1

A Traditional Narrative of the Scientific Revolution

The Rise of Modern Science: When and Why?

R. Hooykaas

Originally appeared as "The Rise of Modern Science: When and Why?" (*BJHS* 1987: 453–73).

Editor's Introduction

Reijer Hooykaas belongs to the generation that introduced the history of science to universities in the United States and Europe. His essay provides us with an excellent starting point for our readings on the Scientific Revolution. For Hooykaas there is no doubt that the sixteenth and seventeenth centuries witnessed a dramatic improvement in what people knew about nature and in the way they studied it. He grants that all discussion about the origins or rise of science depend heavily on the definition of science used, but is confident that the origins of modern science are to be found in the early modern period. Here he is arguing against the claim first put by the French physicist and historian Pierre Duhem that the origins of modern science can be found as early as the thirteenth century.

In Hooykaas's view two developments were most responsible for the rise of science in early modern Europe. The first was the process of discovery begun by the voyages of Portuguese navigators that culminated in the discovery of the New World. The existence of lands, plants, animals, and people in Asia, Africa, and the New World that were not mentioned in any ancient sources undermined their authority. Experience, Hooykaas argues, now took precedence over human authority and reason alone. The second major development was the transition from an organic view of the world to a mechanical one. Nature worked like a machine, consequently it could be studied like one, that is, mathematically.

In Hooykaas's essay we can see a reaction against a view of science as primarily a cognitive activity, one that was essentially distinct from society and other cultural activities. This view held that the task of the historian of science was to trace the red thread of truth through the centuries, while identifying and then pruning away the false shoots of erroneous theories. Hooykaas terms this approach the teleological or progressionist method. Such historians also argued that a dramatic break occurred in science in the sixteenth and seventeenth centuries, but it was a development that was internal to science and not the result of broader historical events. In contrast Hooykaas insists that in order to understand the rise of science we also need to examine factors which create a favorable climate for science, ranging from theological concerns to the rise of the artisanal classes.

Although most current historians of science share Hooykaas's rejection of the teleological approach, many go far beyond him. For example, although Hooykaas emphasizes the importance of facts in the rise of modern science, he does not explore what facts actually are or where they come from. Our later pieces explicitly take up these questions, arguing that the production of scientific facts is in itself a social process. Other essays go beyond Hooykaas's emphasis on the mechanical and mathematical disciplines to include natural history, medicine, and alchemy.

The Rise of Modern Science: When and Why?

*R. Hooykaas**

When did modern science arise?[1] This is a question which has received divergent answers. Some would say that it started in the High Middle Ages (1277), or that it began with the 'via moderna' of the fourteenth century. More widespread is the idea that the Italian Renaissance was also the re-birth of the sciences. In general, Copernicus is then singled out as the great revolutionary, and the 'scientific revolution' is said to have taken place during the period from Copernicus to Newton. Others would hold that the scientific revolution started in the seventeenth century and that it covered the period from Galileo to Newton. Sometimes a second scientific revolution is said to have occurred in the first quarter of the twentieth century (Planck, Einstein, Bohr, Heisenberg, etc.), a revolution which should be considered as great as the first one.

It might be asked: Was there ever something like a scientific *revolution*? Perhaps the term is not well chosen; with the word 'revolution' we usually connect the idea of 'revolt', 'violence' or, at any rate, abruptness; a 'revolution' covering 100, or 150, or 200 years hardly deserves that name.

It must be recognized, of course, that there is an enormous gap between the science of Antiquity and the Middle Ages on the one hand and that of the seventeenth century onwards on the other. Even without analysing their respective contents, their *effects* convincingly show the watershed: on the basis of 'ancient' science one cannot construct locomotives or aeroplanes; on the basis of 'modern' science this has turned out to be possible. The gap between ancient

1 The present author has dealt with some aspects of the problem in earlier publications: (a) 'Science and theology in the Middle Ages', *Free Univ. Qu.* (1954), 3, pp. 77–163 (in particular, pp. 77–82, 88–97, 103–118, 131–137); (b) *Religion and the Rise of Modern Science*, Edinburgh and London, 1972 ff (pp. 9–13, 29–41, 61–66, 88–94); (c) *Das Verhältnis von Physik und Mechanik in historischer Hinsicht*, Wiesbaden, 1963 (reprinted in: R. Hooykaas, *Selected Studies in History of Science*, Coimbra, 1983, pp. 167–199); (d) 'Von der "physica" zur Physik', in: *Humanismus und Naturforschung*, Beitr. Humanismusforschung VI, Boppard, 1980, pp. 9–38 (reprinted in: *Selected Studies*, op. cit., pp. 599–634); (e) *Science in Manueline Style, the Historical Context of D. João de Castro's Works*, Coimbra, 1980 [pre-print of: *Obras Completas de D. João de Castro* (ed. A. Cortesão e L. de Albuquerque), vol. IV, Coimbra, 1982, pp. 231–426 (in particular pp. 3–12, 92–98, 146–152, 163–167)].

* Originally intended to be the closing lecture of the Fourth Reunion of the History of Nautical Sciences, Sagres Portugal), 3–8 July 1983, under the presidency of Professor L. de Albuquerque (Coimbra and Lisbon).

science and Newtonian science is wider than that between Newtonian classical – modern science and Planck – Bohr physics. In the latter case there is a large measure of continuity with the preceding epoch: the new physics does not render the classical – modern invalid, whereas Newtonian and scholastic physics are quite incompatible.

It should be emphasized that before expounding our opinion about the question 'When and why did the great scientific change take place', we have to realize that the answer depends on the (often hidden) methodological principles applied by the historiographer of science, and – secondly – on which characteristics are deemed to constitute 'modern science'.

Historiographical Methods[2]

The approach most attractive to modern scientists is one that could be called 'evolutionistic, 'teleological', 'genealogical' or 'progressionist'. Without any doubt, science bears a cumulative and progressive character, and this confronts a historian of science with problems the historian of art or of theology hardly meets with. Consequently, the historian of science tends to apply to the past the standard of present-day knowledge. Starting from the present-day advanced state of science, the evolutionistic historian goes back into the past with all its conflicting and erroneous opinions, its fertile and its sterile theories, its thoroughfares and its blind alleys, taking the red thread with him, until he arrives at the 'fathers'. Next – and then begins his serious history-writing – he follows backwards his thread of progress, discarding all that does not directly lead to the exit of the maze as aberrations and errors, until he returns to the present situation. He concentrates on the heroes of science and has a keen eye for the 'precursors' who paved the way for them. The past serves mainly to prepare and announce the present: almost unwittingly, a teleological conception dictates the shape of his historiography.

It is understandable that the scientist who writes about the history of his discipline has a predilection for the path that led to present-day science, for he is more interested in finding out how his predecessors escaped from the maze than in studying their unsuccessful efforts.

2 On this topic, see: (a) E.J. Dijksterhuis, *Doel en Methode van de Geschiedenis der Exacte Wetenschappen*, Inaugural address, Utrecht, 1952, pp. 13–20; (b) R. Hooykaas, *L'histoire des Sciences, ses Problèmes, sa Méthode, son But*, Coimbra, 1962 (also in: *Rev. Fac. De Ciências Coimbra* (1963), 32, pp. 5–35); (c) T. Frangsmyr, 'Science or history, G. Sarton and the positivist tradition in the history of science', *Lychnos* (1973–1974), pp. 104–144; (d) F. Krafft, 'Die Naturwissenschaften und ihre Geschichte, *Sudhoff's Arch.* (1976), 60, pp. 317–337; (e) R. Hooykaas, 'Pitfalls in the historiography of geological science', *Nature et Histoire*, (1982), 19–20, pp. 2–33; (f) R. Hooykaas, 'Wissenschaftsgeschichte, eine Brücke zwischen Natur und Geisteswissenschaften', *Berichte z. Wissensch. Geschichte* (1982), 5, pp. 162–170.

