universe, together with a lot of effort by a lot of people over a long period of time. But as with the situation involving the size of the universe, there was a surprising amount of interplay between areas that are often thought to be isolated and separated from one another.

This is just a brief part of a complicated story concerning developments and changes in the 1600s. The acceptance of the belief in a huge, perhaps infinite universe, and the recognition of the principle of inertia, are mainly scientific beliefs. But as we have seen, the recognition and acceptance of these new scientific beliefs involved a surprising number of metaphysical, philosophical/conceptual, and religious beliefs.

CONCLUDING REMARKS

As emphasized at the outset of this chapter, the 1600s were a time of enormous change, including philosophical/conceptual change, religious change, political change, and of course scientific change. Our goal in this chapter was to appreciate some of the ways that philosophical/conceptual ideas, on the one hand, and more straightforward scientific ideas, on the other, can influence and feed off one another. The interactions between such areas are complex and fascinating, and in this chapter we have at least gotten a flavor of this.

CHAPTER TWENTY

Overview of the New Science and the Newtonian Worldview

The development of the new science in the 1600s was the cumulative effort of many researchers. The work that capped these efforts, however, was Newton's 1687 *Mathematical Principles of Natural Philosophy*. The work is generally referred to as the *Principia* (after its Latin title *Principia Mathematica Philosophiae Naturalis*). The *Principia* presented a new physics, compatible with a moving Earth, and provided the core of what we now think of as Newtonian science. This work also provides a convenient means by which to explore the Newtonian worldview, that is, the new jigsaw puzzle of beliefs that would be the successor to the Aristotelian jigsaw puzzle.

Our main goal in this chapter will be to take a look at both Newton's science, and the new (Newtonian) worldview. We will begin with an overview of Newton's science.

THE NEW SCIENCE

The science that went along with the Aristotelian worldview was a common-sense science, and one that fit well with an Earth at the center of the universe. But these scientific beliefs did not fit with a moving Earth, and thus, the acceptance that the Earth moves about the sun requires a new science. The new science was the product of a great deal of work over a number of decades. As mentioned above, this new science culminated in the work of Newton. As such, we will primarily look at Newton's science, although we should keep in mind that his work owes debts to a number of others. (It is also worth noting that Newton developed the calculus, which was also developed at about the same time, and independently, by Gottfried Leibniz (1646–1716). The calculus was an important mathematical tool in the development of Newton's science, and today remains one of the most widely used mathematical tools.)

The *Principia* is a substantial work consisting, in the most recent English translation, of about 600 pages. Newton's science, however, is often characterized as consisting, at heart, of three laws of motion together with the principle of universal gravitation. Certainly, in 600 pages Newton does more than merely present a handful of laws of motion and the notion of universal gravity. Nonetheless, there is a sense in which gravity and the laws of motion are the heart of Newton's science. In what follows, then, we will consider these, as well as discuss some general issues about Newton's science.

The three laws of motion

Newton begins the *Principia* with a section of definitions, in which he explains how he will be using various terms found throughout the book. His next section is a brief (about 10 pages) section in which he presents the three laws of motion.

The first law is what we now commonly term the principle of inertia. We first discussed the principle of inertia in Chapter 12, in which it was presented in the way it typically is today: an object in motion remains in motion in a straight line, and an object at rest remains at rest, unless acted upon by an outside force. Newton's phrasing of the principle is slightly different, but his phrasing, and the usual modern phrasing, are equivalent in meaning.

As discussed earlier, the principle of inertia runs contrary to everyday experience, and it was one of the more difficult principles to work out in the 1600s. Various precursors to it had been widely discussed in the previous century, and in the early 1600s Galileo made a variety of investigations of bodies in motion, in which he almost, but not quite, correctly characterized the key idea of inertia. By the mid-1600s, Descartes had an accurate characterization of inertia, and Newton's first law of motion borrows substantially from Descartes' characterization.

To understand the second law of motion, consider the behavior of hit baseballs. The harder you hit the ball, the faster and farther it goes. That is, the change in the motion of the ball is proportional to the force applied (how hard you hit it). More fully, the second law of motion states that a change in the motion of an object is proportional to the force applied to the object, and takes place along the straight line in which the force is applied. The law is often summarized as "$F = ma$," that is, that force equals the product of mass times acceleration. As with the baseball example, this entails that the acceleration of an object will be equal to the force applied divided by the mass of the object.

The third law states that to any action there is always an opposite and equal reaction. The standard illustration of this law is the recoil of a gun, in which the action of the bullet being propelled in one direction results in an equal and opposite reaction, namely, the recoil of the gun in the opposite direction.

