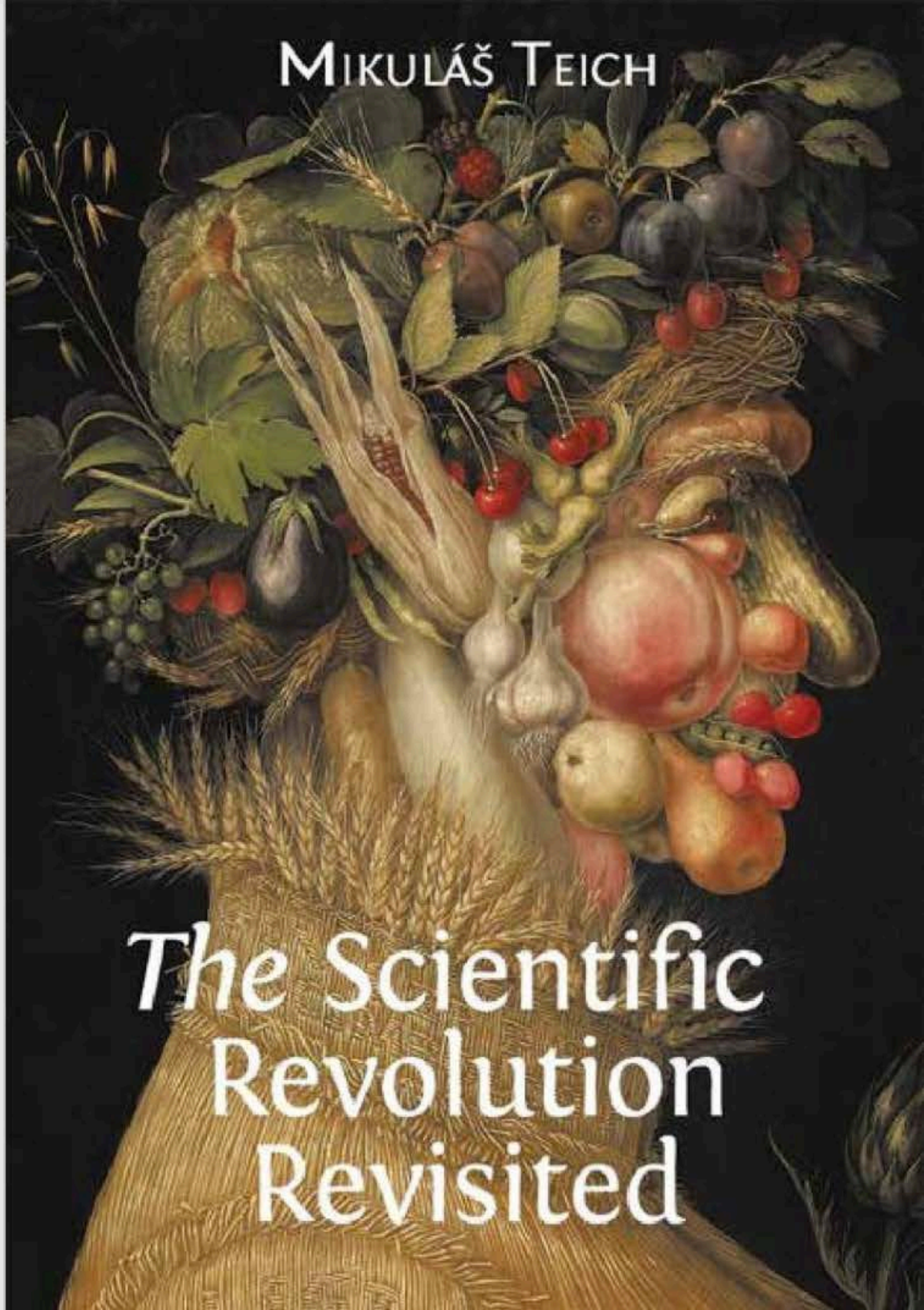

Mikuláš Teich

The Scientific Revolution Revisited

Introduction

I

This book is about interpreting the Scientific Revolution as a distinctive movement directed towards the exploration of the world of nature and coming into its own in Europe by the end of the seventeenth century. The famed English historian Lord Acton (1834-1902) is said to have advised that problems were more important than periods. If he held this opinion, he ignored that problems are embedded in time and place and do not arise autonomously. The inseparability of problem and period has been amply demonstrated in six collections of essays, examining the 'national context' not only of the Scientific Revolution but also of other great movements of thought and action, which Roy Porter and I initiated and co-edited.[1]

In general terms, one way of encompassing the world we live in is to say that it is made up of society and nature with human beings belonging to both.[2] It is reasonable to connect the beginnings of human cognition of inanimate and animate nature (stones, animals, plants) with the ability to systematically make tools/arms within a framework of a hunting-and-gathering way of life, presently traceable to about 2.5 million years ago. It is also reasonable to perceive in the intentional Neanderthal burial, about 100,000 years ago, the

1 Published by Cambridge University Press, the volumes formed part of a sequence of twelve collections of essays which included *The Enlightenment in National Context* (1981), *Revolution in History* (1986), *Romanticism in National Context* (1988), *The Renaissance in National Context* (1992), *The Scientific Revolution in National Context* (1992), *The Reformation in National Context* (with Bob Scribner, 1994), and *The Industrial Revolution in National Context: Europe and the USA* (1996).

2 What follows, draws on the 'Introduction', in M. Teich, R. Porter and B. Gustafsson (eds.), *Nature and Society in Historical Context* (Cambridge: Cambridge University Press, 1997).

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earliest known expression of overlapping social and individual awareness of a natural phenomenon: death.

While the theme of the interaction between the social, human and natural has a long history, there is scant debate over the links between perceptions of nature and perceptions of society from antiquity to the present. This is crucial, however, not only for understanding the evolution of our knowledge of nature as well as our knowledge of society, but also for gauging the type of truth produced in the process. An inquiry into the relationship between science and society takes us to the heart of the issue highlighted by the late Ernest Gellner, noted social anthropologist and philosopher, when he stated that 'The basic characteristics of our age can be defined simply: effective knowledge of nature does exist, but there is *no* effective knowledge of man and society'.[3]

This assertion, indeed Gellner's essay as a whole, gives the impression of a despondent social scientist's *cri de coeur*, made before he sadly passed away with the text yet to be published. By then, Gellner had undeniably come to believe that social knowledge compared badly with natural knowledge. He particularly reproved Marxism because it

> claimed to possess knowledge of society, continuous with knowledge of nature, and of both kinds – both explanatory and moral-prescriptive. In fact, as in the old religious style, the path to salvation was a corollary of the revelation of the nature of things. Marxism satisfied the craving of Russia's Westernizers for science and that of the Russian populist mystics for righteousness, by promising the latter in terms of, and as fruit of, the former.[4]

It is noteworthy that this critique contrasts with Gellner's position five years before the demise of communism in Central and Eastern Europe, a development which he clearly had not envisaged:

> I am inclined to consider the reports of the death of Marxist faith to be somewhat exaggerated, at least as far as the Soviet Union is concerned. Whether or not people positively believe in the Marxist scheme, no coherent, well-articulated rival pattern has emerged, West or East, and as people must need to think against some kind of grid, even (or perhaps especially) those who do not accept the Marxist theory of history tend to lean upon its ideas when they wish to say what they do positively believe.[5]

3 E. Gellner, 'Knowledge of Nature and Society', cited in ibid., p. 9.
4 Ibid., p. 13.
5 E. Gellner, 'Along the Historical Highway', *The Times Literary Supplement*, 16 March 1984.

This was in line with what John Hicks noted a year after receiving the Nobel Memorial Prize for Economics (in 1972). Venturing to develop a theory of history 'nearer to the kind of thing that was attempted by Marx', he declared:

> What remains an open question is whether it can only be done on a limited scale, for special purposes, or whether it can be done in a larger way, so that the general course of history, at least in some important aspects can be fitted into place. Most of those who take the latter view would use the Marxian categories or some modified version of them; since there is so little in the way of an alternative version that is available, it is not surprising that they should. It does, nevertheless, remain extraordinary that one hundred years after *Das Kapital*, after a century during which there has been enormous developments in social science, so little else should have emerged. Surely, it is possible that Marx was right in his vision of logical processes at work in history, but that we, with much knowledge of fact and social logic which he did not possess, and with another century of experience at our disposal, should conceive of the nature of those processes in a distinctly different way.[6]

'Learning from history' is invoked by politicians at will, but avoided by historians. They could do worse than to heed Hicks's observation regarding Marx's approach to encompassing and deciphering human social evolution. It has not lost its force when it comes to analysing the roots of the contemporary troublesome state of world affairs, fuelled by globalisation.

II

There is no point here in recapitulating what is argued in the book. But, as I have found the strongly-disputed Marxist conception of a period of transition from feudalism to capitalism a useful framework within which to locate the forging of the Scientific Revolution, it may be worthwhile to dwell on it briefly.

According to the Marxist historian Eric Hobsbawm,

> the point from which historians must start, however far from it they may end, is the fundamental and, for them, absolutely central distinction between establishable fact and fiction, between historical statements based on evidence and subject to evidence and those which are not.[7]

6 J. Hicks, *A Theory of Economic History* (repr. Oxford: Oxford University Press, 1973), pp. 2-3.
7 E. Hobsbawm, *On History* (London: Weidenfeld & Nicolson, 1997), p. viii.

But what is established fact? Take the categories 'feudalism' and 'capitalism'.[8] There are historians who find them to be of little or no use. There are others who may, curiously, employ both variants in a text: feudalism/'feudalism' and capitalism/'capitalism'. In other words, the categories have the semblance of both fact and fiction. More often than not, the assessment that feudalism and capitalism are not viable historical categories is politically and/or ideologically motivated. This of course is vehemently repudiated on the basis that true historical scholarship does not take sides.

In this connection, Penelope J. Corfield's 'new look at the shape of history, as viewed in the context of long-term-time' comes to our attention. Her interest in this question was triggered by the Marxist historians E. P. Thompson and Christopher Hill (her uncle). Though she clearly disagrees with their world-view, she hardly engages with their work. Criticising the old 'inevitable Marxist stages', she finds that gradually

> over time, historical concepts become overstretched and, as that happens, lose meaning. And 'capitalism'/'communism' as stages in history, along with 'modernity', and all their hybrid variants, have now lost their clarity as ways of shaping history. To reiterate, therefore, the processes that these words attempt to capture certainly need examination – but the analysis cannot be done well if the historical labels acquire afterlives of their own which bear decreasingly adequate reference to the phenomena under discussion.[9]

Corfield's model of making sense of the past is that '*the shape of history has three dimensions and one direction*'. The three dimensions, she argues, are 'persistence/ microchange/radical discontinuity'.[10] While her long-view approach is to be welcomed, her formula gives the impression of being too general to be of concrete value in casting light on, say, the Scientific Revolution.

III

The Scientific Revolution in National Context (1992) illustrated that no nation produced it single-handed. So in what sense was the Scientific Revolution a

8 'Once you accept that feudalism existed, and capitalism does, there's a big academic debate about what caused the collapse of feudalism and the rise of capitalism. Shakespeare managed to get to the essence of it without having knowledge of the terms'. Paul Mason (economics editor of Channel 4 News), 'What Shakespeare Taught Me about Marxism and the Modern World', *The Guardian*, 3 November, 2013.

9 P. J. Corfield, *Time and the Shape of History* (New Haven, CT and London: Yale University Press, 2007), pp. ix, 182-83.

10 Ibid., p. 248.

distinctive movement? In the sense that in Europe it had brought into being 'normal science' as *the* mode of pursuing natural knowledge – universally adopted in time and still adhered to at present. Thus 'when an Indian scientist changes places with an Italian or an Argentinian with an Austrian, no conceptual problems are posed. Nobel Prizes symbolise the unity of science to-day'.[11]

In Europe diverse social, economic, political and ideological conditions brought together the historically-evolved ways of knowing nature and produced the Scientific Revolution. These conditions included procedures, such as classification, systematisation, theorising, experimentation, quantification – apart from observation and experience, practised from the dawn of human history. Still, the social context of this transformation of the study of nature into normal science – institutionalised over time and in certain places – may be understood in terms of the passage from feudalism to capitalism. It was a long-drawn-out process of which the Renaissance, the Reformation and the Enlightenment, along with the Scientific Revolution, form 'historically demarcated sequences'.[12] By the eighteenth century, normal science had arrived in latecoming countries, such as Sweden and Bohemia.

Outside Europe the assimilation of normal science had taken place under different historical circumstances. Indeed, we may witness that it still takes place today as part of a fierce global interchange. Existing Stone Age human groups come into contact with latest scientific technology – ancestrally descended from the Scientific Revolution – and eventually they acquire the skills to use electric saws, mobiles, etc., without having passed through the historical learning process experienced by European and non-European peoples under the impact of early capitalist expansion.

The adaptation to tangible contemporary scientific-technical advances by 'primitives' testifies to lasting legacy of the fundamental transformation of the mode of pursuing natural knowledge, both theoretical and practical, between the middle of the sixteenth and the close of the seventeenth centuries. The much maligned Scientific Revolution remains a useful beast of historical burden.[13]

11 Introduction in Porter and Teich (eds.), *The Scientific Revolution in National Context*, p. 1.

12 D. S. Landes, *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present* (Cambridge: Cambridge University Press, 1969), p. 1.

13 Introduction in Porter and Teich (eds.), *Scientific Revolution*, p. 2.

1. From Pre-classical to Classical Pursuits

The theme

In the main, historians and philosophers of science have come to differentiate between the *Scientific Revolution* and *scientific revolutions*. The former term generally refers to the great movement of thought and action associated with the theoretical and practical pursuits of Nicolaus Copernicus (1473-1543), Galileo Galilei (1564-1642), Johannes Kepler (1571-1631) and Isaac Newton (1642-1727), which transformed astronomy and mechanics in the sixteenth and seventeenth centuries. First, the Earth-centred system based on Ptolemy's (c. 100-170) celestial geometry was replaced by the heliocentric system in which the Earth and the other then-known planets (Mercury, Venus, Mars, Jupiter and Saturn) revolved around the Sun. Second, laws governing the motion of celestial as well terrestrial bodies were formulated based on the theory of universal gravitation.

The origins of the interpretation of these changes in astronomy and mechanics, made between Copernicus and Newton, as revolutionary are to be found in the eighteenth century.[1] Offering an essentially intellectual

1 I. B. Cohen, 'The Eighteenth-Century Origins of the Concept of Scientific Revolution', *Journal of the History of Ideas*, 37 (1976), 257-88. See also idem, *The Revolution in Science* (Cambridge, MA: Belknap Press, 1985). But Robert Boyle (1627-1691) employed the term 'revolution' to describe the transformation in intellectual life he experienced in the middle of the century. See M. C. Jacob, 'The Truth of Newton's Science and the Truth of Science's History: Heroic Science at its Eighteenth-Century Formulation', in M. J. Osler (ed.), *Rethinking the Scientific Revolution* (Cambridge: Cambridge University Press, 2000). For an instructive account of how writers from Bacon to Voltaire discussed the origins of modern science, see A. C. Crombie, 'Historians and the Scientific Revolution', *Physis: Rivista Internazionale di Storia della Scienza*, 11 (1969), 167-80.

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treatment of it, Alexander Koyré is credited with having coined the concept of the Scientific Revolution in the 1930s.[2] Since then much has been written about the periodisation, nature and cause(s) of the Scientific Revolution.[3] Broadly, two seemingly incompatible approaches have been employed. The 'internalist' perspective, greatly indebted to Koyré, identified the Scientific Revolution as a societally-disembodied and supremely intellectual phenomenon. The alternate approach, greatly influenced by Marxist ideas, focused on social, political, economic, technical and other 'external' factors to clarify the emergence of the Scientific Revolution.

Since Copernicus's seminal *De revolutionibus orbium coelestium* was published in 1543 and Newton's no less influential synthesis *Philosophiae naturalis principia mathematica* appeared in 1687, some have been perplexed that a phase in scientific history can be called 'revolutionary' when it lasted around 150 years. Others have dwelt on the fact that the protagonists in the transformation of astronomy and mechanics – deemed to be revolutionary – did not fully divest themselves of traditional ancient and medieval approaches and ideas. This connects with the issue of how to view later scientific breakthroughs associated, say, with Antoine-Laurent Lavoisier (1743-1794),

2 A. Koyré, *Études galiléennes* (Paris: Hermann, 1939-1940), pp. 6-7.

3 For latter-day discussions of 'the state-of-the-art', see I. Hacking (ed.), *Scientific Revolutions* (Oxford: Oxford University Press, 1981); A. Rupert Hall, *The Revolution in Science, 1500-1750* (London and New York: Longman, 1983), R. Porter, 'The Scientific Revolution: A Spoke in The Wheel?', in R. Porter and M. Teich (eds.), *Revolution in History* (Cambridge: Cambridge University Press, 1986), pp. 290-316; D. C. Lindberg and R. S. Westman (eds.), *Reappraisals of the Scientific Revolution* (Cambridge: Cambridge University Press, 1990); R. Porter and M. Teich (eds.), *The Scientific Revolution in National Context* (Cambridge: Cambridge University Press, 1992); J. V. Field and Frank A. J. L. James (eds. and intr.), *Renaissance and Revolution: Humanists, Scholars, Craftsmen and Natural Philosophers in Early Modern Europe* (Cambridge: Cambridge University Press, 1993); A. Cunningham and P. Williams, 'De-centring the 'Big Picture': The Origins of Modern Science and The Modern Origins of Science', *The British Journal for the History of Science*, Vol. 26/4 (1993), 407-32; H. F. Cohen, *The Scientific Revolution: A Historiographical Inquiry* (Chicago, IL and London: University of Chicago Press, 1994); J. Henry, *The Scientific Revolution and the Origins of Modern Science* (Basingstoke: Macmillan, 1997, 3rd ed. Basingstoke: Palgrave Macmillan, 2008); S. Shapin, *The Scientific Revolution* (Chicago, IL and London: University of Chicago Press, 1998); M. Teich, 'Revolution, wissenschaftliche', in H. J. Sandkühler (ed.), *Enzyklopädie Philosophie*, Vol. 2: O-Z (Hamburg: Meiner, 1999), pp. 1394-97; M. J. Osler (ed.), *Rethinking the Scientific Revolution*; J. P. Dear, *Revolutionizing the Sciences: European Knowledge and its Ambitions, 1520-1700* (Basingstoke: Palgrave, 2001); P. J. Bowler and I. Rhys Morus, *Making Modern Science A Historical Survey* (Chicago, IL and London: University of Chicago Press, 2005), pp. 23-53. P. Fara, *Science: A Four Thousand Year History* (Oxford: Oxford University Press, 2009); David Knight's *Voyaging in Strange Seas: The Great Revolution in Science* (New Haven, CT and London: Yale University Press, 2014) appeared just before this book went to press.

