# I

# Nicolaus Copernicus: The Loss of Centrality

*The mathematician who studies the motions of the stars is surely like a blind man who, with only a staff to guide him, must make a great, endless, hazardous journey that winds through innumerable desolate places. [Rheticus,* Narratio Prima *(1540), 163]*

## 1 Ptolemy and Copernicus

The German playwright Bertold Brecht wrote his play *Life of Galileo* in exile in 1938–9. It was first performed in Zurich in 1943. In Brecht's play two worldviews collide. There is the **geocentric worldview**, which holds that the Earth is at the center of a closed universe. Among its many proponents were Aristotle (384–322 BC), Ptolemy (AD 85–165), and Martin Luther (1483–1546). Opposed to geocentrism is the **heliocentric worldview**. Heliocentrism teaches that the sun occupies the center of an open universe. Among its many proponents were Copernicus (1473–1543), Kepler (1571–1630), Galileo (1564–1642), and Newton (1643–1727).

In Act One the Italian mathematician and physicist Galileo Galilei shows his assistant Andrea a model of the Ptolemaic system. In the middle sits the Earth, surrounded by eight rings. The rings represent the crystal spheres, which carry the planets and the fixed stars. Galileo scowls at this model. "Yes, walls and spheres and immobility," he complains. "For two thousand years people have believed that the sun and all the stars of heaven rotate around mankind." And everybody believed that "they were sitting motionless inside this crystal sphere." The Earth was motionless, everything else rotated around it. "But now we are breaking out of it," Galileo assures his assistant. In the new model stars are no longer "fixed to a crystal vault"; they are allowed to "soar through space without support." [Brecht 1963; Blumenbach 1981, Vol. III, 762–82]

In Act Two learned scholars, a Mathematician and a Philosopher, visit Galileo in his study to look at the Jupiter moons through the newly discovered telescope. Galileo briefly explains the failings of the Ptolemaic system to them. It simply is not consistent with the facts. The planets are not "where in principle they ought to be." And the motions of the Jupiter moons around their planet, Galileo's great discovery, can simply not be explained on the Ptolemaic system. So much for words! Seeing is better than talking. Rather naively, Galileo asks his learned guests whether they would "care to start by observing these satellites of Jupiter." Unfortunately for Galileo both the Mathematician and the Philosopher refuse Galileo's invitation. Rather than observations, they demand "a formal dispute" in the scholastic tradition. "Mr. Galileo," asks the Philosopher, "before turning to your famous tube, I wonder if we might have the pleasure of a disputation? Its subject can be: Can such planets exist?" Galileo simply wants them to "look through the telescope" and convince themselves. "Of course, of course," says the Mathematician, "I take it you are familiar with the opinion of the ancients that there can be no stars, which turn round centers other than the Earth, nor any, which lack support in the sky?" Brecht only dramatized a real event. In a letter to Johannes Kepler (dated August 19, 1610), Galileo laments the steadfast refusal of scholastic professors, like Cesare Cremonini, a humanist at the University of Padua, to view the moon and the planets through the newly invented telescope. [Blumenberg 1955, 637]

## 2 A Clash of Two Worldviews

In his play, Brecht captures the clash of two worldviews brilliantly as he charts out the dialogue which might have developed between Galileo and his scholarly visitors. The disputation ends to the dissatisfaction of both parties. Soon the visitors leave without ever having glanced through the telescope. Adherence to the geocentric (Earth-centered) worldview makes Galileo's visitors disparage his appeal to observational evidence. Adherence to the heliocentric (sun-centered) worldview makes Galileo distrust the usefulness of learned disputations. In order to understand how the respective supporters of the two opposing worldviews came to clash so violently, as dramatized in Brecht's play, we have to look more closely at their presuppositions. We have to scrutinize the structure of the geocentric and the heliocentric worldviews.

Geocentrism predates heliocentrism by a millennium and a half. Copernicus knew of an ancient precursor: Aristarchos of Samos, who had proposed the conception of a moving Earth. But geocentrism remained the official explanation of the structure of the universe until its slow erosion in the sixteenth and seventeenth centuries. The dialogue between Galileo and his visitors could have taken place in the summer of 1610. The Copernican hypothesis had been known for 67 years. It would take another 77 years, until the publication of Newton's *Principia* (1687), before the geocentric worldview finally conceded defeat. It took 144 years of active debate and research for the Copernican view to establish itself. Can a scientific revolution take that long? What is important about a revolution is not its length but its depth. What makes a change revolutionary is its upheaval in an established structure, a reversal of viewpoints, a replacement of presuppositions. It is a general rearrangement of elements in a network, be it conceptual, political, or social. Some elements in the system are displaced, some replaced, and others remain. To understand a scientific revolution – the tangle of philosophical and scientific elements – we need to understand the system *before* its rearrangement. So to understand the Copernican revolution, we need to understand the geocentric worldview.

## 2.1 The geocentric worldview

> *Now the ancients build up one heaven upon another, like layers in a wall, or, to use a closer analogy, like onion skins: the inner supports the outer (…). [Kepler,* Epitome *(1618–21), Bk. IV, Part I, §3 (21)]*

Geocentrism is much more than the view that the Earth resides motionless at the center of the universe. It amounts to a worldview that emerged in two phases. First, Aristotle provided a physical cosmology – the larger architecture of the cosmos. His cosmology included an important theory of motion. Aristotle advanced some unsatisfactory ideas about the motions of the planets. In a second phase Ptolemy furnished the mathematical astronomy – the geometry of the planetary motions. The Greek division of labor between physical cosmology and mathematical astronomy hindered the development of astronomy for centuries. [Dikjsterhuis 1956, §77, 146; Mittelstraß 1962, Ch. 4.4; de Solla Price 1962] For it separates the dynamic question of physical causes – why planets move in particular ways – from the kinematic question of motion – how the motion of these bodies can be described mathematically. In his *Almagest* (published around AD 150), Ptolemy explicitly embraces this distinction. Physics deals with the corruptible bodies on Earth; it amounts to no more than guesswork, which is due to the "unclear nature of matter." Mathematics, however, provides certain knowledge, since it investigates the nature of "divine and heavenly things." [Ptolemy 1984, 36] This separation was to last until Kepler's discovery of planetary laws at the beginning of the seventeenth century. As a worldview, geocentricism claimed to provide a scientific account of what was then regarded as the cosmos. It engaged its adherents in a number of philosophical commitments. It presented to its believers a comprehensive and coherent view of the universe. So did heliocentrism. With so much at stake, Brecht's play rightly depicted the frosty encounter of three scholarly men in 1610 as a clash between worldviews.

## 2.2 Aristotle's cosmology

Aristotle constructs his cosmology on the basis of a two-sphere universe and a theory of motion. Later Ptolemy provided some mathematical refinements.

1 Aristotle constructs a **two-sphere universe**. It is divided into the *supralunary sphere*, which includes the moon and the region lying beyond it, and the *sublunary sphere*. This is the region between the Earth and the moon. The Earth is a tiny sphere suspended stationary at the geometric center of the much larger

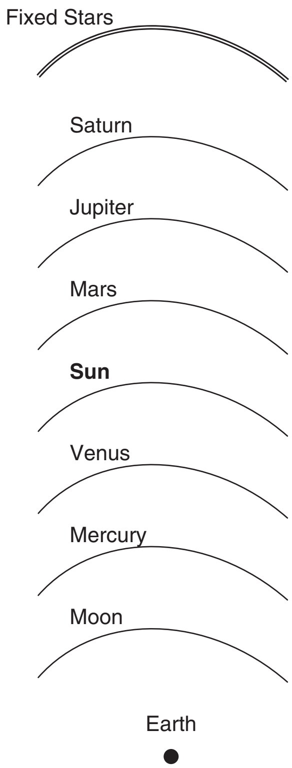
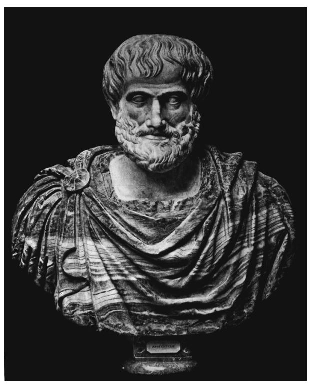



**Figure 1.1** The circular orbs and order of the planets in Antiquity. The sun is situated among the other planets. The Earth sits motionless at the center

rotating sphere which carries the stars. The stars are markings on the outer sphere. In this picture it is the steady rotation of the outer sphere that produces the daily (diurnal) circles of the stars. Between the outer sphere and the Earth, smaller concentric spheres carry the then known six planets, including the sun. [Figure 1.1]

The supralunary sphere is, according to Aristotle, a region of utmost *perfection*, *symmetry*, and *regularity*. The Greeks ordained the *circle* as a perfect geometric shape. It is therefore in accordance with the perfection of the supralunary sphere that the stars and planets should move in perfect circles. By contrast, the sublunary sphere is the region of *change*, *flux*, and *decay*. The sublunary sphere is filled with four elements: earth, water, fire, and air. If undisturbed, they would settle in concentric shells around the central region of the Earth. But owing to the movement of the sphere of the moon, the elements get mixed throughout the sublunary world.



**UF 1.1** Aristotle (354–322 BC)

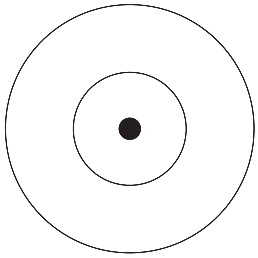


**Figure 1.2** A simple homocentric model. The Earth is located centrally. Nesting concentric rings or shells (orbs) envelop it. [See Andersen/Barker/Chen 2006, Ch. 6.4; Barker 2002] These carry the planets. The outer ring carries the distant stars. The model fails because planets move at varying distances from the Earth

The motions of the lunar sphere are therefore responsible for all change and almost all variety observed in the sublunary world. [Kuhn 1957, 82–3]

This cosmology of a "cosmic onion" sounds very obscure to modern ears. To ancient eyes Aristotelianism presented the most comprehensive and convincing theory of the architecture of the cosmos. It seemed to account for some of the naked-eye observations available at the time. The centrality of the Earth, so it seemed, could be inferred from the path of falling objects on Earth and the circular motion of the stars.

Following the Greek philosopher and astronomer Eudoxos (408–355 BC), Aristotle assumed that the planets and the stars moved in concentric shells (or orbs) around the central Earth. [Figure 1.2] On closer inspection, this simple model must fail. It did not even fit Greek observations. For instance, if the sun were carried around the central Earth on a concentric shell, night and day would always retain equal lengths. Yet the Greeks knew from their observations that day and night have variable lengths, depending on the seasons. [See Section 3.2] The Greeks also noticed that planets move at varying distances around the Earth. The model of homocentric spheres had to be dropped. It was in contradiction with elementary observations. It was Ptolemy's achievement to have constructed a geometric model on the basis of the more complicated geometry. It involved the invention of new geometric devices: eccentrics, epicycles, deferents, and equants. [Dijksterhuis 1956, §68, 147; Rosen 1959, Introduction; Copernicus, *Commentarioulus* 1959, 57; Copernicus 1543, Bk. V, §3; Dreyer 1953, 143]

2 Although Aristotle's rudimentary views of planetary orbs were quickly replaced, his **theory of motion** proved to be a much more lasting contribution. Aristotle devised his influential theory of motion to support his cosmology. His model of the cosmic "onion" made the Earth a central, stationary object. How could this centrality be justified? The theory of motion claimed to provide a physical mechanism to account for the trajectory of all objects – earthly and celestial.

According to the Aristotelian theory of motion, objects either remain at rest or move in a straight line. A stone will fall back toward the center of the universe, occupied by the Earth. Smoke will rise upward toward the sky, in search of its natural place. The upward and downward motions constitute the object's *natural* motions. In order to deflect objects from their natural motions an external push or force is needed. To move, objects need a mover, which moves them. There is no motion without a mover: *Omne quod movetur ab alio movetur*. [Aristotle 1952a, Bk. VII, VIII] Of course, Aristotle could observe that projectiles do not behave in this way. A stone hurled through the air or an arrow released from a bow will normally fly in a parabola before returning to Earth. Aristotle could explain the projectile's motion. After the release of the object from the mover, disturbed air became the source of the external push. It prolonged the projectile's motion.[1] Eventually the object would succumb to its inclination to return to the Earth.

The natural motion for heavenly objects is circular. Circular motion is continuous and infinite. Aristotle states that continuous motion – the rotatory locomotion of the planets – is caused by an unmoved mover, a Deity. [Aristotle 1952a, Bk. VIII, §10]

Thus things have natural and unnatural motions. They also occupy natural places in the universe. Aristotle held that the four building blocks of the universe – earth, water, fire, and air – hold natural positions on and near the Earth. If wrestled from their natural positions, the elements *strive* to regain their natural position. When a stone is lifted from the ground and released, it seeks to regain its natural position. When a fire is lit, flames and smoke leap up toward their natural positions at the periphery of the terrestrial region. The natural position of the Earth is at the geometric center of the universe. For something at rest must exist at the center of the revolving heaven. Therefore, Aristotle concludes, the Earth must exist. [Aristotle 1952b, Bk. II, §3] A piece of Earth will always fall to where it naturally belongs, i.e., the geometric center of the universe. From these arguments from terrestrial physics Aristotle derived not just the centrality of the Earth but also its stability and sphericity. [Aristotle 1952b, Bk. II, §§13–4] In lunar eclipses, he points out, the outline of the Earth's shadow on the moon "is always curved"; and as observers travel north and south along a longitude, different stars become visible to them in the sky. Later Ptolemy added some further arguments. The sun, the moon, and the stars are seen to rise earlier for inhabitants of eastern regions of the globe than "for those toward the west." [Ptolemy 1984, §I.4]

Aristotle's physical cosmology and his theory of motion form a logical link. The theory of motion renders the cosmology reasonable. And his cosmology provides the necessary framework for physical phenomena to be arranged into two separate spheres. The Aristotelian laws of motion govern the sublunary sphere. In the sublunary sphere terrestrial physics rules. The laws of motion account for the apparent observations in this region of space: the drop of heavy objects and the

[1] Kuhn [1957], 119; Dijksterhuis [1956], I, §§30–9. Contrast this account with the Newtonian explanation. According to Newton's First Law objects are either at rest or perform a constant rectilinear motion (if undisturbed). Rectilinear motion has become a "natural" motion, for which no external force is required.

rise of light objects. In the supralunary sphere celestial physics rules. This is the region of perfection. It admits only of spherical shapes and circular motion. It is a finite region. In Brecht's play Galileo complains about the "walls" and "immobility" of the geocentric universe. The distance to the stars was estimated to be 20,000 Earth radii, which is less than today's Earth–sun distance. [Zeilik 1988, 29–31] The outer boundary is marked by the sphere of fixed stars. Although this sphere rotates in a period of 24 hours once around the motionless Earth, the stars appear fixed because after each rotation they reappear in the same location as in the previous periods. The planets, by contrast, are "wandering stars," because they perform observable, traceable movements across the sky. The Aristotelian cosmos is an energy-deficient universe. Its energy-deficiency is a direct consequence of Aristotle's theory of motion. There is no motion without a mover. Heavenly bodies are moved on their spheres by a mover, residing outside the outer sphere. The Aristotelian universe requires an energy-input from beyond the fixed stars – it is finite. As we shall see, the Copernican universe is also finite but it is no longer energy-deficient.

## 2.3 Ptolemy's geocentrism

Aristotle gave us a cosmology and a theory of motion. This was the first step in the construction of the geocentric worldview. The second step was completed several hundred years later. It took a consummate geometer to do it: Claudius Ptolemy. Ptolemy was the first astronomer to design a complete mathematical system of the universe, which accurately predicted planetary motions to within 5° of modern values. His was a *geocentric* model, built by means of *geometric* reasoning. Later Copernicus would construct a *heliocentric* system, also built by means of *geometric* reasoning. Ptolemy uses geometry to describe astronomical observations. He agrees with Aristotle that the celestial spheres, which carry the planets, perform *uniform* motions. He assumes that the Earth is *spherical*, at the *center* of the cosmos, and *stationary*. If the Earth were not central, he argues, the equinox would not occur, and "intervals between summer and winter solstice would not be equal." [Ptolemy 1984, §I.5] Ptolemy offered perfectly good reasons for rejecting as ridiculous any motion of the Earth. Aristarchos of Samos (310–230 BC) is said to have taught the daily and annual rotation of the Earth. [Dreyer 1953, Ch. VI, 136–48; Dijksterhuis 1956, Ch. I, §§78–9; Kuhn 1957, Ch. I; Koestler 1964, 50–2] But if the Earth moved, its inhabitants would feel the effects drastically – objects thrown straight up into the air would not return in a straight line to the spot from where they had been launched; buildings would crumble under the force of the motion; birds would never fly from west to east. [Ptolemy 1984, §I.7; cf. Copernicus 1543, Bk. I, §7] To the Greek mind it was commonsense that the Earth was at rest.

**UF 1.2** Claudius Ptolemy (AD 100–75)

But there was a problem. The Earth-bound observer does not observe the uniformity of planetary motion against the background of the fixed stars. Equipped with his basic presuppositions, Ptolemy, like other astronomers before him, had to explain two main variations in the motions of the planets. *First*, there was their **nonuniform motion** and *second* their **retrograde motion**. The problem arises because the observations do not conform to the Ptolemaic presuppositions about planetary motions. The basic problem of ancient astronomy is to construct geometric models, which satisfy the a priori presuppositions and seemingly account for the apparent motions of the planets. It is the *problem of saving the appearances*, rather than constructing realistic models of the solar system. Like his Greek predecessors, Ptolemy relied on geometric models to solve these problems. Ptolemy tried to fit the observations to his unquestioned presuppositions: the circular motion of celestial objects and the Aristotelian theory of motion. But Ptolemy improved the usefulness of the models. Some of Ptolemy's predecessors, like Hipparchus (190–125 BC), had invented new geometric devices to deal with these problems. *Eccentric motion* was used to solve the first; *epicyclic motion* was used to solve the second. In his *Almagest* Ptolemy made frequent references to Hipparchus's work, usually with the intention of improving it. He introduced a new geometric device (the equant) to achieve a better geometric model of the appearances. He treated each problem separately. For instance, in dealing with the apparent annual motion of the sun around the Earth, he ignored its apparent daily motion. Unlike the Copernican model, the Ptolemaic model does not present a system in which the appearances are due to a common factor – like the motion of the Earth around the sun.

The first problem was the **nonuniform motion** of the planets through the zodiac, irrespective of the effect of retrograde motion. As Kepler later showed, planets do not orbit the sun at uniform speed. The nearer they are to the sun the faster they move, and the further they are away from the sun the more slowly they amble. But the Greeks could not accept such nonuniform motion as real. It had to be apparent.

How can uniform circular motion account for apparent nonuniform motion? The answer is eccentric motion. [Figure 1.3]

The sun is modeled as moving around the Earth on an eccentric circle at uniform speed. The circle is called *eccentric* because the Earth does not occupy its center. While the sun moves around the center of the eccentric, the Earth is slightly displaced from its center. The distance between these two points accounts for the appearance of variation in motion. As seen from the center of the eccentric, the planet moves through equal angles in equal times. But as seen from the Earth, the planet sweeps through different angles in equal times. For the Earth-bound observer, when the planet is closer to the Earth, it *seems* to be moving faster.

The second problem is the apparent anomalous westward motion of a planet with respect to the stars: its **retrograde motion**. It is accompanied by a change in brightness. For outer planets it occurs near the time of opposition, when the planet is opposite the sun in the sky. For inner planets, like Mercury and Venus, it occurs at inferior conjunction, when they are seen close together with the sun in the sky.

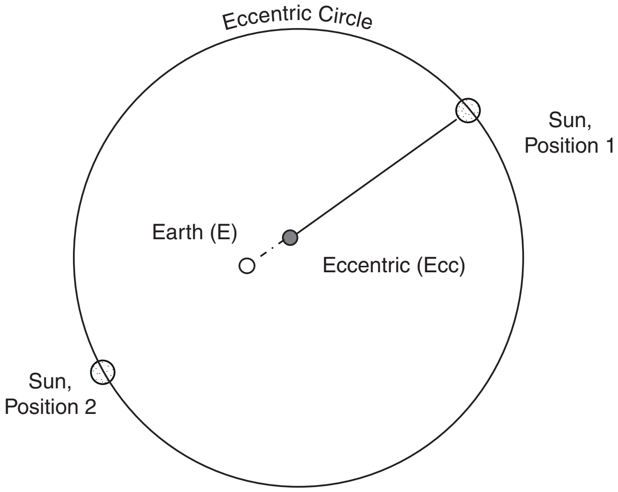



**Figure 1.3** Eccentric motion. Explanation of apparent non-uniform motion on the assumption of uniform motion. The sun moves uniformly around point (*Ecc*). Seen from the Earth (*E*), however, the uniform motion looks non-uniform. At point 1 the sun appears furthest away from the Earth (apogee), while at point 2 it appears at its closest approach to the Earth (perigee)

The ordinary eastward path of planets seems interrupted – for a time, observers see the planets go westward. [Figure 1.4]

The appearance of nonuniform retrograde motion was solved by using the geometric device of epicyclic motion. The planets are carried on smaller circles (epicycles) moving on larger ones (deferents). Although the Greeks observed retrograde motion, it was only apparent, not real motion. The real motion of celestial objects required uniform circular motion. The task consisted in constructing models that fitted the observations without violating the presuppositions. Epicyclic motion is modeled by introducing a *deferent*, with the Earth at the center, and a smaller circle, an epicycle, mounted on the deferent. [Figure 1.5a] The radii of both epicycle and deferent move in the same direction. For an observer on Earth the planet performs a retrograde motion as it passes through the lower part of the epicyclic motion. This model, however, is too simple. It cannot account for the observational variations in retrograde motion of the planets. To explain the variations, Ptolemy invented a new device: the *equant*. [Figure 1.5b] This is an imaginary point on the other side of the center of the deferent as seen from the Earth. At the equant, an observer would see the planet move around its orbit through the sky at a uniform speed relative to the stars. But from a viewpoint on Earth away from the circle's center, the motion appears nonuniform.

For our later philosophical exploration we should note several points. Ptolemy was very well aware of the role of representational models in his theory. His usual method is to use geometric models but in order to represent the fixed stars he chooses a solid globe as a scale model. [Ptolemy 1984, Bk. VIII.3] At the same

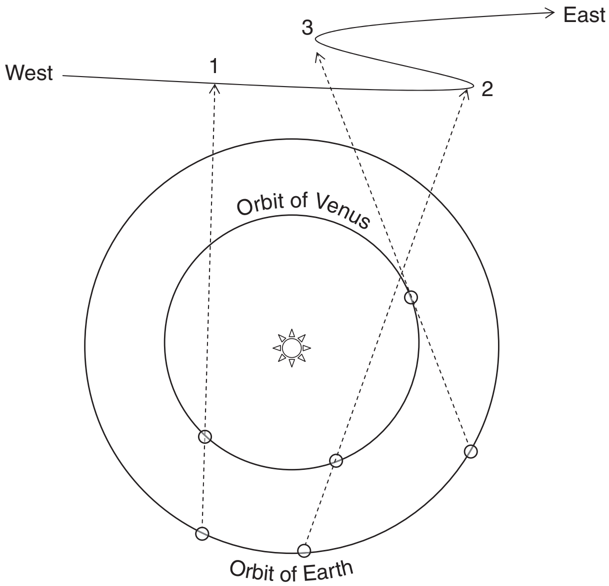



**Figure 1.4** A simplified scheme of the appearance of retrograde motion of Venus as seen from by an Earth-bound observer. The observer "marks" the position of Venus against the background stars as the planet prepares to overtake Earth in its orbit – position 1. When Venus has overtaken Earth, the observer makes a second observation: as expected, Venus has moved from west to east – position 2. But at a later stage, a third observation reveals an apparent and abnormal retracing of the orbit of Venus toward the west. In a heliocentric view this is due to the relative position of the Earth with respect to Venus around the sun. [See Zeilik 1988, 40; Copernicus 1543, Bk. V, §35]

time, Ptolemy worried about the fit of his geocentric hypotheses. He was skeptical enough to warn his readers not to expect his geometric models to properly represent the celestial phenomena. [Ptolemy 1984, 600–1] In the spirit of Aristotle's two-sphere cosmology he cautioned that geometric models invented by an inhabitant of Earth could not do justice to the perfection of the heavenly phenomena. As we shall see, the question of how models manage to represent physical reality is of great interest to philosophers. Finally, Ptolemy agreed with the Greek tradition that the epicyclic and eccentric models were equivalent devices. [Ptolemy 1984, §§III.3, IV.5, XI.5; Rosen 1959, 37; 1984, 27; Dijksterhuis 1956, I, §71] Either of these two hypotheses will account for the appearance of irregular motion of the planet to the Earth-bound observer. Nevertheless, Ptolemy adopts the principle that only the simplest hypothesis be used. [Ptolemy 1984, §§III.1, XIII.2] The acceptance of equivalence raises interesting philosophical issues regarding explanation and representation. If the eccentric circle is as good a representation as the deferent–epicycle device, is there no way of deciding which one fits the actual physical system better than the alternative? Such concerns belong to the philosophical consequences of scientific theories.

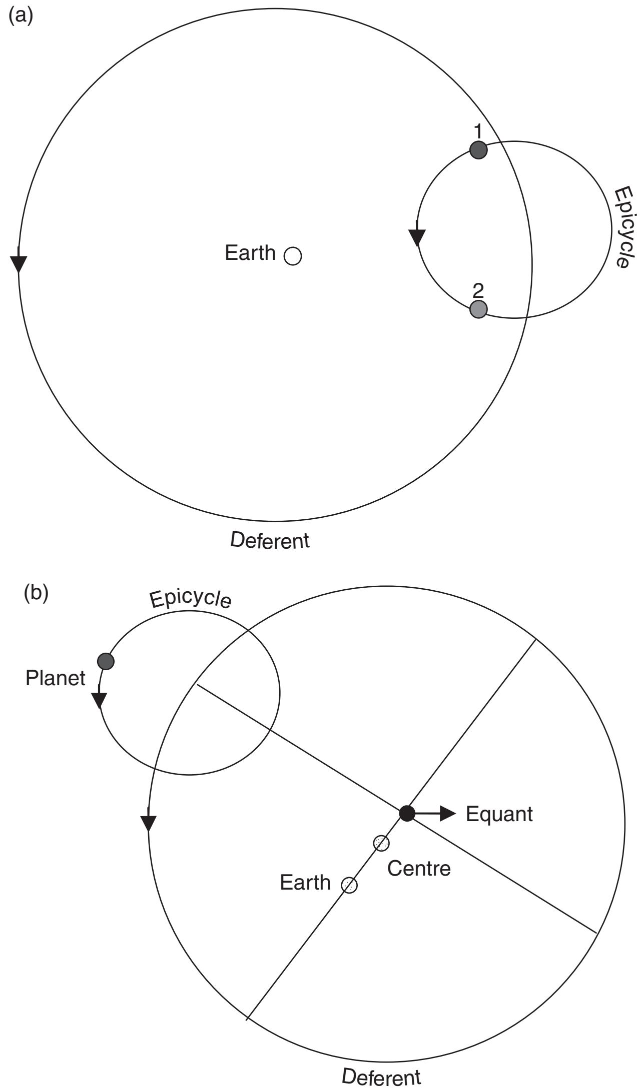



**Figure 1.5** (a) Epicyclic motion. Retrograde motion occurs when the planet moves from P1 to P2 on its epicycle; (b) The equant. Explanation of retrograde motion with a new geometric device, the equant. [See Copernicus 1543, Bk. III, §15–16; Ptolemy 1984, §IX.6; Andersen/Barker/Chen 2006, Ch. 6.3] This representation is supposed to be a closer fit of the model to the data than the elementary model. From the point of view of the equant, the motion of the planet on the epicycle would appear uniform. Further flexibility is introduced by letting the Earth either sit at the center of the deferent or off-center, as indicated in the diagram

Before we mention some of the developments of the thirteenth and fourteenth centuries, which created the conditions for the emergence of the Copernican revolution, we should add another historical dimension. This is the synthesis between *Aristotelianism* and *Theology*. Only this further historical dimension could bring to a head the clash between Galileo and the Church in the seventeenth century. The synthesis was worked out by Thomas Aquinas (1225–74), Albertus Magnus (1206–80), and others.

According to Acquinas, real knowledge is based on sense experience. Albertus Magnus also stresses that the study of nature is based on sense experience, which provides the highest form of proof. Where we lack knowledge we have to appeal to revelation. The perfection of the heavens, postulated in the Greek tradition, is now identified with Divinity. Consequently our knowledge of the world is restricted to the sublunary sphere. The perfection of the heavens transcends our reasoning powers. Aquinas welcomes the systematic study of nature because he sees in it a means to acquire knowledge of the wisdom of God. To put it drastically, Aquinas hopes that a systematic study of nature will help to eradicate superstition. Couched in these terms, no conflict between Reason and Revelation is permitted to arise, for our reason is weak and faulty and in questions of doubt has to submit to the eternal Truth as expressed in the Revelation. This is a common attitude in the Middle Ages. Roger Bacon (c.1210–92) defends a similar idea. The value of science lies in its contribution to the interpretation of the Bible. It helps to glorify God. Once the Church had embraced Aristotelianism, all criticism directed at the geocentric worldview would also be a criticism of theology and the Church.

