Worldviews, by Richard Dewitt

Chapter 21: Development of Newtonian Worldview

From the 1700's onward the Newtonian worldview reordered every branch of science along mechanistic lines. To wit:

Chemistry before the 1700's was entirely qualitative. Chemical reactions were predicted and explained by reference to qualitative similarities and differences between substances, e.g., color, texture, taste, etc. Influenced by Newtonian science, chemists began to conceive of chemical reactions as the interaction of thousand of tiny particles, and this insight resulted, among other things, in various laws concerning the behavior of gases under varying temperature and pressure.

Biologists before Newton universally subscribed to the view that living things depend on a certain vital force or fluid, a view known as vitalism. As scientists began looking more closely at living bodies, they began to understand that what animates a living thing, the nervous system, has an ultimately electrochemical basis. Previous to this time, the substances that make up living bodies- organic compounds- were thought to be unique, and not something that could be generated from inorganic compounds.

Physics: Electricity and magnetism began to be studied in the same careful quantitative manner that Newton had studied gravity, and scientists eventually discovered that the two were inextricably linked (electrical currents always generate magnetic fields, and moving magnets can generate an electrical current), and that that the forces of electromagnetism were governed by an inverse square law, just like the universal law of gravitation. By the mid 1800's James Maxwell had produced equations demonstrating that magnetism, electricity and light were all aspects of the same phenomenon.

Two conceptual truths of the Newtonian Worldview

We saw earlier that Kepler's heliocentric model rejected, or at least radically revised, two conceptual truths of the Aristotelian worldview: planetary motion as (1) circular and (2) uniform.

It turns out that the Newtonian worldview ultimately cracked along the lines of two other conceptual truths, both of which ultimately related to the nature of waves.

Light waves and the Michelson-Morley experiment.

First, on the Newtonian worldview a wave is, by definition, a disturbance of a medium which transports energy through that medium without permanently transporting the matter itself. Water waves move through water, sound waves move through the atmosphere. The idea of a wave moving through nothing makes about as much sense on the Newtonian view as a physical object that is made of nothing.

Newton himself believed that light was made of little particles, but he knew that it also displayed a wave like nature, since this provided the best available explanation of the phenomenon of diffraction. In the 1800's the wave-nature of light was generally accepted even though the medium through which light was propagated had never been detected. This undetected medium was known as the ether, and since light was known to travel throughout the universe the ether was believed to permeate the universe. For a long time it was not particularly disturbing that the ether had not been detected, since it was presumed to be a rather delicate and ethereal substance.

Michelson and Morley used a new device designed by Michelson called an interferometer, that would give indirect evidence of the ether, and actually measure the rate of the earth's motion through the ether.

Your author provides a nice analogy involving the differential paths of swimmers in the medium of water. (p. 194-95.) Here is an animated version. The basic idea is that since the earth is itself moving through the ether, light that sets off on different paths (e.g., one parallel to the direction of motion of the earth through the medium, and the other perpendicular to it) and travels equal distances from the perspective of its original starting place, will actually have traveled different distances through the ether. The interferometer, which looks like this, would detect these differences in the nature of the interference pattern that would result when the waves came back together.

The interferometer was a very sophisticated instrument that could be rotated 360 degrees so as to find the optimal angle for measuring our motion through the ether, however all of their experiments were ultimately consistent with a speed of zero. In other words, physicists were forced to contemplate the possibility that light waves moved through no medium whatsoever.

Black Body Radiation

A black body is an object that, under a certain temperature, absorbs all electromagnetic radiation, and over a certain temperature begins to radiate electromagnetic radiation, radiating all the different wavelengths as the temperature of the body rises.

According to the classical mathematical model of black body radiation the intensity of light emitted by a black body would increase to infinity as the wavelength decreased. This came to be known as the "ultraviolet catastrophe" because the predicted intensity of the radiation became absurdly high in the ultraviolet range of the spectrum.

Experiment seriously disconfirmed the classical model, but fixing it depended on an insight by Max Planck, which ultimately led to the modern theory of quantum mechanics. According to Planck's work, energy does not vary continuously, but can only come in discrete packets or "quanta."

Put differently, Newtonian physics assumed that space, time, motion, energy, etc., could all be modeled as continuous functions, meaning that the spaces, times, energy levels, etc. that one could occupy are as <u>infinite</u> in number as the real numbers themselves. Although the mathematics of the ultraviolet catastrophe is a bit complicated, you can get an idea of the problem if you imagine that the energy level of an object is accurately modeled as 1/x, where x is understood to be a variable that can become indefinitely small. It's easy to see that as $x \rightarrow 0$, $1/x \rightarrow \infty$.

The basic idea then, is that the Newtonian worldview, in assuming that quantities varied continuously, ended up making predictions about the phenomena being investigated that were simply off the charts.

Planck’s work, however, showed that atoms radiated energy only at discrete levels, and when the electromagnetic radiation was finally apprehended to be the result of the excitation of atoms, the quantum nature of energy generally began to fall into place.