Charles Darwin (1809-1882) or Albert Einstein (1879-1955). Are the novelties of Lavoisier's oxygen theory of combustion, Darwin's theory of evolution or Einstein's linking of space and time comparable in revolutionary terms with the Scientific Revolution? If they qualify as 'scientific revolutions', is the Scientific Revolution then first in time among equals?

Fig. 1 Image of heliocentric model from Nicolaus Copernicus' *De revolutionibus orbium coelestium* (c. 1543).

Kuhn's paradigms and normal science

A determined attempt to address the general question of how scientific revolutions emerge, and how they are identified, has been made by Thomas S. Kuhn in his highly influential *The Structure of Scientific Revolutions*, which first appeared in 1962 and was enlarged in 1970, containing a 'Postscript-1969'. Setting out to portray scientific development (as a succession of tradition-bound periods punctuated by non-cumulative breaks),[4] Kuhn's approach centres on the utilisation of three notions: paradigm, scientific community and normal science. He treats them as mutually connected categories.

For the reader, the grand problem is the truly protean notion of 'paradigm'. After being told that the term he had used in at least 22 different ways, Kuhn

4 T. S. Kuhn, *The Structure of Scientific Revolutions*, 2nd revised ed. (Chicago, IL: University of Chicago Press, 1970), p. 208.

admitted: 'My original text leaves no more obscure or important question'.[5] As a consequence, Kuhn preferred to equate a paradigm with 'a theory or set of theories' shared by a scientific community. The question of whether a scientific community's common research activities, designated by Kuhn as 'normal science', determine a paradigm or whether it is sharing a paradigm that defines a scientific community was answered by him as follows: 'Scientific communities can and should be isolated without prior recourse to paradigms; the latter can then be discovered by scrutinising the behaviour of a given community's members'.[6]

To put it succinctly, Kuhn conceives of scientific revolutions as transitions to new paradigms. The motor of this process is not testing, verification or falsification of a paradigm but the scientific community's gradual realisation of a current paradigm's inadequacy. That is, while engaged in normal science, the scientific community finds the paradigm's cognitive utility wanting when confronted with riddles or anomalies which it does not encompass. The response to such a crisis is the emergence of a new paradigm that brings about small as well as large revolutions whereby 'some revolutions affect only the members of a professional subspecialty, and [...] for such groups even the discovery of a new and unexpected phenomenon may be revolutionary'.[7]

The intellectual impact of Kuhn's historical scheme of scientific revolutions was wide-ranging and stimulated much debate during the late 1960s and early 1970s, but it began to wane afterwards. For one thing, on reflection, not only the notion of paradigm but also those of scientific community and normal science appeared to be vague. Take Kuhn's notion of normal science and its association with three classes of problems: determination of fact, matching of facts with theory and articulation of theory. Useful as the concept of normal science is, there is more to it than these three categories, into one of which, Kuhn maintains, 'the overwhelming majority of the problems undertaken by even the very best scientists usually fall'.[8]

Everything has a history and so does normal science. It evolved and materialised first in classical antiquity as *peri physeos historia* (inquiry concerning nature) with entwined elements of scientific methodology, such as observation, classification, systematisation and theorising. By the

5 Ibid., p. 181.
6 Ibid., p. 176.
7 Ibid., p. 49.
8 Ibid., p. 34.

seventeenth century in Europe, these practices, extended by systematic experimentation and quantification, were bringing forth generalisations in the form of God-given laws of nature. Moreover, institutionally shored up by newly-founded scientific organisations and journals, these pursuits paved the way for science to operate as a collaborative body. That is, an integral aspect of these developments was the institutionalisation of scientific activities through scientific societies (academies) and journals in Italy, Germany, England and France. Focusing attention on these historical aspects of normal science, we recognise that essentially they still shape its fabric today.

Neither the duration of the coming of normal science into its own nor the blurred line that separates the old from the new in Copernicus's or Newton's thought is the problem.[9] It is the coming into existence of a methodologically-consolidated, institutionally-sustained mode of 'inquiry concerning nature', that distinguishes the investigations into natural phenomena made during the sixteenth and seventeenth centuries from those of previous centuries, and which lies at the heart of the Scientific Revolution.

What the Scientific Revolution arrived at was the eventual institution of science as *the* human activity for the systematic theoretical and practical investigation of nature. In a complex interactive process, intellectual curiosity and social needs were involved and intertwined; and it is not easy to disentangle the 'pure' and 'applied' impulses and motives which advanced the Scientific Revolution. Historically, perhaps, the most significant achievement of the Scientific Revolution was the establishment of science as an individual and socially-organised activity for the purpose of creating an endless chain of approximate, albeit self-correcting, knowledge of nature – a veritable extension of the human physical and physiological means to understand, interpret and change nature.[10]

9 K. Bayertz, 'Über Begriff und Problem der wissenschaftlichen Revolution', in his (ed.), *Wissenschaftsgeschichte und wissenschaftliche Revolution* (Hürth-Efferen: Pahl-Rugenstein, 1981), pp. 11-28. Take William Harvey's discovery of the circulation of the blood (1618-1628). It was a product of *both* Aristotelian thinking (in which the idea of the circle plays a major role) and non-Aristotelian quantitative reasoning. See W. Pagel, *William Harvey's Biological Ideas: Selected Aspects and Historical Background* (Basel and New York: Karger, 1967), pp. 73f., J. J. Bylebyl, 'Nutrition, Quantification and Circulation', *Bulletin of the History of Medicine*, 51 (1977), 369-85; A. Cunningham, 'William Harvey and the Discovery of the Circulation of the Blood', in R. Porter (ed. and intr.), *Man Masters Nature: 25 Centuries of Science* (London: BBC Books, 1987), pp. 65-76.
10 J. D. Bernal, *The Extension of Man: A History of Physics Before 1900* (London: Weidenfeld and Nicholson, 1972), pp. 16f.

Empirical knowledge

Relevant to the historical understanding of the Scientific Revolution is the need to distinguish between empirical and scientific knowledge of nature, and to be aware of their historical relations. Broadly considered, empirical knowledge of nature derives from human activity based on observation and experience. Whereas scientific knowledge derives, as indicated, from historically-evolved and interlocked characteristic procedures of investigating nature, including observation.

Observation is an activity not specific to humans. The human perceptual experience of nature, attained through observation, differs qualitatively from that of non-human animals in that it entails mental, verbal, manipulatory and societal dimensions which are hard to disentangle. According to the 'food-sharing hypothesis' propounded by the anthropologist Glyn Isaac, 'the collective acquisition of food, postponement of consumption, transport and the communal consumption at a home base or central place' constituted a major stage in human evolution, assisting 'the development of language, social reciprocity and the intellect'.[11]

It is believed that early humans embarked on producing tools and weapons about 2.5 million years ago. These activities, in combination with meat-hunting and plant-gathering, the use of fire and ability to make and control it, stand at the very beginnings of empirical knowledge of nature. Take the making of stone tools: it involved finding out about the relative hardness and cleavability of stones by trial and error. The underlying dialectic between doing and learning has been pinpointed by the anthropologist Nicholas Toth, who spent many years experimenting with techniques for making stone tools, as follows: 'Toolmaking requires a coordination of significant motor and cognitive skills'.[12]

This applies even more markedly to the manipulative prowess of the modern humans (*Homo sapiens*) who created Palaeolithic art, traceable in the Blombos cave in South Africa to about 75,000 years ago, and in the Chauvet cave in France to about 30,000 years ago. Comparable in age are the Sulawesi cave paintings in Indonesia, pointing to African origins of figurative art before *Homo sapiens* spread across the globe. Explanations and interpretations abound, examining, for example, whether mural pictures of

11 G. L. Isaac, 'Aspects of Human Evolution', in D. S. Bendall (ed.), *Evolution from Molecules to Men* (Cambridge: Cambridge University Press, 1983), pp. 532-35.

12 Quoted by R. E. Leakey, *The Origin of Humankind* (London: Basic Books, 1994), p. 38.

animals with arrows in them should be looked upon as a form of hunting magic. Be that as it may, the position of the arrows in the heart region indicates the hunters' familiarity with the (anatomical-physiological) locus where the animal could be mortally wounded. Representations of women with pronounced female sexual attributes (breasts, buttocks, pubic triangle) are evidence that prehistoric humans attached particular importance to fertility and sexual matters. Human interest in reproduction and sexual activity has a prehistoric past.

Fig. 2 Palaeolithic painting, Chauvet-Pont-d'Arc Cave (southern France), c. 32,000-30,000 BP.

It is accepted that the extinct *Homo neanderthalensis* – the evolutionary relations between him and the surviving *Homo sapiens* are still debated – was burying his dead about 100,000 years ago. As previously mentioned, the Neanderthal burials are regarded as the earliest expressions of human awareness of the natural phenomenon of death. With them originates not only the history of human perception of the relation and distinction between life and non-life, but also that of time.

Perception of time and space: early impulses

'Time is a word', we read in an authoritative encyclopaedia of astronomy and astrophysics, 'that eludes definition until it is given some practical application'.[13] The quandary of envisaging time has been reflected in the dichotomy between linear and circular visions of time, depicted vividly by the palaeontologist J. S. Gould as 'time's arrow' and 'time's cycle' respectively. Gould holds that 'time's arrow' – encapsulating the unidirectionality of events – 'is the primary metaphor of biblical history'.[14] Doubtless the lineage of time's cycle is more ancient – it goes back to the hunter-gatherers' observation of recurrent events, such as heavenly cycles, annual seasons or female menstruations.

As to the perception of time's 'twin' – space – it assumes tangible form in terrestrial measurement, in the wake of the growth of permanent agricultural settlements. Heralding the Neolithic Age, agriculture based on the cultivation of soil and the manipulation of plants and animals arrived in parts of Western Asia about 10,000 years ago.[15] It brought about a shift from hunting and gathering to production and storage of food hinged on irrigation and drainage – as in the river valleys of the Nile and the Tigris and Euphrates. The establishment of sedentary life was accompanied by empirically-attained technical developments embodied in a host of arts and crafts, such as pottery, spinning and weaving, dyeing, metal working, house and boat building and others. All these developments contributed to the growth of specialised material production, including that of food. The distribution of products, as well as political, military and religious activities, came under institutional, palace or temple control, administered by officials variously described as 'scribes', 'clerks', 'bureaucrats' – the literate minority of society. Thus the basis was laid for the establishment of socially stratified and centrally governed polities, as encountered in Ancient Egypt and Mesopotamia.[16]

13 W. J. H. Andrewes, 'Time and Clocks', in S. P. Maran (ed.), *The Astronomy and Astrophysics Encyclopaedia* (New York: John Wiley & Sons, 1991), p. 929. It is argued that 'on the cosmic (though not human) scale, size is visible in a way that age is not'. See B. Dainton, 'Past, What Past?', *The Times Literary Supplement*, 8 January 2010.

14 S. J. Gould, *Time's Arrow, Time's Cycle: Myth and Metaphor in the Discovery of Geological Time* (Harmondsworth: Penguin, 1990), p. 11.

15 S. Jones, R. Martin and D. Pilbeam (eds.), *The Cambridge Encyclopedia of Human Evolution* (Cambridge: Cambridge University Press, 1992), p. 378.

16 In a study of Ancient Mesopotamia, Susan Pollock shares the view of critics of the 'overarching notion of the temple economy'. See S. Pollock, *Ancient Mesopotamia The Eden that Never Was* (Cambridge: Cambridge University Press, 1999), p. 119. But even she writes in the concluding chapter: 'Temples, which have been identified as far back as the Ubaid period, are one of the most obvious testimonials to the central place of

Apart from Western Asia where the cultivation of wheat and barley began, other sites of origin for agriculture are recognised. China for rice and millet, for example, or Central America and the northern Andes for maize. Agriculture as a means of supplying the human demand for food turned out to be a worldwide activity. Even today the majority of the world population lives off the land. Because of its unprecedented impact on world history – comparable with the Industrial Revolution – the changeover to economies sustained by agriculture during Neolithic times deserves to be called *the* Agricultural Revolution.[17]

River valley civilisations and knowledge of the natural world

The Neolithic agricultural and craft activities, developed in contact with living and non-living things, broadened the empirical knowledge of diverse natural materials, as well as natural and artificial processes, enormously. The concurrent inventions related to the state, commercial and communication needs of the river valley civilisations – such as measures and weights, numerical symbols and arithmetic, writing and the alphabet – were historically of incalculable import.[18]

The advent of agriculture activated astronomical observations, and with them brought forth the measurement of time as realised in the construction of the calendar. Thus in Ancient Egypt, from about 3000 BC, the length of the

religion within Mesopotamian societies. Yet they were also economic and political institutions; any attempt to apply to them our contemporary notions of the separation of religion, politics, and economy forces us to recognise that our concepts are products of a particular history and culture rather than eternal verities'. Ibid., p. 221.

17 See J. Vandermeer, 'The Agroecosystem: The Modern Vision Crisis, The Alternative Evolving', in R. Singh, C. B. Krimbas, D. B. Paul and J. Beatty (eds.), *Thinking about Evolution, Historical, Philosophical and Political Perspectives*, Vol. 2 (Cambridge: Cambridge University Press, 2001), p. 480. Regarding the juxtaposition of the (disputed) Neolithic Revolution and the Industrial Revolution, see C. M. Cipolla, 'Introduction', in his (ed.), *The Fontana Economic History of Europe: The Industrial Revolution* (London and Glasgow: Collins/Fontana Books, 1973), pp. 7-8. See also, by the same author, *The Economic History of World Population* (Harmondsworth: Penguin, 1962), Ch. 1.

18 The case for making writing, developed in Mesopotamia (about 3000 BC), an integral part of the history of weights and measures has been restated by J. Ritter. 'One outcome of this interplay', he writes, 'was of striking importance at the conceptual level – the development of an abstract use of numbers, independent of any metrological system, and the creation of a positional system of base sixty'. See J. Ritter, 'Metrology, Writing and Mathematics in Mesopotamia', *Acta historiae rerum naturalium necnon technicarum. Prague Studies in the History of Science and Technology*, N. S. (1999), 215-41 (p. 239).

year amounting to 365 days was accepted. The number corresponded to the interval between two observed, predictable events that recurred and coincided annually. That is, the agriculturally vital flooding of the Nile and the rising of the brightest star in the sky (known today as Sirius) after its period of invisibility, just before sunrise in July. The Egyptian year became the basis for calendar computation and reform. It was largely this achievement, together with the recognition of the influence of solar and stellar observations on the alignment of those truly towering works of engineering – the pyramids – that made the fame of pre-Hellenistic Egyptian astronomy.

The emphasis on the agricultural context of ancient astronomy should not obscure other factors at play. Certainly a mixture of religion, astrology and politics was a major stimulant for Babylonian solar, lunar and planetary observations. Take the observations of periodical appearance and disappearance of the planet Venus – identified with the goddess Ishtar – extending over two decades (c. 1582-1562 BC). They were copied and referred to for centuries. The observed phenomena were taken to furnish positive or negative omens affecting the future of the ruler (wars), the community (harvests) and the individual (fertility). Historically noteworthy is the intertwining of astronomy and astrology that went into the construction of the equal-sign zodiac. That is, the circle or belt of star clusters through which the sun was thought to move annually. On the one hand, its division into twelve 'signs' of thirty degrees, named after important star groups, amounted to the construction of a system of celestial coordinates – a significant event in the history of mathematical astronomy (c. early fifth century BC). On the other hand, the old 'signs' have retained their astrological connotation for predicting a person's future to the present. Because of precession of the equinoxes, it is necessary to differentiate between slowly revolving constellations and 'fixed' zodiacal signs carrying the same names.[19]

Regarding the Babylonian observations, what matters in retrospect is not their accuracy – seemingly overplayed – but that 'there was a social mechanism for making and recording astronomical observations *and for storing and preserving the records*'.[20] The 'astronomical diaries', as the resulting records

19 B. L. van der Waerden, 'Basic Ideas and Methods of Babylonian and Greek Astronomy', in A. C. Crombie (ed.), *Scientific Change, Symposium on the History of Science, University of Oxford 9-15 July 1961* (London: Heinemann, 1963), p. 42f; Precession of the equinoxes was recognised by Hipparchus (second century BC); see J. North, *Cosmos: An Illustrated History of Astronomy* (Chicago, IL and London: University of Chicago Press, 2008), pp. 14, 114.