Nevertheless, progress was made and some developments took place toward the end of the Middle Ages. Progress, however, depended on the ability to overcome unquestioned presuppositions, which impose constraints on permissible models. This need to clear away presuppositions before progress could occur could be expressed in Kantian terms. Kant asks very generally in his Copernican turn in philosophy, “What are the conditions of the possibility of knowledge?” By analogy we can ask, “What are the conditions of the possibility of the Copernican, the Darwinian, and the Freudian revolutions?” Which new presuppositions were needed for the Copernican view to be able to arise? The questioning of ancient presuppositions happened in two stages: the Aristotelian theory of motion attracted critical scrutiny before the ideal of circular motion was questioned.

## 2.4 A philosophical aside: Outlook

Let us regard the Aristotelian theory of motion and his physical cosmology or the Ptolemaic devices as instructions in a toolkit, with which we try to build a model of the universe. Our building blocks are fixed stars and planets, circular spheres, a stationary Earth. Our instruction sheet contains a further restriction: the model we build must be as close as possible to naked-eye observations. Most strikingly, we observe the movement of the planets against a background of stars, the succession of the seasons, and the regular sequence of day and night. With these elements at hand we can build only a *geocentric* model. The sun, the planets, and even the fixed background of distant stars must parade before our eyes. The Earth must therefore be located at the center of these movements, for otherwise we could not account for them. [Figure 1.1]

Our ability to build *one* type of model, if we follow the instructions, is at the same time an inability to construct a *different* model. We can think of the toolkit as creating a space, more precisely a *constraint space*, to accommodate cosmological models. Such a constraint space is a logical space, because it creates certain possibilities, whether they materialize or not, for model-building. Geometric-type models will be allowed to inhabit the space; other types of models are excluded. This play of possibilities and impossibilities is regulated by the constraints we accept. Aristotle operated under the constraints of his theory of motion and his two-sphere cosmology. If we change the constraints, a different logical space will appear, which will accommodate other types of models. **Constraints** can be understood as restrictive conditions, which symbolic statements must satisfy in order to qualify as admissible scientific statements about the natural world. This teaches us some lessons, which will interest the philosopher of science.

1. Scientific theories come with certain *constraints*: empirical and theoretical constraints, which can be further subdivided into mathematical, methodological, and metaphysical constraints. Scientific theories operate under such constraints. With the exception of empirical constraints, these constraints form *presuppositions.* Presuppositions are fundamental assumptions, which, at least for the time being, are protected from critical inquiry. They are accepted as "true." They serve as historical a priori. They are not unquestionable but they remain unquestioned for certain periods of time. Whether true or false, they channel research into particular directions. The Aristotelian toolkit contains such presuppositions. The two-sphere cosmology and his geometric devices, including the theory of motion, form the Aristotelian presuppositions. Presuppositions can be exposed to doubt. This happened when Aristotle's concentric shells were replaced by other devices. Under such scrutiny, constraints will be amended or rejected. Already a modification of the model instructions, keeping the elements, will change the possibilities for model construction. The adoption of epicycles, for instance, created the space for the Ptolemaic model. Sometimes a modification of a constraint is more far-reaching. A questioning of the Aristotelian theory of motion and its replacement by the so-called *impetus* theory liberated the constraint space for the development of new theories. It is difficult to imagine how heliocentrism could have emerged, if some fundamental presuppositions had not changed. [Blumenberg 1965, Ch. I] Copernicus, for instance, was able to reject some of the classic objections against the motion of the Earth, because he no longer shared the Aristotelian theory of motion. The development of the impetus theory allowed him to regard the motion of the Earth as natural.
2. We can also see that constructing a cosmological model is not a matter of simply reading it off the available observational data. It cannot be, if presuppositions are as much a reality of scientific thinking as its methods and established results. [Weinert 2004] So a simple inductive view of the scientific method will not do, at least not in the case of scientific revolutions. Let us call the view that sees science as a straightforward generalization from observations

and experiments *induction by enumeration*. Francis Bacon already criticized this view. There is a more sophisticated way, called *induction by elimination*. Francis Bacon recommended this view as a fruitful scientific method. It is called *eliminative induction* because alternative or rival models are confronted with empirical evidence and other forms of constraints. The model, which fares better in view of these constraints, will gain in credibility while the rival model will lose credibility. So this view requires that there are at least two models available, which face the evidence. As we shall see, the Copernican and Darwinian revolutions come about by a progressive elimination of unsuccessful models in the face of an increasing number of constraints. The difficulty with Freudianism is precisely that the available evidence is unable to credit some model at the expense of its competitors. Is the overwhelming method of science eliminative induction or the more familiar method of falsificationism, as proposed by Karl Popper?

Even at this early stage of the argument, it is good to raise these philosophical questions because – and this is one of the **central theses** of this book – philosophical issues are inseparable from more scientific and historical concerns. In other words, *scientific revolutions have philosophical consequences.* We shall witness this logic at many points along the road.

3. An immediate question springs to mind, not just for the philosophically inclined. Do these geometric devices actually represent physical spheres, while the nonuniform variations are just appearances? Do these geometric devices – the epicycle and the deferent, the equant and the eccentric – describe some physical mechanism, which exists in nature? This is the question of the *representational* force of scientific models, which already exercised Ptolemy. Does the distinction between appearance and reality, between how the planets appear to move according to naked-eye observations and how they are said to move according to the Greek presuppositions, correspond to a physical feature of the universe? If we are interested in what science is and does, such questions, although philosophical in nature, are inescapable. Whatever position we adopt in response to these questions, they actually do some real work. The proponents of the geocentric worldview were divided on this question. Aristotle thought that the spheres were real physical spheres. They possess a natural motion: circular rotation. The natural motion of these spheres drives all the heavenly bodies. They depend on an unmoved mover for their energy requirements. Ptolemy was much less certain of the physical reality of the crystal spheres, the epicycles and deferents, which he was employing as geometric devices. True, they served to *save the appearances.* But Ptolemy did not think that the geometric devices fitted the heavenly phenomena very well. [Ptolemy 1984, 600–1; Dreyer 1953, Ch. IX] The Greek models try to match naked-eye observations with a priori presuppositions about the physical world. The postulation of uniform circular motion, of the two-sphere universe, of geometric devices is not based on observations. On the contrary: the observations seemed

to contradict the presuppositions. So much worse for the observations! The separation between physical cosmology and mathematical astronomy did not encourage Greek astronomers to think of observations as tests for the mathematical models. The question is whether models can achieve more than saving the appearances. This question leads to considerations of *instrumentalism* and *realism*, *explanation* and *representation*.

The uncertainty as to the physical reality of the geometric models plagued the geocentric worldview until the moment of its definite demise. Especially the Arab world, which preserved the tradition of Greek astronomy throughout the Middle Ages, voiced much opposition against the "reality" of the geometric devices. [Rosen 1984] But they remained in use for some 1,400 years. They predicted planetary positions to the accuracy needed by astronomers who relied on naked-eye observation. And they conformed to Aristotle's theory of motion and cosmology.

As we can see, the description of the Aristotelian–Ptolemaic geocentric world-view points to some general philosophical issues, which are difficult to separate from the scientific material.

## 2.5 Shaking the presuppositions: Some medieval developments

> *(...) by the purpose of movement it is proved "that movement belongs to the Earth as the home of the speculative creature." [Kepler,* Epitome of Copernican Astronomy *(1618–21), Bk. IV, Part I, §5, 75]*

In Brecht's play Galileo clashes with the representatives of scholastic learning. Galileo is a believer in heliocentrism, observations, and the independence of the scientific method. The Mathematician and the Philosopher represent a world in decline: they put their faith in bookish learning, in the authority of the ancients, and cling to their belief in geocentrism. Galileo attempts to shake his visitors' beliefs. But they are not shallow opinions. They are based on philosophical presuppositions, which define their constraint space. In this constraint space certain models can be accommodated but others cannot. In the fourteenth century, some outstanding scholars became critical of the established doctrines: Nicolas d'Autrecourt (died after 1350), Johann Buridan (c.1300–58), Nicolaus of Oresme (c.320–82) at the University of Paris, and William of Ockham (c.1295–1349) at the University of Oxford. Two developments are particularly noteworthy: 1) Nicolas d'Autrecourt argued that philosophy and theology should be kept apart – a suggestion later taken up by Galileo and Pascal. The general idea is that natural philosophy should investigate the natural world and theology the spiritual world. 2) The Aristotelian theory of motion comes under critical scrutiny. Oresme and Buridan suggested, as Copernicus was later to do, that the diurnal motion of the Earth cannot be disproved by arguments derived from the Aristotelian theory of motion. According to Aristotle, the Earth rests motionless at the center of the world, because it inhabits its natural place. If it were to move, Earth-bound observers should feel the effect of this unnatural motion. Jean Bodin, a famous sixteenth-century political philosopher, echoes this age-old reasoning in 1597, fifty years after the publication of Copernicus's book (1547):

> No one in his senses, or imbued with the slightest knowledge of physics, will ever think that the Earth, heavy and unwieldy from its own weight and mass, staggers up and down around its own center and that of the sun; for at the slightest jar of the Earth, we would see cities and fortresses, towns and mountains thrown down. [Quoted in Kuhn 1957, 190]

As we have seen, Ptolemy advanced similar arguments involving the fall of objects and the destruction of buildings. The rejoinder in all these cases was to make the daily and yearly rotation of the Earth, to which Bodin refers, a *natural* motion. If we participate in this motion, Oresme and Buridan argue, then we do not perceive it. It is not a violent motion, says Copernicus, as Ptolemy thought. True, violent motion has the effect of breaking things up. But the rotation of the Earth "accords naturally with its form," so that every part of the Earth, "the clouds and the other things floating in the air or falling or rising up" take part in this natural motion of the Earth. [Copernicus 1543, Bk. I, §8] Copernicus employs impetus ideas to rebut the ancient, commonsense argument. If the air envelope travels along with the Earth and shares in its natural motion, the lack of violent winds is to be expected. Today we no longer accept the impetus theory. We are, however, all familiar with such phenomena. In constantly moving vehicles, our actions – drinking coffee, playing cards, reading books – happen as if the vehicles were stationary. Galileo's relativity principle serves as our explanation. The impetus theory was an important step toward the modern explanation of motion.

The *impetus* theory of motion was developed in the fourteenth century as an alternative to the Aristotelian theory of motion. According to this theory, as Oresme and Buridan explained it, a motive force is impressed upon an object, which carries it along. Then the argument against the motion of the Earth falls flat. Buridan first argues against the Aristotelian view of motion. If both a blunt and a sharp object are propelled along the same parabola, the air could not push in the same way on the sharp object as on the blunt one. It is better to say that a projector (internal propellant) impresses a certain *impetus* or motive force onto the moving body and that the projectile moves in the direction of the impetus. But air resistance and the "gravity" of the projectile decrease the impetus "till it is so diminished that the gravity of the stone wins out over it and moves the stone down to its natural place."[2]

The impetus theory played an essential role in the Copernican revolution: it was one of the conditions that made it possible. Buridan's pupil, Oresme, also based his refutation of Aristotle's central argument for the immobility of the Earth on the

[2] Quoted in Kuhn [1957], 120; according to Jeans 1943, 106, Hipparchus (c.140 BC) already held an impetus theory; on the impetus theory see the studies of Wolff [1978], Mittelstraß [1962] and Drake [1975].

impetus theory. He turned his attention to the first argument against the mobility of the Earth. It was claimed by the ancients that if the Earth moved eastward on its own axis, then an observer who threw a stone straight up into the air would see the stone return to the ground to the west of his feet. In the absence of the impetus theory, this argument seemed to make sense. On the ancient view the stone would be forced from its natural position and strive to return to it. But while the stone was in the air, the Earth would turn to the east. As the stone could not accompany the moving Earth, it must fall to the west from its point of departure. But Oresme argued that the moving Earth endows the stone with an eastward impetus. It will cause the stone to follow the moving Earth. [Kuhn 1957, 121; Mason 1956, §II.11; Wolff 1978, Pt. II, Ch. 7]

Buridan and Oresme extended this argument to the motion of the Earth. There was no need for "angelic intelligences" to move the celestial bodies. There was no need to postulate friction between the crystalline spheres to keep them moving in their 24-hour rhythm. There was no need for Aristotle's Unmoved Mover. There was no need for an energy-deficient universe. In creating the Earth God imparted a motive force to it, which sustains it in its motion. Unlike projectiles on Earth, which, according to the impetus theory, slow down because they encounter wind resistance and the Earth-bound force of their own gravity, no such forces interfere with the eternal motion of the Earth. More generally, the impetus theory suggested self-sustaining circular motion for the planets too. [Kuhn 1957, 121–2; Dijksterhuis 1956, II, §§111–5]

On the conceptual level, the impetus theory had important consequences. It lifted the ban on the possibility of the mobility of the Earth. The logic of the Aristotelian view immobilized the Earth. The arguments against its motion – falling objects, howling winds, tumbling houses – seemed to make sense. The impetus theory showed that it was conceptually possible for the Earth to move. The impetus theory also hinted at a unification of terrestrial and celestial physics. For it explained the trajectory of objects on Earth and in the heavens according to the same principle. It therefore led to the potential destruction of the two-sphere universe. Aristotle had made a distinction between rotatory locomotion, reserved for heavenly bodies, and rectilinear motion, for earthly objects. He regarded rotation as primary. [Aristotle 1952a, Bk. VIII, §9] The impetus theory held out the prospect of a dissolution of the dichotomy between supralunary and sublunary spheres.

However liberating the impetus theory was, arguments in its favor were never pushed to their logical conclusion. Fourteenth-century thinkers were content to investigate logical alternatives to Aristotelianism. They were not in the business of overthrowing it.

If the impetus theory was one of the conditions of the possibility of Copernicanism, the rise of *humanism* in the Renaissance was another. Renaissance humanism was directed against medieval scholasticism. As the Mathematician and Philosopher in Brecht's play show, the scholastic attitude viewed the Aristotelian tenets as sacrosanct. Scholastic scholarship consisted in the interpretation of Aristotle's texts. The Philosopher in Brecht's play reminds Galileo that "the universe of the divine

Aristotle is an edifice of (…) exquisite proportions." In the spirit of modern science Galileo counters that "the authority of Aristotle is one thing, tangible facts are another." But this objection only provokes the Philosopher into an indignant outburst: "if Aristotle is going to be dragged in the mud – that's to say an authority recognized not only by every classical scientist but also by the chief fathers of the church – then any prolonging of this discussion is in my view a waste of time. I have no use for discussions, which are not objective. Basta."

With humanism emerged a renewed interest in the mathematical and geometrical regularities of the phenomena of nature. This was important because Copernicus was among the first to revive the full Hellenistic tradition of mathematical astronomy, which had flourished in Ptolemy's time. [Blumenberg 1957; 1965; 1981] Humanism also put a new emphasis on human attitudes toward the cosmos. It reversed the age-old tradition, ever present since Ptolemy, that human knowledge could not extend as far as the heavens. Humanism elevates the astronomer to the status of a "contemplator caeli." [Blumenberg 1957, 77] It emphasizes that humans can understand the workings of the cosmos. This emphasis shifts the focus from understanding by way of observation to understanding by way of rational thinking. The emphasis on rational understanding on the basis of perspectival, Earth-bound observation had important implications for the heliocentric worldview.

## 3 The Heliocentric Worldview

> *And why not admit that the appearance of daily revolution belongs to the heavens but the reality belongs to the Earth? [Copernicus,* De Revolutionibus *(1543), Bk. I, Ch. 8 (17)]*

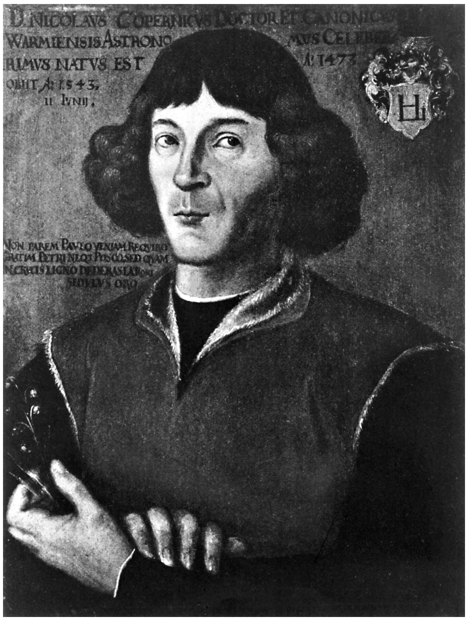
Nicolaus Copernicus died on May 24, 1543. Only a few weeks later his great book *De Revolutionibus* was published. The original title of the book had been *De Revolutionibus orbium mundi*. This intended title was changed, by Andreas Osiander, to *De Revolutionibus orbium caelestium: On the Revolutions of Heavenly Spheres*. [Blumenberg 1957, 79; 1981 Vol. II, 344] Osiander, a theologian and preacher based in Nuremberg, oversaw the publication of *De Revolutionibus*. He also added an anonymous, philosophically significant preface to Copernicus's work. Kepler later identified Osiander as the author of the anonymous preface. It is philosophically significant because Osiander tries to interpret *De Revolutionibus* as a treatise which, contrary to first impressions, does not challenge the accepted worldview. Copernicus had been working on his masterpiece for years but had hesitated to publish it. Like Darwin after him, Copernicus feared that his ideas would meet with a hostile reaction. Nevertheless, prior to the publication of *De Revolutionibus* handwritten copies of his "Sketch of his Hypotheses for the Heavenly Motions," known as *The Commenariolus*, had been circulating. It was written between 1502 and 1514. [See Rosen 1959, Introduction] In these works Copernicus worked out a heliocentric model of the solar system.

9781405181846_4_001.indd 20 5/27/2008 4:01:49 PM

## 3.1 Nicolaus Copernicus

> *Copernicus's achievement was not something forced by fresh observations, but rather was a triumph of the mind in envisioning what was essentially a more beautiful arrangement of the planets. [Gingerich,* The Book Nobody Read *(2004), 116]*

On closer inspection *De Revolutionibus* falls into two parts. In the first chapter Copernicus introduces the general idea of a heliocentric system. He argues that Greek objections to the concept of a moving Earth do not hold water. He points to a number of Greek predecessors of heliocentrism. He claims that heliocentrism provides a simpler or more coherent explanation of the solar system. For Copernicus, as for the Greeks, the solar system, with the fixed stars, constitutes the universe. The second part of the book contains the mathematical determinations of planetary motions. It is much more technical. But Copernicus uses the same geometric devices as the Greeks (eccentrics and epicyles).



**UF 1.3** Nicolaus Copernicus (1473–1543)

Since Kant, it has become customary to describe the result of Copernicus's labor as a **Copernican turn**. [Dijsterhuis 1956, Part IV, I, §§9–10, 18; Blumenberg 1981, Part V, V] This term is very useful: it marks the Copernican achievement without elevating Copernicus's work to a scientific revolution.

The Copernican turn is the conception of a heliocentric universe, in which the planets are carried on their spheres, not around a central Earth, but around a central (mean) sun. This in itself was not an original idea, since it had existed since antiquity. The Greek astronomer Aristarchus of Samos had constructed a heliocentric world system, according to which the Earth rotates daily around its own axis and annually around the sun. Other thinkers, both in antiquity (Herakleides) and in the fourteenth century (Buridan, Oresme, and Nicolaus of Cues), had conceived of a diurnal motion of the Earth. So what is original in Copernicus? Since Aristarchus's work has not survived, he became the first astronomer to have constructed a mathematical system of planetary motion from a heliocentric perspective. Copernicus attempts to derive all the celestial phenomena from a few basic assumptions. [*Commentariolus* 1959, 58–9] All the observations can be explained from the assumption of a nonstationary Earth. Copernicus assumes that the sun is stationary but Kepler later corrects this view: the sun turns on its own axis.[3] [Kepler 1618–21, Pt. II, §1] Copernicus was the first to develop a detailed account of the astronomical consequences of the Earth's motion. [Kuhn 1957, 142, 144] He claims that it accounts for the phenomena and creates a *coherent* system of the orders and magnitudes of all spheres and stars.

Copernicus was well aware that the *interrelatedness* of natural phenomena would lead to a coherent model of the universe. In his Dedication to Pope Paul III he spells out how his reasoning took him from the correlation of natural phenomena to a more adequate heliocentric model:

> And so, having laid down the movements which I attribute to the Earth farther on in the work, I finally discovered by the help of long and numerous observations that if the movements of the other wandering stars are correlated with the circular movement of the Earth, and if the movements are computed in accordance with the revolution of each planet, not only do all their phenomena follow from that but also this correlation binds together so closely the order and magnitudes of all the planets and of their spheres or orbital circles and the heavens themselves that nothing can be shifted around in any part of them without disrupting the remaining parts and the universe as a whole. [Copernicus 1543, 6]

Copernicus and his disciple Georg Joachim Rheticus (1514–1576) claim that the heliocentric hypothesis has many advantages over the Ptolemaic hypothesis. The advantages derive from treating the planets and their motions as a *system*:

- According to Copernicus, the concept of a moving Earth – its daily and annual rotation – naturally explains all the celestial observations. For instance, the two great problems, inherited from antiquity, seem to dissolve in a heliocentric model. The retrograde motions of the (inner and outer) planets become a natural consequence of the motion of the Earth around the (mean) sun. An inner planet, like Mercury, has a shorter orbital period than the Earth. It overtakes the Earth in its annual orbit. For an Earth-bound observer its motion appears as retrograde motion. [Figure 1.3] The second problem was the nonuniform motion of the planets. Planets seemed to require different times to complete their successive journeys around the ecliptic. Part of the solution derives from placing the planets at their correct distances from the sun. The outer planets need longer for their annual journeys than the inner planets. But Copernicus's solution is only partially successful because he still assumes uniform circular motion. Still, the two "appearances" can be explained without the use of major epicycles. The major irregularities of the planetary motions are only apparent. [Kuhn 1957, 149, 166–71; Zeilik 1988, 49] These appearances are produced by the orbital motion of the Earth. As the sun is stationary in the heliocentric

[3] Strictly speaking, the sun is not the physical center of the Copernican system; it is placed near the center of the orbit of Earth. It was only Kepler who attributed to the sun a "vital physical role in keeping the planets in motion." [Gingerich 1993, 42]

**Box 1.1** The order of planets in heliocentrism
**Sun) Mercury) Venus) Earth) $_{\text{Moon}}$) Mars) Jupiter) Saturn) Fixed Stars**
*compared with the geocentric order:*
***Earth) Moon) Mercury) Venus) Sun) Mars) Jupiter) Saturn***

system, it does not have a retrograde motion. [Figure 1.1; Box 1.1] [See Kuhn 1957, 66, 69; Copernicus 1543, Bk. III, §§15–6]

- Copernicus also determines the *relative* distances of the planets from the sun, using techniques known from antiquity. [Copernicus 1543, Book I, §10; Neugebauer 1968, §2; Kuhn 1957, 142, 175; Zeilik 1988, 40–1] If the Earth–sun distance is taken as 1 unit, then Mercury is at 1/3 of the Earth–sun distance, Mars at 1½, Jupiter at 5 and Saturn at 9 Earth–sun distances. Copernicus argues that "the magnitude of the orbit circles should be measured by the magnitude of time." [Copernicus 1543, Bk. I, §10] By this he means that the distance of a planet from the sun is to be determined from its orbital period. Thus he rejects the medieval practice of deriving cosmic distances from Ptolemy's method of nesting celestial shells within each other according to certain proportions. Copernicus argues that only the heliocentric model satisfies the distance–period relationship. In the heliocentric system, the order of the planets is determined by observation of the orbital period of the planets. Copernicus treats the planets as a coherent system. [Figure 1.6]
- Although the assumption of a moving Earth allowed Copernicus to abandon major epicycles, he still needed minor epicycles. Major epicycles were employed to explain the qualitative appearance of retrograde motions. Minor epicycles are small circles, which are needed to eliminate minor quantitative discrepancies between the observations and the geometric models. [See Kuhn 1957, 68] Copernicus needed these minor epicycles because he endorsed the Greek principle of circular motion for the planets. The motion of celestial bodies is "regular, circular and everlasting." [Copernicus 1543, Book I, §4] In fact Copernicus desires to rescue the Greek tradition from Ptolemy. He wants a "system in which everything would move uniformly about its proper center as the rule of absolute motion requires." [Copernicus, *Commentariolus* 1959, 57–8] He swaps the geometric position of the Earth but still clings to the Platonian ideal of the uniform and circular motion, which he attributes to the planet-carrying spheres. [Figure 1.6] He criticizes Ptolemy for his introduction of the equant, although his model used a mathematically equivalent device, an epicyclet. [Gingerich 1993, 36, 175; Neugebauer 1968]

An important aspect of modern science is that observations are regarded as tests of scientific theories. But the Greeks sought to fit the appearances they observed to their prior beliefs about celestial phenomena. Copernicus claims that his work is based on long and numerous observations, his own and those of the Greek tradition. [Copernicus 1543; *Letter Against Werner* 1524; Rheticus 1540; see also

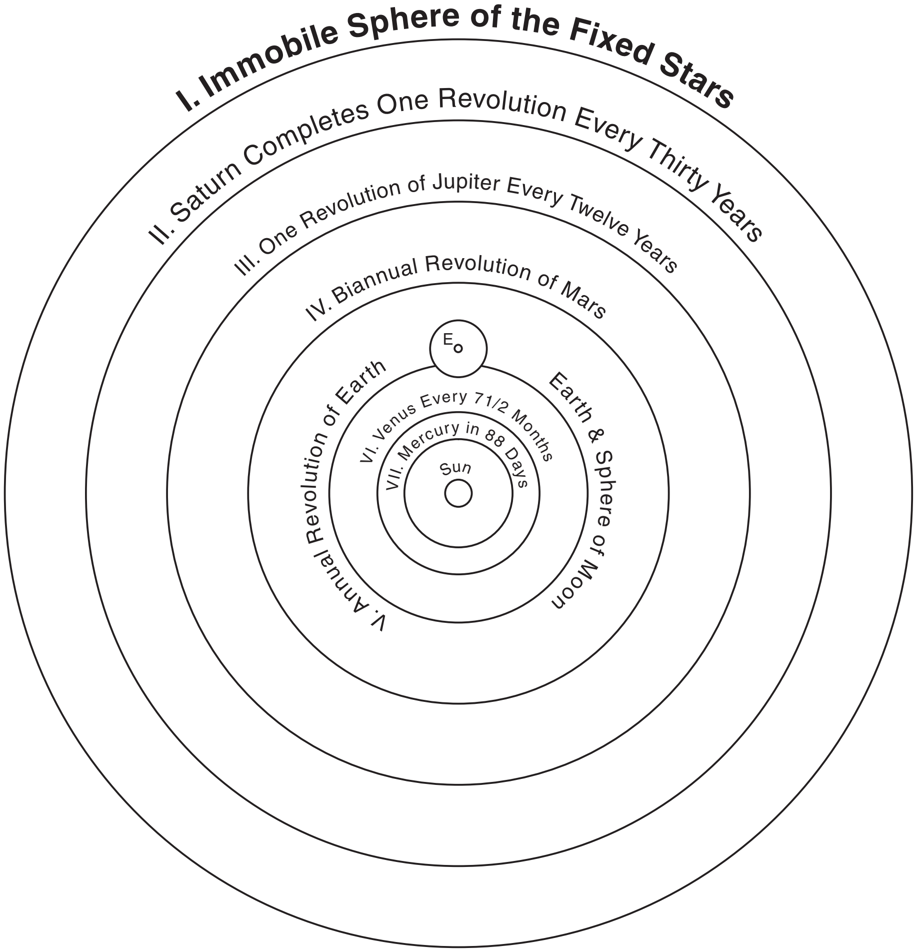



**Figure 1.6** The Copernican model of the solar system

Koestler 1964, 203, 581 n. 20] We do not need to doubt Copernicus's sincerity. His book contains long tables of astronomical data, which are largely derived from ancient observations. But Copernicus was also aware that some of these ancient observations were out of date, when compared with modern values.[4] *De Revolutionibus* contains a long discussion of what he calls "artificial" instruments. Such observational instruments serve to determine "the distance between the tropics," the "altitude of the sun," and "the positions of the moon and the stars." [Copernicus 1543, Bk. II, §§2, 14] Nevertheless Copernicus's observations do not establish any *new* facts. The Copernican observations do not go beyond the discoveries of the Greeks. They do not cast in doubt Greek presuppositions about circular

[4] See for instance his discussion of the precessions of the solstices and equinoxes, *Revolutions* [1543], Bk. II, §14, Bk. III, §1.

motion. It is therefore fair to say that from an observational point of view, the Copernican and Ptolemaic systems were equivalent. [De Solla Price 1962; Gingerich 1982; Heidelberger 1980] No observation available at the time could trench in favor of one of these competing models. When Tycho Brahe and Galileo Galilei provided new observational discoveries, they had significant implications for Copernicanism. Copernicus's main achievement lay in his awareness of the need to treat the solar system as a coherent system. And he worked out the mathematical consequences of a heliocentric universe.

Although the Copernican treatise *De Revolutionibus orbium caelestium* (1543) has many defects, it arguably set in motion the rise of modern science, whose first phase culminated in the publication of Newton's *Principia Mathematica* (1687). Despite its defects, the Copernican model has greater explanatory power than its rival. Representing the solar system as a *coherent* system, it shows the correlations between many celestial phenomena and relates them to one underlying cause. We can see its explanatory power in the explanation of the seasons.