In the end, however, the quantum view of nature probably makes even less sense to laypeople today than a moving earth would have made to a follower of Aristotle.

The Special Theory of Relativity

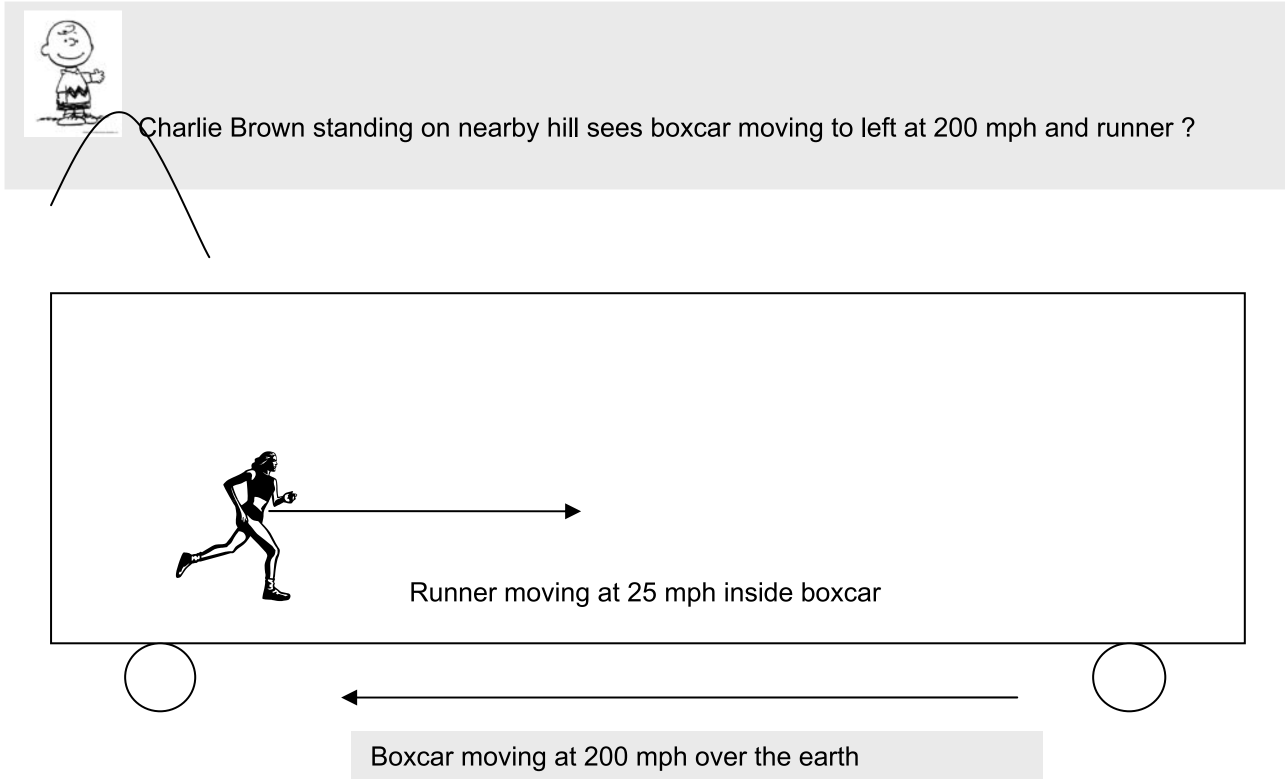
Einstein’s special theory of relativity is best summarized, not as the claim that “everything is relative” but rather as the claim that one thing is absolute, namely, the speed of light. According to the special theory of relativity, the speed of light in a vacuum is always the same, roughly 300,000 km/s.To the uninitiated, this may not sound very interesting, so it is important to try to grasp why it is, in fact, mind-blowing.

To begin to do this we need to go back to the ether which Michelson and Morley famously did not find. Earlier we discussed the ether as something whose existence was a matter of conceptual necessity: since waves just are disturbances in a medium, it follows that if light is a wave, there must be a medium through which it is propagated.

Another way of understanding the importance of the ether is that it would provide an absolute frame of reference for motion. If all of space is pervaded by ether that is not itself moving, then all moving objects are moving relative to the ether. The non existence of the ether is a big surprise then, because it makes the wave nature of light very eerie, and it robs us of an absolute reference frame.