20 J. Evans, *The History and Practice of Ancient Astronomy* (New York and Oxford: Oxford University Press, 1998), p. 16 (italics – JE).

are called, contain astronomical as well as meteorological, hydrological and other entries. The oldest are datable to the seventh century BC but, in view of the age of the observations of the planet Venus, the practice of recording must be even older.[21] Comparable are Chinese records of celestial phenomena beginning in the fifth century BC. Among several affinities between Babylonian and Chinese astronomy is that observation of celestial phenomena fell under state control. In China this control found expression in the setting up of the Astronomical Bureau, as part and parcel of the completion of the unification of the realm under the Han dynasty (202 BC-AD 220). The following comment elucidates the situation neatly:

> Celestial portents were not merely natural phenomena, but expressions of the will of Heaven communicated to the ruler as admonition. According to the Chinese theory of monarchy, the supreme ruler was the Son of Heaven, and through him the celestial will was to be transmitted as the basis of social order. Though the Chinese Heaven is neither a creator nor a god in the theological sense – later, seen more philosophically, it *was* the cosmos or natural order itself – it provided criteria for moral and political conduct and thus occupied a crucial position in Chinese political ideology. To supervise the heavenly ritual was the ruler's privilege as well as his duty, for it was an essential service which only he could perform on behalf of its subjects.[22]

In the light of what has been said, the vital role of empirical knowledge of the natural world, bound up with observation and experience, for early human existence and its advance is manifest. What has to be cleared up is that there is more to the human perception of nature than observations of natural phenomena *per se*. Historically, the names of stars and constellations furnish a striking example. It may be assumed that not a few go back to prehistoric times, when hunters watching the sky with the naked eye 'recognised' figures described as a lion, bear, etc. These names reflected the hunters' preoccupation and familiarity with the world of animals. To them, as indeed to the peoples of the river civilisations, the natural world appeared to be 'alive'. Natural and artificial processes appeared to be 'living' and ideas about 'livingness' were derived from experiences with, and observations of,

21 Ibid.

22 K. Yabuuti, 'Chinese Astronomy: Development and Limiting Factors', in S. Nakayama and N. Sivin (eds.), *Chinese Science Explorations of an Ancient Tradition* (Cambridge, MA and London: MIT Press, 1973), p. 93. For an original account of the history of Chinese astronomy, see J. Needham, *Science and Civilisation in China* (Cambridge: Cambridge University Press, 1959), Vol. 3, pp. 169ff. For critical remarks, see N. Sivin, 'An Introductory Bibliography of Traditional Chinese Science. Books and Articles in Western Languages', in Nakayama and Sivin (eds.), *Chinese Science*, pp. 298-99.

human as well as animal bodily functions. It is not difficult to see that the beginning or origin of everything was linked to human/cattle procreation through sexual union. Akkadian texts refer to male and female stones and metals. The production of metals by the smith was imagined as something related to child birth. From this animate/biological angle to metal extraction, the alchemical idea of a 'marriage of metals' ensued, crystallising eventually into the basic chemical concept of 'combination'.[23]

In Mesopotamia there was a socio-political side to the observation of the celestial world which, as we know in retrospect, was to contribute to the demarcation of pursuits of natural knowledge from other human activities. It concerned the prehistory of the idea of a law of nature, a prehistory that comes to light, as it were, in the process of drawing an analogy between the earthly state and the cosmic state. For example, in a late Babylonian 'creation' poem the sun-god Marduk is pictured as the giver of law to stars. According to Joseph Needham, the prodigious student of the comparative history of science, the genesis of the 'conception of a celestial lawgiver "legislating" for non-human natural phenomena' may be viewed against the background of the unification and centralisation of southern Babylonia by Hammurabi (fl. 1700 BC).[24]

Concept of nature: *phusis*

Before the idea of laws of nature could materialise, the notion of 'nature' had to take shape. Termed *phusis* in Greek, the word (like its Latin counterpart *natura*) is etymologically connected with the idea of genesis or birth.[25]

23 R. J. Forbes, 'Metals and Early Science', *Centaurus*, 3 (1953-1954), 30.

24 J. Needham, *Science and Civilisation in China* (Cambridge: Cambridge University Press, 1956), Vol. 2, p. 533. The conjecture has been heavily criticised. But Descartes, Leibniz, Newton and others returned to the idea that a heavenly legislator (God) enacted the laws of nature underlying the motion of matter. See W. Krohn, 'Zur Geschichte des Gesetzesbegriffs in Naturphilosophie und Naturwissenschaft', in M. Hahn und H.-J. Sandkühler (eds.), *Gesellschaftliche Bewegung und Naturprozess* (Cologne: Pahl-Rugenstein, 1981), pp. 61-70 (p. 68). It has been noted that Descartes, who more or less established the conception of nature as governed by laws to be discovered by those who investigated it, never talked about laws of nature with regard to refraction or optics in general. See F. J. Dijksterhuis, 'Constructive Thinking: A Case for Dioptrics', in L. Roberts, S. Shaffer and P. Dear (eds.), *The Mindful Hand Inquiry and Invention from the Late Renaissance to Early Industrialization* (Amsterdam: Koninklijke Nederlandse Akademie van Wetenschappen, 2007), pp. 63-4. The discovery that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is constant for any material, the 'law of sines', is ascribed to Descartes (1638).

25 See entry 'Nature', in W. F. Bynum, E. J. Brown and R. Porter (eds.), *Dictionary of the History of Science* (London and Basingstoke: Macmillan, 1981), p. 289.

Phusis is traceable, it has long been acknowledged, to speculations in the sixth and fifth centuries BC regarding natural phenomena by so-called Presocratic natural philosophers, who hailed from Ionian cities in Asia Minor. To all intents and purposes, their approach to natural phenomena was free of myths and interventions by personal gods. This is not to say that these 'earth-bound' Greek inquirers into nature, as well as others (including medical writers) who followed them up to Galen (fl. AD 180), were without religious beliefs.

The relative geographical proximity of the Ionian cities to Egypt and Babylon has prompted recurring debates regarding the impact of the ancient Near Eastern civilisations upon the Greek world. Going back to the sixth and fifth centuries BC, the knowledgeable classicist Geoffrey Lloyd confirms that both transmissions and independent developments (writing, numerical notation) took place. Lloyd validates noticeable differences between pre-Greek geometry and astronomy. The Near East possessed knowledge of geometrical truths (e.g. the properties of the 'Pythagorean' right-angled triangle) but not the notion of the proof of geometrical truths, something which did develop in Greece. Whilst Babylonian astronomical practice employed arithmetical procedures with respect to planetary movement, the Greeks turned to geometrical models. As for medicine, Lloyd points out that it 'was one of the chief battlefields on which the attempt to distinguish between the "rational" and the "magical" was fought'. This struggle found expression in the Hippocratic collection of Greek medical texts – the oldest of which belonged to the beginning of fifth century BC – in which magical practices and beliefs come specifically under attack.[26]

What is significant is that no other ancient civilisation evolved a notion of nature equivalent to *phusis*. Multifaceted and disputed as the concept of *phusis* was, it stood effectively for objective, intelligible reality and was thus susceptible to rational inquiry.[27] This was connected to a belief in the orderliness of the cosmos – a word of Greek origin. Etymologically bound

26 G. E. R. Lloyd 'The Debt of Greek Philosophy and Science to the Ancient Near East', in his, *Methods and Problems in Greek Science: Selected Papers* (Cambridge: Cambridge University Press, 1991), pp. 278-98.

27 G. E. R. Lloyd, 'Greek Antiquity: The Invention of Nature', in G. Torrance (ed.), *The Concept of Nature: The Herbert Spencer Lectures* (Oxford: Clarendon Press, 1992), p. 22. Reprinted as 'The Invention of Nature', in Lloyd, *Method and Problems*, p. 432. Aristotle (384-24) in *Physics* seems to be the first to have formulated it clearly: 'Nature is a principle of motion and change... We must therefore see that we understand what motion is; for if it were unknown, nature too would be unknown'. See M. Oster (ed.), *Science in Europe 1500-1800: A Primary Sources Reader* (Basingstoke: Palgrave, 2002), p. 8.

up with the notion of military orderliness, cosmos was used to signify 'order'/'ordered whole' and eventually stood for the world or universe as an ordered entity. The rational inquiry into the origin and make-up of cosmos, inaugurated by the Ionian thinkers, paved the way for knowledge in fields such as medicine, mathematics, astronomy and physics that had to wait 1500 years before it began to be superseded. The concrete attainments of Greek natural philosophers were highlighted by the influential classicist Moses Finley as follows:

> The Hippocratic practice of auscultation of the heart, Euclid's *Elements*, Archimedes' discovery of specific gravity, the treatise on conic section by his younger contemporary Apollonius of Perge, Eratosthenes' estimate of the diameter of the earth to within a few hundred miles of the correct figure, Hipparchus' calculation of the precession of the equinoxes, Hero's steam-operated toys...[28]

No less noteworthy than these achievements is the *modus operandi* that produced them. Underlying them was the unprecedented conviction that the natural as well as the social – perceived as ordered – were comprehensible without recourse to the supernatural. While the originality of this position – an enduring legacy of Greek antiquity diagnosed by some as the 'Greek miracle' – has not been questioned, its origin has been the subject of debate. During the last four decades or so research has gone some way to demystifying, as it were, the phenomenon by looking into its societal context. Here it is pertinent to recall Finley's uncompromising statement regarding slavery:

> This was a universal institution among the Greeks, one that touched upon every aspect of their lives without exception. It rested on very fundamental premises, of human inequality, of the limits authority and debasement, of rights and rightlessness.[29]

What concerns us here is the relevance of ancient Greek slave-owning society to the understanding of ancient Greek 'inquiry concerning nature'.

28 M. I. Finley, *The Ancient Greeks* (Harmondsworth: Penguin, 1977), p. 123. The *floruit* dates (BC) of the named persons are as follows: Euclid (300), Archimedes (250), Apollonius (210), Eratosthenes (250), Hipparchus (135). Hippocrates (425) almost certainly did not author any of the sixty treatises or so ascribed to him. Hero was active in the first century AD (60).

29 Ibid., p. 148.

Slavery and 'inquiry concerning nature' in ancient Greece

Tradition has it that it was the Ionian city Chios where slaves were first bought from the barbarians around 550 BC. This was also the period of the beginning of early Greek natural philosophy, personified by the Milesians Thales (585), Anaximander (555) and Anaximenes (535). The question of the connection between their naturalistic speculations about the ordered cosmos, as well as those of later Ionian thinkers, and the rise of slavery in ancient Greece has remained problematical. They employed notions drawn from legal, social, military and political spheres, such as justice, equality (*isonomia*), war, strife, rule, contract and others. As pointed out by Lloyd, these concepts are used 'by one Presocratic after another to convey different conceptions of how the world as we know it, made up of a variety of different things, is never the less an ordered whole'.[30]

But what we know about the ideas of Presocratics is fragmentary and largely second-hand. Hence their uncertain connotation with regards to the historically developing system of slavery in Greek city-states – within a democracy practised solely by male citizens.

Here, as in other matters, Aristotle proves to be illuminating. If we turn to *Politics*, one of his late writings, he addresses the nature of slavery. On this subject, he generalises that the ruler/master/slave relationship permeates 'every composite thing where a plurality of parts, whether continuous of discrete, is combined to make a single common whole'. Aristotle gives examples of the (inanimate) case of a musical scale ruled by its keynote or the (animate) case of the body governed by the soul 'with the sway of a master'.[31]

Aristotle's position on the relation of soul and body as well as on the cognate, but more general issue of the relation of form and matter – as opposites – is germane to the exploration of the role of dichotomies in the evolution of scientific methodology. While rejecting the separateness of soul and body, form and matter, Aristotle envisaged their union to be founded on the subordination of body to soul and matter to form.

Aristotle's fundamental notions are hierarchically predicated, as in form, the causes of things or the scale of being. It is insufficiently appreciated how much Aristotle's commitment to hierarchy and order owes to his acceptance

30 'Greek Cosmologies', in Lloyd, *Methods and Problems*, p. 150.

31 Aristotle, *Politics*, I, ii, 9-11 (Loeb Classical Library, Vol. 21, transl. H. Rackham) (Cambridge, MA: Harvard University Press and London: Heinemann, 1977), pp. 19-21.

of the naturalness of social and human inequality, manifestly incarnated in the opposition of freedom and enslavement. At the time of the Peloponnesian war (431-404 BC), it is estimated that there were between 60,000 and 80,000 slaves in Athens – the total population (men, women and children, free or enslaved) was about 250,000 to 275,000.[32] Such social reality palpably underlies Aristotle's conviction that authority and subordination of all sorts and kinds conditioned the ordered existence and functioning of both *polis* and *phusis*. *Polis*, the inegalitarian Greek city-state, was the subject matter investigated in *Politics*.

Rooted in observation and experience – the age-old means of gaining knowledge of the world – the idea of opposites (not unlike that of similarity and difference) supplied a vantage point for theoretical and practical classification and systematisation. Aristotle recognised in these procedures attributes of scientific methodology – in effect, its history begins with him.

The propensity for resorting to the value-laden opposites of inferiority and superiority in scientific inquiry, and its place against the background of the Greek system of slavery, is highlighted by Lloyd as follows:

> The Greeks did not deploy opposites to legitimate a single particular type of political regime. But over and over again their uses of opposites mirror an essential feature of the social structures of Greek society, namely the fundamental division between rulers and ruled. A perceived hierarchical distinction within pairs of opposites that we might have expected to have been totally value-free is a feature that is made to do explanatory work in a variety of scientific contexts ... In Aristotle's view ... male is held to be 'naturally' superior to female, the latter said to be a 'natural' deformity. Again the members of the pairs right and left, above and below, front and back, are strongly differentiated as to value. Right, above and front are the principles (*archē*), first of the three dimensions (breadth, length and depth respectively), and then also of the three modes of change in living beings, mainly locomotion, growth and sensation. Moreover, this doctrine provides him with the basis of his explanation of a range of real or assumed anatomical facts (the relative positions of the windpipe and the oesophagus, those of the two kidneys, the function of the diaphragm and the positions of the vena cava and the aorta) and even further afield it is the principle he invokes in his admittedly tentative discussion of the difficult problem of why the heavens revolve in one direction rather than in the other.
>
> The point can be extended to what we might have assumed to be the purely neutral mathematical pair, odd and even. They provide the basis for the Greek classification of integers and are thus fundamental to Greek arithmetic.[33]

32 Finley, *Ancient Greeks*, pp. 72, 55.

33 'Greek and Chinese Dichotomies Revisited', in G. E. R. Lloyd, *Adversaries and Authorities Investigations into Ancient and Greek Chinese Science* (Cambridge: Cambridge University Press, 1996), pp. 134-35.

Lloyd also raises the question of the sociopolitical background of a pervasive element in Greek natural philosophy, mathematics and medicine. That is, the preoccupation of searchers with foundations, certainties and proofs of truthful knowledge in various domains of inquiry. The most telling example of this tendency is provided by the axiomatic-deductive manner of demonstrating geometrical truth that Euclid displays in his *Elements*. Lloyd points out that the astronomer and cosmologist Ptolemy and the physician Galen, canonical figures of Hellenistic science, subscribed to the idea that proof *more geometrico* establishes certainty of knowledge. Lloyd suggests that this may have something to do with the way in which participants in hard-hitting debates and confrontations in the political assemblies and law courts of the city-states argued their case. The winning depended crucially on marshalled evidence and proof.

This approach leads Lloyd to throw open to discussion the vexed issue of the place of experimentation in Greek science. It is particularly striking, he writes,

> that on many of the occasions when deliberate and explicit testing procedures are invoked, the aim was not so much to devise an experimental set-up that could be seen to be neutral between antecedently equally balanced alternatives, but rather to provide further supporting argument in favour of a particular theory. It is remarkable that even in what are some of the best prepared and most systematic experiments carried out in Greek antiquity, the quantitative investigations of the amount of refraction between various pairs of media (air to water, air to glass, and water to glass) reported in Ptolemy's *Optics*, the results have clearly been adjusted to suit his general theory, since they all fitted exactly.[34]

34 Cf. G. E. R. Lloyd, 'Democracy, Philosophy and Science in Ancient Greece', in J. Dunn (ed.), *Democracy: The Unfinished Journey, 508 BC to AD 1993* (Oxford: Oxford University Press, 1993), pp. 41-56 (p. 45).

2. Experimentation and Quantification

Medieval world

At the end of the 1970s, sociologists of science and sociologically-orientated historians of science began to pay attention to experimentation. Even if their claim that experimentation had been neglected was overstated, it is true that historical literature is rich neither in works dealing with experimentation nor with systematisation.

Uncertainties persist regarding experimentation in the medieval world before it began to occupy, jointly with quantification, the centre-stage of scientific activities in the seventeenth century.

This has something to do with the course of the discussion regarding the medieval origins of normal science, stimulated by Alistair Crombie in the early 1950s. It became overshadowed by the debate on the structure of scientific revolutions, engendered by Kuhn's seminal essay and lasting from its publication in 1962 to about the mid-1980s.[1]

1 For what is probably the earliest public presentation of the ideas developed in the essay, see T. S. Kuhn's paper 'The Function of Dogma in Scientific Research', presented at the Symposium on the History of Science, University of Oxford, 9-15 July 1961. See A. C. Crombie (ed.), *Scientific Change, Symposium on the History of Science, University of Oxford 9-15 July 1961* (London: Heinemann, 1963), pp. 347-69. The paper was commented on by A. Rupert Hall and Michael Polanyi, respectively (pp. 370-80). Curiously, neither Kuhn nor Hall mentioned that the latter had already employed the term 'paradigm' in the paper 'The scholar and the craftsman in the scientific revolution' (Hall uses the lower case). It was presented to a history of science conference, also attended by Kuhn (Madison, 1-11 September 1957). See M. Clagett (ed.), *Critical Problems in the History of Science* (Madison, WI: University of Wisconsin Press, 1959), pp. 3-29 (p. 19). Here Hall famously states that although the roles of the scholar and the craftsman in the Scientific Revolution are complementary ones, the former holds the prime place in its story (p. 21).

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Medieval science as such was not a concern of Kuhn's except in the context of his interpretation of scientific revolutions as paradigm shifts. Not surprisingly, to the author of the renowned *The Copernican Revolution* (1957) the emergence of Copernican astronomy represented a classic case of a paradigm change. Kuhn acknowledges, we should note, the role played by 'external' factors in the emergence or transition to new paradigms. Regarding the replacement of Ptolemaic astronomy by Copernican astronomy, Kuhn lists among external factors: calendar reform, medieval criticism of Aristotle, the rise of Renaissance Neoplatonism 'and other significant historical elements besides'. Nevertheless, he chooses not to address them:

> In a mature science – and astronomy had become that in antiquity – external factors like those cited above are principally significant in determining the timing of breakdown, the ease with which it can be recognized, and the area in which, because it is given particular attention, the breakdown first occurs. Though immensely important, issues of that sort are out of bounds for this essay.[2]

By contrast, Crombie was concerned with the medieval origins of modern science which he associated with the use of experiment and mathematics. First he traced them back to the thirteenth century, if not to earlier times. But by 1961, he stated: 'I have been responsible for claims that now seem to me exaggerated'.[3]

Even so, Crombie's approach to medieval theoretical and practical engagement with the natural world is still valuable. As, for example, when he underlines the importance of the study of medieval technical texts for the understanding of the evolution of experiment:

> The technological writings of the Middle Ages are still relatively unexplored, and yet it seems to me that it is there that one must chiefly look for those habits developed by the demands made by the problems themselves for accurate, repeatable results. These are of the essence in practical life where it matters if you are given short measure or the wrong product, are subjected to incompetent surgery, or arrive at an unintended destination. They are also of the essence in experimental science. For the history of science in the whole medieval and early modern period, the relations between the intellectual habits and methods of theoretical science and of practical technology present a vast field of research that has scarcely been investigated. The history of 'practical mathematics' in the Middle Ages would especially repay systematic study.[4]

Let us look at the approach of another authority in this field of historical research – Edward Grant. On the question of experiments in the Middle Ages, taken up in the book in which, as one reviewer put it, he distilled 'a lifetime of scholarly research', Grant has this to say:

> Occasional experiments had been made, and mathematics had been routinely applied to hypothetical, though rarely real, problems in natural philosophy. In the seventeenth century, the new scientists applied mathematics to real physical problems and added experiments to the analytic and metaphysical techniques of medieval natural philosophers. The developments did not emerge from a vacuum.[5]

No doubt, Crombie would have had agreed. The problem is the difference in the thinking of the two historians on what constitutes the milieu or, in Grant's words, the 'societal environment in the Middle Ages that eventually enabled a scientific revolution to develop in the seventeenth century'. Basically, Grant equates this environment with (1) the translation of Greco-Arabic works on science and natural philosophy into Latin, (2) the formation of the medieval university and (3) the rise of the theologian-natural philosopher.[6]

What emerges from Grant's account is that medieval savants set themselves suppositional problems and sought intellectual solutions to them.