Universal gravitation

The three laws of motion, which again are central ingredients in Newton's science, take only about two pages to present in the *Principia*. The other key ingredient, the notion of universal gravitation, is somewhat more complicated to explain. Let's begin with the way universal gravitation is typically presented currently.

Universal gravitation is generally presented as a mutually attractive force between any two objects. For example, the gravitational attraction of the sun attracts the Earth toward the sun, and at the same time, the gravitational attraction of the Earth attracts the sun toward the Earth. Likewise, when I drop a book, the Earth's gravity attracts the book toward the Earth, but at the same time, the gravitational attraction of the book attracts the Earth toward the book. The gravitational attraction of the book has virtually no effect on the Earth because the Earth is so enormously more massive than the book; likewise, in the sun/Earth example, the fact that the sun is so much more massive than the Earth explains why the Earth's gravity has relatively little effect on the sun as compared to the sun's effect on the Earth.

More particularly, the gravitational attraction between two objects is proportional to the product of their masses. That is, the more massive the objects, the greater the gravitational attraction. Also, the attraction is inversely proportional to the square of the distance between the objects, so that as the distance between objects increases, the force of the gravitational attraction between them diminishes rapidly.

Such is the way universal gravitation is typically presented these days. And in fact, this characterization of universal gravitation is presented in the *Principia*. But unlike the laws of motion, which are stated fully and concisely in the beginning of the book, this characterization of gravity emerges slowly.

Not counting the preface, Newton first discusses gravity in the first few pages of the *Principia*, in the section on definitions. At this point, though, Newton uses "gravity" only to refer to the force that attracts objects to the Earth, and he clearly is not using the term in the sense of universal gravitation. Much later in the book (400 pages later, in fact), Newton shows that the Earth's gravity must extend at least to the moon, and is responsible for the orbit of the moon. He also shows that whatever force keeps the moons of other planets (for example, the moons of Jupiter) in their orbits, that force must have the same characteristics as the Earth's gravity (that is, the attractive force is proportional to the masses of the bodies, and is inversely proportional to the square of the distance between the bodies). He also shows that whatever force keeps the planets in orbit about the sun must likewise have the same characteristics as the Earth's gravity. At this point, at Proposition 7 of Book 3, he is ready to generalize the notion of gravity: Gravity exists in all bodies universally.

Here, then, we finally have the radical notion of universal gravitation. And by the end of the *Principia*, Newton has treated us to an impressive display of the explanatory power of universal gravitation, coupled with the laws of motion. The *Principia* is a revolutionary work, and the range of phenomena that can be handled by this small number of ingredients (the three laws of motion plus universal gravitation) is truly impressive.

OVERVIEW OF THE NEWTONIAN WORLDVIEW

Again, the Aristotelian worldview is an Earth-centered worldview. And the belief that the Earth is at the center of the universe is not merely a peripheral belief, but a core belief, one that cannot be replaced without replacing most of the pieces of the jigsaw puzzle. Newton's science provided many of the scientific pieces of a new puzzle – in particular, Newton provided a science with extraordinary explanatory power and, notably, one compatible with a moving Earth. Notably, most of the pieces of the Aristotelian jigsaw puzzle – and not just the scientific pieces, but the philosophical/conceptual pieces as well – are not compatible with the new science. In other words, we needed a range of more philosophical/conceptual pieces to accompany the scientific pieces supplied by Newton.

For example, on the Aristotelian worldview the universe was viewed as teleological and essentialistic. Objects behaved as they did because of internal, essential natures. But with Newton's science, objects no longer behave because of internal essences; rather, objects behave as they do largely because of the influence of external forces. The entire Aristotelian view of the universe as a universe full of goals and purposes doesn't fit with the new science, and indeed, the universe begins to be viewed as more like a machine. In the same way that parts of a machine push and pull against one another, and the behavior of the various parts is due to the forces applied to them by other parts, so likewise the behavior of objects in the universe comes to be viewed as due to the push and pull of other objects and forces acting on them.

This machine metaphor becomes the dominant metaphor for the new worldview. That is, the universe comes to be viewed as a mechanical universe, one that is like a machine. And this sort of universe, in which the push and pull of external forces are central to understanding the behavior of objects in the universe, is very non-Aristotelian. In short, the teleological and essentialistic view of the universe, which went hand in hand with the science of the Aristotelian worldview, is replaced by a mechanistic, machine-like view of the universe, which goes hand in hand with the new science.

