Space, Time, and Gravity

Ever since humans settled enough to worry about more than when they would get their next meal, we have wondered about the universe and our relation to it. This has taken many forms, including music, art, religion, and, eventually, science. The modern scientific approach is, however, a development of only the last few centuries, and many aspects of it still strike people as nonintuitive. In this course we will explore as representatives of scientific thought the subjects of space, time, and gravity. We will show that the scientific study of these subjects, which is collectively objective even if many of the principals were anything but, has led to a host of perspective-changing discoveries culminating in the revelation of the expanding universe and the discovery of black holes. Along the way we will explore the drivers of investigations, and their aesthetic and religious motivations, as well as the general context of their societies. Ultimately, we will indulge in fanciful speculation about what arbitrarily advanced civilizations could do within the context of the known laws of physics.

In this lecture we will first give an overview of the key concepts that we will encounter throughout the course. We will then give a historical overview of concepts of space, time, and gravity, from pre-Greek views through Aristotelian and Ptolemaic systems.

Key concepts

Philosophical concepts:

1. Early philosophers relied largely on aesthetics to support their views. Observations were considered misleading (and in many cases, this is true!).
2. Modern science relies mainly on systematic observations and experiments to test hypotheses. Aesthetics do still have a role, e.g., in the form of Ockham's razor (if you have two models that fit the data equally well, you should be inclined towards the simpler model).
3. Hypotheses are tested in bundles. It is rare that you can make a test of just one thing; you have ancillary assumptions and conditions along the way. For a concrete example, should we discount the attractive nature of gravity because a helium balloon rises?
4. The progress of science in general, and of space, time, and gravity in particular, has had an overwhelming influence on technology. What is not appreciated as much is that science has also had a profound impact on philosophy and our conception of our role in the universe.
5. Nonetheless, there is an extremely common misunderstanding about the nature of scientific models. You can think of the development of a quantitative model (such as is common in physics and astronomy, and less common in the life sciences) in stages:

collect data, look for trends, produce a mathematical model that describes these trends and makes correct predictions, and finally consolidate the model into deeper concepts that allow us to reason our way through situations without solving the equations every time. Fundamentally, though, models are used to describe and predict data, so we shouldn't get too caught up in thinking that the concepts are reality and thus nature has somehow changed her mode of operation when concepts change. Baseballs didn't start traveling differently in 1915 when Einstein introduced general relativity!

Scientific concepts, old and new:

1. At various times people have been convinced that the universe is finite (e.g., the ancient Greeks) or infinite (many mideval and Renaissance conceptions). We can only see a finite portion of the cosmos, so we don't know for sure, but the data are consistent with an infinite cosmos (and if so, bizarre consequences follow).
2. There have been similar oscillations of opinion about whether the universe is infinitely old or of a finite age. There is extremely strong evidence that the universe we see is of an age that is not only finite but is very well determined: 13.7 billion years old. It is, however, possible that there have been oscillations of expansion and contraction, in which case the cosmos might be infinitely old.
3. The perceived nature of gravity has traveled from the natural tendency/desire of matter to reach the lowest point (Aristotle) to an unspecified action at a distance that acts as a universal inverse square law (Newton) to our modern conception that massive objects warp space and time (Einstein). Most physicists think that gravity, like the other fundamental forces, must be quantum in nature, and much effort is being expended but a testable theory has yet to be produced. In our current conception of gravity, highly unexpected phenomena and sources have been predicted and then observed. Two good examples are the expanding universe and black holes.

Pre-Greek views

Prior to the classical Greek era (starting in the sixth to seventh century BC and going for a few hundred years), observations and speculations about the universe were typically at the mythical or conceptual level rather than striving for quantitative predictions. They were often driven by practical considerations rather than by the abstract search for knowledge. With this in mind, we will begin our survey with an overview of early ideas about time.

Anyone who has not spent their life locked in a windowless room realizes that there are a number of natural cycles. Day and night are obvious, simple observation shows that the phases of the Moon change regularly, and over time the seasons are also predictable.

The predictability of the seasons in particular has been critical from time immemorial because knowledge of when to plant and harvest crops can make the difference between starvation and plenty. It is therefore unsurprising that since at least the beginning of agriculture (more than 10,000 years ago), various methods have been used to track days in relation to the year. It happens that neither months nor days divide evenly into a year, which has meant that different cultures have adopted different ways of adding or subtracting time units to compensate for the drift that would otherwise occur. Religious observances that are not bound to crops are sometimes allowed to drift. For example, the Muslim holy month of Ramadan cycles around the year as time goes on.

Shorter intervals of time have also been measured since ancient times. Sundials were used as early as 1500 BC, and fairly precise water clocks (also called clepsydras) were certainly in use by 1400 BC in Egypt, and possibly as early as 2000 BC in Babylon. Chinese use of such clocks goes back to the 6th century BC.