In sharp contrast to the progressionist approach is a more phenomenological and imaginative one. It considers the historian's task to be to revive the past, to enter into the minds of our predecessors, to imagine the political, social and cultural aspects of their environment, to re-enact their metaphysical, ethical and scientific conceptions and to identify himself as much as possible with their personalities. Standing beside them in the centre of the maze, he then enters with them into the blind alleys, too; he positively appreciates their accounts of the then known facts, fitting them into the then generally accepted theoretical system, even when afterwards these theories turned out to be false. He will then recognize that the way out of the labyrinth could hardly have been found without coming to many dead ends. He will also recognize that by entering the blind alleys, our predecessors erected for us warning-posts reading 'no thoroughfare'. This re-enactment of the past will show him that, however incomplete the knowledge of facts and however obsolete the opinions held, the *method* of these pioneers was often 'scientific', even when the result was not 'true'. Scientific results of the past may *now* be known not to conform to physical reality, but these same results may have been conformable to what was *then* considered to be physical reality, as they were obtained by keen observation and consistent thinking.

The distinction between the two approaches should not be considered absolute: because of the cumulative character of science, the historian who is also a scientist cannot leave out of sight the genealogy of present-day theories and concepts. He goes wrong, however, if he thinks that not only scientific knowledge but also the quality of scientific *thinking* has improved and that our predecessors were more primitive or less clever than we are.

The Character of Modern Science

When speaking about the rise of modern science it is necessary first to state what we take to be its characteristics.

1 Modern science acknowledges no authorities (however great they may be) except the authority of nature itself. It does not even acknowledge the authority of the investigator's own reason. In case of a conflict between his rational expectations and his discoveries by observation, the investigator's reason must adapt itself to the data provided by nature. As T. H. Huxley put it: 'Sit down before fact as a little child . . . follow humbly wherever and to whatever abysses nature leads, or you shall learn nothing'. In modern science a rational and critical empiricism triumphs over rationalism (self-sufficiency of theoretical reason).
2 Modern science is experimental. It is built not only upon direct observation of nature, but also upon artificial experiments, conquering

nature by art and obtaining genuine information from it through interference by art.

3 Modern science favours a mechanistic world picture, explaining natural phenomena as much as possible by analogy with a mechanism. Ancient science, on the other hand, tended to an 'organistic' world view, regarding non-living things as to a large extent similar to organic beings.
4 Modern science tries as much as possible to describe or explain natural things and events in mathematical terms and to quantify qualities.

It should be stressed that these characteristics are not wholly absent from ancient science. It had its observations, experiments, mechanistic interpretations and mathematical descriptions, but they did not play so predominant a role as in modern science, although, of course, in the 'mathematical arts' (which, however, did not belong to the 'philosophy of nature' or 'physics') mathematics played an important role.

In order, therefore, to locate the transition from ancient to modern science we have to concentrate our attention on these characteristics. This is no easy task, for some disciplines may show only one or two such characteristics and yet give the impression of 'modernity'. Consequently, there is some vagueness in the data, and difference of evaluation is inevitable. At any rate, in this essay we will not deny the name of 'modern science' to disciplines that show little mathematization (as was until quite recently the case with geological and biological sciences), or which occupy themselves more with classification than with causal explanations and measurement of quantities. When tackling the problem of the 'scientific revolution' we must consider the whole range of sciences of nature and not only the mathematical–physical disciplines (astronomy, physics).

In our search, the following influences might be taken into acount: (1) empiricism; an emphasis on empirical reality over and above speculative reasoning; (2) analysis of phenomena in an experimental way, as against a purely logical analysis; (3) establishment of a science free from the constraint of authority, except that of nature herself; and (4) mathematization of nature and measurement of phenomena.

Moreover, any historical events creating a favourable climate for science should be taken into account, such as: (a) the emergence of theological voluntarism, in opposition to intellectualism; (b) the emergence of mechanistic conceptions over against organistic ones; (c) the emancipation of manual workers and acceptance of manual experiments; and (d) the extension of natural history on the basis of experience rather than book-learning, triggered off by the 'geographical revolution'.

Some of these factors had no immediate and direct effect in science, but they created an atmosphere favourable to the reception of new ideas and methods.

The Middle Ages

All these preliminary remarks warn us that it will be difficult to find a hard and fast answer to the question 'Why and when did modern science begin?' Nobody can completely free himself from subjective predispositions, particularly with regard to general problems like the present one. Nevertheless, we can try to be as objective as possible.

The French physicist and historian of science, Pierre Duhem, has often been accused of giving in to nationalistic prejudices. He claimed that modern science was born in 1277, when the bishop of Paris, at the instigation of Pope John XXI, condemned a great many theses that introduced Greek necessitarianism into theology, putting the Necessity of Nature above the sovereign will of God:

> Étienne Tempier et son conseil, en frappant ces propositions d'anathème, déclaraient que . . . pour ne pas imposer d'entraves à la toute-pouissance de Dieu, il fallait rejeter la Physique péripatéticienne. Par là, ils réclamaient implicitement la création d'une Physique nouvelle . . . Cette Physique nouvelle, nous verrons que l'Université de Paris, au XIVe siècle, s'est efforcée de la construire et qu'en cette tentative, elle a posé les fondements de *la science moderne; celle-ci naquit, peut-on dire, le 7 mars 1277, du décret porté par Monseigneur Étienne, Évêque de Paris*; l'un des principaux objets du présent ouvrage sera de justifier cette assertion'.[3]

Such a precise identification of the date of birth of a modern science is rare, although not unique.

It must be recognized that there is *some* truth in Duhem's verdict. Of course, the bishop was not acting here as an advocate a new science, but as a defender of the ancient biblical faith. He set Christian voluntarism over and above philosophical intellectualism. The then new Aristotelian philosophy (put forward in its most radical version by the Averroïsts) decreed a priori on allegedly rational grounds, that if the heavens were to cease turning round, no change on earth would be possible ('tow would not burn'), that God cannot create new species, and that only uniform, circular motions are possible in the heavens, etc. All these prohibitions or limitations to the natural world were proclaimed because these things were deemed to be intrinsically against the eternal order of Nature and against Reason. Tempier, however, maintained that God's will is more powerful than Nature or pretendedly 'eternal Reason'. He did not say that new species do arise, or that rectilinear motions do occur in the heavens, but only that human reason has no right to put any limits to God's power. This implies that natural science cannot decide a priori with absolute certainty how nature ought to be and must be found to be, but that

3 P. Duhem, *Le Système du Monde, VI*, 2nd edn, Paris, 1954, p. 66.

we have just to accept phenomena as it has pleased the Creator to give them, whether they seem conformable to human reason or not. This is a very important metaphysical standpoint (emphasizing the contingency of nature), which certainly is not anti-scientific. One wonders, therefore, how the historian Lynn Thorndike could dub it 'warfare (of theology) with science' and compare it with the 'silencing' of Galileo.[4]

In the Paris decree, a purely theological issue was at stake, but an issue that could indeed have great, positive consequences for the freedom of scientific theorizing and for the choice between a rationalistic and an empiricalist approach to nature. For the time being, however, it had no influence on scientific speculation, let alone on practical research. Although the Aristotelian world picture was deprived of its absolute authority, it was not seriously criticized or replaced by an alternative system. Tempier's decree could have created a favourable spiritual climate for a more empirical science, but it had no direct consequences in that field. Therefore, it could hardly be called the '*birth* of modern science'.