Crombie impressively returned to this problematic in his massive three-volume *Styles of Scientific Thinking in the European Tradition* (1994), where he discusses the apparent predisposition of Western society to experimental investigation of nature in conjunction with the medieval philosophical theology of the Creator as a divine mathematician. According to this way of thinking, God created the world in which all things were ordered by measure, number and weight. God also created man in his image, endowed with senses and reason to unriddle God's thinking. Such a belief, Crombie argues, offered the way not only to the systematic use of observation, experiment and logical

2 T. S. Kuhn, *The Structure of Scientific Revolutions*, 2nd revised ed. (Chicago, IL: University of Chicago Press, 1970), p. 69.

3 See Crombie's 'Contribution to Discussion of Part Three: Science and Technology in the Middle Ages', pp. 272-91, in his (ed.), *Scientific Change*, pp. 316-23. For Crombie's erstwhile statements, see his *Augustine to Galileo: The History of Science A.D. 400-1650* (London: Falcon Press, 1952); *Robert Grosseteste and the Origins of Experimental Science, 1100-1700* (Oxford: Clarendon Press, 1953).

4 Crombie (ed.), *Scientific Change*, p. 319.

5 E. Grant, *The Foundations of Modern Science in the Middle Ages* (Cambridge: Cambridge University Press, 1996), p. 202.

6 Ibid., p. 171.

argument to bring nature under control, but also to the improvement of the human condition. But Crombie contends:

> The habit of systematic measurement and its instrumentation by appropriate procedures was characteristically a response not to the theoretical demands of natural philosophy but to the practical demands of the technical arts. Academic natural philosophy put a premium on logical precision and internal coherence; practical life required exact and repeatable measures of the external world as experienced and used. Technical ability to specify the conditions for producing a desired result was an essential need of theoretical science and of practical art alike; a quantified experimental science depended on a dialogue between the two. That could take place at a suitable level of education. The technical innovations which came to quantify many aspects of practical medieval life in the 12th century were being matched from early in the 12th century by an increasing attention of scholars to the practical arts, both within general encyclopedias and in more specialized treatises. Intellectual contact was encouraged at once by the improved education of superior craftsmen and by the enlargement of the technical content of the university curricula especially in the mathematical *quadrivium*.[7]

Crombie found confirmation for this viewpoint when he considered the evolution of quantification of fundamental entities during 1200-1500: time, space and weight.

Quantification of time: mechanical clock

Regarding the measure of time, it is accepted that the spread of the mechanical clock effected a radical change in Europe beginning around 1300. Its operation depended on the ingenious combination of a driving mechanism (falling weight) and a regulating mechanism ('foliot-and-verge' escapement).

The perception of time as a continuum was transformed by slicing it into concrete, identical small-time portions (*minutae*). This was due to the mechanical clock's capability to indicate the time of the day – reckoned from

7 A. C. Crombie, *Styles of Scientific Thinking in the European Tradition: The History of Argument and Explanation Especially in the Mathematical and Biomedical Sciences and Arts* (London: Duckworth, 1994), Vol. 1, pp. 416-17. The notion of a 'superior craftsman' originates with Edgar Zilsel's 'superior artisan'. See his 'Sociological Roots of Science' (1942), reprinted in D. Raven et al. (eds.), *Edgar Zilsel The Social Origins of Modern Science* (Dordrecht, Boston, MA and London: Kluwer, 2000), pp. 7-21. The historian T. Inkster differentiates between 'higher artisanal' and 'lower craftsman' knowledge. See his 'Thoughtful Doing and Early Modern Oeconomy', in L. Roberts, S. Schaffer and P. Dear (eds.), *The Mindful Hand Inquiry and Invention from the Late Renaissance to Early Industrialization* (Amsterdam: Koninklijke Nederlandse Akademie van Wetenschappen, 2007), p. 445.

one midnight to the next – split into equal 24 hours, each containing 60 minutes of 60 seconds. It should be added that the weight-driven mechanical clock was not accurate enough for measuring small intervals of time. Nevertheless, in comparison with the contemporary methods of telling day time, by the sundial and astrolabe respectively, the superiority of the mechanical clock as a timer was obvious. Of the two, the fixed sundial was simpler to handle – shadow indicated the sun's progress through the sky. Though portable and usable by day, or night, the astrolabe was a more complicated timekeeping implement, as was the armillary sphere. They were devices for measuring the position of stars; from the obtained values, it was possible, in the thirteenth century, to calculate time reliably to 2-5 minutes.

When and who actually invented the mechanical clock is unknown – the first firm date is 1286.[8] As the eminent historian of technology Donald Cardwell states:

> Its design may have resulted from the speculations of some millwrights who knew about gearing and the problems of uniform motion, and who, moreover, had astonishing insight into mechanical principles.
>
> All we can suppose is that there must have been many attempts to devise a machine to indicate the position of the sun in its daily journey round the earth, and therefore to tell the time. Certainly many of the first clocks were astronomical ones, some of them of such elaborate design that the positions of the sun, the moon, the other five planets and even the motions of the tide could be displayed.[9]

Undoubtedly we are on firmer ground when we inquire about social conditions that favoured the invention of this crucially novel device for measuring time. The mechanical clock was a product of the need to regulate the timing of religious and burgeoning multifarious urban (civic) activities as well as a factor in achieving this regulation. It is no accident that the clock ostentatiously came to adorn monasteries, churches and town halls.

8 By and large, scholars do not accept the claim by Joseph Needham (and his collaborators Wang Ling and D. J. de Solla Price) that the hydro-mechanical escapement of the astronomical clock described by the eminent Chinese scholar and state servant Su Sung (1088) represents an important stage in the development of the mechanical clock, with its verge-and-foliot escapement of late thirteenth-century Europe. 'The Chinese measured time by the continuous flow of water, the Europeans, by the oscillatory movement of a verge-and-foliot. Both techniques used escapements, but these have only the name in common. The Chinese worked intermittently, the European, in discrete but continuous beats'. D. S. Landes, *Revolution in Time* (Cambridge, MA: Harvard University Press, 1985), p. 21.

9 D. Cardwell, *The Fontana History of Technology* (London: Fontana Press, 1994), p. 41.

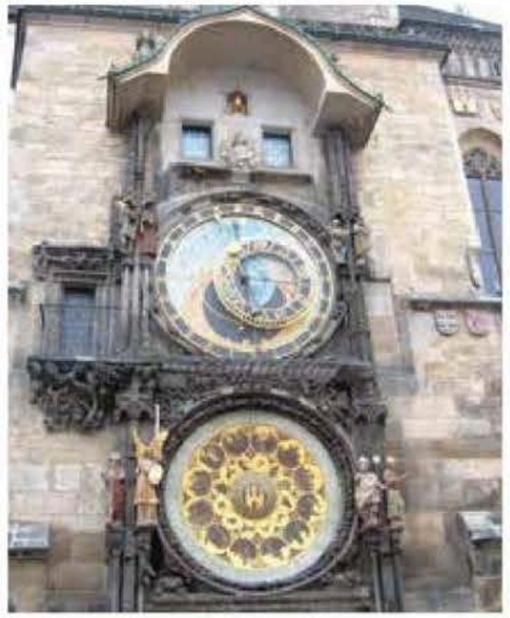

Fig. 3 The Prague Astronomical Clock (Prague Orloj) in Old Town Square, Prague, Czech Republic.

Especially during its early phases, clockmaking was professionally intertwined with astronomy. The ingenuity underlying the making of clocks was regarded so highly that Nicole Oresme (c. 1325-1382), the great French medieval savant, was prompted to visualise God the Creator as a clockmaker. Just as man contrived to produce a self-moving clock, so 'did God allow the heavens to move continually according to the proportions of the motive powers to the resistances and according to the established order (of regularity)'.[10] An early instance of invoking the image of God as the heavenly clockmaker!

Quantification of space: compass and cartography

In some ways, the part played by the magnetic needle compass in the history of space measurement was analogous to that of the mechanical clock in the history of time measurement. The compass is described for the first time in

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a Chinese text dating to about 1088, whereas in Europe the first reference occurs in Alexander Neck(h)am's (1157-1217) *De naturis rerum* (c. 1200). A letter known as *Epistola de magnete* by Petrus Peregrinus (Pierre de Maricourt) (fl. 1269) contains a summary of the European knowledge of magnetic phenomena in the late Middle Ages. Peregrinus conceives the compass both as an astronomical and a navigational instrument.[11]

He describes magnetic compasses without and with a pivot and scale. They were in use in the Mediterranean, clearing the way for the drawing of the first medieval maps, known as *portolani* (compass-charts). Made by practical men, Crombie states,

> and based on the direct determination of distances and azimuths by using log and compass, they were specifically guides to coastlines. From the earliest extant examples of the *Carte Pisane* (1274), the portolans showed scales of distances. By the 16th century they gave two essential pieces of information for navigation: the route to follow and the angle it must make with the north-south axis as given by a magnetized needle; and the distance to run in the direction thus determined.[12]

Compass-bearing in conjunction with observations of currents and winds, rather than methods of astronomical observation, guided the first Portuguese and Spanish voyages of discoveries, including Columbus's transatlantic crossing, in the late fifteenth century.[13]

Against this it is pointed out that Ptolemy's influential *Geography* had become well-known in Portugal and Spain before Bartholomew Diaz, Vasco da Gama and Christopher Columbus embarked on their voyages and thus played a role therein. The Latin translation of the work appeared in print for the first time in Florence in the early fifteenth century. It contained maps drawn on a gridwork of parallels and meridians located with respect to the positions of celestial bodies. Of Ptolemy's coordinate system, Crombie notes that 'by its emphasis on an accurate linear measure of the arc of the meridian it came to transform quantitative mapping'.[14]

Crombie also accepts that Ptolemy's work played a part in the rediscovery of linear perspective. That is, Ptolemy showed how to draw a map as a projection from a single viewpoint. It is generally acknowledged that the technique of linear perspective was invented and demonstrated by Filippo

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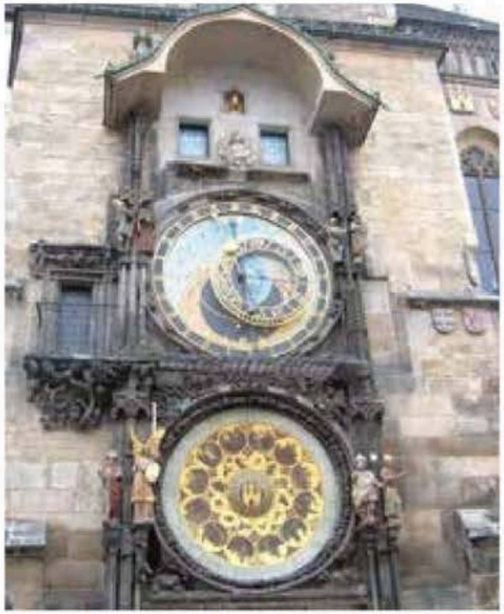
12 Crombie, *Styles*, Vol. 1, p. 420.

13 D. Goodman, 'The Scientific Revolution in Spain and Portugal', in R. Porter and M. Teich (eds.), *The Scientific Revolution in National Context* (Cambridge: Cambridge University Press, 1992), p. 166.

14 Crombie, *Styles*, Vol. 1, p. 433.



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14 Crombie, *Styles*, Vol. 1, p. 433.

Brunelleschi (1377-1446), the eminent Florentine architect, between about 1413 and 1425. Whether he was acquainted with Ptolemy's work is unclear. Be that as it may, the latter guided multitalented men such as P. dal Pozzo Toscanelli (1397-1482), L. B. Alberti (1404-1472), L. Ghiberti (1378-1455), Nicolaus of Cusa (1401-1464) in 'their common search for a quantified space and techniques for its measurement in astronomy, cartography, optics and painting alike'.[15]

Quantification of weight: statics and assaying

Historically, the quantification of weight by measurement has empirical origins going back to the invention of the balance with equal arms. This was in use in Egypt and Mesopotamia from 2700 BC. It seems to have taken about two and a half millennia before the balance with unequal arms was invented.[16] Its principle was known to the author of *Problems of Mechanics* who, it is now accepted, was a follower of Aristotle. He was familiar with the use as well with the properties of the lever. Thus, for instance, he asks:

> Why is it when two men carry a weight between them on a plank or something of the kind, they do not feel the pressure equally, unless the weight is midway between them, but the nearer carrier feels it more? Surely it is because in these circumstances the plank becomes a lever, the weight the fulcrum, and the nearer of the two carrying the weight is the object moved, and the other carrier is the mover of the weight.[17]

What we have here is an empirical recognition of the law of the lever as later presented by Archimedes (287-212) in a formal mathematical language. Archimedes's status as a great researcher in pure and applied mathematics was already acknowledged in antiquity. What has remained unclear was his attitude to practice. On the one hand, the biographer Plutarch (fl. 83) refers to Archimedes's disdain for the work of the engineer and for artisanal activities

15 Ibid., p. 455. For a valuable contribution on the relationship between mathematics and painting in the late Middle Ages, see J. V. Field 'Mathematics and the Craft of Painting: Piero della Francesca and Perspective', in his and Frank A. J. L. James (eds. and intr.), *Renaissance and Revolution: Humanists, Scholars, Craftsmen and Natural Philosophers in Early Modern Europe* (Cambridge: Cambridge University Press, 1993), pp. 73-95. Field underlines the Euclidian rather than the Ptolemaic impulse. English seamen in the sixteenth century began to employ astronomical observations and mathematical calculations in navigation instead of relying largely on practical experience. See S. Rose, 'Mathematics and the Art of Navigation: The Advance of Scientific Seamanship in Elizabethan England', *Transactions of the Royal Historical Society*, 14 (2004), 175-84.

16 Here, and in what follows, I draw on P. Damerow, J. Renn, S. Rieger and P. Weinig, *Mechanical Knowledge and Pompeian Balances*, Preprint 145 (Berlin: Max-Planck-Institut für Wissenschaftsgeschichte, 2000). See also G. E. R. Lloyd, *Greek Science after Aristotle* (London: Chatto and Windus, 1973), p. 48.

17 See Grant (ed.), *Source Book*, pp. 223-24, n. 22.

in general. On the other hand, his own inventive abilities are praised by authors such as Polybios (fl. 164 BC) and Livy (59 BC-AD 17). Apart from the device known as the Archimedean screw, he was said to have invented powerful contrivances for lifting and moving heavy loads, and the steelyard.

What cannot be disputed is that Archimedes thought deeply about methodological questions. That is, he was concerned about the truth of a theorem deduced geometrically. He believed that the truth of the proof demonstrated by geometry follows more easily from knowledge acquired previously through contemplation of a mechanical problem.[18]

Archimedes conceived of a mechanical problem as belonging to statics. In effect, he brought into being scientific statics and hydrostatics as a branch of mechanics with weight as its foundational category – a branch that originated empirically and was rooted in reality. This is clearly shown in the well-known, albeit apocryphal, story of Archimedes's discovery of the hydrostatic principle named after him. It enabled him to solve the problem posed by King Hiero of Syracuse as to whether the royal crown was made of pure gold.

Archimedes's prestige was so great that the authorship of medieval works on statics was wrongly ascribed to him. In comparison with his original text, however, a discernible shift occurred in the attitude towards practice. To the 'science of weights' (*sciencia de ponderibus*), as medieval statics was called, the theory underlying the mechanics of moving heavy objects was of interest. Thus the Toledan translator Domingo Gundissalvo (fl. 1140), drawing on Arabic authors, has this to say about the science of weights:

> The science of weights considers weights in two ways: either (1) according to the weights themselves that are being measured or according to what is measured with them and by them; and this is an inquiry about the principles of the doctrine on weights. Or (2) it considers them in so far as they are moved or according to the things with which they are moved; and this is an inquiry about the principles of instruments by means of which heavy bodies are lifted and on which they are changed [or carried] from place to place.[19]

Evidence for the rising awareness of worldly affairs in medieval intellectual circles is provided by the unknown author of the pseudo-Archimedean

18 Archimedes's thoughts on this are enshrined in *The Method*, an incomplete treatise. They are addressed to Eratosthenes, renowned for his remarkable method of calculating the circumference of the earth. See the translation in T. L. Heath, *The Works of Archimedes* (Cambridge: Cambridge University Press, 1912). Professor Lloyd has commented to me: 'I don't think you have got mechanics in Archimedes quite right. It is not that he tried a mechanical problem first and then turned to a geometrical analysis. The problem is mathematical from the outset. The use of mechanics is limited to the application of the two ideas that a geometrical figure can be thought of as balanced around a fulcrum'.

19 See Grant (ed.), *Source Book*, pp. 75-6.

treatise *De insidentibus in humidum* (c. 1250). He displays distinct familiarity with price-fixing in the market-place and transfers this insight to the solution of hydrostatic problems:

> Since the size of certain bodies cannot be found geometrically because of their irregular shape, and since the price of certain goods is proportional to their sizes, it was necessary to find the ratio of the volumes of bodies by means of their weights in order to fix their definite prices, knowing the volume ratios from the weight ratios.[20]

Propelled by the silver-based economy, the quantification of weight by measurement came into its own in assaying during the Middle Ages. The purpose of assaying was particularly to test for the amount of gold and silver that could be extracted from ores and to find out whether coins and the precious metals used in jewellery were pure.[21]

The assayer essentially reproduced the large-scale smelting operation quantitatively on a small scale. The process involved the recovery of silver and gold, in a stream of air, from lead beads placed in a shallow dish made of bone ash (cupel). The end of the process was signalled by the appearance of a bead of the precious metal in the dish which could then be weighed. The balance's limit of accuracy was about 0.1 milligram.