Ancient peoples came up with many imaginative myths to explain these cycles. For example, in Greek mythology the god Helios drove his chariot of fiery steeds across the sky each day. The goddess Selene similarly represented the Moon, and the seasons were caused by the harvest goddess Demeter reacting to whether her daughter Persephone was imprisoned with the underworld god Hades (during which Demeter let nothing grow, hence it was winter) or in the lighted world. These descriptions, although highly enjoyable, did not attempt any modeling or prediction. For example, the different lengths of days throughout the year would have to be attributed to some whim of Helios, rather than to a physical mechanism.

The situation is similar with respect to space and distance. Very early humans must have been able to communicate something about distance in order to congregate or hunt effectively. In fact, other animals have this capacity as well: a classic example is honey bees, who upon a return from a successful search for food perform a dance that indicates the distance, direction, and even quality of the food. Later, other measures of distance became important, such as the measurement of area (for, e.g., plots of land) or volume.

Early contemplations about the nature of space were almost always bound up with creation myths, some of which were remarkably imaginative. As a later example, the Norse creation myth had it that a frost giant named Ymir, who fed on the milk from a primeval cow (who in turn fed on salty ice blocks), was killed by Odin and his brothers, who used the body (some say the eyebrow) of Ymir to form the world. Fascinating, but again not particularly testable!

Our overall impression of the pre-Greek approach to time and space is that practicality and imagination both played roles, but there is no indication that it had occurred to anyone to look for impersonal mechanisms, let alone quantitative models.

Aristotelian dynamics

Starting around 600 BC with Thales, Greek philosophers began to look for principles that united many phenomena. Of these philosophers, one of the latest and certainly the most influential was Aristotle. We will therefore discuss his assumptions and models.

Although Aristotle was more empirically oriented than many of his contemporaries (for example, he performed dissections), he still relied far more on a priori aesthetic principles than he did on quantitative measurements. Among his assumptions related to dynamics were (see the Wikipedia page http://en.wikipedia.org/wiki/Aristotelian_physics for more details):

- Every thing has a natural place relative to the center of the Earth, which is also the center of the universe. It is not the case, as often assumed, that Aristotle thought that the Earth was glorified by being at the center; in fact, he looked at Earth as something of a cosmic sewer, and felt that it had the lowest place in the universe.
- Objects also have natural motion, and the natural speed is inversely proportional to the density of the medium. Speed in a vacuum would therefore be infinite, and since Aristotle didn't believe in infinite speeds he concluded that a vacuum could never be attained. Evidently Aristotle didn't have drinking straws. Another consequence is that since between atoms would be vacuum, matter has to be a continuum and not atomic.
- Aristotle, like his contemporaries, considered mathematics to be the highest form of intellect and geometry to be the highest form of mathematics. Of all planar geometrical figures the circle is the most perfect, and of all three-dimensional figures the sphere is the most perfect. Therefore, planets are attached to unchangeable celestial spheres centered around the Earth, which rotate and produce circular motion.

From the standpoint of gravity, he believed that heavier things fall faster than light things, and that falling objects have a constant speed (consistent with the "natural speed" assumption).

None of these principles has the virtue of being correct, yet these and other Aristotelian assumptions held sway for more than 1500 years. Why?

I think part of the reason has to be that many of the assumptions seem natural, and indeed in accord with everyday experience. Heavy things really do tend to sink; fire rises; and so on. Regarding gravity, if you drop a brick it actually will fall faster than a feather. Therefore, to the extent that people would check these assertions, many would seem plausible.

Another attractive aspect of Aristotle's physics is that it deals in reassuring aesthetic absolutes. Circles are beautiful (especially to geometers such as the Greeks), so it only makes sense that the basis of perfect heavenly motion should be circles.

It is illuminating to consider how you would proceed if you were an experimentally oriented Greek in the time of Aristotle. Suppose you wanted to explore the nature of motion and gravity, but were limited to the technology of the times. Suppose also that you had no knowledge or preconceptions about how nature or gravity worked. What would you do?

The Geocentric Model of the Universe

We will close our class with a discussion of a model of the universe that held sway for nearly two thousand years. It was the standard in China as well as the West, and it had the interesting property that in its most developed form, it *was* predictive, to a degree that allowed it to hold on for so long.

This is the geocentric, or Earth-centered, model of the universe. The basic ideas are simple:

1. The Earth does not move or rotate.
2. Instead, all objects in the heavens move around the Earth, in their own celestial spheres. The fundamental motion is circular (although see below).
3. The "wanderers" (planetae, or planets) move in different spheres than the fixed stars. Those wanderers were the Moon, Sun, Mercury, Venus, Mars, Jupiter, and Saturn.