Of course, Duhem knew that quite well, for he said also that the consequences were not realized until the fourteenth century (i.e. 100 years later) at the university of Paris. He alluded here to nominalism, the 'via moderna', which by its critique of Aristotelian philosophy had an enormous influence. The nominalists emphasized the contingency (the not rationally deducible, not necessary, character, the just-given-ness) of the world, which has been made by God's incomprehensible will; only a posteriori can we put together a science of nature, as rational as possible in our own eyes; and such a system will be at best highly probable though not absolutely necessary, since God could have willed a different world with different rules.

Nominalism was against eternal Forms or eternal species; a 'universal' is but a name for a group of individuals we deem to belong together. The thoroughgoing philosophical empiricism of the nominalists was thus based on theological voluntarism. Small wonder, then, that the main Parisian protagonists of the 'via moderna', Jean Buridan (*c.* 1300–1358) and Nicole Oresme (*c.* 1323–1382), more than once referred to the decree of 1277 in order to back up their standpoint.[5]

Because of the nominalists' introduction of the impetus theory, their mathematization of physical problems, and their undermining of the dividing wall between terrestrial and celestial mechanics, Duhem on one occasion becomes so enthusiastic that he seems to forget that he has dated the beginning of modern science with Tempier's decree of 1277, and gives the honour to Buridan. He now says that a sharp line separates ancient science from modern

4 L. Thorndike, *A History of Magic and Experimental Science, III*. New York, 1934, p. 470.

5 J. Buridanus, *De Coel et Mundo*, lib. I, qu. 16, N. Oresme, *Le livre du Ciel et du Monde* (*c.* 1370), l. II, 95c (ed. A.D. Menut and A.J. Denomy), Madison, 1965, p. 374.

science, viz. the moment when the stars were no longer held to be moved by divine beings, but heavenly and sublunar motions were considered to depend on the same mechanics:

> si l'on voulait, *par une ligne précise,* séparer le règne de la Science antique du règne de la Science moderne, il la raudrait tracer, croyons-nous, à l'instant où Jean Buridan a conçu cette théorie [de l'impetus], à l'instant où l'on a cessé de regarder les astres comme mus par des êtres divins, où l'on a admis que les mouvements célestes et les mouvements sublunaires dépendaient d'une même mécanique.[6]

According to Duhem, the impetus theory paved the way for Galileo's mechanics and thus marked the beginning of modern physico-mathematical science. Although Buridan may have made (all) change measurable in principle, however, we should note that he and his disciples did not perform any measurement.

It should also be remembered that mathematization and measurement are no prerogatives of modern science alone. Ancient astronomy combined a highly sophisticated mathematical description of heavenly motions with rather exact measurements. In statics and hydrostatics, too, measurements had long been performed. However, those were reckoned to belong to the 'most physical part of mathematics' rather than to physis in the proper sense; that is, they did not belong to 'science' (philosophy of the nature – physis – of things) but rather to the 'lower' of the liberal arts. Nevertheless, today we recognize them as an important part of physical science. In modern times these mathematical 'arts' (astronomy, mechanics, etc.) have become part of science, whereas speculative natural philosophy has been more and more relegated to the periphery. The acceptance of these arts as more than a mere auxiliary part of physical science, however, was to be a difficult process.

Much later, the alliance between theoretical reason and manual experimentation was to play a very important role in the rise of modem science. The decree of 1277 and fourteenth-century nominalism, however, did not at the time cause the slightest change in the physical methods of those who understood their message. The changes caused by the 'calculatores' and the Parisian school needed something from the outside to make them bear fruit.

Natural History

When the Portuguese seafarers discovered that the tropical regions were habitable and inhabited, that there was much land south of the equator, that

6. P. Duhem, *Études sur Léonard de Vinci*, III, p. XI; II, p. 411. Cf. E. Gilson, *La Philosophie au Moyen Age*, 3rd edn, Paris, 1947, pp. 460, 487.

there was more dry land on the globe than had been taught them, that Southern India protruded much farther into the 'Indian Sea' than Ptolemy had told them and that the shape of West Africa (the Gulf of Guinee) was widely different from what ancient maps indicated – all this gave a severe shock not only to them but to the learned world as well. Ptolemy, the great authority in astronomy throughout the later Middle Ages and (since the recent discovery of his 'Geographia') the greatest authority in geography, too, now turned out to be not wholly reliable. He might be a great mathematician, but his 'natural history' was not so good. The same was the case with all those writers of Antiquity who had described peoples, animals and plants. There were many things whose existence they had not known and also many things they had 'known' wrongly. Their knowledge was incomplete and often erroneous.

With these simple seafarers a new natural history arose. They discovered, as Pedro Nunes (1537), following Policiano (1491) put it: 'new islands, new countries, new seas, new peoples and what's more, new heavens and new stars'. Just at the time when humanism (which wanted to go *back* from the 'barbarous' and 'gothic' period to the perfection of the Ancients) was penetrating into Portugal, their own *experience* taught the sailors that those glorified and quasi-infallible Ancients were as fallible and as human as their contemporaries.

The early Portuguese navigators (Diogo Gomes, 1460; Duarte Pacheco Pereira, 1506) testified to how amazed they were by the things seen during their voyages, and time and again they protested that, however strange these phenomena might seem to be, they had 'seen them with their eyes and touched them with their hands'. There are echoes here of the apostle Thomas, whose reason refused to accept the resurrection of the Lord until, as St John relates, having seen and touched Him, he was convinced: experience had overcome aprioristic reasoning.

In the competition between Reason and Experience, the precedence was now reversed. The navigator D. João de Castro (1500–1548) wrote that whereas formerly the existence of antipodes was deemed to be against reason, now that the experience of Portuguese seafarers had proved their existence, it had become 'a thing most conformable to reason'.[7] That is: we do not put experience to the test of theoretical reason, but we submit theoretical reason to the test of experience. These pioneers, who were not hindered by learned prejudices, did not make their decisions whether a certain fact was true by arguments *pro et contra*: for them observation was enough, and facts must be accepted in spite of any apparent 'absurdity'.

Both the scholastic philosophers and the humanists, who tenaciously clung to ancient traditions, were deeply shocked, and at first they tried to

7 D. João de Castro, *Tratado da Esfera* (*c*. 1538), Obras I, p. 58.

save the honour and authority of the Ancients by various exegetical tricks. But it was all in vain, for the evidence of the facts was too strong. Most irksome for them was that all this new and subversive information was adduced by unlearned sailors. These they held in low esteem; yet now it was precisely these uneducated people who had put them to shame. On the other hand, some of them took the lesson to heart. Peter Ramus (1546) wrote: 'The philosophers, orators, poets and scholars of the whole world and of so many ages did not know what navigators, merchants, uneducated people learned, not by arguments but through experience . . . we are compelled by simple examples and immediate experience of the senses to recognize that those very ancient prodigies of wisdom have at last lost their monopoly and have been outdone'.[8] And indeed, as Camões ironically pointed out, there were things he had seen which the 'uneducated sailors' who had only experience as their teacher had proved to be true, yet which those who investigated the secrets of the world by their sharp wits alone had demonstrated to be wrong.

This marks the beginning of *a new, empiricist, non-rationalistic trend in science*: problems are solved by reasoned experience and not by scholastic discussions, which – however clever and logical they might be – brought forth only armchair physics.

The Emancipation of the Burgher Class

All this happened at a time that could hardly have been more favourable. It coincided with the emancipation of the burgher class, in particular in Italy, Southern Germany and the Netherlands. The artisans of the late Middle Ages and early Renaissance became conscious of their dignity and social importance. This self-respect, also in intellectual matters, was evident in people like the Huguenot potter Bernard Palissy (1510–1590), who proudly declared that, although he had not read the books of the great Greeks and Romans and spoke only his mother tongue, he nevertheless had a right to contradict their reported opinions: 'I have read no other book but heaven and earth, which is known to everybody, and it has been given to everyman to know and to read this beautiful book'. Artisans like Palissy, Robert Norman and Albrecht Dürer wrote books – often more lively than the stylish works of the professional scholars – in which they related the results of their personal investigations and the interpretations they gave to these.

