Between Newton and Einstein: confirmation and hints of problems

Reference webpages:

http://en.wikipedia.org/wiki/John_Michell
http://en.wikipedia.org/wiki/Discovery_of_Neptune
http://en.wikipedia.org/wiki/James_Clerk_Maxwell

Last time we talked about Newton and the changes in thought that he initiated. In this lecture we will discuss the intervening years between Newton and Einstein, in which Newtonian theory was strongly confirmed with some spectacular discoveries, but in which there were also the hints of problems that would, in the 20th century, lead to the revolutionary ideas of relativity and quantum mechanics. We will also see the first appearance of black holes, although they are significantly different from the modern conception. Questions to keep in mind are:

1. How does the scientific method work in practice?
2. Can we ever declare a theory true? If not, how do you think this reflects on the utility of science?
3. How important is it for a theory to be quantitatively predictive?
4. Could there be arbitrary freedom in future theories?

A quick history of physical science between Newton and Einstein

Science advances at an ever-advancing rate, so it is barely possible to give a summary of just the physical sciences during this period. In astronomy, bigger and better telescopes were built, leading to the discovery of the planets Uranus and Neptune (more on those below), the first discovery of parallax and aberration of light (which were the last confirmations of the motion of the Earth), asteroids, and the composition of stars and planets via spectroscopy. In physics, in addition to new but equivalent formulations of Newton's ideas that would prove exceptionally useful in the later development of quantum mechanics, the laws of thermodynamics and electrodynamics were established (the former leading to another conservation law that we will discuss in more detail, the latter uniting the previously distinct subjects of optics, electricity, and magnetism). There were also discoveries that, although not of obvious significance at the time, led to rethinkings of many basic principles and led to the dramatic developments of the 20th century. These include the spectrum of thermal radiation, deviations of Mercury's orbit from the predictions of Newtonian gravity, and the stubborn refusal of light to travel at different speeds in different reference frames. We will now explore these topics in more detail.

Astronomical discoveries

The key to astronomical discoveries, from the 1600s onward, has always been bigger and better telescopes. In the 20th century we began to see in other bands than visible light, but we'll come to that story later. Many of the discoveries were made by amateurs, mainly because the idea of a professional scientist was not fully developed; for example, in England and France it was the landed gentlemen who tended to do science in their leisure time (with some exceptions, of course). A notable early discovery in this period was that the speed of light was not infinite. The first demonstration of this was made by the Danish astronomer Ole Rømer, who built on a suggestion by Cassini to show that the systematic drifts in the times that Jupiter's moons passed in front of Jupiter were explicable if light traveled about 300,000 kilometers per second; basically, when we are on the far side of the Sun from Jupiter the passages appear to occur later than when we are on the near side. This plays a key role in the existence of black holes. It also led to the discovery in 1725 of the aberration of light; basically, the direction to a star appears to change depending on the relative motion of the Earth. This therefore demonstrated experimentally that the Earth does indeed move, although no reputable astronomer doubted it by that time.

There were also further separations from the ancients, with one of the most important being the discovery in 1781 of Uranus, a planet that is not naked-eye visible and that dealt the death-blow to Kepler's tidy arrangement of polyhedra. The discovery was made by William Herschel, who also discovered infrared light, two moons of Saturn and two of Uranus, demonstrated that coral is an animal instead of a plant, and composed twenty-four largely forgettable symphonies in his spare time! Herschel's sister Caroline made many important astronomical discoveries in her own right, including eight comets and three nebulae, and she published an updated and corrected catalog of the positions of stars. Together the brother and sister made innumerable observations with successively larger and better telescopes, culminating in a giant 40 foot long, 50 inch diameter Newtonian reflector.