In the Western world, this system was brought to its most sophisticated form by the 2nd century AD astronomer Ptolemy (Claudius Ptolemaeus). His greatest work impressed the Arabs centuries later so much that they named it Almagest (the greatest). Within this model, however, were many complexities that detracted from its aesthetic appeal. As a result, even centuries before Copernicus there were arguments against it.

Let us first consider the simplest such model one could construct. In this model, the Earth is at the center of the perfectly circular, constant speed motion of the planets (recall that the Sun and Moon are included as planets for this purpose). The individual circles might be tilted, they could have any needed radius, and the apparent speed along the circles would be whatever was required to fit the data, but that would be it.

That's all very well, but the problem is that careful observation of the planets from night to night revealed difficulties with this simple model. A classic example is that over many nights Mars appears to drift one way relative to the fixed stars, but sometimes it reverses its direction for a short while. This is called retrograde motion, and is clearly impossible to explain in the simple model outlined above.

In the cartoon version of the scientific method, one would have to abandon the model right here. After all, if an observation contradicts your model then your model must be wrong, correct? But as we said earlier, we always have to take into account that other complicating factors might exist. Not everything falls when you drop it; maybe your object is on a table, or perhaps it is buoyant.

Still, the ancients were cognizant of the problem of retrograde motion, and other models did exist. Aristarchus of Samos proposed that the Sun, not the Earth, was the center of the universe. He was largely motivated by his estimate of the size of the Sun, which put it at 6 times the diameter of the Earth (the real ratio is more than 100!). He thought it did not make sense that a large object would orbit a small one. His model, however, was not at all popular, for two basic reasons.

First, his model required that the Earth move and rotate. It is patently obvious that this is not so. Any time we move, we feel it; in the wind, in our observations of things moving relative to us, and in other ways. This posed a major problem that he was unable to answer.

Second, if the Earth truly moved, then the line of sight to the fixed stars would change. If some stars happened to be closer than others, their apparent position would change relative to their more distant fellows. This is called parallax, and you can see it for yourself if you hold a finger in front of you and focus on a distant background as you first look with one eye, then with the other. No parallax was seen to any star. Theoretically it was possible that even the closest stars were so far away that their parallax would be undetectable, but this would have required absurd distances. Even worse, the distances would have been so large that clearly there would have been vacuum between their respective spheres, and Aristotle's argument of infinite speeds ruled this out.

Therefore, although Aristarchus' model did provide a natural explanation of retrograde motion (as Copernicus would emphasize 1800 years later), it suffered from major physical problems. Hence rather than jumping to this model people looked at additions to the geocentric model.

In its final Ptolemaic form, the added complexities were rather substantial. For each planet:

- There was a main circle, called a *deferant*. The planet, however, did not move directly on the deferant. Instead, it moved on a smaller circle, called an *epicycle*, whose center moved on the deferant. This allowed for retrograde motion, among other things.
- The deferant itself was not centered on the Earth. Instead, the center was offset, and was called the *eccenter*. This was odd enough that our word "eccentric", meaning a bit off, comes from this.
- As viewed from the Earth, and even as viewed from the eccenter, the center of the epicycle did not appear to move at the same speed all the time. Instead, if you drew a line from the Earth through the eccenter and went an equal distance beyond the

eccenter, you got to the *equant*. From the equant, the center of the epicycle had a constant angular speed.

Whew! Man, that's complicated. The specific names of these things are not essential, but it does point out that in order to fit the observations an enormous level of complexity had to be added to the simplest geocentric model. Nonetheless, people stuck with this model for centuries because, at least over decades and to the accuracy needed for sea voyages, the model worked (and every few centuries it was updated with the newest observations). Tables were calculated to indicate when various stars or planets rose and set, and they corresponded to observations. Yes, there were some odd features. For example, in this model the Moon was twice as close to the Earth during the first and third quarters as it was during the full Moon, which anyone with eyes could see was incorrect. But in the large, the model did fine. In fact, from our modern perspective the epicycles, eccenters, and equants all actually mocked up the properties of elliptical orbits. If you have taken calculus, you know that any function can be represented as a sum of many terms of certain types of basic functions; for example, the exponential e^x is equal to $1 + x + x^2/2 + x^3/6 + x^4/24 + \ldots$ In a similar way, adding epicycles really will converge to the right motion.

Our conclusion from this lecture is that viewed from a modern perspective the earliest studies of space, time, and gravity were pursued irregularly. Scenarios were often mythically based, and even those that were more mathematical made fundamental aesthetic assumptions that we know now were incorrect. Note, though, that aesthetic assumptions have played productive roles in modern theories, so we shouldn't discount them entirely. The difference is that now we think nature is the ultimate arbiter, rather than our own preconceptions.