## 3.2 The explanation of the seasons

> *For the sun is not inappropriately called by some people the lantern of the universe, its mind by others, and its ruler by still others. [Copernicus,* De Revolutionibus *(1543), Bk. I, Ch. 10, quoted in Rosen,* Copernicus and the Scientific Revolution *(1984), 132]*

Any human being is aware of the seasons. Any astronomical model must explain this most obvious of phenomena. But if the Earth sits stationary at the hub of the universe, with the sun orbiting it in a concentric circle, the gliding variations of the seasons cannot be explained. A uniformly moving sun would always remain at the same distance from the Earth, resulting in unchanging seasons. The Greeks were aware of this problem. Ptolemy knew from Hipparchus's observations that "the interval from spring equinox to summer solstice is 94½ days, and that the interval from summer solstice to autumn equinox is 92½." [Ptolemy 1984, Bk. III, §4; Kuhn 1957, 67] Ptolemy employed the eccentric or displaced circle to solve the problem. [Figure 1.3] The seasons have unequal lengths, but they are also asymmetrically distributed across the globe. When it is summer in the northern hemisphere, it is winter in the southern hemisphere and vice versa. Let us fix our attention on two cities, Madrid (Spain) and Wellington (New Zealand). The choice of these two cities can easily be explained. If we could drill a hole through the center of the Earth from Wellington we would reemerge in Madrid. How do you achieve the simultaneous asymmetry between the seasons in the northern and southern hemispheres on a geocentric model? As the Greeks observed that the sun rises high in the sky in the summer and remains low in the winter, and as they took the Earth to be stationary at the center of the universe, they assumed that the annual orbit of the sun around the Earth is tilted. They knew that the tilt was approximately 23.5°. The solution of the puzzle of the seasons results from the tilt of the eccentric circle of the sun. It explains nicely why the sun rises high in the sky in the summer and remains low in winter. The tilt of the ecliptic circle explains the sun's variation in latitude in the same location – like Alexandria, where Ptolemy lived – or in two different locations, like Wellington and Madrid. Consider two Greek expatriates, one living in Madrid, the other in Wellington, in AD 150. For them the Earth is stationary, spherical, and the sun, riding on its ecliptic circle, performs an eccentric, tilted motion around the central Earth. When it is summer for the Greek in Madrid, the tilt of the eccentric will raise the sun high in the sky. For his compatriot in Wellington, it will be winter. The tilt of the ecliptic means that the sun rises high above the equator, leading to short days and long nights in the southern hemisphere. For both, the sun occupies the same location on the ecliptic. Six months later the seasons are reversed. When this device is accurately employed, it seems that "the sun's motion on the eccentric can exactly match the unequal length of the seasons." It can also show why the sun's passage from vernal equinox to autumn equinox takes six days longer, according to modern values. [Rosen 1984, 26; Neugebauer 1968, 91, Kuhn 1957, 67]

How does Copernicus explain the seasons? There are a number of phenomena to be explained, which, as Copernicus insisted, are related to each other. Can the Copernican system solve the problem? Apart from the familiar motions of the Earth: the daily rotation and the annual motion, Copernicus stipulates what he calls the "deflexion of the axis of the moving Earth." [Copernicus 1543, Bk. I, §2, §11] It attributes a third motion to the Earth. The third motion has the function of explaining the change of seasons. Rheticus calls it "the motion of its poles":

> The third motion of the Earth produces the regular, cyclic changes of the season on the whole Earth; for it causes the sun and the other planets to appear to move on a circle oblique to the equator (…). [Rheticus 1540, 150–1]

Why does the Copernican system need to assume a rotation of the Earth's axis to explain the seasons? According to Copernicus the Earth is a planet but it is attached to a sphere, which carries it round the sun. This means, however, that the Earth's axis does not remain parallel to itself. An easy experiment will convince the reader that the axis will not keep its fixed orientation in space. All we need is a pen, a rubber band, and a cup. Attach the pen at an angle to the cup and rotate the cup slowly anticlockwise. Let us say that at the start the pen points from northeast to southwest. We now rotate the cup by 90°. The pen will point from northwest to southeast. The rotation of the cup, which corresponds to the second motion of the Earth in the Copernican system, does not keep the orientation of the Earth's axis constant. Copernicus therefore assumed a third, conical motion, which returns the axis to its original orientation in space. [Kuhn 1959, 165] [Figure 1.7b]

A curious situation confronts us. Both the geocentric and the heliocentric models are able to explain the seasons. Yet the Ptolemaic account seems simpler, since Copernicus needs to postulate a third motion of the Earth. Formally, it makes no difference whether we assume a tilted eccentric circle around a stationary Earth or a tilted axis of a moving Earth around a stationary sun. A simpler explanation is, however, not necessarily the most adequate explanation.

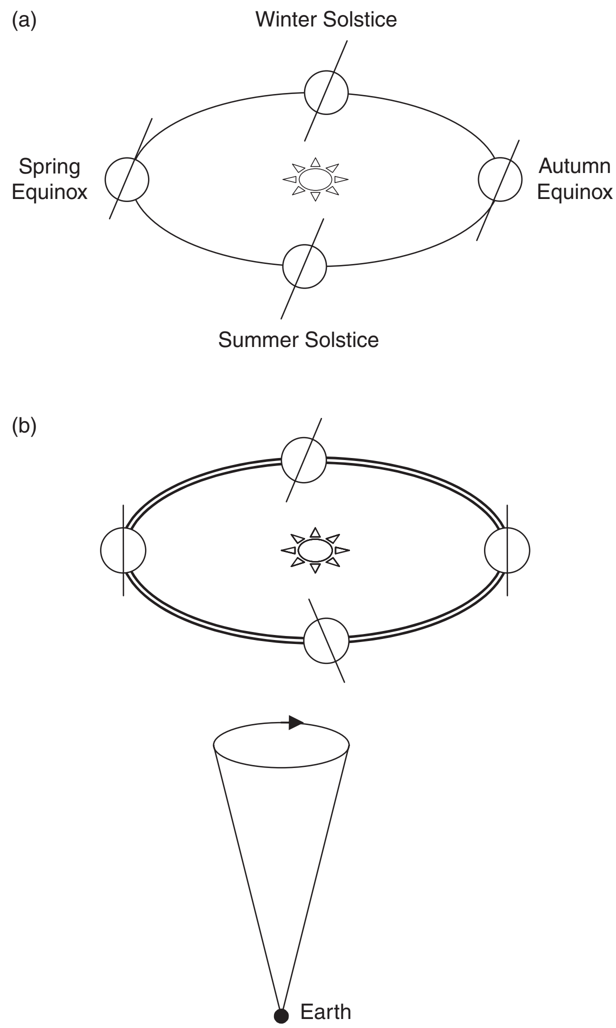



**Figure 1.7** (a) The seasons as seen from the viewpoint of an observer in the northern hemisphere, according to the modern, Copernican view. The central axis of the Earth is inclined at 23.5° and remains constant with respect to the plane of the orbit around the sun. The model illustrates how the summer and winter solstices are linked and result in the different lengths of the day. [Copernicus, *Commentariolus* 1959, 63]; (b) The seasons as seen from the viewpoint of an observer in the northern hemisphere, according to the Copernican view. The central axis of the Earth is inclined at 23.5° but it does not remain constant with respect to the plane of the orbit around the sun. The Earth is carried on a sphere (double lines) around the "central" sun. As the experiment with the cup shows, this leads to a change of the orientation of the axis, which Copernicus calls "the deflexion of the axis" (of the Earth). The motion performs a small circle, in the opposite direction to the motion of the Earth, to compensate for the changing "tilt" of the axis. In his modification of the Copernican system, Kepler dispenses with the third movement

The Ptolemaic explanation derives from a model that captures little of the physical reality of the solar system. Unlike the Ptolemaic model, the Copernican model represents the solar system as a proper system. We would expect that the Copernican system succeeds better at explaining the asymmetry of seasons across the hemispheres. With the stipulation of the three motions of the Earth Copernicus hopes to explain the phenomena conjointly, not separately. (Ptolemy can actually ignore the daily rotation of the Earth, since it plays no part in the explanation of the seasons.) As the Copernican model deals with the planets as a system, it has no difficulty in explaining the asymmetry of the seasons and the varying lengths of the days. In this sense the Copernican system has greater explanatory power: by adopting the mobility of the Earth, it naturally explains retrograde motions, the seasons, and the relative distance of the planets from the sun. But the Copernican system is more unwieldy than the Ptolemaic model, at least in this respect. Nevertheless, it retains a closer fit to the solar system than the Ptolemaic model. It was amended when Kepler pointed out that the third motion of the Earth is not needed. Kepler can dispense with it because there is no need for spheres. Astronomy can easily do "without the useless furniture of fictitious circles and spheres." [Kepler 1618–21, Bk. V, Part I, 124] The Earth moves freely around the sun, always keeping its axis constant with respect to an axis drawn through the center of the sun. [Figure 1.7a]

### 3.3 Copernicus and the Copernican turn

*This transformation of the planetary loops from a physical reality to an optical appearance was an invincible argument for the validity of the astronomy of Copernicus. [Rosen,* Copernicus and the Scientific Revolution *(1984), 115–16]*

It has become customary to speak of the *Copernican turn* since Kant referred to the Copernican hypothesis in his *Critique of Pure Reason.* [Kant $^{2}$1787, Preface]. Kant proposed that philosophy needed a change of *perspective.* Empiricism had regarded the mind as a blank sheet, a *tabula rasa.* Through observation and inductive reasoning humans acquired sense impressions of the material world. From these impressions the mind forms ideas, which slowly fill the *tabula rasa.* Rationalism had equipped the human mind with innate capacities. Through pure thinking the human mind could understand the basic structure of the natural world. Observation was needed only to confirm the postulations of the mind. Kant argued that each approach to knowledge was mistaken on its own terms. What was needed was a synthesis. Empiricism was right to insist on the importance of empirical knowledge. Rationalism was right to insist on the importance of rational principles. The synthesis could be brought about by a Copernican turn in philosophy. Do not look at knowledge either from the perspective of the world–mind relationship, like Empiricism, or the mind–world relationship, like Rationalism. Change your perspective. Knowledge is not the result of an active world etching its stamp on a passive mind (Empiricism). Nor is knowledge the result of an active mind putting its seal on a passive world (Rationalism). Human knowledge comes about through a partnership between an active mind and an active world. The mind already comes equipped with basic principles about causality, substance, space, and time. But they are too abstract to constitute empirical knowledge; they are presuppositions to objective knowledge. They need the encounter with the empirical world to give rise to empirical knowledge. The rational mind seeks a union with the empirical world. This is the Copernican turn in philosophy.

Copernicus himself provides us with a sense, a very primary sense, of what we mean by the Copernican turn. *It is a shift in perspective.* Copernicus invites the reader to change the focus of the explanation. Consider an object, which appears to move. And consider an observer, who appears to be stationary. Sitting on a train at a platform, the passenger is often momentarily unclear as to whether her/his train has started to move or whether it is the train on the neighboring rail which has begun to pull out of the station. If we exchange the perspective between object and observer the motion remains invariant. We can describe it as motion of our train in the forward direction or as motion of the other train in the opposite direction. What is true for the train is true for the planets. If the sun appeared to move past the stationary observer on Earth from east to west, it is now the observer who must move past the "stationary" sun from west to east. In this change of perspective, some features must remain *invariant*. As we saw in the explanation of the seasons, Copernicus exchanges the tilt in the sun's ecliptic against a tilt in the Earth's axis. The tilt (23.5°) remains invariant but the tilted sphere passes from the sun to the Earth. How will this change of perspective work in the case of an observer on Earth? From the point of view of an apparently stationary Earth-bound observer, the fixed stars seem to move from east to west, while the planets generally move from west to east, with the exception of retrograde periods. If we change the perspective and make the Earth-bound observer move from west to east in the daily rotation of the Earth, the movement remains but the direction changes. The sun appears to us to rise in the east and to set in the west. If we hold the sun fixed and make the Earth turn on its own axis from west to east, the orbit of the sun through the sky remains the same but then its direction changes. In fact, all the properties of the apparent movement of the sun through the stellar constellations – the *ecliptic* – remain constant, only the perspective of motion changes. This, as Copernicus argued, is altogether more economical. It is more rational for the motion of the Earth to produce the apparent rapid motion of the fixed stars than it is for the fixed stars to rotate rapidly once on their sphere in a 24-hour rhythm. Copernicus announces his change of perspective very early on in the book:

> Although there are so many authorities for saying that the Earth rests in the center of the world that people think the contrary supposition inopinable and even ridiculous; if however we consider the thing attentively, we will see that the question has not yet been decided and accordingly is by no means to be scorned. *For every apparent change in place occurs on account of the movement of either of the thing seen or of the spectator*, or on account of the necessarily unequal movement of both. For no movement is perceptible relatively to things moved equally in the same directions – I mean relatively to the thing seen and the spectator.

This passage describes the change of perspective, which will have to leave the observations invariant:

> Now it is from the Earth that the celestial circuit is beheld and presented to our sight. Therefore, if some movement should belong to the Earth it will appear, in the parts of the universe which are outside, as the same movement but in the opposite direction, as though the things outside were passing over. And the daily rotation in especial is such a movement. For the daily revolution appears to carry the whole universe along, with the exception of the Earth and the things around it. And if you admit that the heavens possess none of this movement but that the Earth turns from west to east, you will find – if you make a serious examination – that as regards the apparent rising and setting of the sun, moon, and stars the case is so.

Copernicus concludes the argument with a slightly veiled appeal to Ockham's razor. This is the principle, stated very liberally and without respect for its original context, that simplicity of explanation is a great virtue in science. Of two different explanations concerning the same phenomenon, the simpler explanation is generally to be preferred. A simpler explanation is not a simplistic explanation. It is an explanation that leaves fewer things unconnected and explains more things with fewer principles.

> And since it is the heavens, which contain and embrace all things as the place common to the universe, it will not be clear at once why movement should not be assigned to the contained rather than to the container, to the thing placed rather than to the thing providing the place. [Copernicus 1543, Bk. I, §5; Bk. III, §1]

Copernicus hints at a *second* feature of the Copernican turn. The shift in perspective, which occurs on the background of some invariant feature, must be accompanied by some explanatory gain. If it were not, we would have a mere exercise in *perspectivism*. We would have different perspectives, all equally valid, without recourse to an adjudication between them. But such perspectivism would not be true of the history of science. Copernicus takes great pain to argue that the Copernican hypothesis gives us explanatory advantages. He uses the movement of the Earth as the more plausible principle. [Copernicus 1543, Bk. I, §1; see also the seven principles in *Commentariolus* 1959, 58] From this perspective the relative distance of the planets can be determined. Retrograde motion is not a problem of geometry. It is a physical reflection of our position in the solar system. It is true that the explanation of the seasons is more cumbersome from the Copernican perspective. But this could easily be amended by abandoning the spheres. The Copernican explanation is then a better approximation to the appearance of the seasons than the Ptolemaic account.

A shift in perspective is an important feature of the Copernican turn. Many great scientists began with a shift in perspective. Darwin, as we shall see, argued for a shift in perspective with respect to the great problem of his time: the "origin" of species. The scientists argued for a change in perspective to increase the explanatory gain, while keeping other things invariant. What about influential thinkers in the social sciences, like Marx and Freud? These thinkers, too, brought about a change in perspective. But it is a matter of dispute whether the explanatory gain, for which they claimed credit, really does accrue to their shift in perspective. This shadow of doubt also hangs over Copernicus. It explains why Copernicus is not seen as a true scientific revolutionary. A scientific revolution requires a change in perspective. But a mere change in perspective does not constitute a scientific revolution. An important ingredient in a scientific revolution is some "explanatory gain." If doubts remain about the explanatory gain achieved by a turn in thinking, there are doubts about a true revolutionary impact. This was Copernicus's problem, as we shall see. Thinkers like Copernicus and Freud, however, remind us of a further consequence of a scientific revolution: it has a significant impact on the way people begin to perceive the world. In the case of Copernicus this leads to a loss of centrality. In the case of Darwin it brings about a loss of design. And in the case of Freud it results in a loss of transparency.

A scientific revolution may need time to unfold. It is possible for one thinker to introduce a change of perspective and for others to complete the picture. The history of astronomy from Copernicus to Newton illustrates this point. In its etymological sense, the term "revolution" indicates an uprooting, a reversal and an overthrow of old established views or conditions. Working with the notion of "turn of ideas" or "shift of perspective" allows us to focus on scientists who completed the shift of perspective. The Copernican turn consisted in a realignment of the geometric arrangement of the planets. Astronomers built models out the existing material: the six planets known from antiquity to the eighteenth century. Once the components are at hand an immediate question imposes itself. How are these elements to be arranged with respect to each other? The Greeks started a long tradition of model-building in the history of astronomy. It consisted of two tasks: first, to determine a *topologic* structure of the model, which would arrange the planets in a geometric or spatial order. Most Greek astronomers opted for a geocentric arrangement. Copernicus reversed this tradition by choosing a heliocentric arrangement. Once a topologic structure is chosen, an *algebraic* structure for the model must be found. The algebraic structure determines the quantitative relationships between the components in the models. The Greeks worked with various geometric devices: eccentric circles or deferents and epicycles. Copernicus changed the topologic structure of planetary models. But he retained the geometric assumptions of his Greek predecessors. For this reason Copernicus never achieved the explanatory gain associated with a scientific revolution. Any explanatory advance to which Copernicus can lay claim accrues to the topologic structure of the heliocentric model. Copernicus made no contribution to the algebraic structure of planetary models. The explanatory gain in algebraic structure was achieved slowly through the work of Kepler, Galileo, and Newton.

We can applaud Copernicus for his introduction of a shift in perspective, and yet credit his brilliant successors with the completion of the Copernican turn. In a scientific revolution, a change of perspective against the background of invariant elements must be augmented by an explanatory gain in the algebraic structure. We shall see that Darwin's theory was able to offer the explanatory gain, while Freud failed as much as Copernicus. We do no harm in considering Copernicus's work as the dawn of the Copernican revolution and modern science. Copernicus is more a major figure in the history of scientific ideas than in the history of scientific revolutions. [Blumenberg 1957; 1981, Part I, I; Part III, II; 1965, II] Copernicus had a major impact on the way humans placed themselves in the wider cosmos. We shall see that major philosophical questions arise from the Copernican turn and the Copernican revolution. But let us first complete the story of the Copernican revolution.

*3.3.1 A philosophical aside: From empirical adequacy to theoretical validity* The preceding sections harbor some philosophical lessons. The explanation of the seasons in geocentrism and heliocentrism, respectively, shows that in scientific explanation we require more than an agreement of the model with the empirical data. Let us say that two incompatible models, which agree with the empirical evidence, enjoy *empirical adequacy*. Both the Ptolemaic and the Copernican models can explain the available data equally well, but they do so on the assumption of different structures. Both are possible explanations with respect to the available evidence. The Copernican model reveals, however, a better topologic structure than the geocentric model. In order to mark the difference in fit we shall say that it gains *empirical validity*. We also require of a model that its mathematical structure must be in agreement with the structure of the target system. In order to achieve this fit the model must become a structural model or theory. [See Section 6.5.1] As the mathematical structure explains the observable phenomena, we shall say that an explanatory theory must acquire *theoretical validity*. We see the need for theoretical validity in the history of planetary models. The Greeks strived to "save the phenomena." They tried to match their sense observations with their presuppositions about planetary motion. The geocentric model was fairly accurate in its predictions of planetary motion but it was based on a mistaken structure: devices like eccentric and epicylic motion. As these devices do not reflect any physical mechanism, they have no theoretical validity. Although Copernicus also employs these devices, his model arranged the planets in a spatial order, which is close to the spatial (topologic) structure of the solar system. In this respect it was empirically valid. The heliocentric model, in its Keplerian form, enhances the approximation of the model to the reality of the solar system, because it replaces the traditional geocentric devices by a new algebraic structure. With Newton, it finally becomes a theory. As we shall see in the following section, Kepler discovered mathematical laws to describe planetary motion which no longer require the planets to be carried on spheres in circular orbits. The upshot is that we want the model assumptions to be more than instrumentalist hypotheses. The model assumptions must be in agreement with the structure of the natural system. [See Section 6.5] This requirement points us toward a discussion of instrumentalism and realism. [Section 6.2]

## 3.4 Copernicus consolidated: Kepler and Galileo

*Kepler's marvelous achievement is a particularly fine example of the truth that knowledge cannot spring from experience alone but only from the comparison of the inventions of the intellect with observed fact. [Einstein, "Johannes Kepler" (1930), 266]*

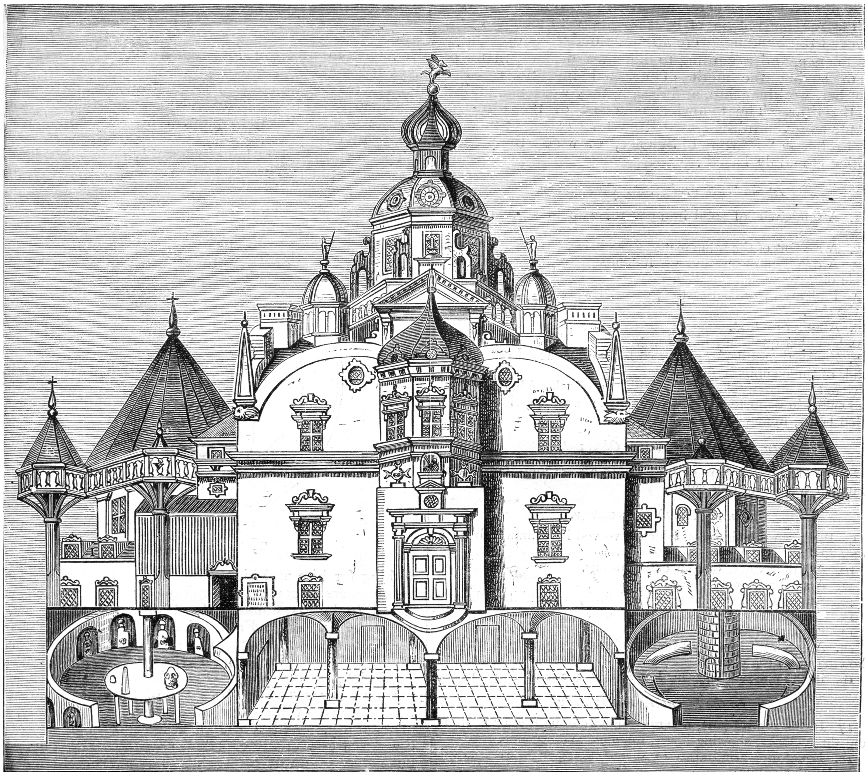


**Figure 1.8** Tycho Brahe's observatory on the Island of Hven. *Source*: *Nature* **15** (1876–7), p. 407


**UF 1.4** Tycho Brahe (1546–1601)

Copernicus launched a new research program, whose completion relied on some groundbreaking contributions. The next central figure to enter the stage is Tycho Brahe, a Danish astronomer (1546–1601). Brahe was a lifelong opponent of Copernicanism. Nevertheless he occupies a pivotal position in the history of heliocentrism. For Brahe developed ingenious observational methods and collected a wealth of new data: [Figure 1.8]

- In 1572 he discovered a new star, which at first shone very brightly in the sky but later disappeared. Brahe had in fact discovered a supernova. This is the appearance in the sky of a very bright light, owing to the momentous explosion of a massive star. The light increases its brightness hundreds of millions of times in the span of only a few days.

- Between 1577 and 1596, Brahe discovered comets in the sky, the orbits of which had to be located beyond the moon's sphere. Perhaps the most famous comet is Halley's comet, named after the Astronomer Royal, who used Newton's theory to predict its orbit. More recently, Earthlings had the visit of comet Hale–Bopp, whose closest approach to Earth occurred on March 22, 1997 at 123 million miles. [Figure 1.9]

These discoveries were highly significant, because they raised serious questions about the immutability of the heavens, a feature of the supralunary sphere in Aristotelian cosmology. The appearance of a supernova far beyond the sublunary sphere was not compatible with the dogma of its never-changing nature. The orbits of comets are highly elliptical. For instance, the orbit of Halley's comet crosses the orbits of the outer planets, reaching almost as far as Pluto before it returns to Earth. Comet Hale–Bopp traversed the solar system from outer space, returning from its last visit in 2214 BC. On the Aristotelian–Ptolemaic view, such orbits should simply not be permitted. Recall that for these reasons Galileo's visitors refused to contemplate the existence of Jupiter moons. An alternative attitude is a kind of

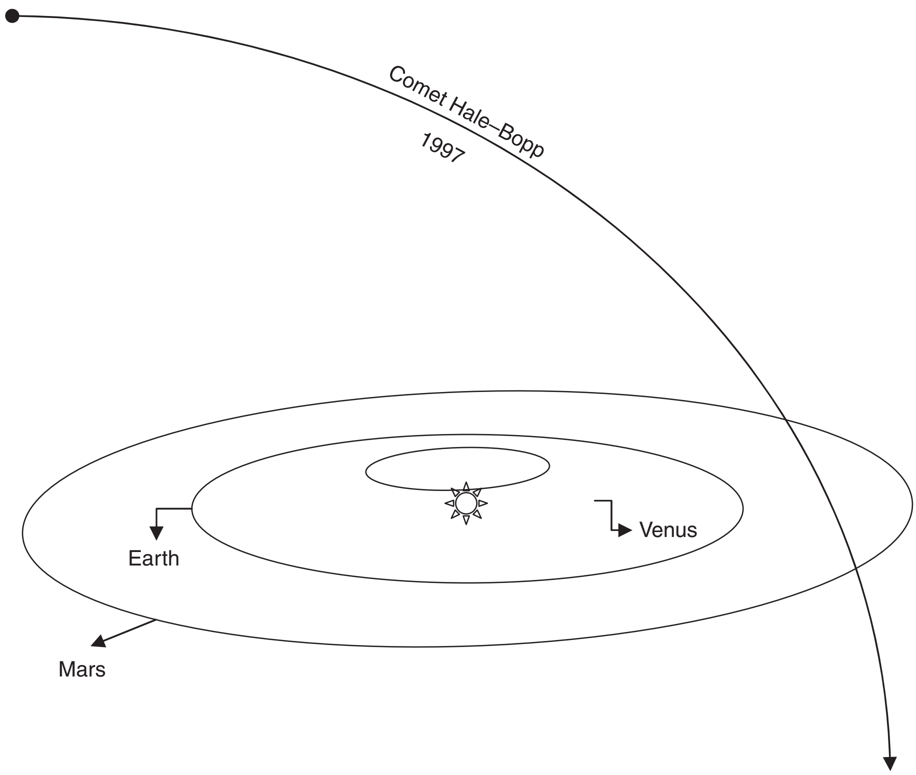



**Figure 1.9** A schematic view of the orbit of comet Hale–Bopp between Venus and Mars on its way through the solar system in June 1997. The orbits of Mars and Venus are inclined with respect to the ecliptic

defeatism, which we find in the concluding part of Ptolemy's *Almagest*. Our knowledge of celestial bodies is so limited that what is impossible according to our model – comets smashing through the spheres – may turn out to be possible in the heavens. [Ptolemy 1984, Bk. XIII, §2]

Tycho Brahe proposed a compromise between the Copernican and Ptolemaic systems. In his system the Earth is at the center of the universe with the moon and the sun circling around it; but the other planets circle around the sun. Brahe's system was important to those astronomers who wanted to use the Copernican system because of its calculational advantages but could not adopt the motion of the Earth for philosophical reasons. [Kuhn 1957, 202] It leads to better astronomical tables.

**UF 1.5** Johannes Kepler (1571–1630)

Without Brahe's astronomical data, Johannes Kepler could not have discovered his three astronomical laws. They are the first mathematically precise laws in astronomy:

1. The **first law** states that the orbit of planets is not circular but elliptical. With this law, the ancient ideal of circular motion is consigned to the dustbin of the history of ideas.
2. The **second law** gives up the notion of a uniform motion, which had still been assumed by Copernicus. It states that the orbital period of each planet varies in such a way that "A line drawn from a planet to the sun sweeps out equal areas in equal times." A planet near the sun moves faster than a planet further away, but a line joining each planet to the sun sweeps through equal areas of the ellipsis in equal intervals of time.
3. The **third law** establishes a relation between the speeds of planets in different orbits, $P$, and their average distance from the sun, $A$: $A^3 \propto P^2$.

Some believe that the statement of these laws makes Kepler the true revolutionary in the history of astronomy. [Koestler 1964, Part IV] Recall the distinction between *topologic* and *algebraic* structure. Kepler rejects much of the Greek tradition to which Copernicus still adhered. The fictitious circles and spheres (Kepler 1618–21, Bk. IV, Part I, 124), and even more importantly the doctrine of circular motion, are rejected as elements of the topologic structure. With his three laws, Kepler makes a major contribution to the improvement of the algebraic structure of the heliocentric model. Further, Kepler wants to build an astronomy based on the physical causes of planetary motion. He makes a proposal that solar heat and light may keep the planets in their elliptical orbits. [Kepler 1618–19, Bk. IV, Pt. II] His intention is to appeal to natural powers, rather than "intelligences," to "move the planets." He attributes a "motor soul" to the sun. Unsurprisingly, Kepler's proposal failed. Several more steps were needed before the Copernican revolution was completed. The completion required that the proponents of heliocentrism shared some but not all of the basic convictions.