Several technological developments in the 1800s vastly improved the ability of astronomers to make repeatable, quantitative measurements. Photography allowed recordings of the positions and appearances of objects that were far more objective than the hand sketches that preceded it. More precise methods of measuring the angular distance between objects (notably the use of the heliometer) allowed, finally, the establishment that some stars show an annual parallax. As a reminder, one of the strongest arguments against the motion of the Earth is that nearer stars should appear to shift relative to farther stars if the Earth truly moved in its orbit. As this was not seen, and as the distance required to make it undetectable was enormous, it seemed more reasonable to the ancients that the Earth did not move. However, it really is the case that the stars are incredibly distant (the nearest star to the Sun is more than 200,000 times farther than the Sun is from the Earth), and this was finally demonstrated in 1838 by Bessel.

Yet another technological advance was spectrometry, by which light from stars and other objects can be broken up into very precise wavelengths. Since different atoms and molecules have different colors, their presence can be determined in spectrograms. This managed to embarrass the philosopher Auguste Comte, who in 1842 announced a limit to knowledge: "Of all objects, the planets are those which appear to us under the least varied aspect. We see how we may determine their forms, their distances, their bulk, and their motions, but we can never known anything of their chemical or mineralogical structure; and, much less, that of organized beings living on their surface...". Poor guy!

Physics discoveries

In the 1700s and 1800s, many of the cornerstone principles of physics were established. One of these led to another conserved quantity, to join linear momentum and angular momentum. This was energy. It is, however, difficult to keep track of energy compared to momentum, because it comes in so many forms: heat, kinetic energy, potential energy, chemical energy, nuclear energy, and so on. It took many careful experiments performed over more than a century to demonstrate that for an isolated system the total is always the same.

Richard Feynman used a nice analogy for this, which I'll paraphrase closely. Suppose a child receives a toy for Christmas: 28 indestructible blocks. He plays with them in his room. He's rather messy, so his father comes in to clean up every once in a while. After a while, the father notices an amazing thing: day after day, there are always 28 blocks in the room! One day, there are only 27 visible; a search reveals that one of the blocks is under the rug, though, so the total is still 28. Another day there are only 26. Careful examination shows that the window is open, and indeed the two missing blocks are outside. Another day there are 30 blocks! Yikes! But it turns out that the child had a friend visiting, and the friend brought two blocks with them, so that's okay. The next day brought a puzzle; only 25 blocks are visible, and the father has searched everywhere but the toy box, which is closed. The child throws a tantrum and refuses to allow the box to be opened. Being clever, however, the father weighs the toy box and discovers that it has excess weight exactly equal to three blocks. On yet another day, only 20 blocks can be seen. After all the other possibilities have been eliminated, the father notes that the bath water is higher than it was when the water was poured in. The bath water is dirty, so the father can't directly check if the blocks are in there, but using Archimedes' principle (in water, an object displaces its volume of water or its weight in water, whichever is less) he finds that just the right amount of water is displaced for 8 blocks. As time goes on, in fact, he discovers that there are always 28 blocks, although creativity may be required to discover where they are.

It was also discovered that the entropy (a measure of the disorder of a system) never decreases with time for a closed system. This is a frequently misunderstood law, and is often used by creationists to argue that evolution (in the sense of the development of more complex lifeforms) could never arise naturally. They forget that the Earth is certainly not a closed system; the Sun pours enormous amounts of energy onto us. Therefore, evolution does not violate the law of increase of entropy. For another example, note that snowdrifts, driven by random undirected processes, can produce exquisite forms. Note also that when water freezes it goes into a much more ordered form (ice is a crystal; liquid water is disordered). Neither of those two examples contradict the law of increasing entropy, because in both cases the *total* entropy of all particles in the system increases (for the freezing of water, heat is released and its increase in entropy more than makes up for the decrease in the entropy of the water).