Accompanying the machine metaphor, the view of God changed as well. Again, for Aristotle himself, the gods were not religious gods at all, but rather were needed to explain what kept the stars and planets in motion. And as previously mentioned, in later centuries Aristotle's conception of the gods was

replaced with the Christian/Judaic/Islamic conception of God. So although the details of the conception of God changed during the Aristotelian worldview, one central Aristotelian conception remained, that being the idea that God was a necessary component in the minute-to-minute workings of the universe. In other words, in the Aristotelian worldview, God, or something like it, was needed to run the universe, as a constant source of the motion of the heavenly bodies.

But with the new science, nothing like this is needed to run the universe. The motion of the planets, for example, is explained as a consequence of inertia (a body in motion remains in motion, so the planets, being in motion, will remain in motion) together with gravity (which explains why the planets move about the sun rather than going off in a straight line). In short, with the new science, God is no longer needed to run the universe.

Religious beliefs tend to be deeply entrenched, so not surprisingly, people did not abandon their religious beliefs. But the concept of God changed considerably. In particular, God came to be viewed as a sort of watchmaker God, that is, one who designed and constructed the universe, and set the universe in motion. But thereafter the universe runs along without the constant intervention needed in the previous worldview.

Likewise, the general conception of an individual's role in society changed. The Aristotelian worldview included what might be considered a hierarchical outlook. That is, much as objects had natural places in the universe, so likewise people had natural places in the overall order of things. As an example, consider the divine right of kings. The idea was that the individual who was king was destined for this position – that was his proper place in the overall order of things. It is interesting to note that one of the last monarchs to maintain the doctrine of the divine right of kings was the English monarch Charles I. He argued for this doctrine – unconvincingly, it might be noted – right up to his overthrow, trial, and execution in the 1640s. It is probably not a coincidence that the major recent political revolutions in the western world – the English revolution in the 1640s, followed by the American and French revolutions – with their emphasis on individual rights, came only after the rejection of the Aristotelian worldview.

In general, the Aristotelian worldview included a conception of a small, cozy universe, with the Earth at the center. The universe was full of natural goals and purposes, and the outlook was teleological and essentialistic. This extended to people as well, who had their natural places in the overall order of things, much as objects have their natural places in the universe. And God, or something like God, was needed on a day-to-day, minute-to-minute basis, to keep the universe in motion.

All of these views change with the emerging new worldview. The universe is now viewed as huge, and perhaps infinite, with our sun merely as the center of the revolution of the planets in our solar system. The universe was now viewed as machine-like, with no purposes or goals to explain the behavior of objects. Rather, objects behaved as they did as the result of external, purposeless forces. Nor was God, or anything like God, needed to run the universe. Rather, the universe ticks on, day after day, much like a watch ticks on.

PHILOSOPHICAL REFLECTIONS: INSTRUMENTALIST AND REALIST ATTITUDES TOWARD NEWTON'S CONCEPT OF GRAVITY

Before closing this chapter, it is worth taking a minute to discuss a rather interesting aspect of the usual Newtonian view of gravity, and one that ties in with some of the key philosophical issues we have discussed. In particular, I want to spend a moment discussing how, when viewed a certain way, the notion of gravity is a quite odd notion. Let me begin with an example I will return to later in the book. Suppose I put a pen on the table, and I ask you to move the pen, but without having any sort of contact whatsoever with the pen. You are not allowed to touch the pen, blow on the pen, throw objects at it, shake the table it is on, or have any sort of contact at all with the pen. Yet I am asking you to move the pen in spite of not being allowed to have any contact with it. You almost certainly will think I am asking you to do something impossible. And our sense that I'm asking you to do something impossible comes from a common conviction, and one that goes back at least to the ancient Greeks, that one thing (for example, you) cannot influence another thing (for example, the pen) unless there is some sort of contact or communication between the two. This conviction is often summarized by saying that there can be no "action at a distance," to use a common phrase.

Now let's return to the notion of gravity. Gravity is usually conceived of as an attractive force between bodies. To use a typical example, the gravitational force of the Earth attracts my pen, so that when I release the pen, it falls toward the floor. And if we ask "why did the pen fall?" the usual answer would be that it fell because it was under the influence of this gravitational force.

Likewise, if we ask whether gravity is a real force, that is, whether gravity really exists, the usual answer is "of course it does." That is, people typically take a realist attitude toward gravity, viewing it as a force that really exists, and that largely explains much of the everyday phenomena we observe around us.