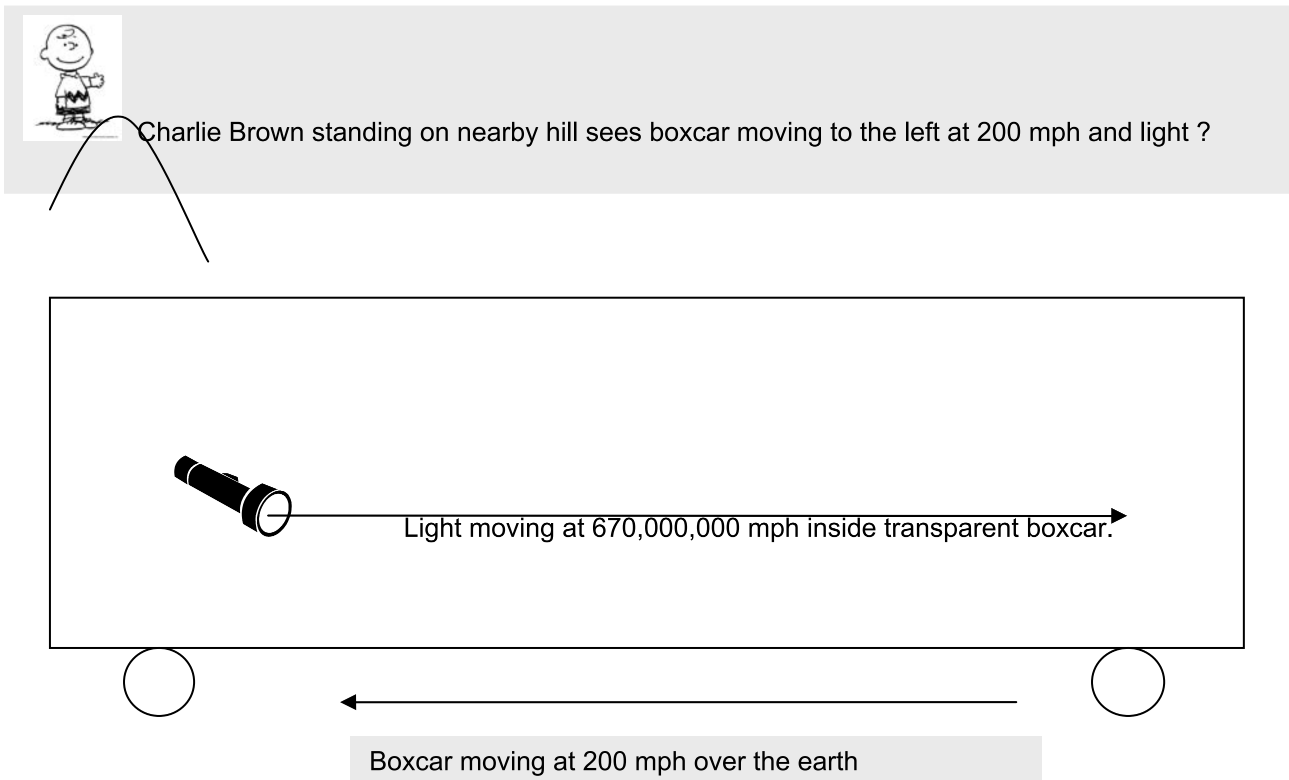
In some ways, the desire for an absolute reference frame was more a philosophical or even religious worry than a scientific one. Although Newton actually believed that space and time were absolute, the mechanics he developed was based on the relativity of motion.

Roughly speaking, according to classical relativity, there is no absolute basis for referring to one object as being at motion and another being at rest. The speed at which things are moving, depends completely on the frame of reference from which they are measured. For example, consider the drawing below to be a large box car moving at 200 mph to the left.



Charlie Brown and the runner occupy different frames of reference. Charlie Brown conceives himself and his hill as stationary, where the runner and boxcar are moving. From the runner's point of view, however, the boxcar is stationary and Charlie Brown and the rest of the world are racing buy. Both the runner's and Charlie Brown's frame of reference are what we call <u>inertial reference frames</u>, which means in this case that the laws of physics apply exactly the same in both reference frames. This means that any experiment performed in the boxcar would, all other things being equal, have exactly the same results as an experiment Charlie Brown performs on the nearby hill.

If you understand the relativity of motion from a classical point of view, then you are in a position to be disturbed by the central postulate of special relativity, that the speed of light is constant. What this means is that if you substitute a light wave for the runner in the boxcar you can not arrive at the speed of light by the same procedure.



The constancy of light together with the relativity of motion has three important implications, all of which have straightforward mathematical derivations.

1. Time passes more slowly for people in motion.
2. Distances shrink for objects in motion.
3. Events that are simultaneous from one reference point are not necessarily simultaneous from another reference point.

Einstein’s proof of the constancy of the speed of light.

Why is the speed of light constant? Basically, the answer is that light is our fundamental measuring stick, and we have no choice but to consider our measuring sticks to be rigid.