This point is well illustrated in the work of Galileo Galilei. Galileo is a Copernican who hardly takes any notice of Kepler's achievement. He ignores Kepler's discovery of the elliptical orbit of all planets and embraces the notion of circular movement as the natural movement of all bodies. Yet his importance for science cannot be doubted. It is threefold:


**UF 1.6** Galileo Galilei (1564–1642)

1. He defends the Copernican worldview and provides new evidence, through his work with the telescope, which discredits the Aristotelian–Ptolemaic view, and bestows credit on the heliocentric hypothesis. As we have already noted, Galileo starts with new presuppositions. What is important, he argues against scholastic scholars, like the Mathematician and Philosopher in Brecht's play, is the use of observations and the mathematical description of nature. All of Galileo's observations provide evidence that the heavens are not immutable.
   (a) The Jupiter moons, which he would like his guests to observe through the telescope in lieu of a scholarly dispute, provide a visible scale model of the Copernican solar system. The moons orbit Jupiter as their center. If Jupiter were carried on a crystal sphere, the moons would break through it. Contrary to the Philosopher's opinion, there are celestial bodies which "orbit around centers other than the Earth."
   (b) The study of the topography of the moon shows the similarity between the Earth and the moon. It casts into doubt the rationale of the two-sphere universe.
   (c) The observations of the sunspots, like the moon's surface, conflict with the assumed perfection of the celestial region of the universe.
   (d) The phases of Venus provide direct information about the shape of Venus's orbit. As Venus lies inside the orbit of the Earth, Earth-bound observers see it illuminated in different orientations. It provides direct proof that at least Venus orbits the sun. [Koestler 1964, 431–5; Kuhn 1957, 222–4; Copernicus 1543, Preface; DeWitt 2004, 156–64]
   (e) The study of the Milky Way hints at the potential infinitude of the universe.
2. Galileo develops the science of mechanics. It paves the way for a modern theory of motion, which dispenses with "pushes" and "impulses." Galileo develops his fall law, according to which all objects fall at the same rate, given by the gravitational acceleration near the surface of the Earth. Galileo also formulated a *principle of relativity.* [Galileo 1953, 199–201] A system at rest and a system in constant motion are equivalent from the physical point of view. The systems are invariant to this change of viewpoint. Galileo offers a famous thought experiment to demonstrate the equivalence of inertial systems. In a cabin below the

deck of a large ship, observe the behavior of "flies," other "small winged creatures," and "fish in a bowl." At first the ship is at rest. When the first set of observations is completed, let the ship proceed with uniform speed. The observations will reveal no difference in the behavior of the creatures. [Galileo 1953, 199–201] Anything that happens to objects in these systems happens according to the same laws. Thus, although we change the perspective, the regularities are invariant. Galileo's discovery of the principle of relativity was vital for the understanding of the most pressing question of astronomy: "How do planets move in their orbits?" It was left to Newton to provide the final answer. [Section 5]

3. Finally, he becomes an ardent defender of the freedom of scientific inquiry against the interference of the Church. Like Roger Bacon in the Middle Ages, Galileo pleads for a separation of theology and natural philosophy. Passages in the Bible may not literally mean what they appear to say. For this reason we should not use biblical passages to call in question what observations or mathematical reasoning teach us.

Kepler and Galileo developed the heliocentric model; standing on their shoulders Newton completed it. We begin to see more clearly why Copernicus was not a scientific revolutionary.

## 4 Copernicus was not a Scientific Revolutionary

> *Therefore, since the sun is the source of light and eye of the world, the center is due to it in order that the sun (…) may contemplate itself in the whole concave surface (…) and take pleasure in the image of itself, and illuminate itself by shining and inflame itself by warming. [Kepler,* Epitome of Copernican Astronomy *(1618–21), Bk. IV, Part I, §2 (20)]*

Ever since Copernicus effected his Copernican turn, the question has been asked whether he was a scientific revolutionary. Copernicus himself and his disciple Joachim Rheticus were aware of the explosive nature of even a Copernican turn. In his Dedication to Pope Paul III, Copernicus admits that his heliocentric hypothesis will strike many of his contemporaries as absurd. Rheticus seems to find it necessary to emphasize that Copernicus was not "driven by lust for novelty." [Rheticus 1540, 187] But the geocentric view is unable to explain the "remarkable symmetry and interconnection" of planetary motions. The ancients failed because they did not regard the planets and their motions as a system. [Rheticus 1540, 138] As we have seen in the foregoing discussion, it is important for a scientific theory to explain all the phenomena that fall into its domain. Rheticus appeals to this criterion when he holds that only those hypotheses that can explain both apparent anomalies of planetary motion are acceptable. [Rheticus 1540, 168]

There was a clear perception that the Copernican turn bore the seeds of a new worldview. But was the Copernican turn revolutionary? Many scholars have considered this question. Some will give Copernicus very little credit. Copernicus's book is "little more than a re-shuffled version of the *Almagest*." [De Solla Price 1962, 215] The heliocentric system is not an improvement in computation over the geocentric system but "it is more pleasing to philosophical minds." [Neugebauer 1968, §10; Koestler 1964, Part III] The Copernican system has aesthetic advantages. [Kuhn 1959, 171–81] It also explains two gross planetary irregularities without resorting to major epicyles: retrograde motion and the varying times planets need to complete their orbits around the sun. [Kuhn 1959, 165–71] As we have seen, it also explains the seasons, although this explanation is aesthetically less pleasing than the Ptolemaic attempt. Most historians of science agree that Copernicus did not accomplish a scientific revolution.[5]

There are many reasons for this judgment. *Firstly*, Copernicus is still committed to the Greek ideals of circular motion. His main objection against Ptolemy is the use of the equant, which violates the ideal uniform circular orbs.

*Secondly*, there is an inconsistency in the Copernican treatment of planetary motion, which reveals itself in a discrepancy between the first part of the *De Revolutionibus* and the rest of the book. In Part I, Copernicus starts confidently with an assertion of the annual motion of the Earth around the sun. He believes that the motion is real and that it has explanatory value. But in the technical sections of his book, we encounter what Ptolemy called the "equivalence of hypotheses." Different geometric techniques are regarded as equivalent for the description of planetary motions. It is true that they may be "sufficient for the appearances" but they do not provide real explanation. Copernicus's indifference toward different methods reveals that he is not concerned with a physical explanation of the appearances. Such a physical explanation is, however, required to advance astronomy beyond a mere description of planetary orbits. Copernicus agrees with the Greeks that "planets are not carried on homocentric circles." [Copernicus 1543, Bk. V, §3] This geometric device fails to account for apparent irregularities in planetary motions. But he relies on the techniques to which the Greeks had already resorted: the use of deferents and epicycles. He regards these alternative techniques as equivalent and as "sufficient for the appearances." [Copernicus 1543, Bk. V, §4] In this respect Copernicus made no progress over Ptolemy. Kepler rightly complained that his predecessors had sought the "equipollence of their hypotheses with the Ptolemaic system." [Kepler 1618–19, Bk. IV, Pt II, §5] For this reason we need to distinguish between empirical adequacy and theoretical validity.

*Thirdly*, there are more dynamic reasons why Copernicus is not regarded as a scientific revolutionary. Copernicus employs the impetus theory to confer natural circular motion on the Earth. This explains why buildings do not crumble to the ground when the Earth turns but it does not answer the central question of sixteenth-century astronomy: why planets orbit the sun at varying speeds and distances. Copernicus offers geometric devices, which Kepler had to replace by physical laws. But Copernicus has no concept of inertia or gravitation. The concept

[5] See Dreyer [1953], 342–4; Dijksterhuis [1956], Part IV, I; Koestler [1959], 148–9, 213; Mittelstraß [1962], IV.6; Neugebauer [1968], 92, 103; Rybka [1977], 171; Wolff [1978], Part III, 8; Gingerich [1982]; Blumenberg [1981], Part I, VI, 99; Rosen [1984], 133.

of planetary motion around the sun allows Copernicus to abandon the major epicycles. But his concept of steady circular motion forces him to adopt minor epicycles. From a mathematical point of view his system is not much simpler; from the physical point of view it leaves unanswered "why"-questions.

Nevertheless, Copernicus initiated a Copernican *turn*. [Dreyer 1953, 342–3] His change of perspective brought some noteworthy advantages to astronomy. The most important is, as Rheticus repeatedly stresses, that Copernicus binds the planets into a coherent system. Move one sphere out of place and you disrupt the entire system. [Rheticus 1540, 147; Copernicus 1543, Preface] As we have seen, Copernicus was very aware of the importance of coherence:

> (The) Mobility of the Earth binds together the order and magnitude of the orbital circles of wandering stars. [Copernicus 1543, Bk. V, Introduction]

Kepler also perceived this advantage very clearly:

> Ptolemy treats planets separately; Copernicus and Brahe compare the planets with one another. [Kepler 1618–9, Bk. I, Part I, §5]

The conception of the coherence of planetary phenomena obliges the Copernicans to build a model of the planetary system which must accommodate all the known empirical data. In this respect the Copernican model is partially successful. By correlating the movement of the "wandering stars" with the "circular movement of the Earth," "all" phenomena follow, so Copernicus claims. [Copernicus 1543, Preface] Although they do not all follow, the Copernican system naturally explains the appearance of retrograde motion of the planets and the seasons; it correctly determines the order and relative distances of the planets from the sun. [Copernicus 1543, Bk. I, §10] It also makes the daily and annual motion of the Earth around the sun a reality, rather than a computational device. [Copernicus 1543, Bk. I, §11] The successes and failures of the Copernican system provide useful indications as to the criteria of scientific revolutions.

## 4.1 The Copernican method

> *In the center of all rests the Sun (…) as if on a kingly throne, governing the family of stars that wheel around. [Copernicus,* De Revolutionibus *(1543), Bk. I, Ch. 10, quoted in Gingerich,* The Eye of Heaven *(1993), 34]*

Although Copernicus relied to a large extent on ancient observations, he was no stranger to making his own observations. At the same time Copernicus was aware of the theoretical work of his predecessors. He shows much respect for Ptolemy. Unsurprisingly, a particular mention is reserved for Aristarchos of Samos who anticipated a heliocentric system. In his appreciation and awareness of the work of his forebears, Copernicus in turn anticipates Charles Darwin. There are two noteworthy elements in these stories of discovery. Copernicus – and this is true of

Darwin, as we shall see – enters a conceptual space in which some theoretical accounts already vie for attention. These theoretical accounts claim to be able to account for the "appearances." The Copernican model arrives in an inhabited niche. This conceptual space already accommodates an elaborate system of geocentrism, a sketchy report of heliocentrism, ancient observations, and the impetus theory of motion. As we know, Copernicus made his own observations, which did not, however, lead to new discoveries. The existence of a conceptual space allows us to infer two points. Copernicus did not arrive at his heliocentric system by way of an inductive generalization over the available observations. And secondly, we find in Book I of *De Revolutionibus* and in *Narratio Prima* an explicit consideration of the virtues and vices of contrasting models of the solar system.

Rheticus has left us a brief statement of the Copernican method. First, he reports, Copernicus compared the ancient and medieval observations with his own findings, "seeking the mutual relationship which harmonizes them all." [Rheticus 1540, 163] He then compared these observations with the "hypotheses of Ptolemy and the ancients." The examination shows that the ancient hypotheses do not stand up to the test. Copernicus was forced to adopt new hypotheses, elements of which, as he himself acknowledged, he found in the existing store of astronomical knowledge. Rheticus embellishes the situation. Copernicus found the geocentric hypothesis wanting for reasons of economy and simplicity, not because it was in direct contradiction with the observations. In his Sketch of the Heliocentric System (*The Commentariolus*), of which only handwritten copies existed during his lifetime, Copernicus admits that the Ptolemaic system is "consistent with the numerical data." However, it also postulates the geometric device of the "equant," which Copernicus finds aesthetically objectionable. It violates his belief in heavenly uniformity and regularity. [Copernicus, *Commentariolus*, 1959, 57; see Rosen 1959, 38; 1984, 67] Copernicus considers a heliocentric hypothesis on the background of the geocentric tradition. By applying mathematics, Rheticus continues, Copernicus

> geometrically establishes the conclusions which can be drawn from them [i.e. the new hypotheses] by correct *inference*; he then harmonizes the ancient observations and his own with the hypotheses which he has adopted; and after performing all these operations he finally writes down the laws of astronomy. [Rheticus 1540, 163; italics added]

The "laws of astronomy" are the circular uniform orbs, which Kepler replaced. What is important in the present context is the observation that Copernicus made *inferences*. He uses the available data to infer that the Ptolemaic model was inadequate. Simultaneously, he infers from the data that the Copernican hypothesis is more adequate. The available data do not just consist of observations. Copernicus employs impetus considerations to parry the traditional plausibility arguments against the motion of the Earth. The Copernican inference is double-pronged. The same observations, which discredit the geocentric models, lend some credit to the heliocentric model. Furthermore, deductive consequences follow from the heliocentric model, which are in better harmony with the observations. For instance, the correct order and the relative distances of the planets are deductive consequences of heliocentrism. It is also a deductive consequence of heliocentrism that retrograde motions are an artifact of geocentrism. As we shall see, inferential practices are of great importance in the history of science. These are not to be confused with simple induction by enumeration. Scientists like Copernicus faced available evidence and competing models. They use observational evidence and other criteria, like the probability of explanation, to infer that some models are more appropriate than others. Observational evidence, probability considerations, and the impetus theory of motion now act as constraints on the acceptability of competing models. In a later chapter we will treat this basic procedure – inferring the cognitive adequacy of one model from the available constraints and simultaneously discrediting a competing model – as the method of **eliminative induction**. We face a competition between rival models, which claim to explain the available evidence. Each model is based on different presuppositions – geocentric vs. heliocentric assumptions – but no model enjoys absolute validity. Rather, it is a question of explanatory weight. Given the observations and other constraints, which system provides the more *likely* explanation? We will find this attitude in Darwin. The hypothesis of natural selection is a more likely explanation of species diversity than the design argument. The Copernicans employed *probability* arguments in favor of heliocentrism. It is physically more probable, they said, that the Earth turns once on its own axis in 24 hours than that the sphere of the fixed stars moved "at incalculable speed," in the same period, around a stationary Earth. [Kepler 1618–21, Pt. I, §3] And so, Kepler continues,

> (…) it is more probable that the sphere of the fixed stars should be 2,000 or 1,000 times wider than the ancients said than that it should be 24,000 times faster than Copernicus said. [Kepler 1618–21, Bk. IV, Part I, §4 (43)]

The annual movement of the Earth around the sun gives us "a more probable cause for the precession of equinoxes." [Kepler 1618–21, Pt. II, Book IV, §5; Copernicus 1543, Book I, §6]

As Copernicus and Kepler clearly saw, some models are better at dealing with the evidence than others. An inference to a model, which is more adequate with respect to the available constraints, is not an inference to *the* true model. The constraints themselves are subject to critical scrutiny. Copernicus still considered uniform circular motion as an all-important constraint and demanded that the Copernican hypotheses save the appearances. [Rosen 1959, 29] The history of heliocentrism from Copernicus to Newton confirms that a better model is better relative to both the available evidence and more theoretical considerations. With his planetary laws, Kepler introduced important changes into the Copernican model. Tycho Brahe and Galileo Galilei recorded observations which are more consistent with heliocentrism than geocentrism. Toward the end of the seventeenth century, Newton combined the idea of inertia and gravitation to arrive at a plausible mechanical explanation of why planets stay in orbits. In 1687 the constraints on an adequate model of astronomy had changed considerably. But now a difficulty confronts us. Recall that the geocentric model explains the seasons as well as the Copernican model. Why should we prefer the latter, given its additional redundant assumption of a third motion of the Earth?

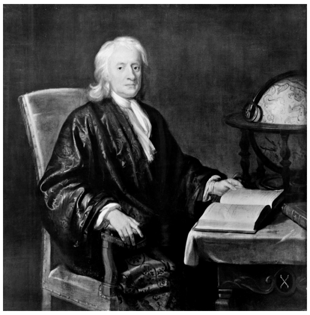
## 4.2 The relativity of motion

Galileo introduced into physics the principle of the relativity of motion. (Einstein later adopted this principle and generalized it.) Insects fly through the cabin in the same manner, irrespective of the inertial motion of the boat. According to the principle of relativity, the kinetic motion of an object can be described from either a stationary or a moving reference frame. As long as the motion is inertial (either at rest or moving at constant velocity), both views are equivalent. They must lead to the same numerical results. It is a matter of choice, which system we regard as the frame at rest and the frame in motion, respectively. This makes no difference to the physics of the situation.

From the point of view of relativity it should therefore make no difference whether we adopt a geocentric or a heliocentric view. [Born 1962, 344; de Solla Price 1962, 198; Rosen 1984, 183–4] We can follow Ptolemy: regard the Earth as a stationary frame and the sun as a moving frame. Or we can follow Copernicus: regard the Earth as a moving frame and the sun as a stationary frame. According to the principle of relativity our choice makes no difference to the physics of the situation. And so it appears to be. The Earth turns on its own axis once in a 24-hour rhythm to give us day and night. If the sun turned around the stationary Earth once in a 24-hour rhythm it would give us day and night. The seasons result from either a tilted orb of the sun around the Earth or a tilted Earth around the sun. However, there is more to a description of the solar system than mere kinematics. From a strictly kinematic point of view, the models are equivalent. The kinematic point of view is concerned only with pure motion, without regard to its causes. [Dijksterhuis 1956, I, §83; IV, §18, IV, C] This is the Ptolemaic and Copernican perspective. But there is also the question of dynamics: What causes the planetary bodies to move? Imagine you sit on a train that has stopped at a station. Through the window you observe a train moving slowly along the rails. Your intuition tells you that you are stationary and the other train is moving. But physics informs us that your train can be regarded as moving and the other train as stationary. The kinematics will be the same. But now imagine that the locomotive has been removed from your train. The dynamic situation is no longer equivalent. The moving train clearly has a locomotive which causes its motion. Your train has lost its cause of motion. Kepler was preoccupied with the question of physical causes. He suspected that energetic rays from the sun drove the Earth around its elliptical orbit. When a planet shows its "friendly face" to the sun, its magnetic lines attract it. When a planet shows its "unfriendly face" to the sun, its magnetic lines repulse it. The game of attraction and repulsion constrains the planet to its orbital motion around the sun. [Kepler 1618–21, Pt. II, §93] As Newton showed, this dynamic explanation was mistaken. Nevertheless, Kepler advanced dynamic arguments in favor of the orbital motion of the Earth. Once Newton showed why the planets stay in their elliptical orbits around the sun, the heliocentric model gave a better representation of physical reality than the geocentric model. Newton improved the algebraic structure of the model. He provided a dynamic explanation of planetary orbits in a heliocentric model. And even if we focus only on the spatial arrangement of the solar system, the heliocentric model captures the topologic structure of the solar system better than the geocentric model. We suspect that the model structures will correspond differentially to the structure of the physical system.

## 5 The Transition to Newton

> *The telescope was a curiosity on display at the annual fair before, in Galilei's hand, it became an instrument of theory. [Blumenberg,* The Genesis of the Copernican World *(1987), 648]*



**UF 1.7** Isaac Newton (1642–1727)

Newton had many reasons to believe that he was standing on the shoulder of giants. But he went one step further and produced the Newtonian synthesis. Newton's physics is not just a body of laws of mechanics, which govern the world of macro-objects both on Earth and in the heavens. It encapsulates a whole new view of the universe – a whole new image of how humans are to conceptualize the material world around them.

We can characterize the scientific revolution by two closely connected features: (A) the destruction of the ancient cosmos and the disappearance of all considerations based on its presuppositions; (B) the mathematization of nature and science. [Koyré 1957, 2, 29, 43, 61–2; 1965, 6–8] Let us look at these features in more detail.

(A) *The destruction of the ancient cosmos.* We have encountered some of the features of the traditional cosmic world-order:

- its hierarchical two-sphere structure between the perfection of the supralunary sphere and the imperfection and decay of the sublunary sphere;
- its distinction between terrestrial and celestial physics;
- its finite and closed nature;
- its energy-deficiency.

We have seen how both astronomical observations and theoretical constructions began to chip away at the traditional cosmic world-order. Associated with the destruction of the traditional world-order is the disappearance of all considerations based on its presuppositions. Material causes replace final causes. It is not the aim of the stone to strive back to its natural place in the universe. The stone is subject to a downward accelerating force. Planets do not stray from their orbits because they obey physical laws. The stars in the firmament do not twinkle for the enjoyment of humankind. [Burtt 1932, 17–24]

Galileo conveys to his pupil Andrea the liberating elation of breaking out of the "walls and spheres and immobility." Once "the breaking of the circle" or "the bursting of the sphere" (Koyré 1965, 7 n. 1) had taken place, the new universe could take on infinite dimensions.

(B) The second feature of the scientific revolution – the *mathematization of nature* – had equally important consequences for the development of Western civilization. It inspired a model of the universe that runs in accordance with deterministic laws. This image of the universe as a clockwork reached as far as Darwinism. [See Burtt 1932, 202, 206; Weinert 2004, Ch. I; Wendorff 1985, 144]

The language of mathematics applies to natural processes. It offers the great advantage of *algorithmic compressibility*. This means that a great number of data can be compressed in a precise mathematical equation. For instance, Kepler's third law establishes a relation between the orbital period of a planet around the sun, $P$, and its average distance from the sun, $A$ (expressed in units of the Earth–sun distance $AU$). The law states that the square of the orbital period is directly proportional to the cube of its average distance from the sun:

$$A^3 \propto P^2.$$

This law can be used to find, for any body orbiting the sun (even a spacecraft), either the average distance from the period or the period from the average distance. For example, if $A = 4$ AU, then $P = 8$ years. Thus, Kepler's third law compresses into one neat formula a great multitude of data. All objects orbiting the sun, from planets to satellites, are subject to this law. The law expresses the structure of the orbits around the sun.

For Galileo and Newton, the book of nature was written in the language of mathematics. Newton's great achievement was to have provided a synthesis between the mechanics of the heavens (Kepler) and of the Earth (Galileo). Newton destroyed the two-sphere universe. Whether or not the apple fell on his head, the lesson from this episode is correct. The same force that makes the apple fall on his head keeps the planets in their orbits. Newton was able to formulate three fundamental mechanical laws to which many terrestrial phenomena – from accelerating cars, to colliding balls, moving elevators, and orbiting planets – were subjected:

1. The law of inertia states that objects retain the same state of motion or rest unless some external force interferes.
2. The force law states that inertial motion can be subject to the application of a force, which changes its direction and momentum.
3. The law of interaction (action–reaction) states that to every action there is a reaction, equal in force and opposite in direction.

The growing mathematization of nature, to which Kepler, Galileo, and Hook contributed, culminates in Newton's axiomatization of classical mechanics. He formulated a few fundamental laws and principles, from which other laws (like Kepler's) could be deduced. Philosophically, Newton's world consisted of four elements:

- **Matter**: an infinite number of mutually separated hard and unchangeable particles, called corpuscles. They possess primary and secondary qualities but only the primary qualities matter to physics. [Burtt 1932, 235–6]
- **Motion**: the motion of the corpuscles can be described by the laws of mechanics.
- **Absolute space**: an imaginary cosmic vessel, within whose walls the corpuscles (and the bodies built out of them) perform their lawful motions; Newton takes absolute space to exist even when there is no matter to fill it.
- **Absolute time**: an imaginary river, whose constant flow sets a unique time metric by which all natural processes can be measured; all observers throughout the whole universe assign the same time to events, however far apart they are. [Weinert 2004, Ch. 4]

There is a distinctly philosophical side to Newton's reasoning.

## 5.1 On hypotheses

Like most great scientists, Newton demonstrated philosophical awareness. He reflected on the philosophical dimensions of physics. Newton is famous for his statement: "Hypotheses non fingo." This Latin phrase can be rendered alternatively as "I do not feign hypotheses"; "I do not make use of fictions"; "I do not use false propositions or premises or explanations."[6] Historians of science have identified several senses in which Newton uses the word "hypothesis." Sometimes he meant a plausible though not provable conception. In his later years he came to regard a hypothesis as a gratuitous fiction. [Koyré 1965, 36–7]

> That which cannot be derived from phenomena is called a *hypothesis* and these do not belong to experimental philosophy. [Quoted in Dijksterhuis 1956, 537]

Newton was not the first to worry about the term "hypothesis." Copernicus and Rheticus had corresponded about the usefulness of hypotheses in astronomy with a figure who will soon come to greater prominence in the discussion: Andreas Osiander. Copernicus and his pupil considered that certain astronomical hypotheses were more probable than others. More probability accrued to the heliocentric hypothesis than to the geocentric hypothesis. Acceptable hypotheses in astronomy had to explain all the observable phenomena. They had to explain the phenomena in a coherent way. The Ptolemaic hypothesis, says Rheticus, does not suffice to establish the harmony of celestial phenomena. [Rheticus 1540, 132; see also

[6] Koyré [1965], 35; Dijksterhuis [1956], 541; Crombie distinguishes three senses of "hypotheses": improvised propositions, heuristic aids, illegitimate fictions; Crombie [1994], Vol. II, 1071.

Correspondence reprinted in Rosen 1959, 31–2; 1984, 125–6, 193–4, 198–205] Kepler later agreed that the Copernican hypothesis enjoyed more probability than the Ptolemaic hypothesis. The notion of hypothesis had great repercussions throughout the next 140 years. The ambiguity of the term, as reflected in Newton's views on hypotheses in science, invited opposing interpretations of the Copernican model. In his *Dialogue Concerning the Two Chief World Systems* (1632), Galileo epitomizes the ambivalent status of hypotheses in the sixteenth and seventeenth centuries. The Preface states that his spokesman, Salviati, will defend the Copernican system but only as a purely mathematical hypothesis. But as the dialogue unfolds, Salviati is drawn toward probability arguments. Eventually he adopts the Copernican position that the acceptance of the dual motion of the Earth as a physical assumption leads to a more coherent explanation of the appearances. Note that these probability arguments invoke belief in a model, because its physical assumptions are more probable. It is not believable, says Kepler, that the "fixed stars move at incalculable speed."[7] [Kepler 1618–21, Pt. II, §5] The Copernican hypotheses are more like conjectures than useful fictions. They have a much closer association with the phenomena than Newton would later accept. They form, as Rheticus tells us, the basis of inferences.

By contrast, labeling hypotheses as "useful fictions" in astronomy reassured Copernicus's adversaries that his heliocentric model did not force them to abandon their cherished geocentric beliefs. Cardinal Bellarmine reminded Galileo that Copernicus had always spoken *hypothetically*: it is possible to use the motion of the Earth as a mathematical device to render the calculations more economic, since fewer epicycles and eccentrics are needed. However, to affirm the centrality of the sun as a physical hypothesis is in conflict with the Scriptures.[8]

In order to soften the clash between the Church and heliocentrism, Osiander inserts his Preface in an attempt to present the Copernican hypotheses as mere calculating devices. They have the license to be false or replaceable as long as "they reproduce exactly the phenomena of the motions." [Osiander, Letter to Copernicus April 20, 1541, quoted in Rosen 1984, 193–4] By the time Newton appeared on the scene, hypotheses did not command a respectable tradition. Rejecting them, Newton claims to be an inductivist. The laws of motion are deduced from

7 Kepler's probability argument states that we should attach more plausibility to the heliocentric view because the evidence – the apparent motion of the "fixed" stars in a 24-hour rhythm about the Earth – is more probable on the view that the Earth rotates on its own axis. These probability arguments can be supported by a consideration of the angular velocities involved under the two scenarios. Under some simplifying assumptions, the angular velocity of the rotating Earth for an observer at the equator is 464 m/s = 1670 km/h The geocentric view, by contrast, has to assume an angular velocity of the "fixed" stars about the stationary Earth. A calculation produces a value of $5.45 \times 10^6$ m/s = $1.96 \times 10^7$ km/h It is such an enormous rotational velocity of the stars – 19.6 million kilometers per hour, compared to 1670 km per hour for the Earth at the equator – which the Copernicans consider implausible on mechanical grounds. By comparison, the orbital velocity of the Earth around the sun is 30 km/h and the velocity of the sun around the galactic center is 225 km/h. The evidence – the observable rotation of the sphere of fixed stars – is more likely on account of heliocentrism than on account of geocentrism.

8 See Koestler [1959], 454; similar statements, reflecting Osiander's instrumentalist attitude, are found in Kuhn [1957], 191, 194; Crombie [1994], Vol. I, 599–600.

Phenomena and made general by Induction, he declares, and this is the highest evidence that a proposition can have in Philosophy. [Koyré 1965, 36–7; Dijksterhuis 1956, 544, 546–7] Phenomena are (reliable) observational or experimental data, from which are derived laws or axioms. Newton rejects any explanation of natural phenomena that appeals to metaphysical hypotheses, for which no evidence can be cited.

This does not mean, however, that the unobservable must automatically be suspect. The interior of the sun, for instance, is unobservable yet it is perfectly possible to make quite definite inferences about the chemical composition of the interior by use of spectral analysis. We have to distinguish *direct* from *indirect* observation. Directly observable phenomena are accessible through our eyesight or through the use of instruments. The directly observable is not necessarily the most reliable. Retrograde motion, as Copernicus reminds us, is a mere deception of sight. Indirectly observable phenomena are inferences from observations, and the use of reliable techniques, to unobservable parts of nature. We cannot directly observe the cause of planetary orbits but we can infer it from our observations and the heliocentric hypothesis. We begin to see that the story of heliocentrism is laced with philosophical lessons.