Magnetism (as in the lodestone) and electricity (lightning bolts) had been known for a very long time, but in the late 1700s and beyond serious experimentation progressed. There were the inevitably silly pseudoscientists who exploited ignorance to make money, as today; for example, Anton Mesmer claimed to possess "animal magnetism" that allowed him to cure some ailments. It also led to remarkable flights of fancy when experiments with the amputated legs of frogs showed twitches in response to electricity, encouraging some people to think that electricity was the key to life and inspiring Mary Shelley to write "Frankenstein". Real experimentation, however, also occurred, with Michael Faraday in England and Joseph Henry in the US taking leading roles. As in chemistry (where scientists would sometimes try to identify a substance by tasting it!), the procedures of some early experimenters was, er, questionable. For example, people would sometimes gauge the strength of an electric pulse by judging the degree of numbness produced when the contact was put on their arm. Even Ben Franklin's kite experiment was extremely dangerous, and some attempted duplications of it led to deaths.

These experiments led ultimately to "Maxwell's equations", a set of four equations developed by James Clerk Maxwell that unified optics, electricity, and magnetism and predicted that not just light but all frequencies of electromagnetism could be produced. A nagging difficulty, however, and one that motivated Albert Einstein to develop his relativity theory, was that it appeared to look different in different reference frames. We will discuss this in more detail in the next lecture, but this was one of several developments that in retrospect paved the way for the understanding of the universe that emerged in the 20th century.

Overall, the 1700s and 1800s were centuries in which our understanding of the universe widened significantly (note that chemistry and biology also took overwhelming steps forward). Indeed, at the end of the 1800s the general feeling was that the basis of the universe had been established, and that the only thing left was some mopping up, maybe a few extra digits of precision in some measurements. This was dramatically wrong, and we'll discuss some examples later in this section, but first let's examine some of the reasons for this feeling.

Confirmations of Newton's universe

A hallmark of a scientific theory is that it is subject to ongoing tests, and if it fails those tests then one may be required to reject it. Newton's laws of motion and gravity had been unerringly successful for more than a century after his death, leading to correct predictions of the return of Halley's Comet and the motion of the planets. However, after Uranus was discovered in 1781 and followed for several decades, it became clear that it wasn't moving quite as it should. Newton's law of gravity is universal, so astronomers understood that in addition to the Sun's dominant influence there would be tugs from Jupiter and Saturn (also the other planets, but they are much less massive and thus contribute little). The motion of Uranus was calculated using these known objects, but it deviated slightly from the predictions. There are three responses one could imagine: (1) sweep this under the rug, ignoring the discrepancy, (2) ditch the theory entirely, or (3) look for an unmodeled feature that might explain the deviation. Independently, British and French mathematicians chose option (3), and specifically they proposed that a previously unseen planet was causing the deviations. In 1846 the planet Neptune was indeed found where predicted. What a tremendous confirmation of Newton's theory! Imagine if astrologers had predicted Uranus prior to 1781, or Neptune prior to 1846, based on unmodeled attributes of human behavior. We would have been much more likely to accept astrology as real, but no such predictions were made or ever have been made.

At around the same time, it became clear that Sirius, the brightest star in the night sky, had an unusual path. Instead of moving in a smooth way, it appeared to wobble slightly in its path. Newton's laws say that this cannot happen without a force being applied, so again we have our three options. Indeed, one might have argued that Newton's laws only apply in our solar system, so that Sirius could have been governed by entirely different laws. However, scientists proposed that an unseen star was orbiting around Sirius to cause its wobble and in 1862 this star was seen. Another tremendous success for Newton, although it turns out that this companion is a white dwarf, a stellar remnant that has properties unlike anything on Earth and that therefore can be considered to be the first step into new physical realms.