Like the great philosophers of Antiquity (Plato, Aristotle, Cicero, Seneca), many of their humanist followers looked down upon the mechanical arts and

8 P. Ramus, 'Scipionis Somnium' (1546), in: *Petri Rami Praelectiones in Ciceronis Orationes octo consiliares*, Basileae, 1580, p. 53.

those who cultivated them, the 'mechanical' workers, engineers, chemists, metallurgists, sailors, etc. The liberal arts, which did not require manual labour, were the only ones befitting a free citizen and a philosopher.

It seems, however, that among scholars in the fifteenth century, respect for the trades was growing in some parts of Europe. Nicolaus Cusanus (the son of a fisherman) in his 'De staticis experimentis' allows a scholar to be instructed by an un-lettered man (the 'Idiota'), a mechanician who tells him how some difficult practical problems may be solved by 'mechanical' means. Luis Vives (1492–1540), when living in the Southern Netherlands, advised students to follow the example of the fifteenth-century Louvain scholar Carolus Virulus, who sought contact with the fathers of his students in order to learn from them about their trades of cobbler, skipper, etc. He deplored that there was no 'history of the arts', the writing of which would be 'an occupation worthy of a burgher'. Although himself an accomplished humanist, Vives shows the burgher influence of his Flemish dwelling-place. He recognized that peasants and craftsmen were often closer to reality than his fellow-scholars, and that they knew nature better than those 'great philosophers' who, in place of real things (about which they were ignorant) imagined another nature, consisting of 'Forms, Ideas, and other chimerae'. In the wake of Vives, Peter Ramus (1515–1572) sought contact with artisans (instrument-makers, painters, etc.) and frequented their workshops in search of information about applications of mathematics.

Many sixteenth-century scholars were at the same time artisans (printers, engravers, instrument-makers). The cartographer Gerard Mercator engraved maps with his own hands; the Nuremberg clergyman Georg Hartmann (1489–1564) was not only an able mathematician and an experimenter on magnetism but also a good mechanician who made astrolabes, globes and sundials.

Mechanicism

The engineers of Antiquity (e.g. Hero of Alexandria) often used 'mechanistic', non-teleological, explanations of the phenomena they evoked artificially, and of 'natural' phenomena as well. The Renaissance period saw a slow penetration of their procedures and ideas into more philosophical and scholarly works, as a consequence of a closer contact between the two groups. 'Mechanical experiments and mechanistic interpretations (even of natural phenomena) became more common. Mechanicians always showed a tendency to make models of natural things and events (globes, planetaria, models of volcanoes). The thirteenth-century author of a book on the magnet, Petrus Peregrinus (1269), who in his experiments was 'ahead of his time', conceived of the outer heaven as a huge magnet, and speculated that an artificial spherical magnet that imitated the heavenly globe would by a sympathetic influence also turn round.

The social changes of the fifteenth and sixteenth centuries went together with a philosophical change: mechanical methods and models inevitably led to mechanistic explanations of phenomena. The organistic world view (which sought to understand all things by analogy with living beings) was penetrated and eventually replaced by a mechanistic world view, which tended to consider even living beings, as far as possible, as analogous to mechanisms. In general, this penetration had nothing abrupt and revolutionary about it. D. João de Castro (1538) applied 'modern' methods in his experiments on earth magnetism, but as he considered his measurements to belong to 'the lowest and most forgotten part of mathematics', this had no influence on his general world view, which was that of an old-fashioned Aristotelian, free of nominalistic taints.

In the early seventeenth century, the physician Angelo Sala (1617) synthesized copper vitriol. He interpreted his artificial product as a mechanical structure, an 'apposition of particles' of the ingredients he had used. This led him to the idea that *natural* vitriol, having the same properties as the artificial product, must also be 'an apposition of particles'. But sea-salt, which he could not synthesize, he considered as a 'unity', perfectly homogeneous, existing under its own specific Form. In the case of this chemist, then, the old philosophy was abandoned only in so far as the *facts* compelled him to do so.[9]

Such mechanistic explanations inevitably undermined the old, organistic, world view. If parts of nature are like mechanisms, it must be possible to *fabricate* them; if they were like organisms – which are propagated only by *generation* – they would be inimitable. So Sala thinks of vitriol in mechanistic terms, as something that can be fabricated, whereas sea-salt he holds to be generated by nature alone. For those natural events which can be artificially reproduced, knowledge of their 'nature' could now be obtained by experiment. We can speak here of an '*experimental philosophy*'.

From the end of the fifteenth century' (da Vinci) to the beginning of the seventeenth (Sala, Sennert, Basso), the motions, arrangements, sizes and shapes of invisible particles played an increasing role in scientific interpretations. About 1600 there was an outburst of these 'corpuscularian' theories, which ended in the comprehensive mechanistic systems of Gassendi, Descartes and others, systems from which the Forms and Ideas that so much annoyed Luís Vives had completely disappeared. It should be stressed, however, that the

9 Cf. (a) R. Hooykaas, *Het Begrip Element in zijn historisch-wijsgeerige ontwikkeling*, thesis: Utrecht, 1933, pp. 148–154; (b) 'The discrimination between natural and artificial substances and the development of corpuscular theory', *Arch. Intern. Hist. Sci.* (1948), 4, pp. 840–858; (c) 'The experimental origin of chemical atomic and molecular theory before Boyle', *Chymia* (1949), 2, pp. 65–80 (reprinted in: *Selected Studies*, op. cit. (1), pp. 285–308).

heuristic value of these corpuscular theories was not great. They 'explained' a posteriori, but they hardly predicted any phenomena. Nevertheless, they gave great support to the mechanistic picture and thus inspired confidence in 'mechanical' (experimental) research.

The work of mechanicians who co-operated with scholars (or were scholars themselves) led to the rise of what was called experimental philosophy (emphasizing the *method* used) or mechanical philosophy (referring to the scientific *models* used), and also to the development of a 'history of the arts' as part of the 'history of nature'. Empiricism (acceptance of facts), experimentalism (eliciting secrets from nature by mechanical means), and mechanicism (interpretation by means of models and images borrowed from mechanics rather than from living beings) all went together in the early seventeenth century. Only certain parts of the new mechanistic world picture, however, could be mathematized.

It is precisely on these mathematizable parts – the measurable, macroscopic phenomena of falling bodies, projected bodies and rotating bodies – that many historians concentrate their attention when considering what Anneliese Maier (1938) termed 'the mechanization of the world picture', which took place in the seventeenth century from Galileo to Newton. They consider this the most weighty factor in the rise of modern science.

Much can be said for this opinion, although there is the risk that the scientific 'revolution' is identified with the rise of modern mechanics, this discipline having become the heart of physics. The mathematization of kinematic and dynamic phenomena, which had been unsuccessful in the hands of the late medieval 'calculatores' (Suisseth) and protagonists of the 'latitude of forms' (Oresme), now at long last was linked with quantitative experiments. There is a clear progression from the speculations of these medieval scholars, via the sixteenth-century Italian engineers (Tartaglia, Benedetti) and Galileo, and then Descartes, Borelli and Huygens, finding its fulfilment with Newton. In this sequence a great step forward was made by Galileo at the beginning of the seventeenth century.

Merged in this sequence is the development of seventeenth-century astronomy under Kepler, Galileo and Huygens and, finally, Newton, who fitted the Copernican model of the universe definitively into a mechanistic system of nature. In his 'Principia' (1687), the synthesis of astronomy and physics, the mathematization that united terrestrial and celestial mechanics, was finally accomplished.