In a noteworthy characterisation of the assayers' and the refiners' craft, Rupert Hall observes that it was

> a *quantitative* craft; profit arose from successful use of the balance, for margins were small. Here, as in navigation, science and craft came close together; but while the navigator was the astronomers' pupil, the chemist descended from the assayer.[22]

A striking early illustration of science and craft connecting, in the context of assaying, is by provided by an edict of Philip de Valois in 1343.[23] It contains two *caveats*, as it were, to be observed by the assayers. First, the balance is to be accurate – leaning neither to right nor left. Second, the assayers are

20 Quoted by O. Pedersen and M. Pihl, *Early Physics and Astronomy: A Historical Introduction* (London: Macdonald and Jane's and New York: American Elsevier Inc., 1974), p. 210.

21 It is of interest that the words 'test' and 'testing' relate to the Latin '*testa*', meaning an earthenware pot or vessel employed in metallurgical operations.

22 A. Rupert Hall, 'Early Modern Technology to 1600', in M. Kranzberg and C. W. Pursell, Jr. (eds.), *Technology in Western Civilization*, Vol. 1 (New York: Oxford University Press, 1967), p. 94.

23 Here I draw heavily on F. Greenaway's 'Contribution to the Discussion of Part Three: Science and Technology in the Middle Ages', in Crombie (ed.), *Scientific Change*, pp. 329-31.

advised to perform a blank test on a sample of the lead to be assayed. The idea was to find out whether it contained silver and, if so, how much. This is not quantitative chemical analysis, but it is a step towards it.[24]

It was in the late Middle Ages that experimental weighing was beginning to interest the learned as a means of acquiring natural knowledge. Among those who realised its importance and wrote about it was that audacious thinker Nicolaus of Cusa, in his *Idiota: De staticis experimentis* (1450). As Crombie points out, Cusa envisaged a programme and proposed experimental procedures for measuring a wide range of properties and for determining by measurement the composition of different materials. Because, according to Cusa,

> By the difference of weights, I thinke wee may more truly come to the secret of things, and that many things may be known by a more probable conjecture.[25]

Cusa himself did not perform experiments. But the idea of comparing the weight of materials, before their starting and after their finishing, was eventually to lead to one of the great scientific generalisations by Lavoisier – the principle of conservation of matter (1789).

Fig. 4 Portrait of Nicolaus of Cusa wearing a cardinal's hat, in Hartmann Schedel, *Nuremberg Chronicle* (1493).

24 A. J. Ihde, *The Development of Modern Chemistry* (New York: Evanston; London: Harper and Row, 1964), p. 23.

25 Crombie, *Styles*, Vol. 1, pp. 421-22.

Fermentational and metallurgical contexts[26]

That Lavoisier formulated the principle of conservation of matter – weight of products equals the weight of reactants – from observing the chemical changes that underline the natural process of fermentation has been regarded as somewhat puzzling. But it should not be cause for surprise, seeing that historically a good deal of chemical knowledge evolved from the experience and problems of fermentation.

In effect, the formulation of the principle was the fruit of the interaction of experimentation, quantification and the theory of phlogiston, created by the German chemist Georg Ernst Stahl (1659-1734). Stahl's thinking about chemical transformation owed a good deal to the examination and discussion of processes associated with the preparation of fermented drinks and the making of bread. This was certainly one of his major interests, as indicated by his first significant chemical work, *Zymotechnia Fundamentalis*, published in Latin in 1697 and posthumously in German in 1734.

Fig. 5 Georg Ernst Stahl. Line engraving (1715).

26 See M. Teich, 'Circulation, Transformation, Conservation of Matter and the Balancing of the Biological World in the Eighteenth Century', *Ambix*, 29 (1982), 17-28.

It is noteworthy that one of the driving forces behind the translation of this work was the high expectancy of its economic effect. In the preface the anonymous translator claims, in the spirit of mercantilism, that Germany could save millions on imports if more attention were paid to the ways in which wines, beers and spirits were produced.

There can be no doubt that the close connection between theoretical chemical knowledge and its practical use accorded well with Stahl's views. Indeed, the actual impetus that got him developing the phlogiston theory was his interest in the process of smelting ores. Stahl elaborated a picture of the reduction process revolving around the release and transfer of a subtle material to the ore, postulated to be present in charcoal, that he came to call phlogiston. That is, he explained the reduction of ores as 'phlogistication' and the combustion of metals as 'dephlogistication'.

Moreover, he envisaged that phlogiston embodied the subtle matter of combustibility that *linked* the vegetable, animal and mineral kingdoms. In fact, he visualised a global circulation of phlogiston. Underlying it was the conjecture that the phlogiston of the air was absorbed by plants during their growth, then taken up in the way of vegetable food by animals, and then passed back into air through breathing.

Regarding Lavoisier, what emerges clearly is the initial impetus he received from the prize-winning essay on wine fermentation and the best way of obtaining alcohol by Abbé François Rozier in 1770. This contained the suggestion that common air played a part in the souring of wine, a process that has worried man since he became involved in its preparation. It was this idea that may have provided the first clue leading to Lavoisier's subsequent interest in the aeriform state: the physical and chemical properties of 'elastic fluids' or 'airs', including the phenomenon of heat and the composition of common air and water. Through investigations of these problems Lavoisier eventually arrived at a new conception of acidity, calcination and reduction of metals – that of combustion and respiration based on oxygen – turning on the principle of conservation of matter.

The analogy between respiration and slow combustion yielding carbonic acid and water was recognised in 1784 by Lavoisier in the quantitative work he did on a guinea pig in an ice calorimeter, conducted jointly with Pierre-Simon Laplace (1749-1827). But it was almost a decade later that this analogy, which included the generation of animal heat, was explained in the light of the transformed chemical thinking by Lavoisier in collaboration with Armand Seguin (1767-1835).

Quantification of qualities: motion, change and money

The reference to the world of commerce in a pseudo-Archimedean medieval treatise may surprise. However, during the last quarter of the twentieth century, studies appeared substantiating the thesis that medieval scholars owed more to their monetised societal setting than was previously conceded or even considered. This is brought to light when we examine the medieval approach to local motion as a problem of quantifying a quality against its socioeconomic background.

But before we return to this, it is useful to recall the strict Aristotelian separation of quality and quantity as incommensurable categories. The Aristotelian denial that qualities could be quantified was called into question, during the fourteenth century, by some of the most eminent scholastics then active in the universities of Oxford and Paris – acknowledged centres of medieval scholarship. Underlying their discussion of 'intension and remission of forms and qualities' was the belief that variations in degree of qualities were measurable (*latitudo qualitatum*).

Their work included queries into the quantifiability of divine grace but also into the quantifiability of local motion, or velocity, comprehended as continuous magnitudes. Here, as in other areas of inquiry into natural and social phenomena, medieval scholarship was confronted with Aristotelian generalisations. Regarding the speed of a body in motion, Aristotle argued that it was directly proportional to its weight ('force') and inversely proportional to the resistance of the medium in which it moved ('density'). Accordingly, any force, however small, could move any resistance, however large.

Perceiving the paradox in Aristotle's position, scholars in Oxford associated with Merton College – known as the Merton School or the Oxford Calculators – challenged it.[27] Conceiving variations in velocity as variations in the intensity of a quality mathematically, they arrived at what became known as the 'mean speed theorem'. It proposed that a uniformly accelerated velocity could be measured by its mean speed. The proposal has been hailed as 'probably the most outstanding single medieval contribution to the history of mathematical physics'.[28]

Other historically notable fourteenth-century challenges to Aristotle's approach to the motion of bodies came from Paris. Certainly Jean Buridan

27 The Merton School included Thomas Bradwardine (c. 1290-1349), John Dumbleton (died c. 1349), William Heytesbury (fl. 1235), Richard Swineshead (fl. 1340-1355).

28 Grant, *Foundations*, p. 101.

(c. 1300-c. 1350) was critical of Aristotle's notion that the movement of a projectile depended on the propelling action of the air. He found Aristotle's explanation unsatisfactory because it was contradicted by experience:

> The first experience concerns the top (*trocus*) and the smith's mill (i.e. wheel-*mola fabri*) which are moved for a long time and yet do not leave their places. Hence, it is not necessary for the air to follow along to fill up the place of departure over a top of this kind and a smith's mill. So it cannot be said [that the top and the smith's mill are moved by the air] in this manner.
>
> The second experience is this: A lance having a conical posterior as sharp as its anterior would be moved after projection just as swiftly as it would be without a sharp conical posterior. But surely the air following could not push a sharp end in this way because the air would be easily divided by the sharpness.
>
> The third experience is this: a ship drawn swiftly in the river even against the flow of the river, after the drawing has ceased, cannot be stopped quickly, but continues to move for a long time. And yet a sailor on deck does not feel any air from behind pushing him. He feels only the air from the front resisting [him]. Again, suppose the said ship were loaded with grain or wood and a man were situated to the rear of the cargo. Then if the air were of such an impetus [that it] could push the ship along so strongly, the man would be pressed very violently between that cargo and the air following it. Experience shows this to be false. Or, at least, if the ship were loaded with grain or straw, the air following and pushing would fold over (*plico*) the stalks which were in the rear. This is all false.[29]

The point of this is to bring to attention that practical activities had affected medieval scholastic thinking. Without doubt Buridan, who was Rector of the University of Paris according to documents in 1328 and again in 1340, took them on board. In the course of his studies of motions of material bodies, Buridan developed the notion of *impetus*. He associated it with the motive force imparted to the body by the agent that set it in motion. Viewed in retrospect, Buridan was coming to grips with the tendency of bodies in motion towards inertia which was to occupy the minds of René Descartes (1596-1650), Gottfried Wilhelm Leibniz (1646-1716) and Newton (1643-1727).[30]

It is noteworthy that Buridan employed *impetus* to discuss whether God is in need of assistance to move celestial bodies. Buridan found that God can do without it – his pervasive sway is sufficient to keep them going.

29 J. Buridan, *The Impetus Theory of Projectile Motion*. Transl., intr., and annotated by Marshall Clagett, in Grant (ed.), *Source Book*, pp. 275-76.

30 According to Buridan, 'by the amount the motor moves that moving body more swiftly, by the same amount it will impress in it a stronger impetus'. Ibid., p. 277. This measure of *impetus*, as has been often observed, recalls Newton's *momentum* as defined by the product of mass multiplied by velocity.

Prefiguring Newton, in fact, Buridan proposed that once launched by God such bodies are on their own – possibly for eternity. However, in order to avoid accusations of advancing opinions contrary to the teachings of the Church, Buridan was at pains to stress:

> But this I do not say assertively, but [rather tentatively] so that I might seek from the theological masters what they might teach me in these matters as to how these things take place....[31]

It remains uncertain whether Buridan's *impetus* theory influenced Nicole Oresme when he compared God to a celestial clockmaker allowing the heavens to move, like clockwork on their own.[32]

Oresme is celebrated more often than not for employing geometrical lines and figures to represent and quantify qualities and motions.[33] His novel method is comprehensibly described in Kaye's account as follows:

> [Oresme's] new approach, which he outlined clearly in the first part of his *De configurationibus*, was to construct a dual system of coordinates capable of representing at the same time the intensity of a quality and the extension of the subject in which the quality inhered. In Oresme's scheme, the extension of a given subject in space or time was measured by a base line [longitude], and the intensities of the quality or motion in that subject were represented by perpendicular lines erected on the base line [latitude]. Greater or lesser intensities at various points in the subject were represented by proportionally longer or shorter lines erected on the base line at these points. When drawn, these measuring lines along two coordinates formed two-dimensional surfaces of varying geometrical configurations and sizes.[34]

Thus the configuration of a quality or motion of uniform intensity – the heights of all vertical lines being the same – had to be a rectangle. A quality or motion of uniformly varying intensity was categorised by Oresme as 'uniformly difform', e.g. uniformly accelerated motion. It was represented by a right triangle.

Oresme was interested not only in the geometric representation of quality and motion but also in the measurement of the quantity of the quality of motion, a quantity which he imagined to be equal to the product of intensity and extension. Moreover, he arrived at what amounted to a geometric proof

31 Ibid., pp. 277-78.
32 See Crombie, *Augustine to Galileo*, p. 255.
33 See N. Oresme, *The Configurations of Qualities and Motions, including a Geometric Proof of the Mean Speed Theorem*. Transl., intr., and annotated by Marshall Clagett, in Grant (ed.), *Source Book*, pp. 243-52.
34 Kaye, *Economy and Nature*, p. 204.

of the mean speed theorem in which the areas of the rectangle (representing a uniform motion) and the right triangle (representing acceleration) are shown to be equal. The geometric demonstration of the theorem was to influence the analysis of motion for the next 250 years or so.

To view Oresme's two-dimensional procedure as foreshadowing Cartesian analytical geometry is problematic. The simultaneous representation of the extension of a given subject in space or time and the intensity of a quality or motion was not equivalent to the axial system, named the 'Cartesian coordinate system'. Rather, it was a device to demonstrate geometrically that 'quantity (extension) and quality (intension) were bound together in a dynamic proportional relationship'.[35]

What marks Oresme off from medieval scholars concerned with proportionality was, as Grant puts it, his 'fascination with the subject of commensurability and incommensurability in mathematics, physics and cosmology ... [as] evidenced by a number of treatises in which he saw fit to discuss or at least to mention it'.[36]

In fact, Oresme's intellectual interests extended beyond the natural world. Among other works, he wrote a very influential treatise on money and minting known under its abbreviated title *De moneta*.[37] The question suggests itself as to whether Oresme's scientific and economic thinking connect and, if so, in which context. This issue has been perceptively addressed by Kaye in his treatment of areas of historical investigation that are rarely considered together: economic history, the history of economic thought and the history of science on which much of what follows is based.[38]

Monetisation and market developments

Kaye's point of departure is the development of the power and weight of the market place within European feudal society during the twelfth and thirteenth centuries. This growth had to do with the development of towns as centres of trade and handicraft production. Factors in this process, as well as products

35 Ibid., p. 206.
36 Grant (ed.), *Source Book*, p. 529.
37 The work's title is given as *Tractatus de origine et natura, iure, et mutationibus monetarum* and is said to have been written sometime between 1355-1360. See Charles Johnson (ed. and transl.), *The "De moneta" of Nicholas Oresme and English Mint Documents* (London: T. Nelson, 1956).
38 Kaye, *Economy and Nature*, pp. 9-10. For a related study, see A. W. Crosby, *The Measure of Reality: Quantification and Western Society, 1250-1600* (Cambridge: Cambridge University Press, 1998).

of it, were widening monetisation and heightening monetary consciousness. These connect to the subject of Oresme's *De moneta*, in which the state's policy of debasement of coinage is critically examined. The devaluation and revaluation of coins were undermining money's role as a socially-accepted general equivalent to the value of commodities. Here was a situation, as Kaye notes, in which society experienced relativity and proportionality on a grand scale. It furnishes the social background to analysis, for instance, of Oresme's and Buridan's relativistic ideas about whether the earth is always at rest in the centre of the universe.

There is a good deal of evidence that the scholastic thinkers of Oxford, Paris and elsewhere were not cloistered intellectuals but engaged in academic and ecclesiastical administration, financial operations and politics. They could not avoid becoming aware of the pervasive social and economic impact of expanding merchant capital on the feudal economy and society.

Indeed, the term 'capital' in its Latin version *capitale* here enters the economic vocabulary for apparently the first time. It appears in a thirteenth-century work entitled *De contractibus usurariis*, composed by Peter John Olivi (Pierre de Jean Olieu), who hailed from the Provence and lived from 1248-1298. He was a member of the Franciscan order and a leader of the faction pressing for a return to the order's original commitment to spiritual things and values. In fact, after Olivi's death the Franciscan superiors deemed his works to be heretical and ordered their destruction.

Though Olivi opposed Franciscan participation in the economic process, he understood that it constituted a core element of social reality, one cardinally affected, as it were, by the exchange of commodities for money. Versed in Roman and canon law-thinking on lending, and familiar with lending practices in the commercial world, Olivi arrived at the notion of *capitale*. At its simplest, it represented the accrued value of borrowed money due to the skilful activities of the investor. Olivi speculated that the relationship between a striker or thrower of an object and the object he sets in motion corresponds to the relationship between an investor and the borrowed money he turns into *capitale*. It has been argued that this analogy amounted to the first formulation of the concept of impetus.[39]

39 Here I draw on M. Wolff's stimulating *Geschichte der Impetustheorie* (Frankfurt am Main: Suhrkamp, 1978), pp. 163f.; see also idem, 'Mehrwert und Impetus bei Petrus Johannis Olivi', in J. Miethke and K. Schreiner (eds.), *Sozialer Wandel im Mittelalter* (Sigmaringen: Thorbecke, 1994), pp. 413-23. For a biological Aristotelian approach to impetus theory, see J. Fritsche, 'The Biological Precedents for Medieval Impetus Theory and its Aristotelian Character', *The British Journal for the History of Science*, 44 (2011), 1-27. For further information, see R. W. Hadden, *On the Shoulders of Merchants Exchange and the Mathematical Conception of Nature in Early Modern Europe* (Albany, N.Y.: State University of New York Press, 1994), p. 100.

Be that as it may, we have here medieval perceptions of economic and natural phenomena interacting which, on examination, led Kaye to conclude:

> While the physical basis of reality does not change, the social basis of reality does. Over this period society was transformed through the many-faceted social processes of monetization and market development. Every level of society and every layer of institutional growth was affected. Philosophers, from their earliest days as students, were presented with social and economic experiences, rules of conduct, avenues of advancements and models of success unknown by previous generations. As social experiences change, so too do perceptions about how the world functions and is ordered.
>
> The rigorous intellectual training of the university and its intense atmosphere of challenge and disputation transformed raw perceptions into insights capable of being elaborated through the technical instruments of mathematics and logic. The scholastic habit of synthesis encouraged the linking of insights and principles between different spheres of thought, between the comprehension of the economic order and the comprehension of the natural order. The result was the creation of a new image of nature based on the experience and observation of monetized society: a dynamic, relativistic, geometric, self-ordering, and self-equalizing world of lines. It was upon this model of nature, first imagined in the fourteenth century, that thinkers from Copernicus to Galileo constructed the 'new' science.[40]

Edward Grant's depiction of the medieval societal environment in which knowledge of nature developed appears distinctly narrow in this light. It is insufficient to equate this environment with the translation of Greco-Arabic learning into Latin, the formation of the medieval university and the rise of the theologian/natural philosopher.