A consequence: John Michell and black holes

Given their confidence in Newton's ideas, a number of his successors worked out consequences of his laws of motion and gravity. One that was recognized during Newton's lifetime is that every object has associated with it an *escape speed*. That is, if we idealize things as usual and imagine an object with no atmosphere or rotation, we can ask how fast we would have to throw something from the object's surface so that it would never return, but just barely (i.e., it would eventually get to infinite distance with zero speed at infinity). For a sphere of mass M and radius R, this escape speed turns out to be $v_{\rm esc} = \sqrt{2GM/R}$ where as before $G = 6.67 \times 10^{-11}\ {\rm m^3\ s^{-2}\ kg^{-1}}$ is Newton's constant of gravity. For example, the escape speed from the Earth is about 11.2 km s^{-1}, or about 7 mi s^{-1}. When it became clear due to Rømer's discoveries that light had a finite speed, which we shall call c ($c = 2.99792458 \times 10^8$ m s^{-1}), a polymath named John Michell (mathematician, physicist, geologist, and theologian!) made the following argument in 1783. Suppose, he said, that we have a very massive object. If this object is also small enough in radius, then it could be that v_{esc} is greater than c. Therefore, light would not be able to escape from this object. As a result, said Michell, the most massive objects in the universe might well be dark.

In retrospect this is often considered the first published idea of black holes. In fact, remarkably, it turns out that the critical radius ($R < 2GM/c^2$ for Michell's dark stars) is the same as the radius for our modern concept of black holes if they do not rotate. This is, however, somewhat coincidental. In addition, Michell was working with Newton's theory of light as composed of corpuscles. He therefore would have imagined that light particles starting from the surface of one of his dark stars would have moved upwards against gravity but would ultimately be brought down, exactly as a ball thrown upwards will move upwards more and more slowly until it falls. He also would have imagined that, just as astronauts leave the Earth by gradually pushing away using rockets rather than leaving immediately at 11.2 km s^{-1}, astronauts could visit his dark stars and then leave. Our modern concept is a lot more ominous: black holes don't have surfaces at all, and once you fall within a radius of $2GM/c^2$ you can't make any outward progress *at all*; you are just plain doomed.

Hints of problems, in retrospect

With the benefit of hindsight we can look back on the 1800s as a time when, despite the tremendous predictive successes of Newton's theories, cracks were beginning to appear in this framework. One involved the motion of Mercury. If Mercury only orbited around the Sun, then Newton's theory would predict that it would move in a perfect ellipse in which it traced over the same figure over and over indefinitely. The gravity of the other planets causes deviations from this, so that the orbit does not quite close. However, careful accounting of that gravity led to predictions of the orbit that were not quite what were observed. Again, as with Tycho's observations of Mars and the orbital deviations of Uranus, the discrepancy wasn't much: the unmodeled drift of the orbit was only 43 seconds of arc per century. Based on the Neptune success people posited a planet interior to Mercury that they named Vulcan, but despite some occasional excitement no such planet was ever found.

Another problem emerged with Maxwell's equations of electricity and magnetism. You may recall Galileo's thought experiment in which a physicist in the hold of a steadily moving ship performed measurements of various phenomena. His argument was that these would be indistinguishable from the same measurements performed in a stationary frame. However, Maxwell's equations seemed to say otherwise or, to put it more objectively, if Maxwell's equations stayed the same for moving frames, then Newton's laws could not, and vice versa.

Given the success of Newton's laws most physicists would have bet in their favor, but by the end of the 1800s Maxwell's equations had accumulated their own list of successful predictions, so the resolution was unclear.

In what turned out to be a related problem, it was thought that like water waves or sound waves, light had to travel through a medium that was named the "ether". Assuming that the ether had some absolute rest frame, this implied that light traveling with the ether would have a measured speed that was different from the speed of light moving against the ether. Among other things, this meant that the speed of light in different directions and at different times in the year would be different. However, in a series of experiments that have been dubbed the most famous null results in the history of science, Michelson and Morley found no speed difference at all.

Yet another problem was the spectrum of a heated source (that is, the proportion of each energy of light emitted). Classical theory suggested a ridiculous answer: that an ideal thermal emitter would radiate infinite power. Given that you are not vaporized when you turn on a light, this is obviously incorrect.