## 6 Some Philosophical Lessons

> *Copernicus reflects the cosmological differentiation between the parochial perspective of his terrestrial "corner" and the central point of construction from which the universe cannot, indeed, be viewed but can be thought. [Blumenberg,* The Genesis of the Copernican World *(1987), 38]*

Copernicanism creates a problem situation from which a number of philosophical consequences follow. As we shall see in later chapters, philosophical consequences also follow from Darwinism and Freudianism. A **problem situation** in science occurs when a number of competing explanatory accounts propose solutions to a perceived scientific problem. The solutions are proposed on the background of a number of accepted presuppositions, techniques, and models. The presuppositions and techniques define acceptable problems and a set of possible solutions to the problem. Consider two famous problems in the history of science: the motion of planets and the existence of different species. In 1543 Copernicus proposed a solution to the first problem. In 1859 Darwin offered a solution to the second problem. Both solutions entered a conceptual space in which certain presuppositions, techniques, and models had already taken root. Copernicus and Darwin proposed rival models. They involved a set of solutions, which differed from previous solutions. They also gave rise to a set of presuppositions and techniques, which diverged from previously accepted presuppositions. The divergence was striking in the case of Darwin, but only partial in the case of Copernicus. At least Copernicus worked with a non-Aristotelian theory of motion. The set of presuppositions, techniques, and models renders certain solutions acceptable, others unacceptable. Certain solutions are possible solutions because they are compatible with the set of accepted presuppositions and techniques. The set also renders other solutions impossible. For instance, a mature form of Copernicanism renders all Greek presuppositions – the circle, the two-sphere universe – and techniques – eccentric circles and epicycles – obsolete. Hence geocentrism can no longer be regarded as an acceptable solution. It is important to distinguish *possible* from *actual* solutions. A certain solution, *S*, may be possible with respect to a cluster of presuppositions. We cannot accept it as the actual solution because other solutions will also be possible with respect to this cluster. For a possible solution to transform itself into an actual solution, it needs to prove its mettle. The actual solution needs to solve some old and some new problems.

Scientific problem situations have an impact on philosophical issues, to which we now turn. Note that there is a difference between the *deductive*, *inductive*, and *philosophical* consequences of a theory. The deductive consequences follow mathematically or logically from the principles of the theory. Deductive consequences can occur in the form of novel predictions or the accommodation of already known facts. In both cases they are often compatible with one theory but, ideally, not its rivals. If this situation obtains, we will later speak of *supportive* evidence. Inductive consequences follow from the theory with degrees of probability. For instance, if a theory is statistical in nature its consequences follow with higher or lower degrees of probability. Consider the difference between "All ravens are black" and "Most ravens are black." If "All ravens are black" and the observation is made that "this is a raven," it follows deductively that "this raven is black." But if the statement merely is that "Most ravens are black," then it follows only inductively that "this raven is black." Philosophical consequences are conceptual issues, as they are dear to the philosopher. Although they are often taken to follow from scientific theories, they are rarely subject to direct empirical testing. Hence they do not command the expert consensus which deductive consequences typically induce. Given one theory, *T*, incompatible philosophical consequences are often drawn from it. Copernicanism, Darwinism, and Freudianism, for instance, raise questions regarding an instrumentalist or realist interpretation of some of their fundamental assumptions. The fact that two incompatible philosophical views (instrumentalism or realism) are compatible with one theory does not exclude the possibility that one view is more in agreement with the principles of the theory than the other. In connection with Copernicanism we first note its impact on general worldviews. Then there arise lessons for epistemological attitudes: realism and instrumentalism and the question of underdetermination. Copernicanism also raises philosophical issues concerning models, theories, and laws. The Copernican turn also calls for an analysis of criteria of scientific revolutions. And finally we tackle the Anthropic Principle and ask whether it constitutes a reversal of the Copernican turn.

## 6.1 The loss of centrality

*Copernicus, through his work and the greatness of his personality, taught man to be modest. [Einstein, "Message on the 410th Anniversary of the Death of Copernicus" (1953), 359]*

In *De Revolutionibus* Copernicus sets out to convince his readers that the heliocentric hypothesis is not as absurd as it may sound. He managed to convince a number of his contemporaries, like Rheticus and Maestlin in Germany. He found some followers in England, like Thomas Digges and William Gilbert, and Italy, like Giordano Bruno. [Dryer 1953, Ch. XIII] Yet at the beginning of the seventeenth century Kepler still reports that many people were shocked by heliocentric ideas. [Kepler 1619, 175] His contemporary Francis Bacon (1561–1626) steadfastly refused to accept Copernicanism.

In many quarters the Copernican treatise was greeted with opposition and hostility. Copernicus's contemporaries did not find discomfort in the mathematical details of his work. Their objections were more philosophical. The Copernican view, if taken literally, displaced the Earth from the hub of the universe. The inhabitants of the Earth suffered a loss of centrality. According to Copernicus, they felt, it was no longer true that the universe had been created for the sake of humankind. Copernicus's heliocentric hypothesis presented more than a mathematical treatise in the esoteric science of astronomy. It was an attack on what people believed about the structure of the world. Especially amongst the Protestant clergy and theologians the heliocentric idea gained little favor. Martin Luther, citing Scripture, dismisses Copernicus as a fool. His chief lieutenant, Philip Melanchthon, calls him simply insolent. The Roman Catholic Church had embraced the geocentric view through the work of Thomas of Aquinas. The resistance of the Catholic Church against the physical motion of the Earth around the sun was partly due to ecclesiastical pressures. The Catholic Church saw its authority under threat from the rise of Protestantism. Copernicanism posed an additional challenge to Catholic dogma.

In their endeavor to cushion the shock of heliocentric ideas, Kepler and Rheticus were eager to employ teleological arguments. While physical centrality had been lost, humankind had not sunk to cosmic insignificance. The heavenly phenomena had been invested with a purpose. The purpose of movement, Kepler proclaims, is to prove that "movement belongs to the Earth as the home of the speculative creature." [Kepler 1618–21, Bk. IV, Part I, §5 (75, 77)] Rheticus even asserts that "the sphere was studded by God for our sake with a large number of twinkling stars." [Rheticus 1540, 143]

The early Copernicans did not accept that a mere physical removal of humans from the hub of the solar system to its third sphere represented a hurtful demotion. The celestial phenomena have a purpose, which remains unaffected by the physical position of the Earth among the planets. Their purpose resides in their service to humankind. Aristotle held that "Nature is a cause that operates for a purpose." [Aristotle 1952a, Bk. II, 8] And "as nature makes nothing purposeless or in vain, all animals must have been made by nature for the sake of men." [Aristotle 1948, Bk. 1, §11, 1256b] Copernicus conceives of his job as understanding the "machinery of the world, which has been built for us by the Best and Most Orderly Workman." [Copernicus 1543, Preface, 6] The dogma of teleology – that "Nature does nothing without a purpose" – reverberates through the history of human ideas about Nature. Rheticus even turns teleology against the Scholastics.

The Wise Maker would have created a heliocentric model, for He would have "shirked from inserting in the mechanism any superfluous wheel." [Rheticus 1540, 137]

It took until Newton to remove teleological thinking from the physical sciences. It took even longer in the biological sciences, as we shall see in Chapter II. It is easier to convince people that stars are not made to shine for their amusement than it is to convince them that eyes are not designed for them to see.

Nietzsche found that "since Copernicus man has been rolling from the center toward x." He saw himself as a second Copernicus who branded the self-deprecation of "European Man" as the greatest danger. [Kaufmann 1974, 122, 288; Nietzsche 1887, Bk. I, §12] Freud, too, interpreted the Copernican turn and the Darwinian revolution as serious blows to the self-image of humankind. The Oxford physicist David Deutsch observes that

> the prevailing view today is that life, far from being central, either geometrically, theoretically or practically, is of almost inconceivable insignificance.

Deutsch disagrees with this assessment. Yet it is a physical fact that

> the solar system is a negligible component of our Galaxy, the Milky Way, which is itself unremarkable among the many in the known universe. So it seems that, as Stephen Hawking put it, "The human race is just a chemical scum on a moderate-sized planet, orbiting round a very average star in the outer suburb of one among a hundred billion galaxies." [Deutsch 1997, 177–8; cf. Weinberg 1977, 148; Blumenberg 1981, Pt. I, VI; 1965]

There is, however, a difference between physical and rational centrality.[9] From a terrestrial perspective humans observe the universe from a particular physical angle, which is defined by the location of the Earth in the Milky Way. This angular perspective has led to misconceptions. The Greeks constructed from the appearances a geocentric worldview. Copernicus does not abandon the tight connection between observational appearances and geometric constructions. But he holds that a heliocentric model accounts better for the appearances, on account of its greater plausibility. Copernicus's change of perspective has two implications. One is that physically humans no longer occupy the geometric center of the universe. Another is that the heliocentric hypothesis affords humans a much better grip on the observational appearances. The change of perspective offers humans a more coherent model of the solar system. The Copernican turn replaces *physical* with *rational* centrality. Through rational thinking humans can construct an accurate model of the universe. Their perspective on the universe is predicated on a particular physical position in the universe. Their centrality is due to a rational comprehension of the universe, which far exceeds what their eyes will allow them to see. "Eyesight," muses Kepler, "must learn from reason." [Kepler 1618–21, Bk. I, Part I, §1]

[9] The distinction between physical and rational centrality runs through the work of Hans Blumenberg on Copernicanism – see Blumenberg [1955]; [1957]; [1965]; [1981], Part I, III; Part II, III, IV; Part VI, I.

Observations confirm that humans do not dwell in a privileged geometric location in the vast cosmos. There is no evidence that the other bodies in the solar system were especially designed for the purpose of human life. In this sense the Copernican hypothesis has led to a loss of centrality. The Copernicans, however, demonstrated that physical centrality is not of utmost importance. The human mind soars far above the physical limitation of its bodily habitat. What humans lost in geometric centrality they gained in rational centrality. Knowledge replaces location, reason enhances eyesight.

A certain symmetry exists between Copernicus and Darwin. Copernicus removed humans from the physical center of the universe. Darwin removed humans from the pinnacle of creation. These philosophical implications of the Copernican turn and the Darwinian revolution have recently been contested. Some modern cosmologists reject what they call the "Copernican dogma." According to them this dogma states that there is nothing special about humans and their habitat. The Earth is one of many planets orbiting a solar body of average size. The solar system itself can claim no central position in the Milky Way. And the Milky Way is just one of billions of galaxies. Darwinian evolution seems to support the Copernican "dogma." Evolution, as Darwin taught, has produced an offshoot of the evolutionary tree, which humans call their home. But evolution is contingent. It might never have brought forth intelligent life.

Some cosmologists argue that the "Anthropic Principle" needs to replace the Copernican dogma. [See Section 8] In evolutionary biology, "intelligent design" is set against Darwin's natural selection. Intelligent design scenarios seek to reinstate teleological thinking in evolutionary biology. [Chapter II, Section 5.4] The Anthropic Principle rejects the implication that human existence is not in any way special. The Anthropic Principle affirms that humans live in a very special epoch of cosmic history. It is special since it has permitted the "evolution of carbon life." [Barrow/Tipler 1986, 601] Before we consider this principle, a number of other philosophical concerns require attention.

## 6.2 Was Copernicus a realist?

Earlier we found that Copernicus was not the author of a scientific revolution. With his shift in perspective against the backdrop of some invariant features, Copernicus planted the seeds of a scientific revolution. The Copernican turn – a shift in perspective with some explanatory gain – was a significant opening move, which enabled the rise of modern science. Copernicus stood at the gate of modernity.

When we think about modern science, three features stand out:

- systematic observation;
- controlled experiment;
- mathematization.

Copernicus reports a number of his own observations, made at Frauenburg, in Prussia. [Copernicus 1543, Bk. III, §2; Rheticus 1540] Otherwise, he relied on numerous Greek observations. Kepler formulated his planetary laws on the basis of Tycho Brahe's discoveries. And Galileo made significant additions to the corpus of astronomical data. They all used observations in a *systematic* fashion. That is, they used them to establish the Copernican hypothesis. **Systematic observation** means that observational data are employed to test the adequacy of a particular model. All these scientists found that, compared to the Ptolemaic model, the heliocentric model was more probable. In the case of astronomy **controlled experiment** does not apply. Controlled experiment is the deliberate manipulation of selected parameters in scientific laboratories. That is, it involves a deliberate exclusion and inclusion of parameters in the experiment. In their famous scattering experiments (1909–11), for instance, Rutherford and his collaborators used ionized helium atoms, fired at gold atoms, to discover that the atom possessed a nucleus. In these experiments Rutherford deliberately neglected electrons because they would not interfere with the trajectory of the heavy helium atoms inside the gold atoms. The experimenters concentrated exclusively on the interactions between the nuclei. We have already seen that **mathematization** offers algebraic compressibility. [Section 5] Ancient astronomy made extensive use of geometry. Angles and circles were the main tools in the hands of the astronomer, even Copernicus. Geometry limits the usefulness of mathematics in the description of nature. The use of geometry made it impossible for Copernicus to provide an accurate quantitative theory of planetary motion, let alone a dynamic analysis. His explanatory gain was limited to the topologic structure of his model.

But does this explanatory gain mean that a better astronomical explanation is at hand? This question lies in the logic of the Copernican problem situation. By changing the perspective between stationary and moving Earth, Copernicus claims to achieve a better explanation of the observable phenomena. A philosophical issue immediately arises, of which his contemporaries were aware: Granted that Copernicus achieved some explanatory gain, does this explanatory gain tell us merely something about the structure of our theories or more informatively about the structure of the physical world itself? Was Copernicus a realist? Osiander raised this question in his anonymous Foreword to *De Revolutionibus*. This question also lurks behind the ambivalent use of the term "hypotheses." We are thus dealing with the philosophical issue of **realism** and **instrumentalism**.

*6.2.1 Lessons for instrumentalism and realism* The most famous testimony to the presence of this philosophical issue in the minds of Copernicus and his contemporaries is buried in Osiander's Preface. It presents the *Revolutions* to the European world of 1543. Osiander saw it fit to add some introductory notes for the benefit of The Reader Concerning The Hypotheses of This Work. [Copernicus 1543, 3–4; Koestler 1964, 169–78; Rosen 1984, 195–6] Note, first, that Osiander follows Copernicus in speaking of *hypotheses*. As we have seen, this innocuous-seeming term developed its own divided pedigree in the span from 1543 to 1687. Osiander, however, employs the term in only one of its senses. Reminding the reader of the newness of the heliocentric hypothesis, he spells out the astronomer's dilemma. On the one hand, the astronomer cannot know the "true causes" of the celestial movements. On the other hand, the astronomer can establish fairly accurate descriptions of "the history of the celestial movements." How is this dilemma to be resolved? Osiander's recipe is the *locus classicus* of instrumentalist philosophy. The astronomer can establish *how* the planets move but not *why*. Yet the human mind is exercised by theoretical curiosity. Even though no true explanation can be given, any explanation is better than no explanation. It is then the job of the astronomer

> to think up or construct whatever causes or hypotheses he pleases such that, by the assumption of these causes, those same movements can be calculated from the principles of geometry for the past and for the future too.

It is therefore not necessary for the hypotheses to be true or even probable. Distancing himself directly from the probability arguments advanced in the main text, Osiander holds that:

> it is enough that they [the hypotheses] provide a calculus, which fits the observations.

Why should the reader then even read the Copernican tract? Osiander makes an appeal to simplicity. Some hypotheses render the calculations simpler, make the observations easier to understand. They may even give rise to more reliable predictions.

> Therefore let us permit these new hypotheses to make a public appearance among old ones which are themselves no more probable, especially since they are wonderful and easy and bring with them a vast storehouse of learned observations. As far as hypotheses go, let no one expect anything in the way of certainty from astronomy, since astronomy can offer us nothing certain, lest, if anyone take as true that which has been constructed for another use, he go away from this discipline a bigger fool than when he came to it. Farewell.

Osiander anticipated Newton's later skepticism regarding hypotheses in astronomy. He permitted heliocentrism as a mathematical hypothesis, but not as a claim about physical reality. As a reality claim it would be a thorn in the theologian's eye. By deflecting the Copernican hypothesis along instrumentalist lines, Osiander sought to remove its sting. It was another mathematical device, with no better claim to reality. It had as little probability as the established Greek hypotheses. The true causes of planetary motion cannot be known, because the human mind is too weak to apprehend the celestial sphere. In the absence of physical understanding, revelation takes its place.

What about Copernicus? Was he a realist? Just as there is no doubt that Aristotle believed in the physical centrality of the Earth, there is no doubt that Copernicus believed in the annual and daily motion of the Earth. Aristotle also believed in the reality of solid spheres, whose function was to carry the planets. But Copernicus was "unsure whether they were real or imaginary." [Rosen 1959, 11–21] Copernicus was uncertain about the physical significance of his geometric constructions. He observes that Ptolemy employed various geometric devices. Unsurprisingly, he finds himself unable to say which one of them corresponds to reality. His solution is to endorse the equivalence of hypotheses:

> It is not easy to determine which of them exists in the heavens (…) except that the perpetual harmony of numbers and appearances compels us to believe that it is some one of them.[10]

Copernicus was not a realist about his geometric devices. He had some difficulty believing that the theoretical structures employed in heliocentrism – the eccentric and epicyclic motions, which serve to account for the observable phenomena – have a counterpart in physical reality. Copernicus was not a realist about the algebraic structure of his model. Copernicus was a realist about celestial objects, their motions, and the system that holds them together. He believed that the place he had assigned to the Earth in the heliocentric model corresponded to a part of the structure of the solar system. Copernicus was a realist about the topologic structure of the heliocentric model. Copernicus's realist arguments are presented in his Preface and Dedication to Pope Paul III and Part I of his book.

First, Copernicus attributes a *causal* role to the movement of the Earth. It is the physical position of the Earth among the other planets that explains the appearance of retrograde motion, the seasons, and the natural length of the day. The observable appearances are causally explained by the physical motion of the Earth:

> We explained the appearances due to the movement of the Earth around the sun, and we proposed by that same means to determine the movements of all the planets. [Copernicus 1543, Bk. IV, Introduction]

As Copernicus believes in the planetary status of the Earth, he believes that the Earth's location is causally responsible for some of the observable phenomena. So Copernicus is not just a realist about the position of the Earth; he must be a realist about the physical consequences of this position.

The second move is Copernicus's *argument from coherence*. We have already noted that Copernicus was very well aware of the fact that natural phenomena are correlated in a number of ways. For Copernicus this meant that the movements of the Earth and the planets are correlated such that a change in one part leads to consequences in another part of the system. According to Copernicus we cannot arbitrarily change the order of the planets, without upsetting the whole cosmic picture. And if we correlate the orbits of the planets, their natural order is revealed to us. The correct choice of the initial position of the Earth – it is an orbiting planet

[10] Copernicus [1543], Bk. III, §§15, 20; Bk. V, §4. According to E. A. Burtt [1932, 49–51] Copernicus is not preoccupied with the question of the reality of the motion of the Earth but with the mathematical simplicity of the system, achieved through shifting the central reference point away from the Earth. This interpretation is true of the later chapters of *De Revolutionibus* but not of Book I; see Cushing [1998], 55.

rather than the stationary center of the universe – leads according to Copernicus to a more adequate model of the universe. Thus Copernicus argues from realism about the celestial objects, including the Earth, to realism about the scientific model he adopts. This realism is, however, restricted to the spatial distribution of the planets. The heliocentric model is a better model of the universe than the geocentric one, because it is more coherent. And its *coherence* provides a certain plausibility that it more correctly captures the structure of the universe than its rival, the geocentric model:

> Now we are turning to the movements of the five wandering stars: the mobility of the Earth binds together the order and magnitude of their orbital circles in a wonderful harmony and sure commensurability … [Copernicus 1543, Bk. V, Introduction]

On the hypothesis that the Earth moves, many observable consequences follow. Once the assumption leads to a coherent model, the coherence boosts the credibility of the original hypothesis. The heliocentric model, on account of its coherence, is a better representation of the interrelatedness of nature than the geocentric model. As Kepler and Newton later realized, the representation of the heliocentric model could be enhanced by abandoning many of the Copernican presuppositions.

## 6.3 Modern realism

> *If, therefore, there is a lesson which scientists should teach realists it is that all-or-nothing realism is not worth fighting for. [Psillos,* Scientific Realism *(1999), 113]*

Some of Copernicus's friends and followers felt outrage at Osiander's instrumentalist tinkering with the Copernican model. The equivocation of the term "hypothesis" pointed them in the direction of realism. With hindsight we can have a more relaxed attitude. Copernicus does not improve on the algebraic structure of the ancient models. Copernicus could advance no striking observational evidence in favor of the motion of the Earth. Osiander's instrumentalist Preface sounded a note of caution. For the technical part of the Copernican treatise, with its acceptance of the equivalence of hypotheses, does not live up to the promise of the first part.[11]

The Copernican model was able to provide a coherent account of the observational data known during Copernicus's lifetime. It was also compatible with later observations. But the original Copernican model lacked a credible mechanism that could explain the observations. The Copernican model enjoyed empirical validity, owing to its topologic structure. But a more sophisticated model or theory must also satisfy the demand for an accurate algebraic structure. The mechanism that

[11] For a defence of Osiander see Dijksterhuis [1956], Part IV, §§14–15; see Rosen [1959] for the correspondence on hypotheses; Mittelstraß [1962], IV, 6, 199–204; Neugebauer [1968], §6, 100; Blumenberg [1957], VIII, 73; [1965]; [1975], Part III, II; Rosen [1984], 125.

explains the "appearances" must correspond to the structure of the real world. A theory that has an accurate algebraic structure enjoys theoretical validity. The philosophical dispute between Osiander and Copernicus, between instrumentalism and realism, has its modern equivalent. The modern-day instrumentalist is as hesitant about mechanisms and structures underlying the observable features as Osiander. The modern-day realist is as confident about the underlying mechanisms and structures as Copernicus was about the reality of the motion of the Earth.

Modern instrumentalists advance two reasons for their caution about unobservable structures. On the one hand, there is the underdetermination of theories by evidence. [Section 6.4] This is the view that the empirical evidence can never clearly decide between any two scientific theories which are empirically equivalent but structurally different. This problem already found its expression in Ptolemy's equivalence of hypotheses. On the other hand, there is the "pessimistic meta-induction." This is the view that many scientific theories, which were once regarded as "true," have since landed on the scrapheap of mistaken ideas. Geocentrism is a case in point. What reason do we have for trusting our current theories? Modern instrumentalism therefore concerns itself with "saving the appearances." Scientific theories can at best be empirically adequate: they fit their domain as far as the observable phenomena are concerned but we have to remain agnostic with regard to the underlying theoretical structures. Two scientific theories may stipulate incompatible, unobservable mechanisms, although they both account for the available evidence. Furthermore, it is always possible to explain the same evidence on the basis of different theoretical structures. The realist wants more. It is not enough for our models to be adequate as far as the observations reach. The underlying theoretical structure, which can explain the observations, must also represent the structure of reality. Copernicus was still hampered by accepting the equivalence of the geometric hypotheses, even though they render the observational data coherent. Kepler, however, was interested in physical causes. The planets move in certain regular ways, expressed in Kepler's three laws. The further question is why they move in this way. It was not until Newton combined the first law of mechanics with the law of gravitation that a viable physical explanation became available. [See Figure 2.15] For the realist such episodes show that our mature scientific theories constitute good approximations to a genuine explanation of physical processes.

The realist claims that realism is the "only philosophy that does not make the success of science a miracle." [Putnam 1975, 73] Yet the story of astronomy shows that the anti-realist seems to have a point. The geocentric and heliocentric models were at first observationally equivalent, both endorsing the "equipollence of hypotheses." Yet, they were structurally different. And much of the theoretical structure ended up in the wastebasket of wrong-headed ideas. Ptolemy made no exaggerated claims about the "realism" of his geometric devices, and Copernicus was only a realist with respect to the spatial arrangement of the planets. Kepler advanced probability arguments in favor of the Copernican model, while jettisoning some of its central presuppositions. Newton abandoned Kepler's "physical" causes, while completing the Copernican revolution.

How can realists accounts for this double aspect of continuity and discontinuity? Recently the thesis of **structural realism** has been advanced to stem anti-realist arguments.[12] [Worrall 1989; Ladyman 1998; Psillos 1999] To account for continuity amid conceptual change, structural realism focuses on the structural aspects of systems. We can approach the idea by reflecting on the fact that science is concerned, quite generally, with natural systems (say, solar or biological systems). To obtain a system it is not enough to juxtapose elements (relata). A collection of planets does not constitute a system. To turn it into a system, the components must be interrelated. Thanks to the achievements of the Copernicans we know that the planets are related in a systematic fashion. The planets are bound into a system by the relations (laws) of the system. What constitutes a system in the natural world is the interaction of the components of the system. Planetary systems have planets as components, and Kepler's laws as their "glue," which holds them together. Biological systems have species or individuals as their components. What hold them together are the laws of evolutionary biology. Human societies have individuals and social groups as their components. What hold them together are the values, norms, and legal rules of particular societies. Apart from the relata of the systems, there must be appropriate relations between the components. It is hard to imagine that a human society could be held together by Kepler's laws.

In natural systems several components combine in a regular fashion. Natural systems therefore display a structure, consisting of the relata of the system and the relations between them. Science attempts to construct theories with models representing such systems. The models must have a model structure, which represents, in symbolic form, the structure of the natural system. If the scientific enterprise is preoccupied with the description and explanation of natural and social systems, structural realism is the thesis that the model structure represents, in approximation, well-confirmed structural aspects of the target system. It is concerned with the theoretical validity of model structures. So a structural realist will want to claim that the models of science aim at representing the (topologic and algebraic) structures of natural or social systems. The model structure, for present purposes,

[12] Structural realism comes in two flavors. *Epistemological* structural realism (ESR) claims that "all we know is structure." ESR stresses the continuity of the mathematical equations as scientific theories undergo drastic changes in their ontology and vocabulary. ESR tends to remain agnostic regarding the question whether there is more to the world than what the mathematical structure reveals about it, since it is conceivable that some elements of reality remain hidden from our view. *Ontological* structural realism (OSR) stresses that "all there is, is structure" and there exist no further constituents of reality beyond this structure; and the job of scientific theories is to capture this structure in symbolic form. OSR is divided over the question whether relations enjoy ontological primacy over objects (relata), in which case objects are just "nodes" in the relational structure, or whether relata and relations are taken to constitute the structure in a union. [See Rickles et al. 2006] The author's own inclination is to adopt a strong version of OSR, according to which all that exists are structured natural systems. OSR, on this strong view, is committed to both the reality of the relata and the relations, which are best captured in structural models. The relations are typically expressed in the laws of science, of which we will in a later section encounter a structural interpretation. Through the employment of equations, models, and theories, science expresses structural aspects of the material world. The existence of natural systems, like planetary and organic systems, shows that there is much structure for science to describe and explain.

consists of the components and their interrelatedness, the relata and the relations. To support this view the structural realist will want to show how to accommodate both the continuities and discontinuities in scientific theories at the level of structures. These features can be considered differentially with respect to both the topologic and the algebraic structures. In the transition from Ptolemy to Copernicus the topologic structure of the models changes but the algebraic structure remains the same, with the exception of the equant and major epicycles. In the transition from Copernicus to Kepler the topologic structure remains unchanged, but the algebraic structure undergoes dramatic changes. From Kepler to Newton, the algebraic structure experiences refinements, but no longer major changes. Since Newton the structural model of the solar system has no longer experienced drastic changes. It is a fact that scientific representations (in terms of models) always face limits in approximation and idealization. For instance, the circle is an idealization of an ellipsis. The structural realist will emphasize that there is enough incontestable evidence in the history of science for the postulation of continuities in the underlying structures. The continuities extend to both the algebraic and the topologic structures. Ultimately, it is only mature models that can be fully representative of the structure of the system modeled. Furthermore, these elements change differentially and usually for good scientific reasons. We may therefore suspect, as we will discuss in Section 7, that even in revolutionary periods in science, a certain chain-of-reasoning process links the transitions from old to new theories.

### 6.4 The underdetermination of theories by evidence

The inability to remove the equivalence of hypotheses was one of the reasons why Copernicus failed to become a scientific revolutionary. Realists must hold that the theoretical structure scientists assign to a set of observational or experimental data refers to some physical process, which can reasonably be taken to explain the observational data. Ideally this amounts to a causal explanation. [See Chapter II, Section 6.6] How can we make sure that our theoretical accounts are approximately true of the material world? This is in part the question of how scientific accounts manage to represent sections of the natural world. This is done, as we shall see, through the use of a variety of models. [See Sections 6.4 and 6.5] Before we turn to these concerns a stumbling block must be removed. There is a famous argument – the Duhem–Quine thesis – which attempts to show that the evidence is *never* strong enough to weed out all competing theoretical accounts. If the argument succeeds, there will always be perhaps infinitely many theoretical accounts, ontologically incompatible, which will be compatible with the evidence. The evidence will be unable to select one account as superior to another. All theoretical accounts will be underdetermined by the available evidence. The instrumentalists will have a powerful argument in their armory.