Social relations of experimentation

The historic issue is the role of the form of capital, termed merchant capital, in the first phase of the transition from feudalism to capitalism. These are Marxist conceptions advanced for the understanding of the pre-industrial phase of capitalism in Europe. That is, the phase in which the control of capital over the monetary exchange was of greater importance than its

40 Kaye, *Economy and Nature*, pp. 245-46. See also J. Day, 'Shorter Notices', *The English Historical Review*, Vol. 109/432 (1994), 701.

domination over the production process, constrained, as it was, by urban guilds.

This dynamic certainly emerges from David Abulafia's incisive review of Italian banking in the late Middle Ages. But, along with other historians, Abulafia appears to be reluctant to employ the term 'capitalism' in the context of pre-industrial economies.[41] Be that as it may, it is worth noting that the prominent non-Marxist student of the Scientific Revolution, Steven Shapin, has recourse to the concept of the transition from feudalism to capitalism in Europe between the fifteenth and seventeenth centuries. He identifies this period as one of recognisable societal change, during which mechanical modes of explaining natural phenomena were in the ascendancy. The transformation of the intellectual climate during this period was fuelled by the mounting awareness of mechanical devices in everyday life, symbolised by the clock:

> The allure of the machine, and especially the mechanical clock, as a uniquely intelligible and proper metaphor for explaining natural processes not only broadly follows the contours of daily experience with such devices but also recognizes their potency and legitimacy in ordering human affairs. That is to say, if we want ultimately to understand the appeal of mechanical metaphors in the new scientific practices – and the consequent rejection of the distinction between nature and art – we shall ultimately have to understand the power relations of an early modern European society whose patterns of living, producing, and political ordering were undergoing massive changes as feudalism gave way to early capitalism.[42]

Thus reflecting the course of events, Leibniz acknowledges in 1671 the preference of contemporary natural philosophers for a mechanistic interpretation over the dominant organicist philosophy of Aristotle: 'All modern philosophers desire to explain natural phenomena mechanistically'.[43] Around this time the term 'mechanical philosophy', coined according to all accounts by Robert Boyle, entered scholarly vocabulary.

41 D. Abulafia, 'The Impact of Italian Banking in the Late Middle Ages and the Renaissance, 1300-1500', in A. Teichova, G. Kurgan-van Hentenryk and D. Ziegler (eds.), *Banking, Trade and Industry: Europe, America and Asia from the Thirteenth to the Twentieth Century* (Cambridge: Cambridge University Press, 1997), pp. 18, 31.

42 S. Shapin, *The Scientific Revolution* (Chicago, IL and London: University of Chicago Press, 1998), p. 33.

43 'Desiderant omnes philosophi recentiores physica mechanice explicari'. Quoted by H. Mayer, 'Gott und Mechanik Anmerkung zur Geschichte des Naturbegriffs im 17. Jahrhundert', in S. Mattl and others, *Barocke Natur* (Korneuburg: Ueberreuter, 1989), p. 12.

Fig. 6 Portrait of Robert Boyle by Johann Kerseboom (c. 1689).

Among the numerous publications dealing with the work and life of the 'father of the steam-engine', Steven Shapin and Simon Schaffer's *Leviathan and the Air-Pump* has attracted wide attention. They wanted 'to understand the nature and status of experimental practices and their historical products' and they wanted their 'answers to be historical in character'. To that end they write:

> we will deal with the historical circumstances in which experiment as a systematic means of generating natural knowledge arose, in which experimental practices became institutionalized, and in which experimentally produced matters of fact were made into the foundations of what counted as proper scientific knowledge. We start, therefore, with that great paradigm of experimental procedure: Robert Boyle's researches in pneumatics and his employment of the air-pump in that enterprise.[44]

Here the reader is reminded that the two essential and intertwined aspects of science – systematic and quantitative experimentation, on the one hand, and institutionalisation (about which later), on the other – were coming into their own in the seventeenth century.

In fact, the vacuum pump was one of the first of the complex and large machines to be developed for laboratory use (the electrical machine was the

44 S. Shapin and S. Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton, NJ: Princeton University Press, 1985), p. 1. Note: 'The father of the steam engine would be a better title for Robert Boyle than the "father of chemistry"'. A. Rupert Hall, *The Revolution in Science, 1500-1750* (London and New York: Longman, 1983), p. 338.

other).[45] According to Shapin and Schaffer, it was the intellectual production ('matters of fact') by means of a purpose-built scientific machine that made Boyle's experimentation an historical milestone. For one thing, the novel technology for the experimental investigation of air-pressure ('spring of air') clarified why suction pumps would not raise water more than about ten metres – an obstacle for the development of mining in the deep. For another, it gave the lie to the denial of a void in nature – an essential component of Aristotelian physics. Last but not least, from the tabulated measurements of pressures and volumes of air it emerged that their product is the same (1662). Historically, the reciprocal relationship, known as Boyle's Law, is considered to be the first experimental physical law.

There is widespread agreement, however, that the celebrated air-pump experiments were performed by Robert Hooke (1635-1703) and not by Boyle, his employer and backer of many years. All the same, Boyle wished to make a personal point when he stated:

> And though my condition does (God be praised) enable me to make experiments by others' hands; yet I have not been so nice, as to decline dissecting dogs, wolves, fishes and even rats and mice, with my own hands. Nor, when I am in my laboratory, do I scruple with them naked to handle lute and charcoal.[46]

Here Boyle, the wealthy gentleman, clearly signalled that it was not socially demeaning to engage in hands-on experimentation. Moreover, he exhorted scientists

> to disdain, as little as I do, to converse with tradesmen in their work houses and shops ... he deserves not the knowledge of nature, that scorns to converse even with mean persons, that have the opportunity to be conversant with her.

In general, what the natural philosophers endeavoured to comprehend in their workshops (laboratories) was matter in motion. It underlay the processes that craftsmen and artisans were empirically mastering while plying their trades in their workshops. The natural philosophers' growing awareness of the contiguity of these activities weakened the reasoning that underwrote the traditional distinction between nature and art – it was not confined to England.

45 S. A. Bedini and D. J. da Solla Price, 'Instrumentation', in Kranzberg and Pursell, Jr. (eds.), *Technology*, Vol. 1, p. 178.

46 This and the following quotation are from J. G. Crowther, *The Social Relations of Science* (New York: The Macmillan Company, 1942), pp. 364-65.

Take the sixteenth-century Czech polymath Tadeáš Hájek z Hájku (1525-1600), also known as Thaddeus Hagecius or Nemicus. He was ennobled on being appointed in 1571 to the post of Chief Medical Officer of Bohemia; moreover, because of his astrological and alchemistic interests he became an influential figure at the court of Emperor Rudolph II (1576-1612) in Prague. In 1585 he published in Frankfurt am Main a small book on brewing: *De cerevisia eiusque conficiendi ratione natura viribus et facultatibus opusculum*.[47]

What lay behind Hagecius's interest in beer? There was the medical and pharmaceutical dimension. It appears that the suggestion to write the booklet came to Hagecius from a personal physician of Rudolph II. But beyond that, there is the growth of a large scale manorial economy in Bohemia to consider. Centred on sheep-farming, brewing and raising fish (carp), as well as on glass and iron making, this economy was directed towards augmenting the declining cash income of the lord of the manor.[48] Thus the lord evolved into a large scale entrepreneur within the feudal system and, unwittingly, into an accessory to its dissolution.

The steps taken by Hagecius to become acquainted with brewing practice recalls Boyle's advice to natural philosophers not to shy away from seeking enlightenment from socially inferior practitioners. Ignorant of brewing, Hagecius consulted with humble brewers who provided him – as he acknowledges – with information that was full, though simple and unsystematic. Poignantly, he regarded the production of beer as a legitimate

47 Hagecius has a place in the history of astronomy. First, his findings related to the discovery of a new star in the Cassiopeia constellation (1572). He established that the star must be further from the Earth than the moon and must therefore be a fixed star. This disclosure contributed to the supplanting of the Aristotelian doctrine of two disjointed regions, sublunary and supralunary. He took a similar line in his writing on the comet that appeared in 1577. Moreover, he was behind Rudolph II's invitation to Tycho Brahe (1546-1601) to move to Prague. The life and work of Hagecius is examined by eighteen authors in the collection edited by P. Drábek, *Tadeáš Hájek z Hájku* (Prague: Společnost pro dějiny věd a techniky, 2000). The stock of factual knowledge about Hagecius's life is critically scrutinised by J. Smolka, 'Thaddaeus Hagecius ab Hayck, Aulae Caesarae Majestatis Medicus', in Gertrude Enderle-Burcel, E. Kubů, J. Šouša and D. Stiefel (eds.), *"Discourses – Diskurse" Essays for – Beiträge zu Mikuláš Teich & Alice Teichova* (Prague and Vienna: Nová tiskárna Pelhřimov, 2008), pp. 395-412. For a brief introduction in English to the period, including Hagecius's significance, see J. Smolka, 'The Scientific Revolution in Bohemia', in Porter and Teich (eds.), *Scientific Revolution*, pp. 210-39. For an English response to the discovery of a new star in Cassiopeia, see S. Pumfrey, '"Your Astronomers and Ours Differ Exceedingly": The Controversy over the "New Star" of 1572 in the Light of a Newly Discovered Text by Thomas Digges', *The British Journal for the History of Science*, 44 (2011), 29-60.

48 The elements of this economy are echoed in a well-known contemporary German saying: 'Schäfereien, Brauereien und Teich, machen die böhmischen Herren reich'.

field for scientific inquiry and rejected the notion that it was an undignified scholarly pursuit. Clearly, Hagecius did not perceive the worlds of intellectual and manual labour to be separated by an impervious wall.

It is in this context that it is convenient to turn to Shapin and Schaffer's account of Thomas Hobbes's (1588-1679) critique of Boyle's methodology. He took issue with the notion that trustworthy natural knowledge can come by way of (air-pump) experimentation.

For Hobbes, the idea that the Boyleian pneumatic experiments, including crucial measurements of 'the spring of air', could establish the existence of the vacuum was defective in three related ways. To begin with, Hobbes held labouring in a laboratory to be akin to the labours of 'workmen', 'apothecaries', 'gardeners' and, therefore, a class-bound manual activity beneath a philosopher's dignity. Experiment was one thing, philosophy another. By its very nature, knowledge produced by the former was inferior to that generated by the latter.

As to philosophy proper, Hobbes subscribed to plenism, a form of materialism asserting that the world of nature is a plenum made of bodies in motion, there being no room for 'free space', i.e. vacuum.

Finally, Hobbes was in matters of politics a fervent advocate of absolute monarchy. Shapin and Schaffer stress that 'Hobbes's philosophical truth was to be generated and sustained by absolutism'.[49] This serves to remind us that they – unorthodoxly – seek 'to read *Leviathan* as natural philosophy'.[50] Unorthodoxly in the sense that the book has been perceived as a political tract, indeed, as 'the greatest work of political philosophy ever written in English'.[51]

Shapin and Schaffer's exegesis of Hobbes's rejection of vacuism on political grounds is bold:

> ...the argument against vacuum was presented within a political context of use … He recommended his materialist monism because it would assist in ensuring social order. He condemned dualism and spiritualism because they had in fact been used to subvert order … For Hobbes the rejection of vacuum was the elimination of a space within which discussion could take place.[52]

The employment of the term 'social order' is not clear. Does it refer to a 'political order' (probably) or to a type of society (feudal, capitalist – less likely)?

49 Shapin and Schaffer, *Leviathan*, p. 339.

50 Ibid., p. 92.

51 Cf. promotional description of *Hobbes and Republican Liberty* (Cambridge: Cambridge University Press, 2008), authored by Quentin Skinner.

52 Shapin and Schaffer, *Leviathan*, pp. 99, 109.

At all events, the cited passage and other statements hinge on Shapin and Schaffer's introduction and usage of the term 'space' in a wider sense. Thus 'experimental space' refers to congregations in laboratories for performing/witnessing experiments. Whereas 'philosophical space' or 'intellectual space' bear upon participation in scientific debates and the meetings of groups such as the newly founded Royal Society.

Hobbes denies natural philosophers the right to such activities because they could undermine the sovereignty of absolute monarchy, in his understanding of it. As noted by Shapin and Schaffer:

> Speech of a vacuum was associated with cultural resources that had been illegitimately used to subvert proper authority in the state.[53]

The state in question is absolute monarchy. Absolutism is said to be 'the first international State system in the modern world'.[54] Concurrent to its development, the institutional pursuit of natural knowledge (through scientific societies and journals) was evolving and transcending national boundaries. The contemporaneousness is not accidental: both realms, the political and the scientific, were products of and agents in the transition from feudalism to capitalism. The complexities of the transition over time, involving multiple factors (politics, economy, ideology, wars, etc.), do not allow here for an analysis directed towards a primary cause. But it is worth noticing that during its early phase, systematic and quantitative experimentation became an integral part of the pursuit of natural knowledge opposed by Hobbes, acquiring in the long run a degree of relative autonomy in relation to the state.

Regarding the status of experiment in scientific advancement, Boyle prevailed over Hobbes. What about the status of hypothesis which, famously, was of great concern to Newton? Can it be said that Boyle's empiricism triumphed over Hobbes's rationalism? That would be a simplistic choice with regards to the philosophies of both protagonists. Certainly, it does not reflect the position of the Royal Society, which from its inception (1600) until the early eighteenth century 'was the chief European centre of experimental

53 Ibid., p. 91. Here, perhaps, it is appropriate to refer to the attention Quentin Skinner pays to Hobbes's description of liberty in *Leviathan* 'according to the proper signification of the word': 'As soon as we leave the world of nature, however, and enter the artificial world of the commonwealth, we are no longer simply bodies in motion; we are also subjects of sovereign power'. Skinner, *Hobbes*, pp. 162-63. Shapin and Schaffer's book is not listed among Skinner's 'Printed secondary sources'.

54 P. Anderson, *Lineages of the Absolute State* (London: New Left Books, 1974), p. 11.

physics'.[55] As Marie Boas Hall puts it in her close analysis of science in the Royal Society in the seventeenth century:

> However much the Society as a body might hesitate to favour hypothesis, its aim was to establish something more than a collection of random experiment. Mere matter of fact was not valued for itself, but for light it could shed on the Society's object, the establishment of a true philosophy of nature.[56]

55 Rupert Hall, *Revolution*, p. 260.

56 M. Boas Hall, 'Science in the Early Royal Society', in M. Crosland (ed.), *The Emergence of Science in Western Europe* (London and Basingstoke: Macmillan, 1975), pp. 61-2.

3. Institutionalisation of Science

England

The founding of the Royal Society has been linked to the thinking of Francis Bacon (1561-1626) on organised science (about which more in the next chapter). The Royal Society is the premier scientific body in Britain, and some would claim the world, but it is not the oldest.

Two short-lived Italian organisations, Accademia dei Lincei (Academy of the Lynxes) in Rome (1609-1630, or 1603-1651) and Accademia del Cimento (Academy of the Experiment) in Florence (1657-1667), are usually listed as the earliest instances of the modern institutionalisation of science. The distinction of the oldest continuously active scientific society belongs to the Deutsche Akademie der Naturforscher Leopoldina (German Academy of Naturalists Leopoldina). Its founding preceded the incorporation of the Royal Society of London by ten years (1652).[1]

The Royal Society's proximate beginnings go back to 1660, when a group of mathematicians, astronomers and physicians, interested in promoting systematic and experimental knowledge of nature, began meeting weekly at Gresham College in the City of London. The meetings had an informal character but very soon developed into the formal operations of a private

1 It was founded as the Academia Naturae Curiosorum on 1 January 1652, by four physicians in the then Imperial Freetown of Schweinfurt (now Bavaria). In 1670 Emperor Leopold I (1640-1705) ratified it as the Sacri Romani Imperii Academia Naturae Curiosorum. In 1687 he sanctioned its prerogative as an independent imperial institution (a rare if not unique case in fragmented Germany), and it became known as the Sacri Romani Imperii Academia Caesareo Leopoldina Naturae Curiosorum. See L. Stern, *Zur Geschichte und wissenschaftlichen Leistung der Deutschen Akademie der Naturforscher "Leopoldina"* (Berlin: Rütten & Loening, 1952). On the neglected Florentine Academy, see M. Beretta, A. Clericuzio and L. M. Principe (eds.), *The Accademia del Cimento and its European Context* (Sagamore Beach, MA: Science History Publications, 2009).

http://dx.doi.org/10.11647/OBP.0054.03

society. It was granted two royal charters by Charles II (1630-1685), in 1662 and 1663 respectively, and was denominated Regalis Societas Londini pro Scientia naturali promovenda. From the start the Royal Society became, and has since remained, a self-governing organisation whose members – Fellows of the Royal Society – are charged a fee for belonging to a social club, as it were.[2]

Fig. 7 View from above of Gresham College, London, as it was in the eighteenth century. By unknown artist, after an illustration in John Ward, *Lives of the Professors of Gresham College* (1740).

The founding of Gresham College (still in existence) goes back to a bequest by Sir Thomas Gresham (?1515-1579). One of the great merchants of the day, he also founded the Royal Exchange of London (1568). Gresham College was primarily an educational institution providing instruction in divinity, astronomy, music, geometry, law, medicine and rhetoric. By 1645, it had also become one of the venues for the coming together of persons interested in discussing scientific problems and in experimenting. In the wake of the Puritan Revolution, some members of the group moved to Oxford (1648-1649) where the Oxford Experimental Philosophical Group at Wadham College

2 The origins of the Royal Society have been the subject of a seemingly unending series of studies. Thomas Sprat (later Bishop of Rochester) compiled its first history when it was five years old (1667): *The History of the Royal Society in London*. It has been reprinted and edited with critical apparatus by J. I. Cope and H. W. Jones (St. Louis, MI: Washington University Studies, 1958). It is still of value, as are T. Birch, *The History of the Royal Society of London, for Improving of Natural Knowledge, from its First Rise*, 4 vols. (London: printed for A. Millar, 1756-1757) and C. R. Weld, *A History of the Royal Society*, 2 vols. (London: J. W. Parker, 1848). Charles Webster provides a perceptive picture of the complex origins of the Society in his encyclopaedic *The Great Instauration: Science, Medicine and Reform, 1626-1660* (London: Duckworth, 1975). He discusses the roles of controversial figures such as Robert Boyle, Samuel Hartlib (c. 1600-1652) and Comenius (Jan Amos Komenský (1592-1670)). The 350th anniversary was marked by 22 contributions to B. Bryson (ed. and intr.), *Seeing Further: The Story of the Royal Society* (London: HarperPress, 2010).

was established. According to the mathematician John Wallis (1616-1703), the London group (meeting weekly) agreed that

> (to avoid diversion to other discourses, and for some other reasons) we barred all discourses of divinity, of state-affairs, and of news, other than what concerned our business of Philosophy.[3]

This emphasis on the separation of questions belonging to the province of natural sciences from those concerning theology and politics is significant. The same idea reappears in the widely quoted draft preamble to the Statutes of the Royal Society ascribed to Hooke in 1663:

> The business and design of the Royal Society is – To improve knowledge of naturall things, and all useful Arts, Manufactures, Mechanick practises, Engynes and Inventions by Experiments – (not meddling with Divinity, Metaphysics, Moralls, Politicks, Grammar, Rhetorick, or Logick).[4]

It was after the restoration of the monarchy that Gresham College became the venue for weekly meetings of the Royal Society. Composed at the time, the following four sextains (from a poem containing twenty-four) are of more than passing interest. They document the contemporary awareness of the intertwined worlds of science and overseas commerce. In this context the problem of determining longitude loomed large – not to be solved until 1764 by the Yorkshire carpenter John Harrison. Significantly, what was taught at Oxford and Cambridge is here derided in comparison to the learning of the Greshamites. While the Aristotelian rejection of atomism is laughed at, the Epicurean view that nothing exists besides the atoms and the void is approved of:

> The Merchants on the Exchange doe plott
> To encrease the Kingdom's wealthy trade;
> At Gresham College a learned knott,
> Unparallel'd designs have lay'd,
> To make themselves a corporation,
> And know all things by demonstration.
>
> This noble learned corporation,
> Not for themselves are thus combin'd,
> But for the publick good o' th' nation,
> And general benefit of mankind.
> These are not men of common mould;
> They covet fame, but condemn gold.