This story has the advantage of presenting a clearly continuous development and it rightly implies that the really 'modern' phase of physics started with the mathematical-descriptive work of Galileo and Kepler, and the outburst of explanatory corpuscular theories at the beginning of the seventeenth century. However, most people who accept the pattern depicted above, and hold that the 'scientific revolution' in mechanics took place about

1600, nevertheless see its astronomical root – and the real beginning of the revolution – in the publication of Copernicus' main work in 1543 – i.e. in an age of chaotic competition between various world views (Aristotelianism, Platonism, Pythagorism, Hermeticism). By the beginning of the seventeenth century, on the other hand, a certain unity had begun to emerge: both the mechanistic conception and the heliocentric theory were on their way to victory.

Copernicus was no adherent of a mechanistic world view, and his way of thinking was that of the Ancients rather than of the Moderns; yet he is inserted in the series of modern astronomers, because it was *his* model of the universe that formed the basis of the work of the great innovators, Kepler and Galileo. Understandably, this 'insertion' of Copernicus into the series has led to the widespread belief we have noted, that he was a 'revolutionary' who overturned the ancient dogmas and inaugurated 'modern science'.

Copernicus

Should Copernicus thus be regarded as the initiator of modern science, the first in the series of heroes of the scientific revolution: Copernicus – (Tycho) – Kepler – Galileo – Huygens – Newton? In order to answer this question it seems useful to consider first the 'novelty' of his work and its scientific character, and secondly its influence and evaluation during the sixteenth century and the evaluation by modern scholars.

Copernicus' dissatisfaction with the Ptolemaic system was hardly caused by its factual errors: large parts of Copernicus' data were borrowed from his ancient and medieval predecessors and he did not claim that his own measurements were more exact than theirs. But Ptolemy had introduced the equant (i.e., movements uniform with respect to a point away from the centre of the circular path). This was a deviation from the 'Platonic' rule that in astronomy the motions of the planets have to be reduced to combinations of perfectly *uniform* circular motions. To Copernicus, this violation of uniformity was the first reason why he became dissatisfied with the current system. The second was its lack of harmony: for each planet there had been introduced a specific set of circular motions, which had no interconnection with those of the other planets.

Now Copernicus, as a typical humanist, began perusing the works of the Ancients in order to see whether better solutions had been given in the past. He found then the daily motion of the earth mentioned by some Pythagoreans, whereas he seems to have believed that they also accepted the annual revolution of the earth round the sun (which at any rate he had found expounded by Aristarchus of Samos). He was thus able to appeal to the most ancient sources, and his contemporaries recognized this by dubbing his world system ‘Pythagorean’.

As to the daily rotation of the earth, Copernicus knew quite well that ‘mathematically’ speaking it made no difference whether the heavens turn round in twenty-four hours or whether the earth does so. But physically it made a great difference, and as he claimed that his system was conformable to physical reality he had to offer a *physical* alternative to the Aristotelian arguments for the immobility of the earth. It was no new problem, for it had been a frequent topic in scholastic discussions. Most of Aristotle’s and Ptolemy’s arguments had already been answered in the fourteenth century by Nicole Oresme, but this philosopher finally rejected the earth’s motion. The idea of the earth’s rotation had the great disadvantage that it broke the unity of the scholastic philosophy of nature by maintaining that the natural motion of the four elements was not rectilinear but *circular*, and that falling heavy bodies moved towards the earth not because they wanted to approach the centre of the universe (as the Aristotelians held), but because a separated piece of ‘earth’ wanted to be united with the planetary globe to which it belonged. (In the same way, according to Copernicus, a piece of lunar matter would try to unite itself with the Moon.[10])

Copernicus’ greatest achievement was his introduction to the annual motion of the earth. The apparently retrogressive motions of the planets could be attributed to this. Instead of a specific set of two circles (deferent and epicycle) for each planet, now one of these two was recognized to be the same for all planets: a projection of the earth’s orbit. In this orbit Copernicus now found the ‘common measure’ of all other planetary motions (1514). Thus, a ‘certain bond’ of harmony in the universe, which he had so sorely missed in the ‘vulgar’ system, had been found. It should be mentioned, however, that some decades later Tycho Brahé (1588) reached the same result in his geo-heliocentric system, although without abandoning the immobility and central position of the earth.

Having expounded his cosmological system and physical tenets in the first Book of ‘*De Revolutionibus*’ (1543), Copernicus dealt with the astronomical calculations in the Books II–VI. Although he had explained the ‘second inequality’ of the planetary motions, he still had to account for the ‘first inequality’, while discarding the equants. In order to reach this aim he had again to resort to the traditional device of combining circular motions. The greater simplicity of his system suggested by the famous diagram in the first Book could not be maintained in the other five.

The equant had not been the only fly in the ointment of the current astronomy: several minor irregularities had crept into the system during the Middle

10 Cf. R. Hooykaas, *Science in Manueline Style*, op. cit. (1), pp. 50–61.

Ages. It was found, for instance, that the slow uniform motion of the equinoctial points along the ecliptic ('praecession') was subject to superimposed oscillatory movements ('trepidation') which, apart from disturbing the uniformity of the progression, were not circular. Copernicus now managed to reduce these motions (as well as some other irregularities in astronomy) to a combination of two uniform circular motions.

If we consider Copernicus' work from the standpoint of most sixteenth-century scholars, we would assume an amused or sceptical or even hostile attitude towards the contents of the first of the six books '*On the Revolution of the Heavenly Orbs*', whereas we would praise the other five as an outstanding contribution to one of the important liberal arts. These books were highly appreciated as a 'mathematical' account of the heavenly motions, while strictly keeping to the ancient fundamental rule of astronomical art, viz. that only perfectly uniform and circular motions should be admitted. When Copernicus managed to eliminate the equants from his computations, he was regarded by most sixteenth-century astronomers as a *restorer* of the ancient purity of astronomy: the greatest astronomer since Ptolemy. The mobility of the earth they could regard as a 'mathematical' hypothesis which need not claim to be conformable to nature but only helpful as a practical device. It is true that not long afterwards the trepidation turned out to be a spurious phenomenon; nevertheless, at that time it belonged to the generally accepted 'facts' of nature. To bring it within the 'Platonic' framework was therefore considered a great scientific achievement.

If we were to take the standpoint of 'modern' science, however, our attitude would be quite the reverse: we would ignore Books II–VI as obsolete, and concentrate our attention on the first book, of which, to us, the most salient features are the introduction of the heliocentric system of the universe and the daily and annual motions of the earth. This interest of the modern scientist in Book I is thus very selective; it pays little attention to the *physical* explanations Copernicus put forward as an alternative to Aristotelian physics that lay behind the geocentric astronomy. To modern science the more or less pythagorico-platonic arguments then adduced by Copernicus are as obsolete as the Aristotelian and Ptolemaic views they replaced.

The first book, moreover, attracts attention from historians of all kinds because of the controversies it created after the Galileo trials; the conflict with the literalistic interpretation of some biblical texts then caused a great stir, of which even outsiders are aware up to the present day. It should be realized, however, that Copernicus' astronomy was not based on better observations than the Ptolemaic. Moreover, his physics was not more modern; it merely advanced more or less Platonic ideas over and above prevailing Aristotelian tenets. It set arguments against other arguments, but no decisive fact could be adduced in support. Whereas (before Copernicus) the seafarers had convinced everybody by *observations* proving that Ptolemy's *geography* was wrong in many respects, Copernicus could not adduce similar proofs that the physical basis of Ptolemy's *astronomy* was also wrong. Copernicus' advocacy was just a great achievement in the *art* of astronomy; it did not add new data to the 'history of nature'.