There were therefore many problems that existed in physical theory at the end of the 1800s. If you had asked physicists of the time what they thought of these, most if not all would probably have dismissed them as minor, in the sense that additions to the existing models would suffice. This is not an unreasonable point of view; you only want to take major steps when they are really required. This is indeed what would happen in the 20th century.

Some thoughts about the scientific method

We have now come far enough in the course to meditate about the scientific method, both the simplified version you may have encountered and the way it is in reality. Note that this method is far from obvious, and it took a good two millennia from the original explorations of the Greeks to reach something approaching its current form.

Let's start with the version that you might have first encountered in high school. In this, you have the following steps:

1. Gather data.
2. Formulate hypothesis to explain data.
3. Make predictions with hypothesis.
4. Do experiment or perform observations to test predictions.
5. If predictions are successful, repeat from step 3 with new predictions.
6. If predictions are unsuccessful, discard hypothesis and go back to step 1 or 2.

Nice and tidy, isn't it? It is especially comforting, and unique in human endeavors, that if you are proven wrong (step 6), then you must objectively dump your ideas and start afresh.

It is perhaps unsurprising that reality is a lot more complicated. One example, which we encountered earlier, involved the discovery of Neptune. Here, we had a clear prediction (the motion of Uranus given the Sun and other planets) that was falsified. Using the simplistic version of the scientific method, we would have had to discard Newton's theory of gravity. Why wasn't this done?

The reason is that in reality, to use a quote I've seen attributed to Pierre Duhem, "hypotheses are tested in bundles". What this means is that it almost never happens that an experiment can test one and only one hypothesis. At the very least, in addition to whatever physical (or chemical or biological or...) hypothesis you are testing, you are also implicitly testing the notion that your equipment is working the way you think it is, and that you are not misinterpreting the results. A classical example of the latter is the announced discovery of "N-rays" by Blondlot, which he proudly thought would be a French contribution to match the discovery of X-rays by the Prussian Wilhelm Röntgen but which turned out to be entirely illusory.

Therefore, in principle ancillary hypotheses can always be added to save an idea. This, however, gets unsatisfactory after a while. For example, those of you with experience in calculus may know that a polynomial series (called a Taylor series) can be used to represent any nonpathological function to an arbitrary degree of accuracy. In the same sense, the geocentric model would work beautifully in describing planetary orbits if one added on additional epicycles, equants, and eccenters. What is one to do?

The solution is that when deciding between two hypotheses, one first compares their agreement with observations and experiments. Then, one compares the complexity of the models; all else being equal, one tends to favor the less complicated model (this is known as Ockham's razor). This rewards simple models as opposed to ad hoc ones. For example, if astronomical observations don't confirm my predictions I could claim that every single telescope that made such observations was flawed, but that would be an unnecessarily complicated explanation!

Another aspect of the scientific method that does not always make it into the simplistic explanation is the way that people generate hypotheses. Indeed, sometimes I get the impression that in the public eye scientists are just soulless calculating machines. If you ask an average person to name a profession that involves creativity, you are likely to hear suggestions about music or art, but rarely will someone suggest science.

And yet this is misleading. One of the joys of the scientific method is that inspiration for your hypothesis can come from *anywhere.* A classic example involves the chemist Fredrich Kekule, who in 1865 came up with the structure of benzene (involving a carbon ring) after falling asleep in front of the fire and dreaming about a snake grabbing its own tail! There are no limits to the source of a hypothesis. The difference is that whatever it is, no matter how beautiful and correct it might seem to its inventor, it has to be subject to tests against experiments or observations. Therefore, although Kepler was put into a rapture by his contemplation of nested spheres and polyhedra, the model simply doesn't work.

In addition, sometimes a scientist does not generate a hypothesis based on data, but instead based on their own aesthetics. Albert Einstein was such a person, and although his aesthetics worked extraordinarily well for relativity they led him astray with respect to quantum mechanics. Science is unique in all fields of human activity in having an ultimate arbiter (nature) as opposed to having to rely on personal convictions or competing holy texts.