3 See Sprat's *History of the Royal Society*, Appendix A.
4 Weld, *Royal Society*, Vol. 1, p. 146.

This College will the whole world measure,
Which most impossible conclude,
And navigation make a pleasure,
By finding out the longitude:
Every Tarpaulian shall then with ease
Saile any ship to the Antipodes

The College Gresham shall hereafter
Be the whole world's University;
Oxford and Cambridge are our laughter;
Their learning is but pedantry;
These new Collegiates do assure us,
Aristotle's an ass to Epicurus.[5]

John Wallis was one of the original Greshamites, active in discussing the new scientific advances. Another member of the group was Theodore Haak (1605-1690), a native of the Rhenish Palatinate, who is reputed to have initiated its meetings in 1645, after returning from a diplomatic mission in Denmark in the service of the English Parliament. Also, he was erroneously reported to have invested the group with the name of the 'Invisible College'. As Charles Webster points out, this was a separate body, small and short-lived (?1646-1647), in which Boyle was involved. Webster's scepticism regarding the bearing of the Invisible College on the genesis of the Royal Society stems from Boyle's limitation of 'the principles of our new philosophical college' to 'natural philosophy, the mathematics, and husbandry ... that values no knowledge but as it hath a tendency to use'.[6]

Comenius and the Royal Society[7]

In accordance with this utilitarian thinking, Boyle was drawn to the circle around Samuel Hartlib that was concerned with what may be briefly described as 'practical millenarianism'. He hailed from Prussian Elbing (now Elbląg in Poland), which had strong commercial ties with England. Hartlib's mother was English and, like Haak (who belonged to the same circle), he settled

5 Ibid., pp. 79-80, n. 10. Peter Dear points out that Gresham College intended to provide instructions to sailors and merchants in useful arts, and especially in practical mathematical techniques. See his *Revolutionizing the Sciences: European Knowledge and its Ambitions, 1520-1700* (Basingstoke: Palgrave, 2001), p. 53.

6 Webster, *Great Instauration*, p. 61, n. 100.

7 What follows draws in part on my article 'The Two Cultures, Comenius and the Royal Society', *Paedagogica Europea*, 4 (1968), 147-53.

in England. There he became known as a patron and instigator of projects sustaining human progress through improvements in agriculture, reforms of education and promotion of religious peace. Though sympathetic to Bacon's vision of an organised empirical interrogation of nature, he considered it to be too secular.

It is in this context that Hartlib found the writings of the exiled Czech educational reformer Comenius more congenial. In the wake of the Counter-Reformation, after the defeat of the rebellious estates of Bohemia and their allies in the Battle of White Mountain near Prague (1620), Comenius – a member and priest of the proscribed Unitas Fratrum – in 1628 was forced to emigrate, first to the Polish Leszno. There he composed *Conatuum Comenianorum praeludia etc.*, published at Hartlib's behest in Oxford (1637). The work contained an outline of Comenius's 'pansophic' Christian epistemology, rooted in the amalgamation of the senses, reason and revelation.[8]

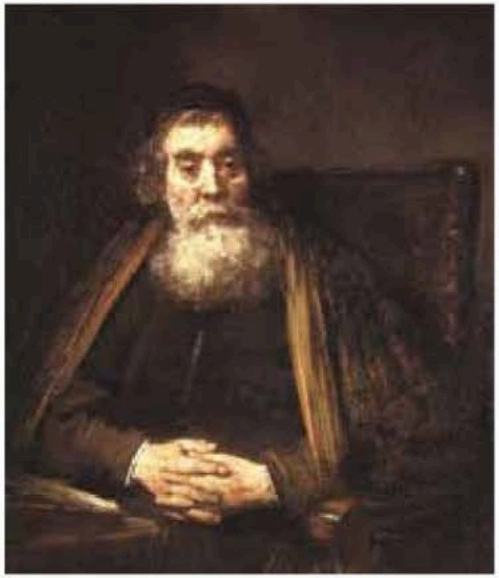

Fig. 8 Portrait of an old man thought to be Comenius (c. 1661) by Rembrandt. Florence, Uffizi Gallery.

8 For Descartes's critique, see his letter to Hogelande, August 1638 (?), in A. Kenny (ed. and transl.), *Descartes Philosophical Letters* (Oxford: Clarendon Press, 1970) pp. 59-61. An up-to-date account of Comenius's life and work in English is badly needed. For a brief and convenient treatment in Czech, see J. Polišenský, *Komenský: Muž labyrintů a naděje* [*Komenský: Man of Labyrinths and Hope*] (Prague: Academia, 1996).

Hartlib, who corresponded with Comenius from 1632 and procured some financial aid for him, was the leading spirit behind attempts to move him to England. Arriving on 23 September 1641, it appears that Comenius was to head a body that

> would assimilate the most advanced information in each sphere of knowledge, their collaborative enterprise leading to an encyclopaedic understanding of the material world and the solution of religious controversies among the Protestants, to assist the subsequent reform of the church and education.[9]

The social and political upheavals following the outbreak of the Civil War prevented the realisation of this plan and, in the end, Comenius left England via Holland for Sweden on 21 June 1642. A glimpse of Comenius's vision what this body of scholars could have done may be obtained from the work written during his stay in England. Briefly entitled *Via Lucis*, it was printed in Amsterdam in 1668 and dedicated to the Royal Society. The rational kernel of *Via Lucis* is usually summarised as a plan for a universal language, universal schools and a universal college.[10]

It is no accident that Comenius decided to publish *Via Lucis*, after such a long interval since its composition, within a year of the *History of the Royal Society* being issued by Sprat. While paying respect to Bacon's ideas on collective scientific endeavour, Comenius considered the Royal Society to be *the* body which could and should have carried out his ideas in practice. Yet he clearly perceived that this happened only in part and that there were important differences between the project set out in *Via Lucis* and the route taken by the Royal Society.

Comenius points out that the glorious efforts by the Fellows of the Royal Society, as shown by the published records, have a beautiful affinity with those aims put down in chapter XVI of *Via Lucis*, beginning with paragraph 12. This part of the book deals with Panhistoria. What Comenius had in mind was to compose a critical inductive historical survey of man's knowledge of natural and artificial, moral and spiritual processes in order to sift truth

9 C. Webster (ed.), *Samuel Hartlib and the Advancement of Learning* (Cambridge: Cambridge University Press, 1970), p. 29.

10 The full title: *Via lucis, vestigata et vestiganda, hoc est rationabilis disquisitio, quibus modis intellectualis animorum Lux, Sapientia, per omnes omnium hominum mentes, et gentes, jam tandem sub mundi vesperam feliciter spargi posit. Libellus ante annos viginti sex in Anglia scriptus, nunc demum typis exscriptus et in Angliam remissus* (Amsterdam: Apud Christophorum Cunradu, 1668). At the time of writing, I was informed by Cambridge University Library that the copy of the English translation by E. T. Campagnac (Liverpool: Liverpool University Press, 1938) had been missing since 2007. I used the Czech-Latin version instead: *J. A. Comenii Via Lucis J. A. Komenského Cesta světla* (Prague: Státní Pedagogické Nakladatelstvi, 1961).

from error.[11] In light of this, it is not without interest to learn that some of the Fellows of the Royal Society, according to Sprat, were required

> to examine all Treatises, and Descriptions, of the Natural, and Artificial productions of those Countries in which they would be inform'd ... They have compos'd Queries, and Directions, what things are needful to be observ'd in order to the making of a Natural History in general: what are to be taken notice of towards a perfect History of the Air, and Atmosphere, and Weather: what is to be observ'd in the production, growth, advancing, or transforming of Vegetables: what particulars are requisite for collecting a compleat History of the Agriculture, which is us'd in several parts of this Nation.[12]

Sprat then offers particular cases of these inquiries concerning the history of weather, saltpetre, gun-powder and dyeing.[13]

The dedication to the Royal Society in *Via Lucis* is as much laudatory of its pursuits to acquire knowledge in the school of nature (*physics*) as it is exhortatory, asking scientists not to leave out consideration of the study of man with his inborn qualities and faculties (*metaphysics*), and finally of the realm where God is the supreme teacher (*hyperphysics*). Though the senses may apprehend nature, they are useless for the understanding of man which can only be achieved through reason (Comenius calls reason the internal light or the eye of souls). But both senses and reason are equally of no avail when it comes to the comprehension of God's own province, inquiry into which Comenius apparently limits to the 'ultimate' type of question such as: what was it like before the world existed and what will it be like when the world exists no more, and what exists outside this world? According to Comenius the only counsellor and guide within this sphere can be faith in revelation.[14]

The Royal Society's declared policy to exclude all subjects not pertaining to the exploration of nature from the consideration of its members was strictly pursued. But it would be wrong to insist that the problems raised by Comenius had appeared to his contemporaries or those who came after them as pseudoproblems. However, an individual Fellow of the Royal Society had to solve them for himself. The relation of science to religion played an

11 Ibid., pp. 242-43.

12 Sprat, *History of the Royal Society*, pp. 155-56.

13 Ibid.: 'A Method For Making a History of the Weather' by Mr. Hook, p. 173; 'The History Of the Making of Salt-Peter' by Mr. Henshaw, p. 260; [Mr. Henshaw], 'The History Of Making Gunpowder', p. 277; 'An Apparatus to the History of the Common Practices of Dying', by Sir William Petty, p. 284. For an account of the Royal Society's early interest in securing natural history, including human society overseas, see J. Gascoigne, 'The Royal Society, Natural History and the Peoples of the "New Worlds", 1660-1800', *The British Journal for the History of Science*, 42 (2009), 539-62.

14 Comenii, *Via Lucis*, pp. 155-56.

important role in Boyle's and Newton's lives, to mention just two of the outstanding figures of the Royal Society. Boyle as a young man came under the direct influence of the Hartlibian/Comenian group, and he retained its belief that revelation and scientific truth are perfectly compatible. The position of Newton, who did not believe in the Trinity, is more complex. Newton thought about theological matters very deeply and had difficulties in reconciling his religious belief with the conception of the mechanical universe.[15]

Comenius was a devout Christian, but it would be misleading to think that his criticisms of the Royal Society derived from the fear that natural sciences would intrude on theology's territory. He merely believed that the answers provided by scientific inquiries amounted only to 'the alphabet of divine wisdom and this was by no means sufficient'.[16] Comenius advanced the view that the natural sciences should set a good example to the politicians and theologians because the principles by which the politicians directed the world were unstable. These principles should be examined and everything untrue should be cast aside. The efforts of the Fellows of the Royal Society to penetrate to the truth on the basis of observations and exact experiments ought to set a wonderful example to those who stood at the helms of human society, either as civil administrators or spiritual guardians of the conscience, encouraging them to fear no examination of their actions.[17] Comenius believed then that statecraft and Christian practice could have learned from the methods employed by natural scientists in their quest for truth. But to leave it at that would not do him justice because he was also concerned with the universality of knowledge and education, and sensed the danger in the Royal Society's one-sided preoccupation with nature.

On the continent many scientific societies and academies, founded after the Royal Society, took up a different attitude and established sections (classes) not only for the study of nature, but also for the humanities (philology, history, philosophy etc.). In this respect, they came much closer to Comenius's project for the organisation of universal knowledge than the Royal Society; at the same time, however, important differences should be noted. Knowledge became specialised and the specialists who met in their respective sections became gradually estranged from their colleagues in other fields – they had nothing or very little to say to each other. These societies

15 On this subject chapter IV in J. H. Brooke, *Science and Religion: Some Historical Perspectives* (Cambridge: Cambridge University Press, 1991), is rewarding. See also M. Hunter's intellectual biography *Boyle: Between God and Science* (New Haven, CT and London: Yale University Press, 2009).

16 Comenii, *Via Lucis*, pp. 158-59.

17 Ibid., p. 160.

provided a common roof to a house whose inhabitants largely tended to shut themselves in rooms with no common doors.

The universality which these societies aspired to existed on paper and this became to a great extent the basis of educational theory and practice. This universality was certainly of a different nature to that which Comenius desired. Of course, it could be argued that the societies' method was historically inevitable since scientific knowledge of nature and society could be accumulated only by investigations of relatively isolated facets of natural and social reality. Nevertheless, this was the historical root of the polarisation which eventually formed the basis for the development of the 'two cultures', and which today's educational theory and practice still struggles to come to terms with. In the light of this, Comenius's exhortation to the Royal Society in the preface to *Via Lucis*, and the work itself, merit more than a passing glance.

As for Comenius's visit to England and its disputed relevance to the foundation of the Royal Society, perhaps Rupert Hall's observation is apposite:

> No one has yet succeeded in disentangling completely the personal relations of all those who figure more or less largely in the scientific world of mid-seventeenth-century England. It is likely that most of the forty or fifty men concerned knew something of each other, though mainly associated with one of three chief groups – the Hartlib circle, devoted to social and ethical reform and more occupied with technology than abstract science; or the club of mathematicians, astronomers and physicians meeting at Gresham College; or the Oxford Philosophical Society. There were no barriers between them.[18]

France[19]

The Royal Society was 'Royal' de jure but not de facto. Independent of the state, it was a self-governing organisation of members who were originally asked to pay one shilling for expenses. This was not a hardship as the majority of Fellows were persons of independent means ('gentlemen'). While social rank retained its significance, the Fellows were – as Sprat put it – a '*mix'd Assembly* [Sprat's italics] which has escap'd the prejudices that use to arise

18 A. Rupert Hall, *The Revolution in Science*, p. 142.

19 What follows under this and the ensuing heading owes much to my 'Tschirnhaus und der Akademiegedanke', in E. Winter (ed.), *E. W. von Tschirnhaus und die Frühaufklärung in Mittel- und Osteuropa* (Berlin: Akademie Verlag, 1960), pp. 93-107. R. Hahn's *The Anatomy of a Scientific Institution: The Paris Academy of Sciences, 1666-1803* (Berkeley, CA and London: University of California Press, 1971) is still relevant.

from Authority, from inequality of Persons...'[20] The state kept its distance from the pursuits of the London Royal Society, be they practical or theoretical.

This distance did not apply to the Parisian Académie Royale des Sciences, established four years later (1666). Its origins also go back to private gatherings of persons with common interests in expanding the knowledge of nature. It was Jean-Baptiste Colbert's (1619-1683) grasp of the import of scientific investigations which led to King Louis XIV (1643-1715) giving his assent to their institutional embodiment. Judging by his correspondence with a number of scientists, the mercantilist Colbert (surprisingly?) did not adopt a narrow utilitarian attitude towards research. He understood that investigators had to have room for the pursuit of knowledge for its own sake. Therefore, the thirty to forty members of the Académie were freed from financial worries. They received an annual pension and a notable allowance for instruments and other research needs. This enabled the Académie to become a centre of collective and conscious efforts to place scientific pursuits at the service of the state. Considerable attention was paid to the analysis of the modes of handicraft production, including assessment and efficiency of novel mechanical contrivances. The foundation of the Paris Academy and its state-link corresponded to the mercantilist policies vigorously pursued by the French government in the seventeenth century.

Prussia and Saxony

The foundation of the Royal Society in London and the Académie des Sciences in Paris made a strong impression on scientists in other countries, including Germany. Reproaching the members of the Leopoldina for not working creatively, Leibniz noted that the organisation lacked sufficient means and social prestige. Altogether, the social conditions for the development of scientific activities were not propitious in a Germany fragmented in the aftermath of the Thirty Years War.

Indeed it was Leibniz who drew a sombre picture of the plight of the scientific-technical personnel in Germany at the time. While there was no shortage of mechanicians, artisans and experimenters, the governments of the various kingdoms and principalities showed little interest in them. Thus they were really faced with two options: either give up and bury their talents, or leave behind the beggarly living conditions at home and seek

20 Sprat, *History of the Royal Society*, pp. 91-2.

opportunities abroad to the detriment of Germany. Leibniz made this point when he submitted a proposal for founding a scientific society in Prussia (approved in 1700 but established in 1711).[21]

Ever intent on promoting the institutionalisation of science in Germany, Leibniz corresponded on this subject (1693-1708) with the mathematician Ehrenfried Walther Tschirnhaus (1651-1708). He also was a constructer of circular and parabolic mirrors with which he succeeded, by focusing sunlight, in obtaining high temperatures.[22]

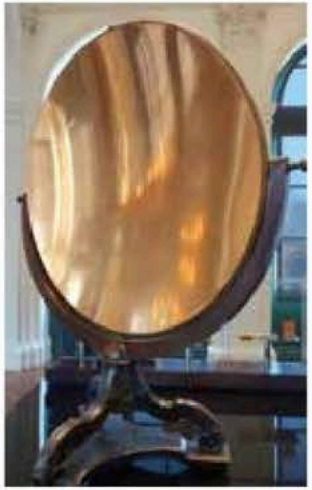

Fig. 9 Spherical burning mirror by Ehrenfried Walther von Tschirnhaus (1786). Collection of Mathematisch-Physikalischer Salon (Zwinger), Dresden, Germany.