In consequence, the publication of Copernicus' theses caused far less stir than did the appearance of a new star in Cassiopeia in 1572. Thanks to Tycho Brahé's demonstration, the astronomers were compelled to recognize that it belonged not to the 'changeable' sublunar region, but to the allegedly unalterable sphere of the fixed stars which now turned out to be liable to change. This discovery was indeed a severe blow to ancient Aristotelian physics: it overthrew one of the central dogmas – the immutability of the heavenly regions. Controversy over the location of the *nova* led to a vast number of publications *pro et contra* – a number considerably greater than that caused by the appearance of Copernicus' book in 1543. What was now at stake was a controversy not between adherents of rival theoretical systems, but between a 'system' and a 'hard fact' – and *facts* counted heavily in the sixteenth century.

By 1600 there was still no observational proof for the Copernican system. In 1609, however, Galileo, with the help of his new telescope, discovered first the satellites of Jupiter and soon afterwards, the phases of Venus. The Jupiter satellites demonstrated that a planet could have moons, and thus made it plausible that the Earth, having a moon, was also a planet. Within the geocentric framework it was thought impossible that Venus would go through all the phases, whereas in Copernicus' system this must be the case. It should be pointed out, however, that this fact also fitted into Tycho's system. It was these observed *facts* that helped to turn Galileo from a lukewarm adherent of the Copernican system into its zealous apologist.[11]

11 With Galileo the relation between reason and observation was rather ambiguous. He was no empiricist in the Baconian sense – perhaps even less so than Kepler (he never abandoned the circularity of the celestial motions). He seems to have put greater trust in the reliability of human reason than in that of the human senses. He praised Aristarchus and Copernicus for having maintained that Venus revolves around the sun, although its apparent size seemed to remain the same: with them, according to Galileo, reason so much overpowered the senses that they made it 'the mistress of what they believed' and made the choice that has turned out to be the right one, as is now shown by the telescopic observations of the changing size and the phases of that planet. 'Nor can I sufficiently admire the eminence of these mens' wits that . . . have been able to prefer that which their reason dictated to them, to that which sensible experiments represented most manifestly on the contrary' (*Dialogue* III). Nevertheless, he was immensely proud of 'the perfection of our sight' by the invention of the telescope, for he, too, finally recognized that Experience is 'the true Mistress of Astronomy' (ibid.)

In many cases, better methods of observation confirmed his trust in Reason, but in his account of ebb and flood [1616; *Dialogue* IV (1633)] it led him astray. He selected experimental data that seemed to favour his mechanistic theory of the tides, according to which the basic phenomenon recurred in periods of twelve (instead of six hours). He ignored the generally known relation

Tycho Brahé's very precise observations of planetary motions were the basis of Kepler's '*Astronomia Nova sive Physica Coelestis*' (1609), a book that indeed inaugurated a new epoch in astronomical science. It was a mere difference of eight minutes which, in Kepler's own words, 'paved the way for the reformation of the whole astronomy'. Kepler now discarded all 'hypotheses' of excentres and epicycles from astronomy by introducing elliptic orbits. This, too, was an 'absurdity' – to Copernicans and Aristotelians alike – but the abolition of the epicycles was such a simplification that, in spite of the 'laws' of uniformity and circularity, ellipticity of orbits was gradually accepted as a physical fact. Kepler also made a first attempt at a mechanical explanation of the planetary motions (although he always wavered between the organistic and the mechanistic conceptions of the universe).

'Modern' astronomy, therefore, really began with Kepler who, though vainly searching for a satisfactory synthesis of physics and astronomy, nevertheless managed (on the basis of Tycho's exact measurements) to enunciate his three famous laws, which Newton later inserted into his system of cosmic physics. Taking together Kepler's astronomical discoveries and Galileo's telescopic observations, with their strong convincing power for many contemporaries, we may conclude that these two great scientists did indeed originate a new astronomy, based on new facts – an astronomy henceforth tending to go with a new mechanistic philosophy.

Historians of science who apply the evolutionistic method will tend to select the motions of the earth and the quasi-heliocentric structure of our planetary system as the features of the Copernican system that really matter. Still part and parcel of science, these enable us to trace a genealogical line from the initiator Copernicus to Newton, showing no deviation from the right path of progress. It is understandable that they then have some difficulty in evaluating Tycho, who gets good marks only for the reliability of his measurements, while his system is criticized as a regrettable step backwards. Although these historians may deplore or ignore the 'remnants' of Pythagorean and Aristotelian philosophies still extant in the works of Copernicus and some of his disciples, they easily pass them over as irrelevant to the progress of science.

If, on the other hand, a more phenomenological standpoint is taken, the re-enactment in our imagination will make us share the admiration of Copernicus' contemporaries for his restoring the self-consistency of the astronomical theory (eliminating equants and explaining trepidation) and we will see him as a representative of those humanists who sought the progress of science by a restoration of forgotten truths rather than by a revolution –

between the moon and the tides. According to his erroneous theory, ebb and flood could not occur if the earth were immovable. Consequently, he considered his theory of the tides one of the three main proofs of the Copernican system (the other two being the revolution of the sun around its axis and the retrogradations of the planets).

and also as a representative of that current of thought among Renaissance scholars which showed a predilection for Pythagorean and Platonic ideas.

With hindsight, we know that Copernicus' system did indeed provide the basis for Kepler and Galileo, but we should not forget that he himself was on the other side of the great watershed: his physics was organistic and not mechanistic. The great discoveries that undermined the Aristotelian philosophy of nature we owe not to him but to Tycho, and Galileo, whose telescopic observations greatly favoured the cause of heliocentric astronomy.

Francis Bacon and the New Philosophy

We have now to consider what the generations that came after the rise of sixteenth-century empiricism, who had witnessed the triumph of mechanistic philosophy, had to say about our problem.

The new philosophy advanced by the engineers, navigators and physicians, as well as by some philosophers, had sometimes been quite emphatically proclaimed; but more often it had been dispersed throughout their works in stray remarks and descriptions of experiments. It was finally put together in an eloquently worded programme by Francis Bacon (1561–1626). He contrasted the science of the future with that of past ages, and he did so in a quasi-biblical language that easily stuck in the minds of his contemporaries. Bacon was not very generous in mentioning the names of the sixteenth-century innovators he followed; but he formulated more elegantly and more systematically the ideas they had almost unwittingly and naively advanced, in a 'rude' style. Consequently, in the seventeenth century the names of his less sophisticated sixteenth-century predecessors remained in the shadow, and Bacon became the great prophet of the new natural history and the new experimental science.

Some of the great mathematico-physical scientists of the seventeenth century, who had themselves a considerable share in the mechanization of the world picture, praised Bacon highly.[12] Robert Boyle (1627–1691) was a thoroughgoing Baconian in his general approach; he called Bacon 'the great architect of experimental History'. Robert Hooke (1635–1703) larded his works with Baconian phrases, and although an outstanding mathematizing physicist, he agreed with Bacon that the 'history of nature and the arts' is the basis of science. Even Christiaan Huygens (1629–1695), the greatest of the mathematical physicists between Galileo and Newton, deemed Bacon the founder of a better 'philosophy', namely that which starts by experiments. Huygens and Leibniz agreed that experiments should be discussed methodi-

12 Cf. R. Hooykaas, 'De Baconiaanse Traditie in de Natuurwetenschap', *Algemeen Ned. Tijdschr. v. Wijsbegeerte* (1961), 53, pp. 181–201.

cally according to Bacon's plan, although both deplored his lack of mathematical knowledge.

The founders of the Royal Society (Boyle, Wallis, etc.) and of the Académie des Sciences started under the Baconian banner. Huygens, reporting at Colbert's request on the plan for the new academy, advised that it should mainly occupy itself with a 'natural history' of observations and experiments 'according to the plan of Verulamius (i.e., Bacon of Verulam).

Newton, although mentioning neither the rationalist Descartes nor the (rational-)empiricist Bacon, in his *'Principia'* (1687) took the side of the latter, as became explicit in Roger Cotes's preface to the second edition. The editor of the third edition, Henry Pemberton, wrote that Bacon was the first to combat speculative science and that he founded the true method of investigation of nature. Having expatiated on Bacon's principles Pemberton went on to expound Newton's methodological principles and showed their congruity with those of Bacon.[13] In the fierce battle of the Newtonians against Cartesian rationalism, Bacon's name came up again and again as that of the founder of 'experimental philosophy'.