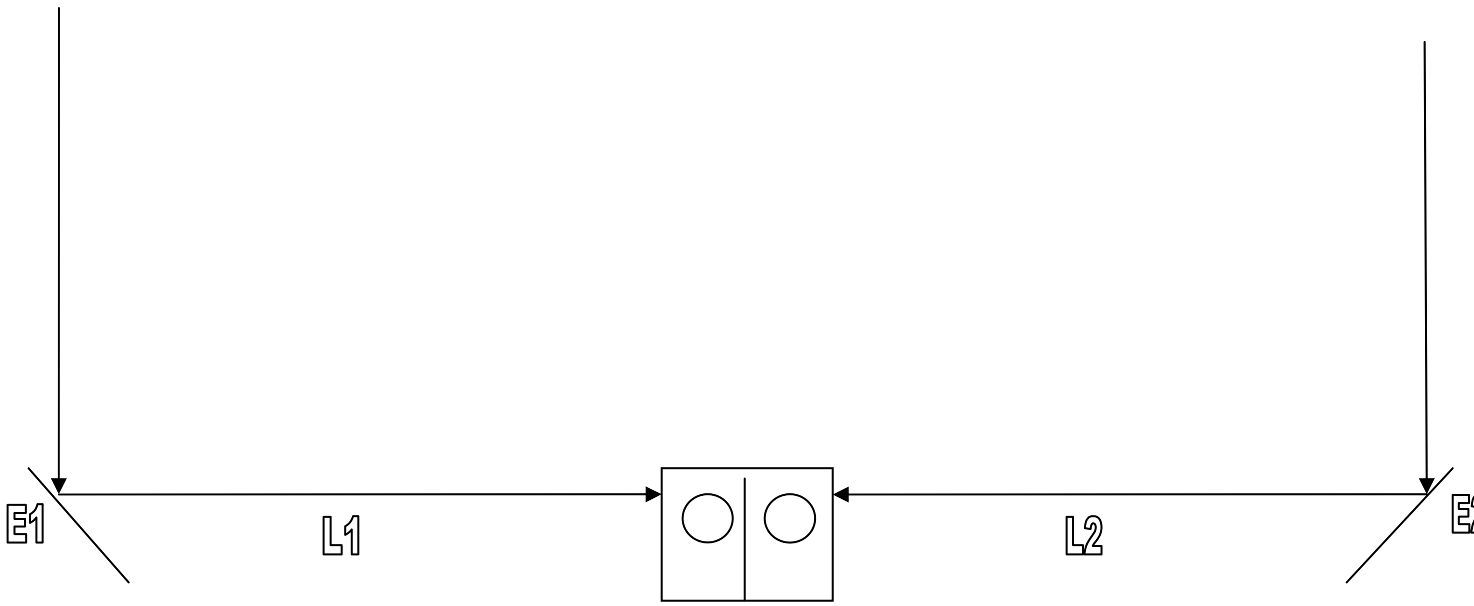
Let’s see if we can make some sense of this by thinking about the process of measurement itself. How do we do it? Imagine that you are shipwrecked and trying to build a raft from available materials. Miraculously you have a saw and a hammer and some nails, but no measuring devices. So you find a nice straight seeming stick and cut it to some random length, and this will be your way of measuring the wood you cut to construct your raft. You can call your new measurement length “stick”.

Now notice that when you go about measuring off materials to cut you must define a measurement procedure, which will presumably be laying your stick end to end. For example, to cut a board that is five sticks long you will laying the stick end to end five times. This, of course, is not a trivial procedure. To be sure that you are doing this in a straight line you will need something else, like a piece of twine to hold taut from one end of the board to the other.

So notice that in building your raft you need to make certain assumptions about your measuring instruments. Specifically, you need to assume that they are rigid, i.e., that they do not themselves change their size or physical properties when you are using them to measure other things.