I suspect that most of us take gravity with a realist attitude largely because we have been raised with the notion of gravity from an early age, and so we tend not to notice that there are some rather odd features of this realistic view of gravity. To see these odd features, contrast gravity with other cases where there is attraction between objects. For example, suppose I put a rubber band around two pens, and pull the pens apart, thereby stretching the rubber band connecting them. In this case, the pens are, in a sense, attracted toward each other. And if I release the pens, they will quickly move toward each other. But in this case, the nature of the attraction is easily understood – the pens are connected by a stretched rubber band, and it is exactly this stretched rubber band that is the cause of the attraction between the two pens.

We can easily understand the nature of the attraction in the case of the pens attached by a stretched rubber band. But now return to the dropped pen example, and note that there seems to be no connection between the pen and the Earth. There is no rubber band connecting the Earth and pen, no strings, no nothing. Yet in spite of the fact that there seems to be no connection whatsoever between the pen and Earth, the pen moves toward the Earth when released. Viewed this way, gravity doesn't sound like science; it sounds like magic.

In short, if taken with a realist attitude – that is, if gravity is thought of as a really existing force – then the effect of gravity sounds a great deal like some sort of mysterious action at a distance. And in fact, when Newton first published the *Principia*, there were quite a number of critics who attacked him for introducing a force that required mysterious action at a distance. Some of these critics were quite influential, including (to name just one among many), Gottfried Leibniz (noted earlier as the co-developer of the calculus). Leibniz criticized Newton for introducing "occult" forces into science, and the basis of this criticism was exactly the problem that gravity seemed to involve mysterious action at a distance.

One solution to this problem was to take gravity with an instrumentalist attitude, and indeed Newton himself typically professed to take an instrumentalist attitude toward gravity. To get a better sense of what this would amount to, consider again the dropped pen. Newton's equations, including those concerning gravity, can be used to make excellent predictions about how the pen will fall (for example, the rate of acceleration of the pen). Taking an instrumentalist attitude would essentially involve viewing such equations as providing an excellent account of the way *that* objects behave, while remaining agnostic on the issue of *why* they behave that way. In other words, one can use the equations, especially those involving gravity, to provide excellent predictions, while remaining silent on the issue of whether gravity is a "real" force.

Newton did hold out the hope that a realistic account of gravity could be given, consistent with the mathematical treatment he provided in the *Principia*, and in a way that involved only mechanical interactions with no action at a distance. But although the next two centuries would see somewhat different treatments of gravity (for example, the notion that objects are responding to a gravitational field acting locally, that is, without requiring action at a distance, would be one alternative approach), no completely unproblematic account would be forthcoming. (At least, the accounts are not unproblematic when viewed from a realist perspective. None of the accounts, including Newton's, is problematic so long as one adopts a purely instrumentalist stance. But again, to repeat a point made above, most people raised in the Newtonian worldview tend to take a realist, not instrumentalist, view of gravity.) Eventually, as we will discuss in later chapters, Einstein's general theory of relativity will provide an account of gravity that does not involve action at a distance. But as we will see, Einstein's account of gravity is very different from the Newtonian view of gravity that most of us were raised with.

CONCLUDING REMARKS

The old Aristotelian worldview was incompatible with the new discoveries of the 1600s. Its replacement certainly did not develop overnight, but eventually the new outlook described above emerged, and it is this outlook that we will refer to as the Newtonian worldview. As with the Aristotelian worldview, the Newtonian worldview developed over time, but it retained the key view of a mechanistic, machine-like universe. In the next chapter, we will explore some of the ways the Newtonian worldview developed over the next two centuries.

CHAPTER TWENTY-ONE

The Development of the Newtonian Worldview, 1700 to 1900

As with the Aristotelian worldview, the Newtonian worldview is not a static set of beliefs. It developed and changed in the centuries following the 1600s, but throughout the changes, the core elements of the worldview remained steady. Our goal in this chapter is to illustrate some of the developments that took place between roughly 1700 and 1900.

In general, our approach will be to try to convey a flavor of how promising the development of the Newtonian view was during this period, such that, by 1900, it appeared that most of the major questions about the world had been answered within a Newtonian framework. We will look specifically at the development of several of the major branches of science during this period, and end with a discussion of some of the issues still unresolved at the beginning of the twentieth century.

THE DEVELOPMENT OF THE MAJOR BRANCHES OF SCIENCE, 1700 TO 1900

Our first task will be to take a brief look at how some of the major branches of science, such as chemistry and biology, developed during the time in question. Although we will be looking at the development of these sciences only in outline, even this outline should serve to illustrate the ways in which the various branches of science became "Newtonized," that is, the modern versions of these sciences developed, and did so within the broad Newtonian framework. We will begin with the development of modern chemistry.