Consider some alien creatures that are able to utter the number "9" when shown a set of objects. How do they arrive at this answer? There are obviously several mechanisms we can ascribe to them: (1) $3 \times 3$; (2) $4.5 + 4.5$; (3) $\sqrt{81}$; (4) $1 + 2 + 6$; etc. If we learn nothing else about the creatures' abilities it will be difficult to decide. But imagine we learn that the aliens only possess mastery of natural numbers 1 to 10 and are not aware of fractions. Then we can exclude hypotheses (2) and (3). In this way we can build up evidence, which strongly suggests that a certain mechanism must be at work. This seems to have been the history of the Copernican hypothesis. In 1543 the observational evidence was simply not strong enough to favor the Copernican system over the Ptolemaic one. But then Tycho Brahe and Galileo made their significant empirical discoveries. They were difficult to reconcile with the Ptolemaic system. Through the discovery of his planetary laws, Kepler significantly improved the Copernican system. Finally, Newton crowned its success when he showed that inertia and gravitation could account for the elliptical orbits of the planets. As we shall explain in detail in the chapter on Darwinism, a process of elimination of rival accounts takes place. This elimination is possible, as the history of Copernicanism makes clear, because theoretical accounts run up against a number of constraints: the stubbornness of the phenomena is one such constraint, coherence and the probability of explanations are others. If it is a reality of the solar system that the Earth orbits the sun, and not the other way round, it will be hard for theoretical accounts to evade this fact. The Ptolemaic system survived for 1,500 years because of the paucity of the evidence. Once the evidence hardened, the Ptolemaic system floundered on the stubbornness of the facts and the implausibility of its assumptions.

A determined instrumentalist may not be swayed by such arguments. The instrumentalist will point out: (a) that it is always possible to dismiss the evidence as unreliable; the Mathematician and Philosopher in Brecht's play were right, it may be said, to be skeptical about the telescope, which in 1610 was not yet a reliable instrument; (b) that it is always possible to change certain background assumptions to save the theory; (c) that the history of science is full of cases of underdetermination. Until the beginning of the seventeenth century astronomical models were incompatible with each other, yet equally compatible with the evidence. A similar situation prevailed in evolutionary biology until the beginning of the twentieth century. And social-science models of societal phenomena still suffer from the scourge of underdetermination.

*6.4.1 The Duhem–Quine thesis* Consider Popper's falsificationist scheme: from a scientific theory, $T$, we derive a testable hypothesis, $H_E$; this hypothesis is then subjected to "severe" tests; if the hypothesis does not survive the tests, $\neg H_E$, the theory, from which it was deduced, will be falsified, $\neg T$. Against this falsificationist move Duhem and Quine hold that it is the theory, $T$, and background assumptions, $A$, together that face experience; if the tests fail to confirm the hypothesis there is some latitude of choice. Either we reject the hypothesis, $H_E$, or we change the background assumptions, $A$, to save the theory. [See Box 1.2 for a more logical statement]

Before we turn to an example, some preliminary remarks are in order. First, the disjunction, $\neg H_E \vee \neg A$, is not a definite result. Some reason should be advanced for retaining either $H_E$ or $A$. Second, we should consider that the background hypotheses, $A$, and the hypothesis under test, $H_E$, may not have equal

**Box 1.2** The Duhem–Quine thesis in logical terms
*Popper's falsificationist scheme*:

$$\left[(T \Rightarrow H_E)\,\&\,\neg H_E\right] \Rightarrow \neg T$$

*Duhem–Quine Thesis*:

$$\left\{\left[(T\,\&\,A) \Rightarrow H_E\right]\&\,\neg H_E\right\} \Rightarrow (\neg H_E \vee \neg A)$$

To save the theory, $T$, Duhem–Quine envisage that the background assumptions can be changed, say to $A'$, so that from the conjunction of $T$ and $A'$ the negation of $H_E$ can be deduced:

$$\left\{(T\,\&\,A') \Rightarrow \neg H_E\right\}$$

*Key to symbols*:
$T$ = theory; $H_E$ = testable hypothesis; $\neg$ = negation; $\vee$ = logical disjunction; $\Rightarrow$ = deductive consequence; $A$ = background assumptions

epistemological weight. Often in science, there are fairly well-established theories, or results, which are presupposed and not currently under test. Third, the evidence, $E$, which is used to test the hypothesis, will often be fairly robust in the sense that it has been arrived at through independent methods. The Duhem–Quine thesis ignores these reservations. It holds that it is always possible to save $T$, despite $\neg H_E$, if we are prepared to make appropriate changes in the background knowledge, say from $A$ to $A'$.

The history of astronomy provides us with nice examples to illustrate and evaluate the Duhem–Quine thesis.

Let us first enrich Popper's falsificationist scheme with some additional background assumption $A$. Let $T$ be Ptolemaic astronomy, let $A$ stand for the immutability of the supralunary sphere in Aristotelian cosmology; we take $H_E$ from the Mathematician's assertion, in Brecht's play, that according to the ancients "there can be no stars, which turn round centers other than the Earth," that is, Jupiter can have no moons; finally let $\neg H_E$ stand for Galileo's discovery of the Jupiter moons. Galileo's discoveries, including the phases of Venus, and Tycho Brahe's observation of the appearance of the supernova of 1572 demonstrate the mutability of the heavens. Such empirical discoveries are difficult to accommodate in the geocentric model, which explicitly postulates the immutability of the heavens. It is difficult to see how the background assumption, $A$, could have been changed in order to accommodate the empirical results. Changing $A$ to, say, $A'$ – the mutability of the heavens – would have destroyed the structure of the geocentric model. The empirical discoveries were robust. "The universe of the divine Aristotle is an edifice of such exquisite proportions," declares the Philosopher, "that we should think twice before disrupting its harmony." The Philosopher's strategy is therefore to deny Galileo's evidence, $\neg H_E$. This is a legitimate move as long as the evidence is not robust. Once the evidence is fairly reliable, this strategy degenerates quickly into dogmatism. Galileo's visitors appear dogmatic because they insist on the "truth" of the Aristotelian dogma. Their skepticism would have been more justified had they questioned the reliability of the telescope.

There are, however, cases where it is perfectly reasonable to reject background assumptions. Let $T$ be Copernican astronomy, let $A$ stand for the assumption of uniform, circular orbs in the supralunary sphere, which Copernicus shared with the Greeks; we take $H_E$ to stand for the circular motion of a planet around the central sun; finally let $\neg H_E$ stand for Kepler's discovery of the elliptical, nonuniform motion of this planet. We know that Kepler rejected the background assumption, $A$, of circular orbital spheres. He replaced it with nonuniform motion, $A'$, as expressed in Kepler's laws. As Kepler considered the basic approach of Copernicus to be correct, he could not really reject the theory, $T$. To do so would have meant to return to earlier theories, like Ptolemy's geocentrism or Brahe's compromise system. These earlier theories held few attractions for Kepler, since they were not compatible with the observational evidence. It is true that Kepler saved the Copernican theory, $T$, by changing the background assumption, $A$. As required by the Duhem–Quine strategy, the conjunction of $T$ and $A'$ now had the deductive consequence $\neg H_E$: $\{(T \,\&\, A') \Rightarrow \neg H_E\}$. But note that it was the background assumption, $A$, that Kepler could not make compatible with the evidence. It was not a matter of saving $T$ come what may. $T$ was a relatively successful theory. But it could not account for the observations with the accuracy required by Kepler, since it was based on a background assumption which it shared with geocentrism.

These two examples suggest that we should distinguish a logical from a practical point of view. From a logical point of view it may indeed be possible, as Duhem and Quine suggest, to save a theory, $T$, by a number of stratagems: changing the background assumptions, denying the evidence. But from a practical point of view, scientists are usually faced with a limited number of theoretical accounts, which they assess, as Einstein showed, by submitting them to the power of constraints. [Einstein 1918; 1919; Weinert 2006]

→ *6.4.2 The power of constraints* A practical solution to the Duhem–Quine thesis relies on the appeal to constraints. Constraints can generally be regarded as restrictive conditions on admissibility. They either control which parameters are to be admitted into a scientific theory or model or, more generally, which theories and models are admissible as scientific constructs. Consider a doorman outside a nightclub. This nightclub serves alcohol but only to punters who are over a certain age limit. The doorman must make sure that only punters who satisfy the age limit are admitted. If you are an under-age punter, the doorman imposes a restrictive condition on your admissibility to the nightclub. If he does his job properly, you will not be admitted. As we shall discuss now, a variety of constraints operate in scientific theorizing. Basically, there are empirical and theoretical constraints, which can be further subdivided.

Consider scientific models and theories as embedded in some *logical space*, which is structured by a range of empirical and theoretical constraints. The mathematician regards an equation as a **constraint** on the set of possible solutions. Consider the equation for a parabola: "$y = x^2 + 1$." The equation excludes as possible solutions all those numbers smaller than one (<1), since numbers <1 do not satisfy the constraint imposed by the equation. Scientific constraints are restrictive conditions on models and theories "such that out of a set of available parameters only those which satisfy the constraints constitute admissible inputs." With the development of science and the emergence of new discoveries, these restrictive conditions can change in various ways. [Weinert 1999, 308–13] Thus for the Greeks, as for Copernicus, circular motion was a powerful constraint on model building. As broad categories, we encounter in science empirical and theoretical constraints. Within these broad categories, further distinctions can be made. Under *empirical constraints* we understand the availability of stable, repeatable empirical data (experimental and observational results), but also the existence of fundamental physical constants (like *h* and *c*, see Weinert [1998]), which may appear across quite different models or theories. Scientific theories are to be testable against such empirical constraints. Under *theoretical constraints* we understand physico-mathematical principles (like the relativity principle); methodological norms: simplicity, unification, logical consistency, and the conceptual coherence of a theory (by which is meant here the maximization of the logical connections, mathematical derivations, and evidential relations); and finally metaphysical postulates (the uniformity of nature, causality, circular orbits, determinism, perfection and harmony in nature). A conjunction of these different constraints can delineate a number of different constraint spaces, in which models and theories can be embedded. Geocentrism and its constraints constitute one constraint space, while Kepler's heliocentrism constitutes another constraint structure. The idea of a set of constraints operating on scientific constructs is useful for the elimination of inadequate models: the latter founder on the rock of constraints. We have already alluded to the procedure of eliminative induction, which we shall discuss in Chapter II. Its strength lies in the fact that it can eliminate not just individual models but whole sets of models that satisfy a particular set of constraints. [Norton 1995; Earman 1996]

A *constraint space* is a structure, defined by various types of constraints, into which actual and possible models can be embedded. The constraints operate on admissible and inadmissible constructs. The constraints are always finite, but the constraint space permits an infinity of possible (unarticulated) models and theories. However, a finite number of constraints can govern a potentially infinite number of models or theories, just like an infinite number of specific cases, both actual and possible, falls under one scientific law. A small number of constraints can eliminate an infinite number of models and theories, just like one doorman can turn back a large number of punters. Thus a heliocentric structure, combined with Kepler's laws, eliminates all geocentric-type models as unsuitable constructs. The elimination succeeds because the geocentric models become incompatible with the new constraints. In other words, the attempt to insert old models into new constraint spaces produces inconsistencies.

For the purpose of discussing the Duhem–Quine thesis, in the light of constraints, we shall appeal only to empirical data, as examples of empirical constraints, and coherence, as an example of a theoretical constraint.

Let us first look at some examples of how the appeal to *empirical* constraints helps to alleviate the Duhem–Quine problem, at least from a practical point of view. Recall the situation of geocentricism around 1600. In 1572, Tycho Brahe had discovered a new star (supernova). In the period 1577–1596 he discovered comets. He proved that they were located beyond the moon's sphere. These observations posed a serious problem for one of the central dogmas of geocentrism: the immutability of the supralunary sphere. It cannot be excluded, from a logical viewpoint, that geocentrism may have found a way to accommodate these phenomena. In the later parts of his *Almagest* Ptolemy suggests that any precise knowledge of the supralunary sphere is beyond human understanding. A strange way of accommodation is to plead ignorance. It is important to emphasize that geocentrism would have *had* to accommodate the phenomena. They were stubborn phenomena, whose denial would lead to the dogmatism of the Philosopher. The question is which cost the accommodation would have incurred. [Kitcher 1993, 247–56; Quine 1990, 3–21] As we have seen, the accommodation was natural to heliocentrism. From a practical point of view, the cost of accommodation would have placed a severe strain on geocentrism. It is not coherent to postulate the immutability of the heavens and accept the evidence of mutability.

Let us also look at some examples of how the appeal to *theoretical* constraints, like the coherence of a scientific theory, helps to alleviate the Duhem–Quine problem. Coherence means that the elements of a scientific theory form a tight network. Coherence measures the number of interconnections of the components and deductive consequences of a theory. To make coherence act as a constraint means that only those elements which do not upset the coherence of the system are allowed to enter. The coherence of scientific theories can be compared to a crossword puzzle. As we fill the columns and rows of the puzzle with answers, we begin to see a tight fit. A crossword puzzle has only one solution, which determines which answers are permitted. If a column answer is correct, it exerts a constraint on all the row answers. With almost all columns and rows filled, the puzzle becomes a rigid system. The filled columns and rows impose severe constraints on entries in the remaining blank spaces. With this conception of coherence in mind, consider how an attempt to fit the Jupiter moons into the Ptolemaic model would fare. It would upset the coherence of the system, which was based on the metaphysical belief in supralunary perfection. The non-circular, elliptical orbit of comets would not only have posed considerable problems for the geometric construction of the system. [Figure 1.9] It would have destroyed its coherence. Why did Kepler's introduction of real, nonuniform velocities of planets not destroy the coherence of the Copernican system? Kepler accepted the spatial arrangement of the planets in the Copernican system. Circular orbits can be regarded, mathematically, as good approximations of the near-elliptical orbits of the planets. But Kepler had to abandon the metaphysical need for spheres and circular motion.

We are not arbitrarily imposing philosophical ideas on the Copernicans. We have seen that Copernicus expresses a strong belief in coherence in his Preface to *De Revolutionibus.* He stresses that if the movements of the "wandering stars" are correlated to the circular movement of the Earth, many observable phenomena follow. Taking up these thoughts on coherence, his pupil Rheticus is even more explicit on this score. The great astronomers of the past, he declares,

> fashioned their theories and devices for correcting the motion of the heavenly bodies with too little regard for the rule which reminds us that the order and motions of the heavenly spheres agree in an absolute system. [Rheticus, 1540, 145]

If it is true, however, that scientific theories tend to display a great amount of coherence (interconnectedness) between their components, then it is hard to believe, with Duhem and Quine, that a scientific system only faces the verdict of evidence as a whole. As we have just seen, the coherence requirement seems to limit the number of changes that can be made. It also limits the nature of the changes that are acceptable. We can target particular elements of a system, knowing that it will affect the whole system. The Copernican hypothesis targeted individual components of geocentrism: the topologic position of the earth; the algebraic tool of the equant. Kepler targeted the dogma of circular orbs.

## → 6.5 Theories, models, and laws

In the preceding pages we have spoken of astronomical theories, geocentric and heliocentric models, and planetary laws. The scientific enterprise rests on a number of pillars: theories and models, laws, and constraints. How are they related to each other? How does a theory differ from a model? What is a law of nature? The constraints, as we have emphasized, constitute a constraint space. We can enlarge the constraint space by introducing further constraints, as the history of astronomy illustrates. Tycho Brahe enlarged the observational basis on which astronomical models had to be built. When Kepler rejected the metaphysics of circular spheres he became the author of the most fundamental change in the constraint space of astronomy for two thousand years.

*→ 6.5.1 Theories and models* We can think of a scientific theory as a coherent conceptual system, linking a number of theoretical elements, which are important for the scientific exercise. A scientific theory applies to a domain. The domain comprises all the phenomena in all the possible systems to which the theory applies. The Copernican theory takes all inanimate planetary systems as its domain. The Darwinian theory takes all animate biological systems as its domain. The theories claim that they can account for all the relevant types of behavior in the systems which fall within their respective domains. The Copernican theory wants to account for the distribution of solar systems and planetary motions. The Darwinian theory wants to account for all evolutionary phenomena. To a certain extent scientific theories also provide worldviews. That is, they deliver a particular perspective on

the natural or social systems that make up their respective domains. Worldviews tell people what the world is like and what place humans occupy in it. Heliocentrism, Darwinism, and Freudianism express such metaphysical views of the world. When a theory changes, these worldviews come under threat. Such moments in the history of science are the occasions for scientific revolutions. The resistance to a change of scientific theories can partly be explained by their association with worldviews. This process is well illustrated in the transition from geocentrism to heliocentrism. We shall see this process at work in the transition from pre-Darwinian to evolutionary accounts of biological systems.

Scientific theories usually embody a number of fundamental principles, which act as constraints. Copernicus, for instance, states in his *Commentariolus* seven principles of astronomy, including the movement of the Earth. [Copernicus, *Commentariolus* 1959, 58–9; Copernicus 1543, Bk. I, §11] There are *metaphysical principles*, like the belief in circular motion, the unity of nature, and the postulate that every natural event is determined. Galileo's belief that the book of nature is written in the language of mathematics is also a metaphysical conviction. There are *methodological principles*, like the belief in a coherent system, the simplicity of explanation, and the empirical confirmability of the theory. There are *mathematical principles*, like the geometric devices of the Greeks or, after Kepler, the use of algebra. Apart from these principles, most modern scientific theories contain a body of *mathematical laws*. This became evident, for the first time, in the work of Kepler. Later, as the heliocentric model became more sophisticated, the theory could show how the various laws are connected to each other. Newton showed how Kepler's laws could be derived from a more fundamental law, the law of gravitation. Finally, scientific theories must embody a body of *empirical hypotheses*. They face the empirical constraints, the empirical evidence. These must be derivable from the abstract principles. This can be seen at work in, say, heliocentrism. A heliocentric theory makes a very general statement that *all* planetary systems, not just the solar system, consist of a number of satellites, which orbit around a central gravitational body. In order to confirm such a universal theory it is necessary to derive testable statements about a particular system. The solar system was particularly convenient because it could be observed with the instruments available to Galileo and his contemporaries. We can treat these principles as constituting a constraint space. The constraint space consists of empirical and theoretical constraints. Scientific theories also comprise a number of models. The models allow the theory to represent particular aspects of the world. The job of a scientific theory is to throw a blanket of coherence over all these elements. The theory shows how all these elements fit together and how the models of the theory are connected. It shows how the observational and experimental data are deductive or inductive consequences of the principles of the theory.

**Models** are of particular interest, because they provide the theory with the means of representation. A theory needs models to represent particular aspects of the world. The idea can be quickly illustrated. The Copernican theory is easily confused with a model because it is a theory with only a very restricted domain. For Copernicus the solar system and the fixed stars constituted the universe.

Strictly speaking, the Copernican theory is only a Copernican model. But this is just an accident of discovery. The Copernican theory is not restricted to the solar system. Its intention is to include in its domain not only the known planets of the solar system, but all planetary systems, in any galaxy. If we extend it in this way, it becomes a theory. The Copernican theory includes in its domain all planetary systems in all galaxies. But its extension is much wider. It also includes all artificial systems, like satellites, which may be sent into orbit. One essential feature of models is that they cover only a limited domain of data. The solar system provides the data to construct various astronomical models.

The ability of models to bind selected parameters into a system is one of their most important functions. We may call this function *coherence* or *interrelatedness*. Copernicus was keenly aware that the heliocentric model must represent the planetary system. To enable the models to perform this role, they must serve three other functions: abstraction, idealization, and factualization.

Models concentrate on a few manageable parameters of the target system and *abstract* from a number of interfering factors. The interfering factors are neglected for the purpose of modeling. This operation is called *abstraction*. These interfering factors may be demonstrably negligible, in which case the model will justifiably ignore them. For instance, planetary moons are routinely neglected in the models. The model focuses on a central body and its satellites. However, closer scrutiny may reveal that the abstracted factors have a non-negligible influence on the relationship between the parameters, in which case they need to be incorporated in the model. The Earth moon has an important effect on the tides.

The real factors, which operate in the material world, may be too complicated to compute, in which case a model needs to introduce mathematical simplifications. The models *idealize* the parameters to make their relationships computable in the models. This operation is called *idealization*.[13] Once the dogma of circular motion has been cast aside, it becomes computationally easier to regard the circle as an idealization of the ellipsis.

Again, more complicated models may be able to reduce the idealization of the parameters. The inclusion of non-negligible factors and the elimination of idealized parameters are called *factualization*. In the history of astronomy the most important case of factualization is Kepler's introduction of his planetary laws.

There are also various types of model. Most models have *representational* functions. In this way most models in science serve a practical function. A distinction between various types of model will help to clarify what it means for models to represent. The job of models generally is to capture structural aspects of the natural systems modeled. Recall that models either emphasize the *spatial* ordering of the components in the system – as for instance the spatial distribution of the planets around the sun in the solar system – or place more emphasis on the *mathematical*

[13] There has been a considerable amount of literature on abstractions, idealizations, factualizations in science: Krajewski, *Correspondence Principle* [1977]; Nowak [1980]; McMullin [1985]; Brzeziński et al. [1990]; Brzeziński/Nowak [1992]; Herfel et al. [1995]; Cartwright [1999], §9.5; Sklar [2000], Ch. 3; see also Morgan/Morrison [1999].

relationships between the parameters – as for instance in the functional dependence of one parameter on another. When the models emphasize the spatial order, they represent the *topologic structure* of the system modeled. When the mathematical relationship between the parameters comes to the fore, the models represent the *algebraic structure* of the system modeled.[14] In sophisticated models, these two ways of representing will often appear combined, as in the mature Copernican model.

We will briefly distinguish different types of model:

- *Analogue models* represent the unfamiliar or unobservable in terms of the familiar or observable. This type of model suggests that there is an analogy between certain elements of already known systems and some elements of unknown systems. Analogue models are based on formal or material similarity relations. In order to consider a physical cause of planetary motion, Kepler uses the analogy of magnetic rays of the sun, ensnaring the planets. But the mere analogy does not assure that the real systems will resemble the analogue model. The sun does not "lead" the planets by magnetic rays; and planets do not display "friendly" or "unfriendly" faces. Analogies often exploit visual resemblances between the models and the system modeled. The sun seems to attract the planets like a magnet attracts a piece of metal. Analogue models are a useful, if limited, step in an attempt to achieve physical understanding. They suggest useful approaches to problem situations. However, we want more from models than just analogies. We want the models to represent structural features of the natural systems being modeled. To achieve real physical understanding we need more sophisticated models.
- *Hypothetical models* – or *as if* models – incorporate idealizations and abstractions. They claim to represent the system modeled *as if* it consisted only of the parameters and relationships stipulated in the model. Graphic representations of the solar system are typical hypothetical models. [Figure 1.6] They represent the solar system *as if* it consisted only of, say, six planets, without moons, and *as if* they orbited the sun in circular orbits. However, we know that such idealized factors are mathematical simplifications and that abstracted factors are present in the real systems. (We shall later argue that hypothetical models play an important part in the social sciences.)
- *Scale models* represent real-life systems either in reduced size (the solar system) or in enlarged size (planetary models of atoms). Geocentric and heliocentric models are typical scale models, which represent, in different ways, the solar system. Scale models are usually three-dimensional and require a fairly precise knowledge of the operation of the system. The history of astronomy shows that an accurate representation of the solar system was difficult to obtain.
- *Functional models*, as the name suggests, represent the functional dependence between several parameters. They are widespread in science, ranging from the

[14] This distinction between *topologic* and *algebraic* structures is due to P. Roman [1969], 363–69; see Weinert [1999], 313–17.

Carnot cycle of an ideal gas to space-time diagrams and supply and demand curves in economics. There is no need to assign precise values to the symbols that stand for the parameters. What counts is the nature of the *functional* relationship between some parameters. We obtain a functional model, if the functional relationship between various parameters is represented in a diagram or graph. A functional relationship is captured in *Bode's law*. This relationship was discovered by Johann Titius. But it became better known through Johann Bode (1772). Bode's law states that the distance of the planets from the sun (measured in units of the Earth–sun distance, AU) follows the rule:

$$r_n = 0.4 + 0.3 \cdot 2^n (n = -1, 0, 1, 2....8)$$

Thus the distance, $r$, varies with the exponent $n$. When $n = 1$, for instance, we find $r_n = 1$, which is the distance between the sun and the Earth in the chosen units. When $n = 4$, $r_n = 5.2$ (AU), which is the distance of Jupiter from the sun. In these models, the basis of representation begins to shift from the topologic to the algebraic structure.

- *Structural models* typically combine algebraic and topologic structures in order to represent how some underlying structure or mechanism can account for some observable phenomenon. Structural models are very useful in the representation of macroscopic systems, like planetary systems, and microscopic systems, like atoms. Kepler's heliocentric model combines Copernicus's topologic structure of the solar system with an improved algebraic structure. As we have seen, Copernicus's geometric arrangement of the planets is structurally correct, but the failure of his model lies in the algebraic structure. Once the topologic structure is combined with Kepler's laws and later Newton's theory of mechanics, a fairly accurate structural model of heliocentrism emerges. As we shall see in Chapter II, structural models can also be used to provide structural explanations.

→ *6.5.2 Laws of nature, laws of science* A scientific theory usually comprises a number of scientific laws. In the history of science, Kepler was one of the first to introduce mathematical laws of planetary motions. [See Ruby 1995] Kepler's work allows us to distinguish between the *laws of nature* and the *laws of science*. [Weinert 1995a, b] The laws of nature are the empirical regularities that exist in nature, irrespective of human awareness. The laws of science are symbolic expressions of the laws of nature. For instance, prior to Kepler's discoveries, the planets moved in near-elliptical orbits around the sun. They moved approximately according to Kepler's three laws of motion. But before Kepler, astronomers assumed that the planets moved in circles, which were modeled using eccentric or epicyclic motion. All these geometric devices were human artifacts. But when Kepler wrote down his three laws of planetary motion, he employed symbolic expressions, which encode the real motion of the planets. Recall Kepler's third law: $A^3 \propto P^2$. This symbolic expression tells us, in terms of averages, that the cube of the average distance of the planet from the sun varies as the square of its orbital period around the sun.

This law of science conceptualizes the phenomena. It provides what has been called "algorithmic compressibility." [Davies 1995] That means that all the observational data about planetary motions can be compressed into a succinct algebraic formula. The equation spares us the tedious task of recording or remembering all the data about these motions. In Kepler's law we have a polynomial formula, which expresses the relations in a structure: we expect the trajectory of a planet, any satellite, to follow a physical pattern according to this formula. Once the formula is at hand there is no need to observe and measure the position of *every* planet. Formulae like Kepler's laws or Bode's law inform us, in compressed algebraic form, of the trajectories of the planets. It is therefore not difficult to conceive of laws as structural constraints on objects. They lay down how a body like a planet must move. They prohibit any other type of behavior of such bodies. Of course, a scientific law may be wrong, as the impetus theory illustrates. But the point is that the regular behavior of natural systems can be expressed in the language of mathematics. If it is the case that planets and satellites behave according to Kepler's laws and that bodies fall according to Newton's laws, then the laws of science give us, in algebraic form, the structure of the behavior of physical systems. The mathematical relationship defines a graph, so to speak, on which the observational data of planetary motion can be arranged. If many of these data cannot be arranged along the prescribed path of the graph, then the mathematical formula is mistaken.

→ *6.5.3 Philosophical views of laws* The algorithmic compressibility offered by the laws of science is extremely convenient. Laws of science express systematic relationships between parameters, enabling us to make inferences from a known to an unknown case. Laws allow scientists to find answers to what looks like insoluble problems. For instance, Newton's laws allowed them to determine the mass of the Earth. The virtues of the laws of science are so great that philosophers have constructed a number of conceptual models about them.

→ *6.5.3.1 The inference view* According to the *inference-license* view, laws are licenses, which allow scientists to infer *A* from *B*. The scientist has a certain set of empirical data – the height of a projected ball, the orbital period of a planet – and with the help of appropriate law statements, the scientist is able to work out another set of data: the initial velocity of the ball, the average distance of the planet from the sun. Wittgenstein calls it an illusion "that the so-called laws of nature are the explanations of natural phenomena." [Wittgenstein 1921/1978, §6.371] He compares scientific theories, like Newtonian mechanics, with conceptual networks, which bring "the description of the universe to a unified form." (§6.341) Anticipating the Duhem–Quine problem, he adds that there can be different networks to which different systems of describing the world correspond. The fact that the world can be described by Newtonian mechanics "asserts nothing about the world," according to Wittgenstein. (§6.342)[15] The inference-license view expresses the gist of instrumentalism, since it holds: (1) that laws of nature are "laws

[15] Similar instrumentalist views on laws in Toulmin [1953], Ch. 3; Hanson [1958], Ch. 5; Watson [1938]; for a discussion of these different accounts, see Weinert [1995b]; Carroll [2003].

of our method of representing nature" (Hanson, quoted in Musgrave [1979–80], 69); (2) laws permit us to infer particulars from other particulars (for instance, from the position of a planet today, we can infer its position 300 years ago) (Toulmin, quoted in Musgrave [1979–80], 73); (3) they are just rules of inference, so that laws cease to be true or false "empirical" statements.