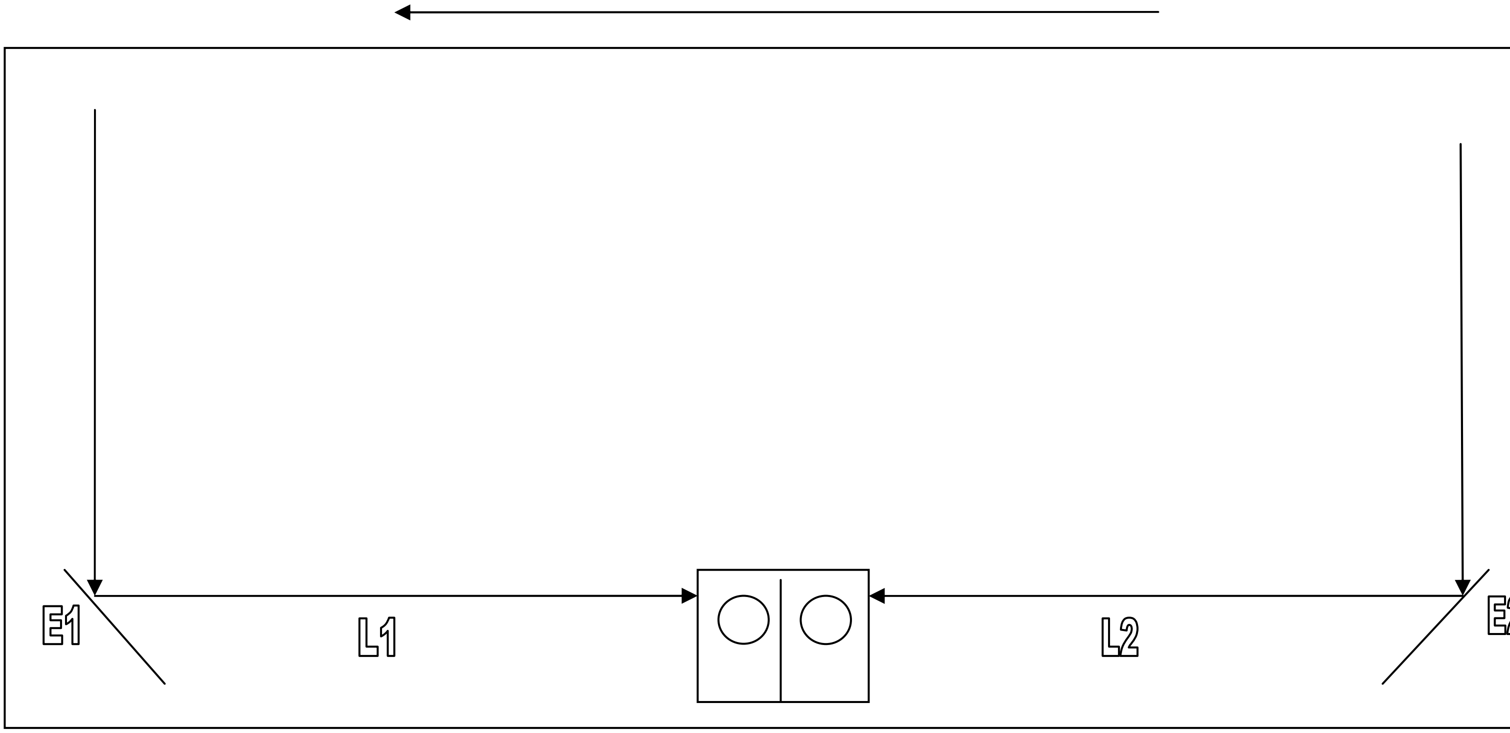
One practical way of understanding this would be to imagine that your stick gets, hence a bit longer when wet. So if you have precise measuring requirements you need to protect it from the weather. But you can also understand this concern more generally. Basically, you have <u>absolutely no way of determining</u> whether your <u>fundamental</u> measuring stick changes in size, and in length because it is what you use <u>to determine</u> changes in length. Put differently, it actually doesn't even <u>make any sense</u> to talk about your fundamental measuring stick changing its length because <u>length just is</u> what your fundamental measuring stick measures.

Back to Einstein. Einstein pointed out that whenever we make measurements we assume that the speed of light is constant. Why is that? Because light is the fundamental means by which information is conveyed. Einstein made this point by asking us to consider how we determine whether two remote events are <u>simultaneous</u>. For example, imagine that we are trying to determine whether two rays of light reached two different places at the same time. One way to do this is to set up a device like Michelson and Morley’s interferometer.



Our question is whether E1 and E2 happen at the same time. We set up the experiment so that two synchronized clocks are placed equidistant from the mirrors. (L1 = L2). The arrival of the light waves will stop the clocks. If they stop at the same time, then E1 and E2 must have occurred at the same time. But note that in designing the experiment in this way we had to assume that light would travel over L1 and L2 at the same velocity. This sounds like a perfectly reasonable assumption. But now suppose that you are doing this experiment in a train who is passing by Charlie Brown on a nearby hillside.

Once again, the train is moving 200 mph to the left.



Because both you and Charlie Brown assume the speed of light is constant, then what are simultaneous events for you, will not be simultaneous events for Charlie Brown. This was Einstein's proof that there is no such thing as <u>absolute</u> simultaneity.

Although your author just gives these as facts, we are going to take the time to understand the arguments behind them.

<u>Time Dilation</u>

The argument for time dilation, that time passes more slowly for people in motion proceeds by reasoning very similar to that which established the basis of the Michelson-Morley experiment. The reasoning and graphic illustration is presented here.

Length Contraction

The implication that distances shrink follows from the correctness of time dilation, and the requirement that special relativity remain internally consistent. The reasoning and graphic illustration are presented here.

Relativity of Simultaneity

The relativity of simultaneity can be easily demonstrated from the reality of length contraction, here.

The Twin Paradox

Finally, we have the twin paradox. This is a thought experiment that assumes the reality of time dilation, and argues that it is incoherent. The response to this argument defends the internal coherence of special relativity.

General Relativity

The twin paradox gets resolved within special relativity in the sense that it can be shown to be perfectly internally consistent. If we assume that there is no fact of the matter which twin is moving, but only a choice between two equivalent reference frames, then there is simply no fact of the matter which twin is older when they return. But this of course leaves open the question whether this assumption is correct, and it turns out that it is not. There is a difference, but it is a difference that special relativity can not itself comprehend.

