at that same moment


Lamp Post
Bob
Albert

■