What are we to think of this view? It is true that scientists do not inductively read off the laws of science from the regularities of nature. As they scrutinize the natural world, they construct the laws of science. Nevertheless, the idea that laws of science are not about nature, but about the conceptual networks according to which we describe nature, is very unsatisfactory. The mathematical formulations, which the scientists construct, must fit the observational data. Even though the scientist may be regarded as free in their formulations of the laws of science, the laws must fit the constraints of the empirical world. In this sense the lawful regularities of nature act as a constraint on the formulation of the laws of science. This empirical check often leads to a modification of law statements. With the emergence of Kepler's laws, for instance, the ancient worry about the equivalence of the geometric devices lost its rationale. If laws of science were inference tickets, we would always face the question: "Why are some inference tickets better than others?" "Why are Kepler's laws better than epicycles?" The problem with the inference view is that rules of inference cannot be confirmed or disconfirmed. They are simply adequate within a certain scope of applicability. But a rule can be adequate without being valid. Ancient astronomy made many adequate predictions, although the planetary "law," on which they were based, was mistaken. The adequacy of a law of science is not exhausted by its ability to make successful predictions. The law must be valid. It must accurately describe, within acceptable limits of approximation, the underlying pattern of regularity. The law is the spine that holds the observational bones together. It states a structure, which governs the behavior of the observables. But inference rules cannot be refuted. They can only be shown to be inadequate for a task at hand. A hammer is an inadequate tool to fasten a screw but not to drive in a nail. Rules need not be eliminated. As science works by a process of elimination, instrumentalism cannot explain the progress of science. [Popper 1963, 112–14; Musgrave 1979–80, 97]

The conclusion has to be that the instrumentalist account of the nature of physical laws is inadequate. Laws of science express more than a license to draw an inference from one particular set of data to another.

→ *6.5.3.2* *The regularity view* The *regularity theory* of natural laws is a more ambitious program. According to this account, the statement,

> "It is a law that Fs are Gs,"

must be analyzed as the statement,

> "All Fs are Gs."

(Let F stand for "planets" and G for the predicate "circular motion." This statement then tells us that all planets move in circles.) If we look at Kepler's and Newton's laws, it may strike us at first that none of them look like universal propositions of logic:

> "All Fs are Gs"

or, in logical symbols,

$$(\forall x)(Fx \supset Gx).$$

Newton's second law and Kepler's third law do not, admittedly, appear as universal propositions in the textbooks of science. But, say proponents of this view, they can be cast in logical symbols. All we have to do is let the symbols *F* and *G* be placeholders for the parameters involved in these two laws. The logical form expresses the universality. [See Hempel 1965, 25–30, 40, 271]

The distinctive feature of the regularity approach is its portrayal of the natural world as governed by uniformities in the Humean sense. That is, if we observe that all instances of *A* precede *B*, then we have reason to believe that whenever *A* occurs, *B* will follow. Thus we infer from the occurrence of sunrise in the past that the sun will rise in the future.

The regularity theory claims that the world is governed by *contingent* uniformities, which we express symbolically in our laws of science. The theory denies that any form of necessity is involved in natural laws. In a way, this approach seems to be quite plausible. Even though the sun has "risen" in the sky for thousands of years, this is not a sufficient reason for the assertion that the sun *must* rise tomorrow. All observed swans (*S*) may have been white (*W*) up to a certain moment in time. But this observation does not forbid the occurrence of black swans. Nothing forbids the non-occurrence of *W*, even when *S* occurs. But consider the two propositions:

> (1) "All sodium salts burn yellow."
> (2) "Nothing travels faster than the speed of light."

It is tempting to smuggle in a modal operator:

> (1a) "All sodium salts *must* burn yellow."
> (2b) "Nothing *can possibly* travel faster than the speed of light."

This temptation stems from the intuitive feeling that laws of nature comprise more than contingent uniformities. An intuition tells us not only that *A*, *B*, and *C* have a certain property *P*, but that if some objects have the properties *A*, *B*, and *C*, then they also must exhibit the property *P*. We feel that natural laws must not give us accidental generalities, but unrestricted, cosmic uniformities. It must not simply be the case that a certain number of objects under investigation (planets, sodium salts) share certain respective properties (elliptical orbits, yellow flames). They must possess these properties essentially. Can the regularity theory capture this intuition? For the regularity theory to be viable, it must endorse a crucial distinction between *accidental* and *cosmic* uniformities. Consider the difference between

(3) "All lumps of gold have a radius smaller than 1 mile"

and

(4) "All atoms have a radius smaller than 1 mile."

The first statement looks like an accident of nature. Nothing in nature seems to forbid the formation of lumps of gold with a radius larger than 1 meter. The second statement looks like a universal regularity of nature. It is not simply the case that no scientist has ever observed an atom of a larger size. Science tells us that no atom *can* exist if it exceeds a certain size. Only cosmic uniformities should count as laws of nature. The challenge is to formulate a set of criteria, which make that distinction. regularity theorists define a statement, *P*, as a law of nature by a number of conditions:

i. *P* is either a universal or a statistical proposition.
ii. *P* is true at all times and all places.
iii. *P* is contingent.
iv. *P* contains only non-local empirical predicates, apart from logical connectives and quantifies. That is, *P* is purely descriptive.
v. *P* takes the form of a conditional ("$\subset$").

[See Swartz 1985, 28–29; Molar, quoted in Armstrong 1983, 12] Physical laws, according to the regularity view, are descriptions of actualized, empirical, contingent connections between states and events in the physical world. [Swartz 1985, Chs. 2, 3]

Stated in this way, the regularity theory suffers from a number of weaknesses. A consideration of these weaknesses has led to a much stronger view, the necessitarian account of laws. What are the weaknesses?

One worry is that the regularity account cannot properly distinguish between accidental generalizations and cosmic uniformities. There are widespread accidental generalizations, which we would not be tempted to count as laws of nature. Statement (3) is an accidental generality, whilst statements (2) and (4) are true cosmic uniformities. But statement (3) satisfies the conditions imposed by the regularity theory on the laws of nature. On the other hand, certain statements, like (1), only express a restricted uniformity. Yet they qualify as lawful regularities, just like Ohm's law

(5) $V = IR$,

which states that voltage, *V*, is the product of current, *I*, and resistance, *R*. Ohm's law is only true at constant temperatures. Unrestricted universality is not a necessary condition for laws of nature.

Therefore we must make a distinction between *fundamental* and *phenomenological* laws. Fundamental laws, like statements (2) and (4), are valid for all physical systems. Phenomenological laws, like statements (1) and (5), only apply to physical systems under certain restrictive conditions.

A further unwelcome consequence of the regularity theory is its exclusion of unrealized physical possibilities. Unrealized physical possibilities are an important feature of science, which often lead to technological innovations. For instance, 60 years ago, satellites were unrealized physical possibilities. One hundred years ago, lasers were unrealized physical possibilities. And two hundred million years ago most of today's species were unrealized biological possibilities. All these unrealized physical possibilities, had they been realized at the time, would have been subject to the same laws that govern them today. Satellites are subject to Kepler's laws. Lasers are governed by the laws of quantum mechanics. Species are subject to the laws of evolution. But according to the regularity theorist, unrealized physical possibilities are physically impossible. This account only accepts as laws of nature the actualized cosmic uniformities. The regularity view cannot deal with *counterfactuals*, as they occur in the contemplation of unrealized physical possibilities.

The regularity theory faces, perhaps surprisingly, a great number of problems. A philosophical account of laws should account for counterfactuals, the distinction between unrealized physical possibilities and genuine physical impossibilities, and the difference between accidental and cosmic uniformities. It should also justify our confidence in making inferences from known to unknown cases. A philosophical account should explain how scientific laws are employed in our explanations of the behavior of physical systems. This is a tall order. The instrumentalist and regularity views have not lived up to expectations. Can a stronger view, the necessitarian account, help?

→ *6.5.3.3* *The* necessitarian view The *necessitarian view* has a straightforward answer to all these problems. Natural laws are relations between universals. The necessitarian account transforms the formula, used by the regularity theorist,

> "It is a law that Fs are Gs"

into the much stronger claim:

> "It is physically necessary that Fs are Gs."

In terms of our previous distinction between the laws of science (scientific laws) and the laws of nature (natural laws), the necessitarian view states that

> Laws are (expressed by) singular statements describing the relationships that exist between universal qualities and quantifiers.
>
> To say that it is a law that Fs are G is to say that "All Fs are G" is to be understood, not as a statement about the extensions of the predicates "F" and "G" but as a singular statement describing a relationship between the universal properties F-ness and G-ness (where properties can be magnitudes, quantities, features). [Dretske 1957, 252–3; cf. Leckey/Bigelow 1995; see also Weinert 1995b]

The necessitarian approach to laws of nature is based on two essential notions: (a) laws involve universals and (b) laws are relations between universals.

**Ad (a)** According to David Armstrong, a proponent of the necessitarian view, "universals are either properties or relations of some, or holding between some real particulars." [Armstrong 1983, Ch. 6] Universals are the repeatable features of the spatio-temporal world.

**Ad (b)** If we accept this Aristotelian characterization of universals, we are left to specify the relation between universals. Given that some entity is $F$ and we know that it is a law of nature that $(\forall x)(Fx \supset Gx)$, we can conclude that *F must be G*, unless there are some intervening factors. It is physically necessary for $F$ to be $G$, given the law of nature. The relation, which is postulated as holding between universals, is one of nomic necessitation. Yet nomic necessitation is only contingently true as it may not hold in all possible worlds.

The logician's symbolic formulation highlights the difference between the necessitarian and the regularity views. From the postulation of nomic necessitation, $N(F, G)$, it follows that for all entities, $x$, if they have property, $F$, they must have property, $G$. The relation of nomic necessitation between F-ness and G-ness entails the corresponding cosmic uniformity:

$$N(F,G) \to (\forall x)(Fx \supset Gx).$$

But the converse does not follow. Each $F$ may be $G$ but this does not mean that F-ness necessarily entails G-ness, as the case of accidental regularities demonstrates:

$$(\forall x)(Fx \supset Gx) \xrightarrow{\neg} N(F,G)$$

Accidental generalities allow exceptions, nomic necessity does not (barring domain restrictions). One criticism leveled against this theory is that nomic necessitation is not observable. Nothing in our observational evidence points to the existence in nature of physical necessity, which the necessitarian theory requires. Armstrong postulates nomic necessity as an unexplicable primitive notion of his theory. [Armstrong 1983, Ch. 6.4] Science observes repeatable features between spatio-temporal events. We are free to label such features – ravenhood and blackness – as Aristotelian universals. Even if we grant that science observes universals, we cannot leap to the conclusion that physical necessity holds between them. Cosmic universality does not imply nomic necessity. (Other necessitarians go beyond Armstrong and stipulate the existence of uninstantiated universals, thus embracing Platonism.)

We should distinguish two senses of physical necessity. On the one hand we have the necessitarian sense of nomic necessitation between universals. This physical necessity between universals constitutes the laws of nature. On the other hand we have the scientific sense of necessity. This sense states that certain physical systems are subject to the laws of nature. Planets must orbit the sun, because they are constrained by Kepler's laws to do so, given initial conditions. On the necessitarian account, all uniformities in nature reduce to just one connection: nomic necessitation between universals. But the laws of science teach us that there are many different mathematical relations between many different systems. They can be expressed in precisely defined parameters. Furthermore, these systems are interrelated. The laws of science express a number of different algebraic relations between relata of physical systems. For the laws of science to express the laws of nature, they must approximate the lawful regularities in nature.

The necessitarian view tells us very little about how laws are used in science. If we are interested in how the laws of science express nature's regularities, we should turn to an account of laws, which takes us closer to scientific practice. Let us call this view a structural approach. The basic idea behind this approach is that the laws of science encode the relations in the structure of physical systems.

→ *6.5.3.4 The structural view* Karl Popper rightly points out that "natural laws" are logically stronger than true, strictly universal statements. This observation takes care of the need to distinguish natural laws from mere accidental generalities. But they are logically weaker than logical necessities. While logical necessities are true in all possible worlds, the laws of nature are contingent. We expect them to be true in the actual universe, not just on Earth, but they may not be true in all possible worlds. What logical character do the laws possess? Popper shifts necessity from the laws of nature to the laws of science.

> If we conjecture that "a" is a natural law – he writes – we conjecture that "a" expresses a structural property of our world; a property, which prevents the occurrence of certain logically possible singular events. [Popper 1959, 432]

Thus physical necessity means that the laws impose structural constraints upon the natural world. [Popper 1959, 430] According to Popper, scientific laws express certain structural properties about the physical world. Popper's *structural* view of laws stands in direct opposition to Wittgenstein's instrumentalist view. Popper stresses that the laws of nature forbid certain structural properties of the actual universe. The laws forbid circular planetary motions, perpetual motion machines, and superluminal velocities. The reverse of this characterization is that the laws will also enable certain physical events. The laws lay down structural constraints, according to which individual objects must behave. But the singular facts continue to enjoy a certain freedom within the structural grid that binds all the facts together. Autumn leaves, carried by the wind, "defy" the law of gravity. A planet on a collision course with a meteorite may be knocked out of its orbit. Evolutionary mutations are the result of genetic chance.

The structural view accounts quite well for some of the main features of scientific laws. It accounts for the unavoidable abstraction and idealizations involved in the scientific laws. It shows why we cannot deduce nomic necessity from the available evidence. It stays close to scientific practice. [Weinert 1993; 1995a, b] The laws of nature encode the structural properties of physical systems. The laws of science are the symbolic expressions of these structural aspects in mathematical language. The structural account makes the distinction between the laws of science and the laws of nature, which we find in scientific practice. It marks the distinction between accidental and cosmic uniformities. Accidental uniformities – "All solids of gold are smaller than 1 mile in diameter" – are not structural features of the natural world. There is nothing in the atomic structure of gold to forbid large solids of gold. Cosmic uniformities – "All atoms are smaller than 1 mile in diameter" – express the structure of atoms. There could be *no* atoms if they had these dimensions. It explains unrealized physical possibilities as possibilities allowed by the structures. It explains counterfactuals by relying on what the structures allow and what they forbid. "If there were a tenth planet, it would obey Kepler's laws" means: the structure of the solar system is such that a tenth planet may orbit the sun in accordance with Kepler's laws. It covers the distinction between fundamental and phenomenological laws. Fundamental laws express the structure of all or numerous systems; phenomenological laws are restricted to a few systems, requiring many boundary conditions.

According to the structural view of laws, the laws of nature constitute constraints on the possible trajectories of material objects in our universe. For mathematicians equations are constraints on the possibility of solutions. Imagine a mathematician who has taught algebra for many years. The mathematician has patiently explained to students the use of functions. A function f($x$) is an equation of a certain degree: (a) $y = 2x^2 + 3x + 4$ is a quadratic equation while (b) $y = 3x^3 + 2x^2 + x + 1$ is a polynomial expression. As Descartes discovered, functions can be represented in Cartesian graphs. Irrespective of the particular equation, a mathematical function displays typical algebraic structures, depending on the exponentials involved. Consider two material objects in our universe, one of which behaves according to (a) and the other according to (b). Even if we know nothing more about these objects, the *structure* of their trajectory is laid down in their respective graphs. (The details of the graphs change if more boundary conditions are included.) [Figures 1.10a, b]

These graphs represent the permitted trajectories of the object, under the constraint of the respective function. More precisely they represent a mathematical pattern, which says that any object, subject to the given algebraic structure, $y = x^2$, will display a behavior pattern of this structure. Similarly for objects, which are subject to the algebraic structure, $y = x^3$. The laws of science represent, in mathematical language, structural aspects of the world around us. The laws specify the relations in the structure, according to which material objects must behave. In this sense the laws of science impose constraints on the possible trajectories of objects through the material world. As we noted earlier (Section 6.3), a structure consists of relata and relations; the relations bind the relata together. In the case of planetary systems, the relata are planets, moons, comets, meteorites, and satellites; the relations are the mathematical relationships that hold between the relata; or the relata may be biological systems between which evolutionary relations hold. On the structural account, the laws of science determine mathematically specifiable correlations between the relata. As the graphs illustrate, the laws specify the

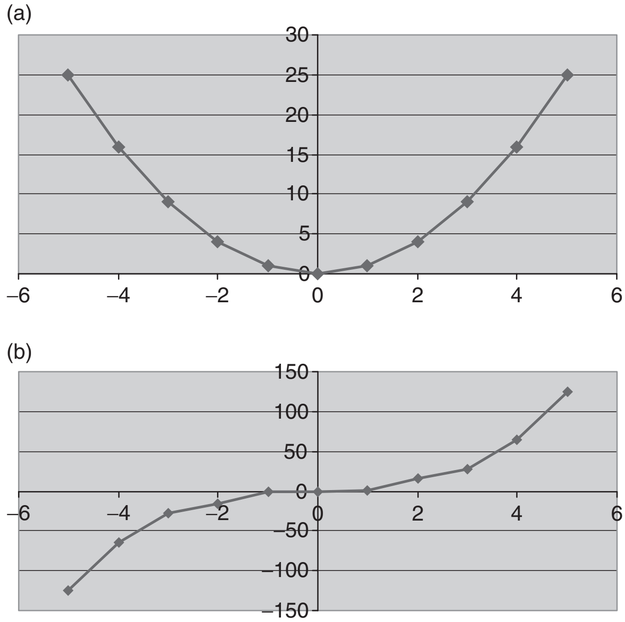



**Figure 1.10** (a) The quadratic function leads to a parabola; (b) The polynomial function leads to a polynomial graph

trajectory of material objects as they weave their paths through a material world in the neighborhood of other objects.

We have now discussed a number of philosophical issues, which arose out of the problem situation of Copernicanism. Copernicus stood at the threshold of modern science. The Copernican turn pushed open the gates to the Copernican revolution. Can Copernicanism tell us something about the process of scientific revolutions?

## 7 Copernicus and Scientific Revolutions

> *One measure of the depth of a physical theory is the extent to which it poses serious challenges to aspects of our worldview that had previously seemed immutable. [Greene,* The Elegant Universe *(2000), 386]*

We have argued that Copernicus is the author of a change of perspective. Copernicus initiated the Copernican turn. Although his system had several advantages, it did not amount to a scientific revolution. On the one hand, Copernicus adheres too much to his Greek predecessors and their geometric methods. He adopts a purely kinematic view. He adds no significant new observations to the available catalogue of data. On the other hand, he leaves in place the equivalence of hypotheses.

He finds it acceptable to use a number of geometric devices interchangeably, without asking which one corresponds better to the physical mechanism of planetary motion. But his model is in better agreement with the topologic structure of the solar system. In this respect it enjoys greater empirical validity. However, its algebraic structure is deficient. For this reason the Copernican model fails to reach full theoretical validity.

If the Copernican turn was a first step in the direction of a scientific revolution, what criteria are available to judge an episode of science as a scientific revolution? Several models of scientific revolutions have been proposed.

A *Kuhn's paradigm model of revolutions.* According to Thomas S. Kuhn, the history of science consists of a series of "normal" and "extraordinary" periods. [Kuhn 1970; Hoyningen-Huene 1993] A normal period of science is marked by the presence of a dominant paradigm. This paradigm is accepted as a valid framework for ongoing research. During periods of normal science, scientists are involved in problem-solving. The accepted problems and solutions are set by the ruling paradigm. Typical examples of paradigms are heliocentric astronomy, Newtonian mechanics, and Darwinian evolutionary biology. During normal periods of science, the practitioners of a scientific discipline accept the basic presuppositions of the paradigm. Their work consists in refining the representational force and explanatory power of the paradigm. Kepler, Galileo, and Newton all accepted the heliocentric hypothesis. Newton accepted Kepler's laws, although Galileo chose to ignore them. But Galileo's observations made significant contributions to heliocentrism. In their own way they all refined the paradigm and improved it. Eventually, however, any period of normal science faces a crisis. It then enters a period of extraordinary science. A crisis in science can happen for a number of reasons. It is, according to Kuhn, mostly associated with the failure of a paradigm to deal with all the phenomena in its domain. A crisis occurs because a paradigm faces a significant *anomaly*. An anomaly is not just the failure of a prediction or a discrepancy between theory and observations. Such discrepancies are unavoidable: the observational devices are not perfect and the theory always makes a number of abstractions and idealizations. An anomaly occurs when there is a persistent disagreement between a theory and its predictions. An anomaly arises when the theory claims that the world is one way and our observations tell us that it is another way. The Greek theory of concentric circles quickly faced an anomaly. The theory implied that the planets are always at a constant distance from the Earth. Observations told the Greeks otherwise: the planets change their distances from the Earth. The geocentric view forbids the appearance of comets beyond the lunar sphere. The Mathematician and Philosopher in Brecht's play insist that Jupiter can have no moons. Yet Brahe's and Galileo's observations told them otherwise. These theories faced anomalies. They could not accommodate the observations, which clearly fell within their domains. When such events happen, the once dominant paradigm enters a crisis. The practitioners try to solve the problem in a number of ways. If they succeed the paradigm may continue its rule. But if they fail, the scientific discipline enters a *revolutionary period*. During a revolutionary period, according to Kuhn, the old paradigm is dismantled and replaced by a new one. A scientific revolution is a replacement of a paradigm.

A paradigm is a conceptual scheme which mediates the interaction between the scientist and the world. It facilitates the mapping of symbolic structures onto the empirical world. Later, Kuhn preferred to speak of a "disciplinary matrix": an ordered set of elements. A matrix comprises a number of conceptual elements: symbolic generalizations, like fundamental laws; exemplary problems, on whose solutions students can practice the techniques of the discipline; scientific values, like consistency, coherence, testability, unification; and metaphysical convictions, like a belief in an ordered universe, an independent, external reality, and deterministic laws. Kuhn renamed a paradigm of science "a disciplinary matrix" to indicate that the conceptual constructs form a coherent network. A distinctive feature of Kuhn's paradigm model of scientific revolutions is that scientists are taken to be fundamentally committed to their paradigms. A paradigm gives them a firm foothold that enables them to approach the natural world in a principled manner. According to Kuhn, the scientists begin to see the world in terms of the ruling paradigm. It is as if a scientist was wearing glasses – Newtonian spectacles, Darwinian spectacles – through which alone s/he could see the world. According to Kuhn, scientists can inhabit only one paradigm at a time. If this is the case then paradigms which spell out completely different problem situations make the scientists see the world completely differently. They find it difficult to talk to each other, because they inhabit "different worlds." The Aristotelians in Brecht's play embrace geocentrism and inhabit a geocentric world. It makes sense to them to refuse to look through the telescope, because Neptune's moon "cannot exist." By contrast Galileo defends heliocentrism. He inhabits a heliocentric world. His appeal to the observational evidence cuts little ice with the Mathematician and Philosopher. He speaks from the platform of a paradigm, whose language they cannot understand. There is an abandonment of critical discourse.

If this scenario describes the history of science correctly, Kuhn faces the question of how scientific change is possible at all. For both parties in the dispute seem to be absolutely convinced of the truth of their respective paradigms. Kuhn uses the term "incommensurability" to describe the stalemate. The term indicates that it is not possible to translate each element of a paradigm into the elements of its rival paradigm. It is possible to compare paradigms globally but it is not possible to map each conceptual element of one paradigm onto another. [See Andersen/Barker/Chen 2006, Ch. 5] We may ask why this should be important or even a problem. If there is no equivalent of an "epicycle" in Kepler's model, this seems rather a gain than a loss. Kuhn, however, considers the incommensurability of paradigms to be an important feature of the history of science. So he has to explain how paradigms can change at all, if scientists are chained to them like worldviews. Kuhn's answer is that the seeds of revolutionary change are built into each paradigm. Each paradigm eventually encounters an anomaly. It is the persistent non-agreement between theory and empirical data that precipitates a paradigm into a crisis.

Eventually a new paradigm emerges. With the new paradigm, a new period of normal science sets in. Most practitioners are now in fundamental agreement with the presuppositions of the new paradigm. Again it imposes a vision on the scientist, which differs markedly from the previous vision. "What were ducks in the scientist's world before the revolution are rabbits afterwards." [Kuhn 1970, 111] According to Kuhn, the quantum jump from one paradigm to another has drastic consequences. First, the whole conceptual network changes. There are vast differences in ontology – of the things which are supposed to exist in the world – between the old and the new paradigms. Kepler, for instance, replaced the solid spheres with free-floating planets. The Greek geometric devices are replaced by Kepler's planetary laws. The abrupt change also affects the range of acceptable problems and the accepted techniques. From Kepler to Newton the dominant problem became the question: "Why do planets move in orbits?" Geometrical methods became obsolete and were replaced by more sophisticated mathematical techniques. Second, a communication breakdown occurs, as Brecht's play seems to illustrate. Kuhn is not always clear about the extent of the communication breakdown. After criticism he seemed to accept that the communication breakdown was only partial. [Kuhn 1983; Nola 2003, Ch. 1.4.1] The scientists will at least partly agree on some continuity between the old and new paradigms. But rational reasons alone are not compelling enough to convince a doubting scientist of the virtues of the new paradigm. Kuhn explains the adoption of the new paradigm as a case of conversion and persuasion. The reality is more complicated, as Kuhn eventually admitted. There are continuous and discontinuous links between the paradigms. An intensive discussion took place between the Copernicans, the Ptolemaists, and the theologians. The correspondence between Osiander, Copernicus, and Rheticus has survived. The dispute lasted for 150 years. This was enough time for many different models to be marshaled. The Ptolemaists provided arguments against the motion of the Earth. Copernicus adopted the impetus theory to reject their arguments. Tycho Brahe adopted a compromise position. An inveterate Copernican like Galileo simply ignored Kepler's laws. Some converted to Copernicanism, like Rheticus in Germany and Digges in England. Until the beginning of the seventeenth century there was insufficient evidence of the heliocentric hypothesis so that some accepted only parts of the Copernican system. [Rybka 1977; Dreyer 1953, Chs. XIII, XIV] The Copernicans finally prevailed when Newton combined the law of inertia with the law of gravitation.

The Copernican turn does not really fit the Kuhnian paradigm model. [Heidelberger 1980] It did not constitute a paradigm shift. The Copernican version of heliocentrism is hardly incommensurate with geocentrism because of the large overlap between the two systems. Copernicus uses many of the Greek observations. He invents no new method. On the contrary, he wants to be purer than Ptolemy, since he objects to the use of the equant. As the discussion around the term "hypothesis" shows, it is hard to detect as much as a partial breakdown of communication. Of course, the opponents did not agree. The ambiguity of the term "hypothesis" seems to have provided a bond between proponents and detractors of Copernicanism. Later on, the Copernicans did not even agree on some of the central elements of the disciplinary matrix. Galileo continued to believe in circular motion. The Copernican position is compatible with both instrumentalism and realism. By concentrating on the equivalence of hypotheses, Osiander argued in favor of instrumentalism. By focusing on the topologic structure of his model (in Book I of *De Revolutionibus*), Copernicus arrived at a realist position.

The conceptual network did change but by a slow transition rather than quantum leap. Tycho's observations, Kepler's calculations, Galileo's findings provided powerful arguments in favor of the Copernican hypothesis. These achievements constituted powerful constraints, which the geocentric system could not accommodate. Let us therefore consider some alternative models of scientific revolutions.

B *Cohen's four-stage-model.* Bernard I. Cohen, a historian of science, proposed a model, according to which a scientific revolution unfolds in four stages. [Cohen 1985] The *first stage* consists of a conceptual innovation, as we find in Copernicanism and Darwinism. We discussed this stage earlier as a change in perspective. A change in perspective is, however, not sufficient to constitute a revolution.[16] The *second stage* consists of new methods and techniques. We have found that Copernicus did not introduce new techniques, so he would fail this second criterion. In this regard both Kepler and Newton made the greatest advances. Darwin, too, proposed a new method: the Darwinian inferences. His principle of natural selection, as we shall see, incorporates a new algebraic structure. The *third stage* Cohen calls "dissemination." In this stage the revolution occurs on paper. It is given a voice in the public arena. In modern terms, we would say the work finds a publisher. There are some famous publication dates in science, which illustrate this stage: Copernicus's *De Revolutionibus* (1543); Darwin's *The Origin of Species* (1859); Einstein's special theory of relativity (1905). These publications submit the revolutionary ideas to public scrutiny. The *fourth stage* consists in the adoption of the new ideas by the scientific community. This is not a question of an instant conversion. The new ideas usually find some proponents but they also meet with skepticism and opposition. In such a situation intensive debates ensue. They do not have to take the turn of the unfortunate encounter of Galileo with the Mathematician and the Philosopher. Attempts to persuade are often based on arguments. In his *Narratio Prima* (1540) Rheticus tries to convince his contemporaries of the superiority of the Copernican system. At the beginning of the seventeenth century Kepler wrote the first textbook of astronomy. The *Epitome of Copernican Astronomy* (1618–21) is a long argument in favor of a modified Copernican system. Darwin conceived his *Origin of Species* as a "long argument" in favor of evolutionary explanations. If there is no instant conversion, most successful scientific theories experience a *convergence* of

[16] It may be asked whether a change in perspective is also a necessary condition for a revolution. This will be too strong a requirement for it amounts to the thesis that a scientific revolution cannot occur without a change in perspective. But even if this were true of all past revolutions in science, we cannot be committed to the view that it will also be a condition of all future revolutions in science.

expert opinion. After some period most scientific practitioners become convinced of the validity of the new theory. According to the evidence gathered in this and later chapters, this is mostly a matter of persuasion by argument. For the evidence, as we have seen, also converges on to one model or theory. What is more, the same evidence that increases the creditability of one theory begins to discredit rival theories.

Cohen's four-stage model sees scientific revolutions as temporally extended processes. They are transitions rather than abrupt conversions. The first two stages – the conceptual innovation and the new techniques – intimate an important aspect of scientific revolutions, namely the problem-solving abilities of new paradigms. This aspect was already emphasized in Kuhn's paradigm model. It becomes the focus of the chain-of-reasoning model.