The difference to focus on is that the twin on earth <u>experiences</u> no acceleration. We can talk about this subjectively, in terms of how it actually <u>feels</u> to take of in a rocket ship. We experience ourselves being thrown back against our seats as the rocket accelerates rapidly. But the point is not about how it feels, but what actually gives rise to those feelings, i.e., forces that are acting on the rocket ship twin, that are not acting on the earthbound one.

General relativity, then, is essentially the attempt to grasp the nature of the forces that give rise to acceleration. Now, if you go back to Newton's equations, you'll recall the second law and the universal law of gravitation.

- $F = ma$
- $F = \frac{G m_1 m_2}{r^2}$

The second law is what we typically use to make calculations about how bodies will accelerate when they are pushed or pulled by some force: a pull, a push, an explosion, or whatever. The universal law of graviation is used to calculate how bodies will accelerate in a gravitational field. Within the Newtonian system, there is no theoretical connection between these two forces.

What this means, is that the mass in the second law, what we call inertial mass, is actually not conceptually the same thing as the mass described in the law of gravity, what we call gravitational mass. Now, in fact, measurements of gravitational mass and inertial mass always yield exactly the same result, so it was postulated within Newton's theory that they are in fact the same. But it was a kind of miraculous coincidence, for which there existed no explanation whatsoever.

Here is another way to describe the situation. On Newton's theory there is no conceptual connection between the acceleration we experience as a result of gravitation, and, say, the sideways force you experience as your car accelerates through a turn. You might think this makes sense, that the pull of gravity and the pull that results from accelerating from a turn have completely different origins, but that is actually exactly what General Relativity denies. According to general relativity, these forces are the same.

Einstein motivates this point very elegantly, and your author cites his example on page 225. Suppose you are in an enclosed room, like an elevator that you can't see out of. Now here are two different situation.

1. The elevator is sitting on earth.
2. The elevator is far removed from earth or any other significant mass, but it is being accelerated upward at a rate of 9.8 m/s^2.

The number 9.8 m/s^2 is the rate at which bodies accelerate in earth's gravitational field. The question is, do you think you will be able to tell, from within the elevator, which is which?

The answer is you will not. The forces you are experiencing are identical in both cases. The upwardly accelerating elevator will provide you exactly the same "laboratory environment" as you would have on earth. You can do all the basic Newtonian experiments and they will all turn out the same just as if you were on earth.

The miraculous coincidence between the forces of acceleration and the forces of gravity within Newtonian theory are made plain in a famous and very simple

experiment, performed by Newton himself, now known as Newton's Bucket.
It is not covered in your book, but it is worth your time to go through it.

Like Einstein's elevator thought experiment, Newton's bucket shows that there is an intimate connection between gravity and the force of acceleration, one that Newton's laws fail to explain.

Einstein's General Theory of Relativity captures the connection between acceleration and gravity in two principles:

The principle of general covariance

1. *The principle of general covariance* is a generalization of the principle of the relativity of motion employed both in classical mechanics and in special relativity. According to the latter, the laws of physics are the same in all inertial reference frames. Recall that inertial reference frames are those that are not experiencing any form of acceleration. The principle of general covariance generalizes this to all reference frames, including those that are experiencing acceleration.

Here is one way to get an intuitive handle on the importance of this idea.

First, recall that on the Aristotelian worldview the "natural state" of objects (except for heavenly bodies) is rest. It is motion that requires explanation. On the Aristotelian world view motion was explained teleologically, as the result of an internal striving toward a particular goal.

Now, recall that the Newtonian worldview denied that there is an essential difference between rest and constant uniform motion. An object at rest from one inertial reference frame may be described as being in motion from another. Hence, from within the Newtonian worldview, the natural state of an object is inertial motion. It is acceleration, or change from one state of motion to another, that requires explanation. On the Newtonian worldview acceleration was explained mechanistically, as the result of being acted upon by a force. One of these forces is the force of gravity.

However, Newton himself understood that the force of gravity was no less magical than the teleological striving postulated by Aristotelian physics. As we saw in The Elegant Universe Newton understood the force of gravity as something that acted both instantaneously, and at a distance. (According to Newton's theory if the sun were to suddenly blink out of existence, at that very moment, the earth would go spinning out of orbit.) The concept of action at a distance does not make sense on Newton's mechanistic conception of the universe. The idea that gravity can exert it's effects instantaneously does not make sense either mechanistically, or in light of special relativity, according to which nothing can travel faster than the speed of light.