The seventeenth-century founders of physico-mathematical science, therefore, regarded Bacon, in spite of his non-mathematical approach, as *the* great pioneer. But what did Bacon in fact bequeath to them, and – even more important for the problem we are now dealing with – what did Bacon himself think about the origin of the new science?

Bacon stressed above all other factors the fundamental role of *experience* over against speculative preconceptions. He warned his readers not to take 'authority for truth, instead of truth for authority'.[14] Like the sixteenth-century voyagers and the theological voluntarists, he insisted that facts must be accepted, however much they might seem to be against reason. Humility of spirit, obedience to the revelation in nature, he deemed indispensable to the investigator of nature. A philosophical conversion similar to a religious conversion was needed. This analogy of Bacon's is picked up by the late Benjamin Farrington, a well-known marxist historian of science and classical scholar, who succinctly expressed it in the heading of a chapter of his book on some of Bacon's minor works: 'Out with Aristotle, in with the Bible'.[15]

'What has been touched and seen' has to be accepted in spite of all rational prejudices; this tenet of the old navigators was also Bacon's: 'The entrance into the kingdom of Man, founded on the sciences, is not very different from the entrance into the kingdom of Heaven, whereinto none may enter except as a little child'.[16]

13 H. Pemberton, *A View of Sir Isaac Newton's Philosophy*, London, 1728, pp. 5 ff.

14 F. Bacon, 'Historia naturalis et experimentalis', in: *The Works of Francis Bacon* (eds J. Spedding, R. L. Ellis and D. D. Heath), London, 1857–1874, vol. II, p. 14.

15 B. Farrington, *The Philosophy of Francis Bacon*, Liverpool, 1964, p. 21.

16 Bacon, *Novum Organum I*, aph. 68; *Works I*, p. 179.

Secondly, Bacon, who realized how the great extension of knowledge caused by the voyages of discovery had exposed the old science as incomplete and often erroneous, wanted the development of a new Natural History to be the beginning of a scientific revolution.

Thirdly, for Bacon a new natural history should lead to a new natural philosophy. According to him, those who had handled science hitherto were either 'men of experience [solely]', or 'men of dogmas'.[17] The former he compared with the ants, which only collect extrinsic materials; the latter, the 'reasoners', with spiders which make cobwebs out of their own substance. But the true business of philosophy, so Bacon argues, is to act like the bee, which gathers material from the flowers and then digests and transforms it by a power of its own. The true philosophy neither relies chief on the powers of the mind, nor does it just collect the data provided by 'natural history and mechanical experiments'.

Fourthly, Bacon set natural history and 'mechanical experiments' on the same level. For him experiments are 'nature coerced by arts'; they yield reliable information, because even in *artificial* experiments we have to follow *nature,* which 'we cannot conquer, except by obeying her'. 'Therefore, from the closet and purer league between these two faculties, the experimental and the rational . . . much may be hoped'.

Apart from the general principles of the new science, Bacon tried also to give more precise methodological rules for 'digesting' the facts of natural and experimental history. He did not expect everybody to apply his rules, and he was open-minded enough to admit that the general principles of empiricism' and the art of experimentation could also be put into practice by adherents of the old school, or of new systems other than his own: '. . . when a true and copious history of nature and the arts shall once have been collected and digested . . . those great wits I spoke of before . . . will raise much more solid structures, and that too though they may prefer to walk on the old path, and not by way of my *Organum*, which in my estimation if not the only is at least the best course . . . My *Organum*, even if it were completed, would not without Natural History much advance the Instauration of the Sciences, whereas the Natural History without the *Organum* would advance it not a little.'[18]

Bacon's seventeenth-century disciples used the liberty granted to them: they wisely ignored most of his rules of inductive philosophy (though – also wisely – they did apply some of them). Practical men are, in general, too pragmatic to let themselves be shut up in a system, all the more so if this system shows signs of the limitations of an outsider who, although he delineates a marvellous general programme, does not know the whimsical tricks of nature from his own experience.

17 Bacon, *Nov. Org. I,* aph. 95; *Works I,* p. 201.
18 Bacon, *Historia Nat. et Exp.: Works II,* p. 15.

Bacon was at his best when contrasting the 'new' philosophy' with the old. Natural philosophy, said he, had been tainted either by logic (Aristotle) or by natural theology (Plato), or by mathematics (Proclus). Mathematics, in Bacon's opinion, should serve only to give definitions to natural philosophy, not to generate it.[19] This means that mathematics is useful for precise determination and measurement (i.e., for scientific 'description'), but that it ought not to be the basis of science. Evidently he was here rejecting the then widespread meta-mathematical, neopythagorean speculations about the ontological value of numbers and figures.

Bacon on the Voyages of Discovery

Bacon was firmly convinced that the voyages of discovery had coincided with the beginnings of the new natural history, and that the latter inevitably had to be followed by a new philosophy (i.e., science): '. . . by the distant voyages and travels which have become frequent in our times, many things have been laid open and discovered which may let in new light upon philosophy. And surely it would be disgraceful if, while the regions of the material globe – that is, of the earth, of the sea, and of the stars – have been in our time laid widely open and revealed, the intellectual globe should remain shut up within the narrow limits of old discoveries'.[20]

The opening up of the geographical globe by the voyages of discovery clearly caused the opening up of the intellectual globe, the new science and the new technological achievements: 'And this proficience in navigation and discovery may plant also great expectations of the further proficience and augmentation of the sciences; especially as it may seem that these two are ordained by God to be coevals, that is to meet in one age. For so the prophet Daniel [Dan. XII, 41], in speaking of the latter times, foretells: 'That many shall go to and fro on the earth, and knowledge shall be increased", as if the opening and thorough passage of the world, and the increase of knowledge, were appointed to be in the same age; as we see it is already performed in great part'.[21]

Bacon's *religious* interpretation of the coincidence of the two events, as divinely pre-ordained, goes together with a *natural* explanation: there is a causal relation between the voyages and the ensuing astounding increase of knowledge of the 'history of nature and the arts', and the rise of new philosophy; the voyages are 'the causes and beginnings of great events'.

19 Bacon, *Nov. Org. I*, aph. 96; *Works I*, p. 201.

20 Bacon, *Nov. Org. I*, aph. 84; *Works I*, p. 191.

21 Bacon, *De Augmentis*, lib, II, c. 10; *Works I*, p. 514. Also: *Nov. Org. I*, aph. 93; *Works I*, p. 200.

Bacon clearly recognized, of course, that the voyages of discovery could not all of a sudden bring forth a new scientific system. But this process, he claims, has already begun though it seems hardly perceptible, and it will go on: ‘This beginning was from God, the Father of Lights . . . Now in divine operations even the smallest beginnings lead of a certainty to their end. And as it was said of spiritual things, “The kingdom of God cometh not with observation”, so it is in all the greater works of Divine Providence; everything glides so smoothly and noiselessly, and the work is fairly going on before men are aware that it has begun’.[22] It could hardly have been stated more clearly: the voyages of discovery (which drew everybody’s attention!) were giving rise to a new science, initially almost imperceptible (or at any rate not yet perceptible by the multitude).

In Bacon’s view – which we think was correct – the rise of the new science was not marked by a spectacular singular event. With him there are no stories like that of a stone dropped from Pisa’s leaning tower, or an apple falling from a tree, or Haüy’s calcspar crystal slipping from a visitor’s hand. He does not offer material for hero-worshippers and hagiographers. On the contrary, he sees the rise of the new science as a general and gradual change of the intellectual climate, a change of method; and secondly, a change of world picture not restricted to one particular science (e.g., as astronomy), but affecting all scientific disciplines.