C *The chain-of-reasoning model.* Seen against the background of Copernicanism (and Darwinism), Kuhn's model suffers from two defects. With its thesis of incommensurability it overemphasizes the disruptive discontinuity between successive paradigms. And it often portrays a breakdown of communication between scientists, as parodied in Brecht's play, when the reality of scientific revolutions is often more sophisticated. Cohen's model may satisfy a historian of science but it does not emphasize sufficiently the conceptual continuity between successive revolutions. Successive revolutions display a transitional nature, which can be made more precise. Let us speak of *traditions*, rather than paradigms, to designate the conceptual networks in the history of science. Their respective elements can change *differentially*. That means, as the history of Copernicanism has shown, that the geocentric tradition did not collapse all at once. Rather, the Copernican spatial rearrangement of the planets was preceded by an abandonment of the Aristotelian theory of motion. Only later was the notion of circular notion discarded. This differential surgery means that we can look for *reasoned* transitions between the conceptual components of the network. [Shapere 1964; 1966; 1989; Chen/Barker 2000] We can follow the career of, say, the concept of circular orbs from Greek to post-Copernican astronomy. We will observe that it became obsolete and ask why this happened. Or we can study the role of theories of motion in the history of astronomical models. The theorists of the Parisian School replaced the Aristotelian theory of motion with the impetus theory, because they found that the latter gave a better explanation of motion. The impetus theory helped the Copernican model along the way. But it was not until the middle of the seventeenth century that the concept of inertia was developed. [Drake 1975; Wolff 1978; Dijksterhuis 1956] These are examples of *reasoned* transitions. They are reasoned transitions because they arise from problem situations, in which attempted solutions are evaluated through chains of reasons and arguments. In the history of astronomical models we can follow the career of constituent presuppositions. They are judged as to their ability to provide solutions to the problem of planetary motion. The transitions lead to the reorganization of at least part of the conceptual scheme. The transitions are part of problem-solving attempts. These attempts leave traceable lines of descent between astronomical models. There are *deletions*: the Aristotelian theory of motion; there are *modifications*: the circle gives way to the ellipsis; there are *replacements*: mathematical analysis replaces geometric methods. We can trace the lines of arguments in the development of conceptual traditions and their components: of theories of *motion* and the arrangement of *planets* from geocentrism to heliocentrism. We can evaluate these operations in the chains of reasoning. Chain-of-reasoning transitions emphasize the slow transformations of conceptual networks, traditions, through the weight of arguments and evidence. Integrating these insights we arrive at an analytic four-stage model of a scientific revolution as a series of successive events:

1. a turn or switch of perspectives, which often involves a questioning of existing presuppositions;
2. the introduction of new methods and techniques with problem-solving ability;
3. the emergence of a new tradition through differential chain-of-reasoning transitions, as a result of the problem-solving success of the emergent tradition;
4. convergence of expert opinion on to a new tradition; we shall note in Chapter II that this convergence does not exclude the coexistence of alternative models within the new tradition.

There is no guarantee that once a component is secured within a tradition, its position will remain unchallenged by further arguments. Ironically, this fate befell the Copernican principle itself. If we follow this particular chain of reasons into contemporary debate, it will lead us to a questioning of the Copernican principle: that we do not occupy a privileged position in the universe.

## 8 The Anthropic Principle: A Reversal of the Copernican Turn?

*To paraphrase Descartes, "cogito ergo mundus talis est." [Carter, "Anthropic Principle" (1974), 294]*

Freud considered that human self-pride had suffered serious blows from Copernicanism and Darwinism. It is true that the Copernican hypothesis dethrones humans from their imaginary physical center in the universe. And Darwin seems to have robbed humans of their "crown of creation." But the Copernican change in perspective also demonstrates the power of the human mind. Copernicus and his successors showed that the supralunary sphere was not forever veiled from human comprehension. The human mind, as Kepler insisted, is more penetrating than the human eye. What humans can see is not the limit of what they can comprehend. As we seem to be the only intelligent species in our immediate cosmic neighborhood, spanning several light years in all directions, humans can at least claim rational centrality. The Copernican turn shows that rational centrality does not depend on physical centrality. Once this had been understood, modern science could get off the ground. Humans will not be able to leave the solar system in the foreseeable future. Humans cannot even visit all parts of the solar system. Yet cosmologists know much more from scientific analysis than they would learn from cosmic sightseeing. Cosmologists have mapped the structure of the solar system, the Milky Way, and the cosmos to an extent that could not be matched by mere observations.

For some cosmologists this rational centrality is not enough. They have proposed an *Anthropic Principle* (AP), which attempts to restore some of the pre-Copernican pride to the human species. The Anthropic Principle seeks a reversal of the Copernican turn. It reasons from the existence of intelligent life on Earth to the special physical conditions that render intelligent life possible. Our position in the universe may not be central, but it is privileged. [Carter 1974, 291] There are in fact two versions of the Anthropic Principle.

- **The Strong Anthropic Principle (SAP)**: *The Universe must have those properties which allow life to develop within it at some stage in its history.* [Barrow/Tipler 1986, 21; Carter 1974, 294]

  This is a very stringent requirement, since it postulates that the physical layout of the universe is such that it inevitably becomes a self-cognizant universe. The universe will eventually lead to the creation of intelligent human observers. [Barrow/Tipler 1986, 248, 523; Breuer 1991, Ch. I] The strength of this requirement is also its weakness. On the one hand, the Strong Anthropic Principle embodies a determined anthropomorphism, which is no longer part of a physical explanation. Since the scientific revolution of the seventeenth century there has been a radical tendency to eradicate anthropomorphic reasoning first from the physical sciences, and subsequently from the biological sciences. On the other hand, the SAP runs directly counter to evolutionary explanations of life. Biological principles, like natural selection, do not claim that new species evolve along a linear path, whose terminus is the emergence of human beings. It was one of the consequences of Darwin's work that any teleological thinking in evolutionary biology, which treated humans as the telos of evolution, was a misconception. Most cosmologists therefore prefer a weak version of the Anthropic Principle.
- **The Weak Anthropic Principle (WAP)**: *We must be prepared to take account of the fact that our location in the universe is necessarily privileged to the extent of being compatible with our existence as observers.* [Carter 1974, 293; Dicke 1961; Breuer 1991, 8]

  This postulate states that the existence of human life can be used to explain the delicate values of the fundamental physical constants:

  > The observed values of all physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirement that the Universe be old enough for it to have already done so. [Barrow/Tipler 1986, 16; Dicke 1961]

  The idea is that the intricate balance between the fundamental physical constants cannot be a cosmic accident. Even the slightest changes in these values would destroy the possibility of human life. The precise numerical values of the fundamental constants are held to be necessary for human life to become possible. The stability of matter and three-dimensional space, for instance, is essential for life. A slight change in these numerical values would have launched the universe onto a completely different trajectory. Even more dramatically, there are key properties of the universe, without which biological evolution would have been impossible. Our discovery of these key properties "may in some sense be necessary consequences of the fact that we are observers" of them. [Barrow/Tipler 1986, 383] The basic idea is that human existence imposes severe constraints on the numerical values of the fundamental constants. The constants must have the values they possess *because* we are here. Couched in counterfactual terms, if the fundamental physical constants had acquired slightly different values, human beings would not have evolved. As humans have evolved, the constants must possess these specific values.

Consider, for instance, the age and size of the universe. Proponents of the Weak Anthropic Principle maintain that these properties can be explained by considerations of the condition of human existence. Clearly the Earth must have been physically hospitable to the evolution of organic life. The transformation of hydrogen and helium into life-conducive molecules happens primarily in stars. But the production of the heavier molecules, on which life depends, takes billions of years. The universe must be sufficiently old for life forms to be present. Therefore, proponents of the WAP argue, the existence of human life can explain the age of the universe. And the age explains its size. "Many observations of the natural world (…) can be seen in this light as inevitable consequences of our own existence." [Barrow/Tipler 1986, 219]

For proponents of the WAP this reasoning restores a form of special centrality and reverses the Copernican turn. If only very special conditions produce a self-cognizant universe, a close link between the human race and the cosmic environment is reestablished. The Anthropic Principle puts constraints on the structure of a self-cognizant universe. It asserts that intelligent life in some ways selects the actual universe. [Barrow/Tipler 1986, 510; Breuer 1991, Ch. I] Solely such a universe gives rise to intelligent observers who can recognize their privileged position.

One problem with the Anthropic Principle is that it is at best only approximate. It invites the observer back into physical theory. But even then it can only state the order of magnitude of the fundamental constants, not their precise values. The WAP masquerades as a physical explanation when it is no more than an unobjectionable inference. From the fact that human observers inhabit a small corner of the universe it is inferred that this place must be hospitable to life. But our existence does not retrospectively explain why the universe possesses the physical conditions that have made intelligent life possible. [Salmon 1998, 396] Even proponents of the AP admit that the principle may ultimately be replaced by a physical explanation. [Carter 1974, 292, 295; Carr/Rees 1979, 612]

There is a certain similarity between arguments advanced by proponents of the AP and those of modern advocates of intelligent design. Advocates of intelligent design argue that many biochemical processes are too fine-tuned for natural selection to explain them. [See Chapter II, Section 5.4]. They consider that such organs as the eye are so complex that they could not be the result of slow evolutionary adaptation. Advocates of the AP point to a similar delicate balance in the fundamental constants. They argue that the existence of intelligent observers can explain the fine-tuning of the fundamental constants. In both cases teleological explanations play an important part. Proponents of intelligent design infer design from the complexity and improbability of biological systems. Proponents of AP infer a special place and time for humans from the specific values of cosmic parameters. The problem is that the fundamental constants do not possess their particular values, *because* we are here. A slight change in the value of the fundamental constants in the distant past might indeed have rendered the evolution of life on Earth impossible. But our presence *now* does not make it necessary that in the past the constants acquired their particular values. It is true that we can infer special values of the fundamental constants from our presence. But this does not explain the values. The SAP seems to imply that observers are the goals of evolution. [Barrow/Tipler 1986, 28] Such teleological thinking, as Chapter II will show, has been prevalent for most of the history of ideas. It is strongly contradicted by the history of Darwinism. Even the WAP fails to show that the sizes of stars, planets, and people are the necessary consequences of the constants of nature. [Barrow/Tipler 1986, 387] One reason is that cosmic evolution is contingent. The Earth is not shielded from the rest of the solar system. For millions of years the Earth was subject to the bombardment from outer space. The cosmos is a vast system. According to the Alvarez hypothesis, the extinction of the dinosaurs, 65 million years ago, was the aftermath of a collision of the Earth with an asteroid. When they disappeared their lifespan had already stretched over 200 million years. Had they continued to thrive, humans might never have seen the day of light. During the dinosaurs' reign conditions were favorable to organic life. But this does not mean that human observers had to appear. There is another reason to be suspicious of anthropic reasoning, which follows from the first criticism. Anthropic reasoning ignores chains of causation. We cannot causally explain the occurrence of an earlier event through the occurrence of a later event. Yet anthropic reasoning leaps from a distant event in the past to present-day events. It answers questions like, "Why is the universe isotropic?" with statements like "because we are here." [Barrow/Tipler 1986, 426] However, the contingency of physical events forbids us from skipping several links in the chain of causation. It would be faulty reasoning to claim that I am here *because* my great-grandparents met in the 1870s. Physical thinking tells us that interferences can divert an event from its "predetermined" path. Evolutionary thinking tells us that the tree of life sprouts in a contingent manner. If we accept these insights, then humans are not a necessary consequence of evolution. Such an explanation sounds suspiciously like Lamarck's progressive evolution. As we shall see, Darwin's revolution led to the loss of rational design.

The Copernican turn, we may conclude, led to a loss of physical centrality. But human existence is still precious in a dual sense. We are the only intelligent species within our cosmic neighborhood. As such we do not depend on any physical centrality. Through the force of abstract reasoning human minds crisscross the universe. We know more from thinking than from seeing. This is a worthier kind of centrality. It is rational centrality.

## Reading List

Andersen, H./P. Barker/X. Chen [2006]: *The Cognitive Structure of Scientific Revolutions.* Cambridge: Cambridge University Press

Aristotle [1948]: *Politics*, transl. E. Barker. Oxford: Oxford University Press

Aristotle [1952a]: *Physics.* Great Books of the Western World, The Works of Aristotle, Vol. I. Chicago: Encyclopaedia Britannica

Aristotle [1952b]: *On the Heavens.* Great Books of the Western World. Chicago: Encyclopaedia Britannica

Armstrong, D. [1983]: *What is a Law of Nature?* Cambridge: Cambridge University Press

Barker, P. [2002]: "Constructing Copernicus," *Perspective on Science* **10**, 208–27

Barrow, J. D./F. J. Tipler [1986]: *The Anthropic Cosmological Principle.* Oxford: Oxford University Press

Blumenberg, H. [1955]: "Der kopernikanische Umsturz und die Weltstellung des Menschen," *Studium Generale* **8**, 637–48

Blumenberg, H. [1957]: "Kosmos und System," *Studium Generale* **10**, 61–80

Blumenberg, H. [1965]: *Die kopernikanische Wende.* Frankfurt a./M.: Suhrkamp

Blumenberg, H. [1981]: *Die Genesis der kopernikanische Welt.* 3 vols. Frankfurt a./M.: Suhrkamp [English translation: *The Genesis of the Copernican World*, transl. R. M. Wallace. Cambridge, MA: MIT Press, 1987]

Born, M. [1962]: *Einstein's Theory of Relativity.* New York: Dover

Brecht, B. [1963]: *Leben des Galilei.* Berlin: Suhrkamp [English translation: *The Life of Galileo.* London: Eyre Methuen, 1963]

Breuer, R. [1991]: *The Anthropic Principle: Man as the Focal Point of Nature.* Boston: Birkhäuser

Brzeziński, J./F. Coniglione/Th. A. F. Kuipers/L. Nowak *eds.* [1990]: *Idealization II: Forms and Applications.* Atlanta, GA: Rodopi

Brzeziński, J./L. Nowak *eds.* [1992]: *Idealization III: Approximation and Truth.* Atlanta, GA: Rodopi

Burtt, E. A. [$^2$1932]: *The Metaphysical Foundations of Modern Physical Science.* London: Routledge & Kegan Paul

Carter, B. [1974]: "Large Number Coincidences and the Anthropic Principle in Cosmology," in M. S. Longair *ed.*, *Confrontation of Cosmological Theories with Observational Data.* Dordrecht: D. Reidel 1974, 291–8

Carr, B. J./M. J. Rees [1979]: "The Anthropic Principle and the Structure of the Physical World," *Nature* **278**, 605–12

Carroll, John W., "Laws of Nature," in *The Stanford Encyclopedia of Philosophy* (Fall 2003 Edition), Edward N. Zalta *ed.*, URL = <http://plato.stanford.edu/archives/fall2003/entries/laws-of-nature/>.

Cartwright, N. [1999]: *The Dappled World: A Study of the Boundaries of Science.* Cambridge: Cambridge University Press

Chen, X./P. Barker [2000]: "Continuity through Revolutions," *Philosophy of Science* **67**, S208–S233

Cohen, I. B. [1985]: *Revolution in Science*. Cambridge, MA: Belknap Press at Harvard University Press

Copernicus, N. [1543/1995]: *On the Revolutions of Heavenly Spheres.* Amherst, NY: Prometheus Books

Copernicus, N. [1959]: The *Letter Against Werner*, in E. Rosen *ed*. [1959], 93–106

Copernicus, N. [1959]: *The Commentariolus*, in E. Rosen *ed*. [1959], 55–90

Crombie, A. C. [1961]: *Augustus to Galileo.* London: Mercury

Crombie, A. C. [1994]: *Styles of Scientific Reasoning in the European Tradition*. London: Duckworth

Cushing, J. T. [1998]: *Philosophical Concepts in Physics.* Cambridge: Cambridge University Press

Davies, P. [1995]: "Algorithmic Compressibility, Fundamental and Phenomenological Laws," in F. Weinert *ed*. [1995a], 248–67

Deutsch, D. [1997]: *The Fabric of Reality.* London: Penguin

DeWitt, R. [2004]: *Worldviews*. London: Blackwell

Dicke, R. H. [1961]: "Dirac's Cosmology and Mach's Principle," *Nature Letters* **192**, 440–1

Dijksterhuis, E. J. [1956]: *The Mechanization of the World Picture*. Oxford: Clarendon 1961

Dirac, P. M. [1961]: "Dicke's Cosmology and Mach's Principle," *Nature* **192**, 440–1

Drake, S. [1975]: "Impetus Theory Reappraised," *Journal of the History of Ideas* **36**, 27–46

Dreyer, J. L. E. [1953]: *A History of Astronomy from Thales to Kepler*. New York: Dover

Dretske, F. I. [1977]: "Laws of Nature," *Philosophy of Science* **44**, 248–68

Duhem, P. [1962]: *The Aim and Structure of Physical Theory.* New York: Athenaeum

Einstein, A. [1918]: "Prinzipien der Forschung," in A. Einstein [1977], 107–10; English translation in Einstein [1954], 224–7

Einstein, A. [1919]: "Was ist Relativitätstheorie?," in A. Einstein [1977], 127–131; English translation in Einstein [1954], 227–32

Einstein, A. [1930]: "Johannes Kepler," in A. Einstein [1977], 147; English translation in Einstein [1954], 262–6

Einstein, A. [1953]: "Message on the 410th Anniversary of the Death of Copernicus," in Einstein [1954], 359–60

Einstein, A. [1954]: *Ideas and Opinions.* London: Alvin Redman

Einstein A. [1977]: *Mein Weltbild*. *Hrsg*. von Carl von Seelig. Frankfurt a./M: Ullstein

Galilei, G. [1953/1632]: *Dialogue on the Great World Systems.* G. de Santillana *ed*. Chicago: Chicago University Press

Gingerich, O. [1982]: "The Galileo Affair," *Scientific American* **247** (August), 118–27

Gingerich, O. [1993]: *The Eye of Heaven: Ptolemy, Copernicus, Kepler*. New York: American Institute of Physics

Gingerich, O. [2004]: *The Book Nobody Read*. London: Heinemann

Greene, G. [2000]: *The Elegant Universe*. New York: Vintage Books

Gutting, G. *ed*. [1980]: *Paradigms & Revolutions.* Notre Dame, IN: University of Notre Dame Press

Hacking, I. *ed*. [1981]: *Scientific Revolutions.* Oxford: Oxford University Press

Hanson, N. [1958]: *Patterns of Discovery.* Cambridge: Cambridge University Press

Heidelberger, M. [1980]: "Some Intertheoretic Relations between Ptolemean and Copernican Astronomy," in G. Gutting *ed*. [1980], 271–83

Hempel, C. [1965]: *Aspects of Scientific Explanation*. New York: The Free Press

Herfel, W. E. et al. *eds*. [1995]: *Theories and Models in Scientific Processes.* Amsterdam: Rodopi

Hoyningen-Huene, P. [1993]: *Reconstructing Scientific Revolutions*. Chicago: Chicago University Press [German original: *Die Wissenschaftsphilosophie Thomas S. Kuhns*. Braunschweig: Vieweg & Sohn 1989]

Jeans, J. [1943]: *Physics and Philosophy*. Cambridge: Cambridge University Press

Kaufmann, W. [$^4$1974]: *Nietzsche*. Princeton, NJ: Princeton University Press

Kepler, J. [1619]: *The Harmonies of the World*, in J. Kepler [1995], 1–164

Kepler, J. [1618–21]: *Epitome of Copernican Astronomy*, in J. Kepler [1995], 165–245

Kepler, J. [1995]: *Epitome of Copernican Astronomy & Harmonies of the World*. Amherst, NY: Prometheus Books

Kitcher, P. [1993]: *The Advancement of Science*. Oxford: Oxford University Press

Koestler, A. [1964]: *The Sleepwalkers*. London: Penguin

Koyré, A. [1957]: *From the Closed World to the Open Universe*. Baltimore, MD: John Hopkins University Press

Koyré, A. [1965]: *Newtonian Studies*. Chicago: University of Chicago Press

Koyré, A. [1978]: *Galileo Studies*. Hassocks (Sussex): The Harvester Press

Krajewski, W. [1977]: *Correspondence Principle and Growth of Science*. Dordrecht: D. Reidel

Kuhn, T. S. [1957]: *The Copernican Revolution*. Cambridge, MA: Harvard University Press

Kuhn, T. S. [$^2$1970]: *The Structure of Scientific Revolutions*. Chicago: The University of Chicago Press

Kuhn, T. S. [1983]: "Commensurability, Comparability, Communicability" (PSA 1982). P. D. Asquith/T. Nickles *eds*. East Lansing, MI: Philosophy of Science Association, 669–88

Ladyman, J. [1998]: "What is structural realism?" *Studies in History and Philosophy of Science* **29**, 409–24

Leckey, M./J. Bigelow [1995]: "Necessitarian Perspective: Laws as Natural Entailments," in Weinert [1995b], 92–118

Mason, S. F. [1956]: *Main Currents of Scientific Thought*. London: Routledge

McMullin, E. [1985]: "Galilean Idealization," *Studies in History and Philosophy of Science* **16**, 247–73

Mittelstraß, J. [1962]: *Die Rettung der Phänomene*. Berlin: Walter de Gruyter

Morgan, M./M. Morrison *eds*. [1999]: *Models as Mediators*. Cambridge: Cambridge University Press

Musgrave, A. [1979–80]: "Wittgensteinian Instrumentalism," *Theoria* **45/6**, 65–105

Neugebauer, O. [1968]: "On the Planetary Theory of Copernicus," *Vistas in Astronomy* **10**, 89–103

Nietzsche, F. [1887]: *On the Geneology of Morals*. New York: Vintage 1967 [Translation of *Über die Geneologie der Moral*, 1887]

Nola, R. [2003]: *Rescuing Reason*. Dordrecht: Kluwer

Nowak, L. [1980]: *The Structure of Idealization*. Dordrecht: D. Reidel

Popper, K. [1959]: *The Logic of Scientific Discovery*. London: Hutchinson

Popper, K. [1963]: *Conjectures and Refutations*. London: Routledge & Kegan Paul

Psillos, St. [1999]: *Scientific Realism*. London: Routledge

Ptolemy, C. [1984]: *Ptolemy's Almagest*. G. J. Toomer *ed*. London: Duckworth [German translation: *Des Ptolemäus Handbuch der Astronomie*. Bd. 1, 2, übersetzt von Karl Manitius. Leipzig: B. G. Teubner, 1912]

Putnam, H. [1975]: *Mathematics, Matter and Method*. Philosophical Papers, Vol. 1. Cambridge: Cambridge University Press

Quine, W. v. [1990]: *The Pursuit of Truth*. Cambridge, MA: Harvard University Press
Rheticus, J. [1540]: *Narratio Prima*, in E. Rosen [1959], 107–96
Rickles, D./S. French/J. Saatsi *eds.* [2006]: *The Structural Foundations of Quantum Gravity*. Oxford: Clarendon Press
Roman, P. [1969]: "Symmetry in Physics," in R. S. Cohen/M. W. Wartofsky *eds.*, *Boston Studies in the Philosophy of Science*, Vol. V. Dordrecht: Reidel, 363–9
Rosen, E. *ed.* [1959]: *Three Copernican Treatises*. Mineola, NY: Dover
Rosen, E. [1984]: *Copernicus and the Scientific Revolution*. Malabar, FL: Robert E. Krieger
Ruby, J. [1995]: "Origins of Scientific 'Law'," in F. Weinert *ed.* [1995a], 289–315
Rybka, E. [1977]: "The Scientific Reception of the Copernican Theory," *Studia Copernicana* **17**, 158–71
Salmon, W. [1998]: *Causality and Explanation*. Oxford: Oxford University Press
Shapere, D. [1964]: "The Structure of Scientific Revolutions," reprinted in G. Gutting *ed.* [1980], 27–38
Shapere, D. [1966]: "Meaning and Scientific Change," reprinted in I. Hacking [1981], 28–59
Shapere, D. [1989]: "Evolution and Continuity in Scientific Change," *Philosophy of Science* **56**, 419–37
Sklar, L. [2000]: *Theory and Truth*. Oxford: Oxford University Press
Smolin, L. [1997]: *The Life of the Cosmos*. New York: Oxford University Press
Solla Price, D. J. de [1962]: "Contra-Copernicus," in M. Clagett *ed.*, *Critical Problems in the History of Science*. Madison: University of Wisconsin Press, 197–218
Swartz, N. [1985]: *The Concept of Physical Law*. Cambridge: Cambridge University Press
Toulmin, S. [1953]: *The Philosophy of Science*. London: Hutchinson
Watson, W. H. [1938]: *On Understanding Physics*. London: Cambridge University Press
Worrall, J. [1989]: "Structural Realism": The Best of Both Worlds?" *Dialectica* **43**, 99–124
Weinberg, S. [1977]: *The First Three Minutes*. London: Deutsch
Weinert, F. [1993]: "Laws of Nature: A Structural Approach," *Philosophia Naturalis* **30**, 147–71
Weinert, F. *ed.* [1995a]: *Laws of Nature – Essays on the Philosophical, Scientific and Historical Dimensions*. Berlin: de Gruyter
Weinert, F. [1995b]: "Laws of Nature – Laws of Science," in F. Weinert *ed.* [1995a], 3–64
Weinert, F. [1995c]: "The Duhem–Quine Problem Revisited," *International Studies in the Philosophy of Science* **9,** 147–156
Weinert, F. [1998]: "Fundamental Physical Constants, Null Experiments and the Duhem–Quine Thesis," *Philosophia Naturalis* **35**, 225–52
Weinert, F. [1999]: "Theories, Models and Constraints," *Studies in History and Philosophy of Science* **30**, 303–33
Weinert, F. [2004]: *The Scientist as Philosopher*. New York: Springer
Weinert, F. [2006]: "Einstein and the Representation of Reality," *Facta Philosophica* **8**, 229–52
Wittgenstein, L. [1921/⁸1971]: *Tractatus Logico-Philosophicus*. Frankfurt a./M.: Suhrkamp
Wendorff, R. [³1985]: *Zeit und Kultur*. Opladen: Westdeutscher Verlag
Wolff, M. [1978]: *Geschichte der Impetustheorie*. Frankfurt a./M.: Suhrkamp
Zeilik, M. [⁵1988/⁹2002]: *Astronomy*. New York: John Wiley & Sons

## Essay Questions

1 Greek astronomy was concerned with '**saving the appearances**'. Explain what this means and what impact it had on the philosophical status of scientific theories.

2 Greek astronomy assumed a '**two-sphere universe**'. Explain what this means and what impact it had on the philosophical status of scientific theories.

3 What is the structure of **geocentrism** and why did the Greeks find it so compelling?

4 Explain how the replacement of the Aristotelian theory of motion by the **impetus theory** was a logical precondition for the development of Copernicanism.

5 Explain the major achievements of the **Copernican revolution**.

6 Explain why the Copernican worldview was only completed in the **Newtonian synthesis**.

7 What is the structure of **heliocentrism** and why did the Copernicans find it so compelling?

8 **Realism** is "the belief that a mere description of data is not all that should be required of a theory." [Bernard d'Espagnat] Discuss the significance of this statement, using appropriate examples.

9 There are two views on theories: **realism** and **instrumentalism**. Explain what they are. What arguments does the realist produce against the instrumentalist?

10 In which sense could you use *Copernicanism* to support, respectively, **instrumentalism** and **realism**?

11 Explain how the issue of **realism** versus **instrumentalism** arises from the Copernican turn and discuss some of the arguments in favor of realism and instrumentalism, respectively.

12 Explain, illustrate, and evaluate some of the typical arguments for and against **realism** and **instrumentalism**.

13 If **models** are ways of **representing** the natural and social world, how is this representation achieved?

14 Explain the role of **models** in science. What types of models are there and why are models important? Illustrate with respect to Copernicanism.

15 The DN model assumes the **symmetry** of **explanation** and **prediction**. Use examples from astronomy to evaluate the appropriateness of this assumption.

16 Explain and illustrate the role of **hypotheses** in the history of astronomy, from Ptolemy to Newton.

17 Explain the **underdetermination thesis** (Duhem–Quine thesis). What arguments can be advanced against it?

18 Explain and illustrate the **reversal** of **perspective** in Copernicanism.

19 What do we understand by a **scientific revolution**? Were *Copernicanism* and *Darwinism* scientific revolutions?

20 Explain why the Copernican heliocentric hypothesis was a **Copernican turn** rather than a scientific revolution.

21 Explain why it took **140 years** – from 1543 to 1687 – to complete the Copernican revolution.
22 If Copernicus initiated only a Copernican turn, why is Darwin's *Origin of Species* (1859) a scientific revolution and Copernicus's *Revolutionibus* (1543) not?
23 Explain what **advantages the Copernican model** had over the Ptolemaic model. Why do historians of science not regard Copernicus as a "true" revolutionary in science?
24 Critically discuss the applicability of **Kuhn's paradigm model** of scientific revolutions in the context of the Copernican model.
25 Explain for what reasons **J. Kepler** is regarded as the **true revolutionary** in the history of astronomy.
26 Critically analyze the role of **constraints** in science by reference to Copernicanism and Darwinism.
27 Explain the difference between the **laws of nature** and the **laws of science**. Why is this distinction important?
28 Critically evaluate the distinction between **theories** and **models**.
29 Critically discuss arguments in favor of and against the **structural view** of laws.
30 Critically discuss arguments in favor of and against the **necessitarian view** of laws.
31 Critically discuss arguments in favor of and against the **regularity view** of laws.