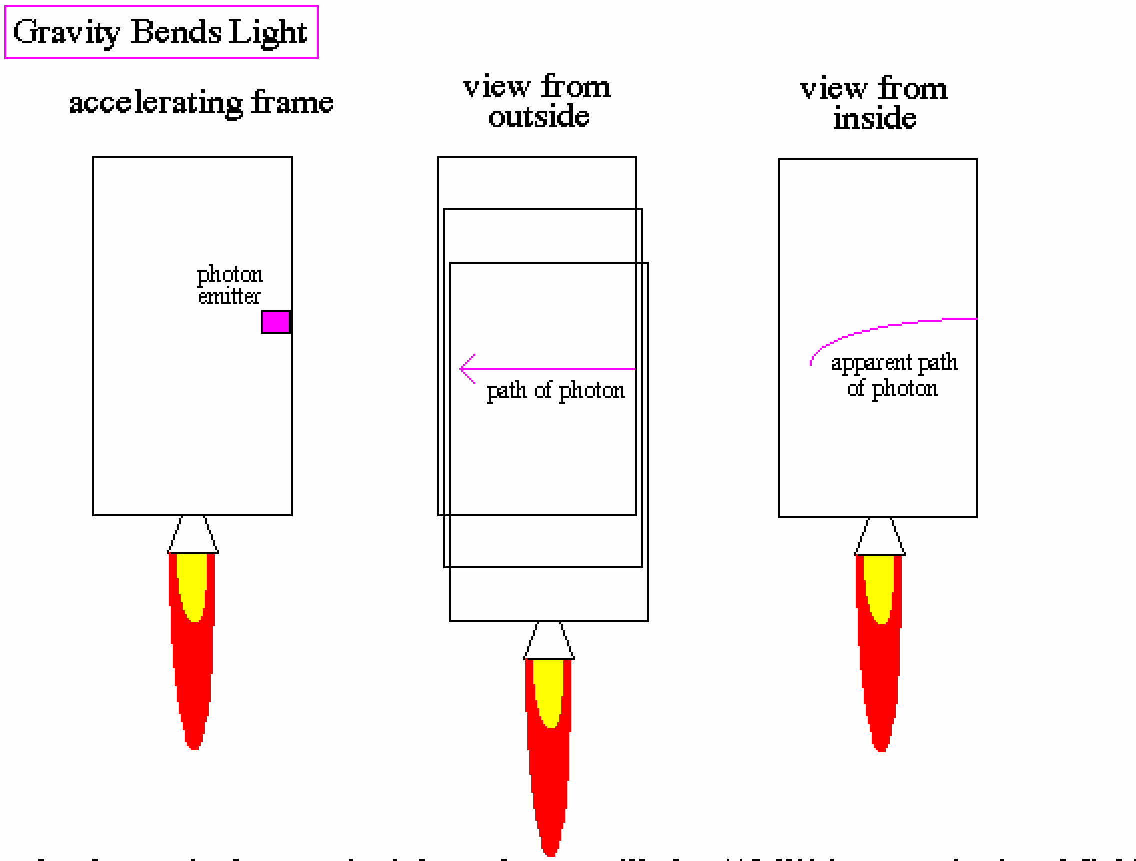
Einstein solved this problem by an insight similar to the one that allowed Newton to transcend the Aristotelian worldview. Although Einstein essentially agreed that it is acceleration that needs explaining, he disagreed about when we actually <u>are accelerating</u>. For Einstein, the “natural state” of an object is “free float”. The state that you would be in if you were simply floating in the middle of space. What’s interesting is that you are <u>actually in this state</u> when you are in “free fall” toward the earth. Absent the frictional forces of the earth’s atmosphere, there is absolutely no difference between falling with constant acceleration toward the earth’s surface, and floating freely through space. They both feel exactly the same, and all of the experiments you could conduct in a free floating laboratory would come out the same in a free falling laboratory.

Of course, you do notice a difference when you hit the earth after a period of free fall, but Einstein’s insight was to have noticed that this inconvenient fact is something that was given undue weight in Newtonian theory. According to Einstein, you are actually not accelerating when you are in free fall. Rather, you are accelerating when the earth is pushing on your feet, (a state that Aristotle would have described as a state of rest.) For this is the only time that your body actually experiences any forces. The force you experience is not the force of gravity, for on Einstein's theory gravity is not a force at all. Rather, it is the electrostatic forces of the earth's matter which are preventing you from your natural state of free fall. (Here it will be helpful to recall Einstein's elevator thought experiment. Being "at rest" on earth is equivalent to being accelerated upward outside of any gravitational effect at 9.8 m/s^2.)