Conclusions

The rise of modern science had two major causes: firstly, the new natural history and the methodological epistemological changes connected with it; and secondly, the transition from an organistic to a mechanistic view of the world, a change closely connected with experimental philosophy and the contribution made to it by engineers, physicians, alchemists, cartographers, pilots and instrumentmakers.

Without any doubt, the view of nature held by modern science is mechanistic, so that ‘mechanization’ is one of the characteristic features of its rise. The term should, however, be taken in a wider sense than that of the mathematical formulation of the laws of statics, kinematics and dynamics. It also implies the use of mechanical (non-natural; artificial) instruments for the investigation of nature, the effacing of any radical distinction between the natural and the artificial, and the introduction of mechanical models of natural things.

22 Bacon, *Nov. Org. I*, aph. 95; *Works I*, p. 200.

Moreover, the new science is something cultivated by 'mechanicians' – mechanicians of the learned, liberal professions (physicians) as well as mechanicians in the proper sense of cultivators of illiberal arts (engineers, artisans, navigators). 'Mechanization' refers not only to a theory but also to a method; in a wider sense it embraces the contents (the substance) of science (nature as a mechanism, mechanistic philosophy) as well as its method (experimental philosophy). But perhaps the epistemological aspect of the new science is even more general. In natural sciences there were always rather reliable relations between Reason and Experience. Both of them have always been recognized as indispensable for the sound advancement of science, which has to steer through the narrow thoroughfare of rational empiricism, avoiding the rocks of both rationalism and naive empiricism.[23] Now Science, as a description and systematization of the facts given in nature, is a product of Reason: not of a sovereign, 'free' Reason, but of a Reason bound to 'data' and 'facta'. In physics, says Pascal, 'experience has a greater convincing power than reason': for we have to deal with nature, which remains just the same, regardless of the opinions we foster about her. In Science, therefore, the facts are the basis and touchstone of the theories. The great change (not only in astronomy or physics, but in *all* scientific disciplines) occurred when, not incidentally but in principle and in practice, the scientists definitively recognized the priority of Experience. The change of attitude caused by the voyages of discovery is a landmark affecting not only geography and cartography, but the whole of 'natural history'. It led to a reform of all scientific disciplines – (not only of the mathermatical – physical) – because it influenced the *method* of all the sciences, however much their mathematization might be delayed (as was the case, for example, with chemistry).

In discussing the rise of modern science, our educational past often influences our choice when deciding whether to lay emphasis upon the 'mechanization' or upon the new 'natural history'. Cultivators of the so-called 'exact' sciences will tend to concentrate attention on the rise of the new mechanics, together with the new astronomy. For them, therefore, the scientific 'revolution' begins with Galilean mechanics and ends with Newton's synthesis between the new astronomy and the new mechanics.[24] Copernicus' position

23 See fn. 11, on Galileo.

24 The late Professor E. J. Dijksterhuis (*De Mechanisering van het Wereldbeeld*, Amsterdam, 1950, pp. 319–332) allowed the period of the building up of the modern mechanistic world picture to run sharply from 1543 (Copernicus) to 1687 (Newton) (op. cit., p. 317). Further on, however, he said of Copernicus's work that 'apart from the use of the trigonometrical modes of computation, there is nothing in it that could not have been written in the 2nd century A.D. by a successor of Ptolemy' (op. cit., p. 319). Dijksterhuis's outline of Copernicus's theory is not essentially different from that we have given now. Moreover, he was an outspoken advocate of what he termed the 'phenomenological method' in historiography of science (cf. His *Doel en Methode* mentioned in fn. 2).

in the series of creators of classical – modern sciences then becomes ambiguous. With necessary reservations, one can draw some analogy between the relation of Kepler and Galileo to Copernicus and that of Lenin to Marx: both Copernicus and Marx put forward some fundamental ideas whose practical application did not come until six decades later.

Our choice of starting point may perhaps be determined even more by the historiographical method we apply, in particular when deciding whether we prefer to stress the importance of the geographical revolution or that of Copernicus in astronomy.[25] In the former case we will obviously emphasize the new natural history (geographical discoveries; revival of descriptive botany; observation of a new star and eventually Galileo's telescopic discoveries). Both parties, however, have to agree that it was not until 1600 that the sudden outburst of mechanistic philosophy and the astronomical reforms by Kepler and Galileo inaugurated the new astronomy and the new mechanics.

The considerable time lag between the earliest Portuguese oceanic voyages and the work of the early modern seventeenth-century scientists was an incubation period, in which the 'new philosophy' had already arisen, albeit almost noiselessly. In 1600, Gilbert published the results of research on magnetism performed in the past century (his own experiments included) under the title *Physiologia Nova*; and Kepler (1609) called his main work *Astronomia Nova*. Long before them, however (1513), a series of '*Tabulae Modernae*', based on the recent voyages of discovery, was added to Ptolemy's *Geographia* by its editor Waldseemuller. The 'geographical revolution' had preceded them by a whole century.

Henry the Navigator, who organized the first great voyages of discovery, was no scientist, and he had no scientific aims. But it was his initiative that

He, too, was of the opinion that modern astronomy really began with Kepler's *New Astronomy*: 'here we are confronted with one of the most important events in the history of thinking, perhaps even the real turning-point of the innovation that forms the theme of this book' (op. cit., p. 338). It hardly needs mentioning that Dijksterhuis found neither new important facts nor traces of a mechanistic world picture in the works of the astronomer, whom he nevertheless highly admired. (The title of Professor H. F. Cohen's recent inaugural address at the Technical University of Twente, *On the Character and Causes of the 17th Century Scientific Revolution* (Amsterdam, 1983), implies that in his opinion the 'revolution' did not start with Copernicus. His lecture develops a plan for a thorough investigation of the present topic.)

25 In particular, historians of science who have been educated as mathematicians, astronomers or physicists will have an open eye to the fact that physical (or mechanical) processes form the basis of all change in nature, and thus physics (or mechanics) is the most fundamental discipline. But not all sciences of nature have as yet been mathematized (or 'mechanicized'), although, nevertheless, they may claim to be 'scientific': empirical knowledge and classification are also 'science'. Many scientific discoveries, e.g., in chemistry, have been made without mathematization or mechanization (see: *Het Begrip Element – The Concept of Element*, pp. 145–159); this is even more so in botany and zoology. On the other hand, *all* sciences of nature are based on 'natural history': we start from facts and we end with facts which we classify, either in a mathematical or in a non-mathematical way.

triggered off[26] a movement which, growing into the avalanche of upheaval in sixteenth-century geography, opened the way for the reform, sooner or later, of all other scientific disciplines.

26 Aristotle made a distinction between the cause of a 'motion' (the transition from potentiality to actuality) and the incidental so-called 'cause' which is nothing but the removal of an obstacle hindering the true cause of nature ('. . . if anyone removes the obstacle he may be said in one sense – but in another not – to cause the movement; e.g. if he removes a column from beneath the weight it was supporting . . . for he accidentally determines the moment at which the potential motion becomes actual'. *Physica VIII*, 4; 255b, 20 ff).

The physicist Robert Mayer, in an article 'Ueber Auslösung' (1876), spoke of 'loosening' (untying) or 'releasing' causes, in which there is no proportionality between cause and effect: a very small 'Anstoss' will, in general, have a much greater effect, e.g. when a light pressure of the finger 'causes' the enormous effect of a gun. He distinguished such release-causes from those about which he posited the thesis that 'the cause is equal to the effect', which he applied in his law of conservation of energy (R. Mayer, *Die Mechanik der Wärme* (ed. J. J. Weyrauch), Stuttgart, 1893, pp. 400–447). Such 'amplifying' processes are of course the basis of modern information technology.