Sharing Leibniz's concerns, Tschirnhaus speculated on the possibility of collective forms of scientific activity in Saxony, particularly after his dream of becoming a pensioner of the Paris Academy came to nothing (1682). Of historical interest is Tschirnhaus's letter to Leibniz (13 January 1693) in which the idea of holding a scientific congress is raised for perhaps the first time:

21 See Leibniz, 'Errichtung einer Societät in Deutschland (2. Entwurf)', in A. Harnack, *Geschichte der königlich preussischen Akademie der Wissenschaften zu Berlin*, Vol. 2 (Urkunden u. Actenstücke) (Berlin: Reichsdruckerei, 1900), p. 23.

22 The extent to which Tschirnhaus's expertise with high temperatures contributed to the discovery of the Meissen porcelain by J. F. Böttger (1682-1719), and thus made him a co-discoverer, has been the subject of much discussion.

> Merchants gather at the Leipzig Fair because of their perishable earthly things [*vergänglichen Dinge*]; could not also learned people meet here one day [*einmahl alda*] because of important reasons.[23]

In response to a letter from Leibniz, who was thinking of a self-financing scientific society, Tschirnhaus suggested that the revenues could derive from the exploitation of scientific discoveries, such as his own in optics (27 January 1694). He also specified strict criteria to apply to the selection of the society's members: 1. The aspiring member was truly to employ scientific methods in his work; 2. Science and the desire to obtain the truth was to be his main passion; 3. Self-interest was not to be his main motive; 4. Nor was hankering after personal glory to be his reason for doing research.

At the same time, Tschirnhaus informed Leibniz that he had freed himself from these weaknesses. As proof, he offered to publish his own work anonymously – only under the name of the society. He would not ask for a greater share from the common purse than he was entitled to. He was also prepared to hand over to the common purse all monetary gain he derived from his own optical inventions. But in the end, Tschirnhaus doubted that there were scientists who would match his own example. Leibniz agreed that such persons did not exist. Moreover, he observed that not much was to be expected from 'persons of high rank' (*grosse Herren*), however well-intentioned they were.

History confirmed this view. Tschirnhaus became involved, with the help of Prince Fürstenberg, in setting up a manufactory for producing large mirrors in Dresden (1707). These mirrors did not distort, owing to an innovation of Tschirnhaus in the handling of molten glass. Tschirnhaus hoped that the revenue would secure the foundation of a scientific society. It did not materialise, nor did other plans considered by the two scientists. For example, there was a proposal (not theirs) to establish a central German institution for the improvement of the calendar, out of which an academy was to grow – financed from the proceeds of the monopolised sale of calendars. Tschirnhaus and Leibniz's own exertions to establish an academy in Dresden also came to nothing. While Tschirnhaus remained optimistic, Leibniz tended to succumb to depression, especially in view of obstructions to his plan in Berlin, which came to fruition five years before his death.

23 Teich, 'Tschirnhaus', in E. Winter (ed.), p. 101.

Bohemia[24]

Traditionally the rise of organised science in Bohemia is linked to the activities of an informal body known as the Private Learned Society. Founded around 1774, it included the humanities from the outset as an integral part of its concerns, in addition to the natural sciences. This breadth was clearly reflected in the title of its journal, *Abhandlungen einer Privatgesellschaft in Boehmen, zur Aufnahme der vaterlaendischen Geschichte und der Naturgeschichte*,[25] published under the editorship of Ignaz (Inigo) von Born (1742-1791). It appeared six times as an annual between 1775 and 1786. The ideology that informed both the formation of the Society and its journal was Bohemian patriotism to which practitioners of both historical and natural historical disciplines confessed. They were not only a socially mixed assembly (like the Royal Society), but also an ethnically diverse one. The Czech- and German-speaking members considered themselves heirs to a long and honourable tradition of learning effectively inaugurated by the foundation of a *studium generale* in Prague, the first university in Central Europe (1348). Patriotism lay behind their call not only for the exploration of the economic resources but also of the historical past of Bohemia. They agreed that critical analysis and rationalism, so relevant to the scientific study of nature, could be equally successful in the scholarly study of history.

The scientific-technical-economic interests of the founders of the Private Learned Society paralleled those of the founders of the Royal Society and other scientific societies in Europe. These societies were concerned with gaining systematic knowledge of nature for practical use in manufactories and agriculture.

The Oxford English Dictionary locates the first use of 'manufactory' in the year 1618. To all intents and purposes, it meant a place of work in which operations were carried out manually. By the 1690s, economic thinkers (W. Petty, J. Locke) were writing about improving the productivity of labour through its division – machinery was largely limited to watermills and windmills. The classical analysis of the role of the division of labour played

24 What follows draws greatly on my previous treatments of the subject. See 'Bohemia: From Darkness into Light', in R. Porter and M. Teich (eds.), *The Enlightenment in National Context* (Cambridge: Cambridge University Press, 1981), pp. 141-63; 247-53; 'Afterword', pp. 215-17.

25 Available at http://babel.hathitrust.org/cgi/pt?id=nyp.33433009935119;view=1up;seq=11

in raising the productivity of labour was offered by Adam Smith (1723-1790) in *The Wealth of Nations* (1776). It influenced Marx to perceive in manufacture the characteristic mode of production of the pre-industrial phase of capitalism. He called it the 'period of manufacture' (*Manufakturperiode*) and thought that it extended roughly from the middle of the sixteenth to the end of the eighteenth century. While this approach informed historians in the former socialist countries, it was largely ignored by Western historiography. Inasmuch as historians variously adopted the concept of 'proto-industrialisation', beginning in the 1970s, they found the Marxist framework of the manufactory stage of industrialization, in certain economically active European states or regions, wanting.[26]

Be that as it may, manufactories needed raw materials, the existence of which could be ascertained through surveys of natural resources. Hence the surveying of natural resources, famously represented in the Swedish context by Carolus Linnaeus (Carl von Linné) (1707-1778), became one of the important tasks the scientific societies set themselves.

The need for an organised scientific survey of the Habsburg dominions had already been proclaimed by Philipp Wilhelm von Hornigk (1638-1712), the leading thinker of Austrian mercantilism, in 1684. Hornigk (Hornick, Hoernigk) recognised the importance of mathematics and mechanics for the development of manufactories. He emphasised that they should use indigenous raw materials. He called for surveys and experiments on the acclimatisation of foreign plants and animals. He also thought it highly desirable to publish a technological encyclopaedia which would explain the significance of physics and mechanics for productive purposes. This task – according to Hornigk – could not be performed by a single person but only by a group of disinterested specialists in various subjects, scientists who would not keep their knowledge to themselves but place it at the public's disposal.[27]

Hornigk's agitation against secretiveness and his request for specialists to combine their scientific and technical knowledge for production and commerce was not accidental. The principle of cooperation based on the

26 For an introduction and survey, see S. C. Ogilvie and M. Cerman (eds.), *European Proto-Industrialization: An Introductory Handbook* (Cambridge: Cambridge University Press, 1996); see also M. Berg, *The Age of Manufactures, 1700-1820: Industry, Innovation and Work in Britain*, 2nd ed. (London and New York: Routledge, 1994). For a non-Marxist critique of the theory, see D. C. Coleman, 'Proto-industrialization: A Concept too Many', in his *Myth, History and the Industrial Revolution* (London and Rio Grande, OH: Hambledon Press, 1992), pp. 107-22.

27 [Ph. W. Hornigk], *Oesterreich ueber alles wann es nur will*, 2nd edn ([n.p.]: [n. pub.], 1685), pp. 94f., 99, 261-63.

division of labour, so characteristic of operations in manufactories, was also penetrating the world of science. In some ways artisans and scientists had developed a similar attitude in refraining from divulging what were believed to constitute 'trade' secrets. With the growth of specialised scientific knowledge the need arose for an exchange of observational and experimental results that could be tested and expanded, leading to the foundation of scientific societies and journals. Through them scientific activity became 'socialised' in terms of organisation and also in the sense that its results became public property, available at no cost to those interested in its practical utilisation in industry, agriculture and medicine.[28]

The conditions for Hornigk's suggested association of scientists working for Austria's economic benefit matured only slowly, and it took almost one hundred years before one was founded in Bohemia. The background to the establishment of the Private Learned Society will become clearer in reference to the exploration of the natural resources of Bohemia and the Austrian Salzkammergut, as instigated by Empress Maria Theresa (1740-1780) and her husband Francis of Lotharingia (1745-1765), a leading entrepreneur himself in the 1750s and 1760s. They charged with this task Jan Křtitel Boháč (Johan[n] Tauffer Bohadsch), a professor and leading official of the Prague medical faculty.

One of the distinguished microscopists of his time, Boháč (1724-1768) was also a commercial counsellor to the Bohemian *Gubernium*. Though a university professor, Boháč was not isolated from life and had not the slightest doubt that the development of the natural sciences, the arts and manufacturing formed an inseparable unity. With great clarity he defended the social function of scientific investigations against those who tended to underrate it.

In the eighteenth century, under the influence of the much-travelled Linnaeus, systematics came to occupy a central place in natural history. Sometimes these endeavours degenerated into aimless classifications of plants, animals and minerals for their own sake. Boháč condemned such tendencies, holding that the classification of natural objects should be a means towards utilising them in material production. His comprehensive approach led him to appreciate the dependence of manufacture on agriculture. For instance, his concern with the cultivation of woad for animal feeding and for dyeing indicated the connection between scientific, technical, economic and political aspects of his work.[29] It was to be crowned by a comprehensive survey of

28 See K. Marx, *Capital* (London: George Allen & Unwin, 1938), Vol. 1, p. 383.

29 J. T. Bohadsch, *Beschreibung einigen in der Haushaltung und Faerbekunst nutzbaren*

the plant, animal and mineral wealth of Bohemia. However, because of Boháč's untimely death, it remained as a manuscript that has since been lost. There can be little doubt about the social and economic impetus that turned Boháč and others to apply their expert knowledge of the properties and processes of nature, inanimate and animate, to practical fields, including the systematic survey of the natural wealth of Bohemia. But an individual, unaided financially, could hardly complete this work alone.

A body of individuals could, and it might have been expected that Prague University would eventually house such a body because it counted among its members prominent scientists interested in the practical use of natural knowledge, like Boháč or the able mathematician and physicist Joseph Stepling (1716-1778). At the order of the Empress Maria Theresa, a kind of university scientific society presided over by Stepling had been established in 1753. University teachers used to meet and hold lectures, but within less than a decade the society ceased to function, possibly due to the antagonism of the Jesuit order still in control of university life and imbued by thinking derived from the Aristotelian-Thomist synthesis.[30]

To complement this account, mention should be made of the earliest scientific society in the Czech Lands and, indeed, in the Habsburg Empire. It was the short-lived *Societas eruditorum incognitorum in terris austriacis* at Olomouc (the former capital of Moravia). It was founded in December 1746, with the backing of Maria Theresa, by Joseph von Petrasch (1714-1772), a former *aide-de-camp* to Eugene of Savoy. The Society of Unknown Scholars arose from informal gatherings of laymen, clergymen and military officers interested in discussing literary and scientific developments at home and abroad in an atmosphere free of the limitations imposed by the Jesuits on the

Kraeutern, die er in seinen durch drey Jahre unternommenen Reisen im Königreich Böheim entdecket hat (Prague: Franz Ignatz Kirchner, 1755); *Abhandlung vom Gebrauch des Waides in der Haushaltung* (Prague: [n. pub.], [n.d.]); *Dienst- und Nutzbarer Patriotischer Vorschlag, wienach dem Königreich Böheim ein ungemeiner Vortheil von sonderbarer Beträchtlichkeit jährlich zuwachsen könnte* (Prague: [n. pub.], 1758). See Z. Frankenberger, 'Jan Křtitel Boháč: Jan Křtitel Boháč: život a dílo', *Věstník Královské české společnosti nauk*, 12 (1950), 1-122.

30 Except for scattered remarks in eighteenth-century records, there is little solid information on these meetings, variously called *consessus philosophicus, consessus philosophici* and *consessus literarii*. As to Jesuits in Bohemia, it is necessary to differentiate between the unprogressive attitude of the order delaying the advance of science, and the progressive role of its individual members in furthering and participating in astronomical, mathematical and physical inquiries (e.g. J. Stepling). See also E. Winter, 'Die katholischen Orden und die Wissenschaftspolitik im 18. Jahrhundert', in E. Amburger, M. C. Cieśla and L. Sziklay (eds.), *Wissenschaftspolitik in Mittel- und Osteuropa* (Berlin: Camen, 1976), pp. 85-96.

spiritual life of the fortress and university town. Containing only reviews and no original contributions, two volumes of its journal *Monathliche Auszuege Alt, und neuer Gelehrten Sachen* were issued at Olomouc in 1747 and 1748. Apparently to avoid censorship, the third volume of the journal was printed outside Austria (1750) and afterwards its publication ceased.[31]

About two decades elapsed before the idea of a scientific society was taken up again by the well-known mineralogist Ignaz von Born. Writing to his friend Count F. J. Kinsky(ý) (1739-1805), Born emphasised that nobody had thought of setting up a learned society for the exploration of Austria's widespread territory, to assemble the observations made by naturalists and scientists. This is evidence that a scientific society, whether centred on Austria as a whole or restricted to Bohemia, did not exist before 1774.

Born criticised the aristocracy for its lack of comprehension of the utility of natural history. He stressed that those who took interest in it and had the ability to work creatively did not possess the means to explore nature. He explicitly mentioned the case of Boháč, who on his travels had collected natural objects at his own expense and on his death left his wife penniless. Whereas, according to Born, the nobility had the means but did not encourage people of talent to investigate the natural wealth of the monarchy. Furthermore, in his letter he elucidates the usefulness of science to the economy, the state, the church, the doctor and the poet.[32]

He was particularly concerned with the perniciousness of not making scientific observations and technical discoveries available to all, under the cloak of state secrecy. Born here was condemning an official practice which had already almost landed him with the charge of treason. In 1771 he had published N. Poda's (1723-1798) descriptions of machines used in the mining district of Banská Štiavnica, one of the classical texts on eighteenth-century mining in Central Europe.[33] At that time, he occupied the post of assessor of

31 There is as yet no reliable treatment of the subject. Under these circumstances what can be said, in general, is that the *Societas incognitorum* embodied an effort to organise scientific and cultural life at an early stage of the Enlightenment in the Habsburg dominions, but the social, intellectual, local and personal circumstances that engendered its birth were not adequate to keep it alive. See E. Wondrák, 'Die Olmützer "Societas incognitorum". Zum 225. Jubiläum ihrer Gründung und zum 200. Todestag ihres Gründers', in E. Lesky, D. S. K. Kostić, J. Matl and G. v. Rauch (eds.), *Die Aufklärung in Ost- und Südosteuropa* (Cologne and Vienna: Böhlau, 1972), pp. 215-28.

32 *Schreiben des Herrn Ignatz von Born … an Herrn Franz Grafen von Kinsky, Ueber einen ausgebrannten Vulkan bey der Stadt Eger in Boehmen* (Prague: Gerle, 1773), pp. 1-3, 11-16.

33 N. von Poda, *Kurzgefasste Beschreibung der, bey dem Bergbau zu Schemnitz in Nieder-Hungarn, errichteten Maschinen etc.* (Prague: Walther, 1771).

the Mint and Mining Head Office in Prague, from which he chose to resign. The defence of open scientific communication was crucial to Born's drive to organise scientific life in Bohemia between 1770 and 1776, and afterwards in Vienna and, indeed, on an international scale.[34]

Major-General Franz Joseph (František Josef) Kinsky was descended from one of the great Czech aristocratic houses. A keen geologist and educationalist, he eventually became the head of the Military Academy at Wiener Neustadt. He supported Born's vision of putting scientific life in Bohemia on an organised basis for economic, technical and educational reasons. Together with Born and aided by the head of the *Gubernium*, Prince Karl Egon Fürstenberg, he was instrumental in founding the Natural History Museum (1775) and bringing into being the Prague University Library (1777), of which he became the first director.[35]

Kinsky shared Born's concern that the aristocracy as a social class was apt to regard science and technology with disdain. In a letter to Born published in the first volume of *Abhandlungen* (1775), Kinsky complained that the nobility were not properly informed that the administration of their domains required knowledge of natural and agricultural sciences. In his answer Born wrote that a mineralogical and geographical description of Bohemia was needed, adding that there were only a few mineralogists available. According to Born, they ought to follow the example of Saxony, where specialists financed by public funds were preparing a mineralogical map.[36]

The Private Learned Society's transformation into a public institution occurred when it became the Bohemian Society of Sciences in 1784 and the Royal Bohemian Society in 1790. The problems which the scientists in Bohemia tried to solve, especially those associated with the Royal Bohemian Society of Sciences or within its orbit during the first period of its existence, were closely related to the idea of a scientific survey of Bohemian natural resources.

The Society approached the problem of a scientific survey of Bohemia basically from two angles. It launched prize essay competitions and organised expeditions for the purpose of surveying various regions of Bohemia. The aim of these endeavours was to collect a large amount of scientifically verified information for a map of Bohemia.

The members of the Society embarked upon this plan because they were convinced that the development of manufacturing depended above all on knowledge of domestic economic resources. However, the social, financial and personal situation did not favour the transformation of this awareness into reality. For one thing, the continuing feudal relations and undeveloped capitalist relations effected negative progress in agriculture and industry. For another, the Bohemian Society of Sciences was in continuous financial difficulties which were not alleviated despite the support of a few interested aristocrats. In addition, the number of individuals able to perform a large-scale survey of the country was then small. The Society included amongst its members (nearly all non-nobles) the most distinguished scholars in Bohemia, but that amounted to no more than a few persons. As a consequence it succeeded only partially in achieving its aim.

34 The definitive study of this leading figure of the Enlightenment in the Habsburg monarchy still remains to be written. See H. Reinalter (ed.), *Die Aufklärung in Österreich. Ignaz von Born und seine Zeit* (Frankfurt am Main; Bern; New York; Paris: Lang, 1991).

35 Kinsky has received little serious attention. For an appreciation, see J. Haubelt, 'František Josef Kinský', *Věstník Československé akademie věd*, 78 (1969), 560-77.

36 'Schreiben des Herrn Grafen von K… an Herrn von Born ueber einige mineralogische und lithologische Merkwuerdigkeiten', *Abhandlungen*, 1 (1775), 243-52; 'Antwort des Herrn von Born, auf das Schreiben des Herrn Grafen von K.....', ibid., 1 (1775), 253-63.