The principle of equivalence

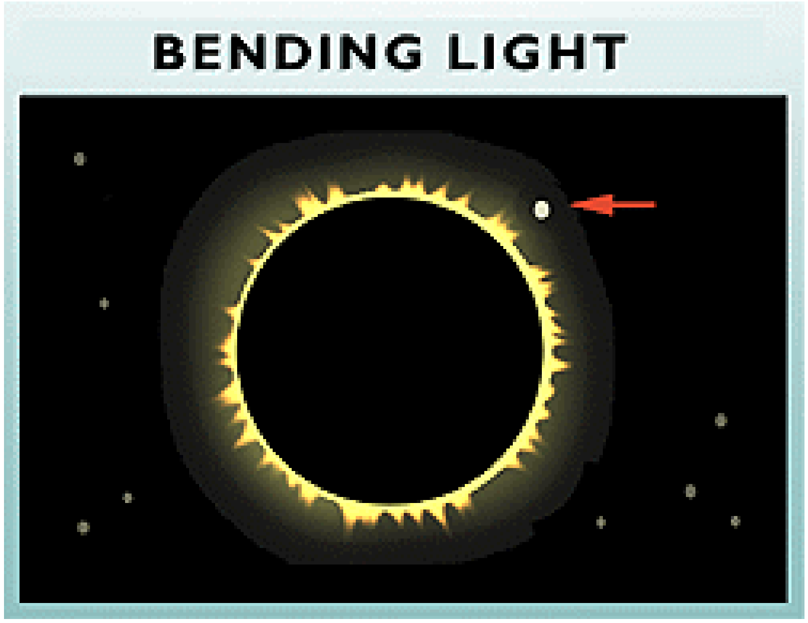
The principle of equivalence is the now familiar claim that there is no difference between the acceleration of an object (elevator being pulled upward) and the existence of a traditionally postulated gravitational force.

It is the principle of equivalence that results immediately in an empirically verifiable prediction of general relativity, viz., the bending of light. (I stole the drawings below from this excellent website on general relativity.) Since the force experienced by an accelerating rocket are the same as those experienced in a gravitational field, we can conclude that anything that happens on the rocket, will happen in a gravitational field. The bending of light from a perspective within the rocket is easily grasped.



by the equivalence principle, a photon will also ''fall'' in a gravitational field

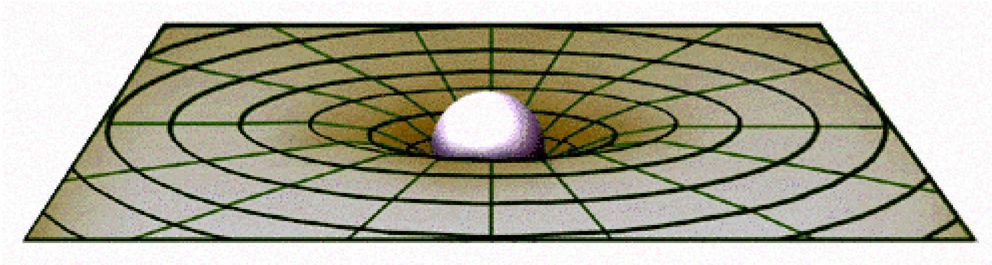
Light bends around stars. This bending can be measured. The first measurement that confirmed Einstein's prediction took place in 1919. Scientists wait for the moon to block the Sun and then look for stars that should not be observable unless their light has been bent to come toward us.



By similar reasoning, because being “stationary” within earth’s gravitational field is equivalent to accelerating motion, the relativistic effects we associate with motion, i.e., time dilation, and length contraction, are experienced within a gravitational field.

<u>Spacetime curvature.</u>

The actual mathematics of General Relativity isn’t accessible to laypeople, but the idea behind them is. As we have already seen, on Einstein’s view space and time are one thing: spacetime. It can be imagined as a flexible material that responds to massive objects by bending in the vicinity of the object, just like a stretched sheet of elastic material will bend when a heavy object, like a ball, is placed at its center.



As we saw in The Elegant Universe, it is this picture that allowed Einstein to replace Newton's instantaneous-action-at-a-distance model with a picture that was consistent with the special relativity. Matter moving through space-time creates wave-like disturbances that are propagated through it. The effects of gravity are not instantaneous. They occur at roughly the speed of light.

When we say that time is curved in the area of massive objects, we mean that it passes at a rate that is proportional to the strength of the gravitational field where it is being measured. As noted above, time passes more slowly- it gets stretched out- in strong gravitational fields.

Your book notes a further prediction of general relativity, the advance of the perihelion of Mercury. The perihelion is the point in a planet's orbit that is closest to the sun. With Mercury, this point is not stable, but precesses measurably. This effect theoretically occurs in all of the planets, but it is most pronounced in Mercury because Mercury's orbit is closest to the sun. The effect is due to the warping of space-time.

- This animation compares Newton and Einstein's predictions regarding the precession of Mercury's orbit, without explanation.

- http://faraday.physics.utoronto.ca/PVB/Harrison/GenRel/Flash/Precession.html

- This animation represents the effect as the result of space-time warpage.
  - http://io.uwinnipeg.ca/~vincent/4500.6-001/Cosmology/Precess.mpg

Instrumentalism/Realism Revisited

In closing this chapter on general relativity your author makes the very useful point that GR requires us to take an instrumentalist position on gravity considered as a force. This is interesting, because it shows that something that may initially have been accepted just for its instrumental value, but which over time, as a result of extraordinary predictive and explanatory success, becomes accepted realistically- and, of course, most laypeople today believe that gravity is a real force- may be returned to a purely instrumental status. Today we regard all of Newtonian physics as having a great deal of instrumental value- we still use it to do virtually all of our civil engineering- but we look to general relativity and quantum mechanics for our picture of reality.