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THE SCIENCE OF NATURE IN THE SEVENTEENTH CENTURY

Patterns of Change in Early Modern Natural Philosophy

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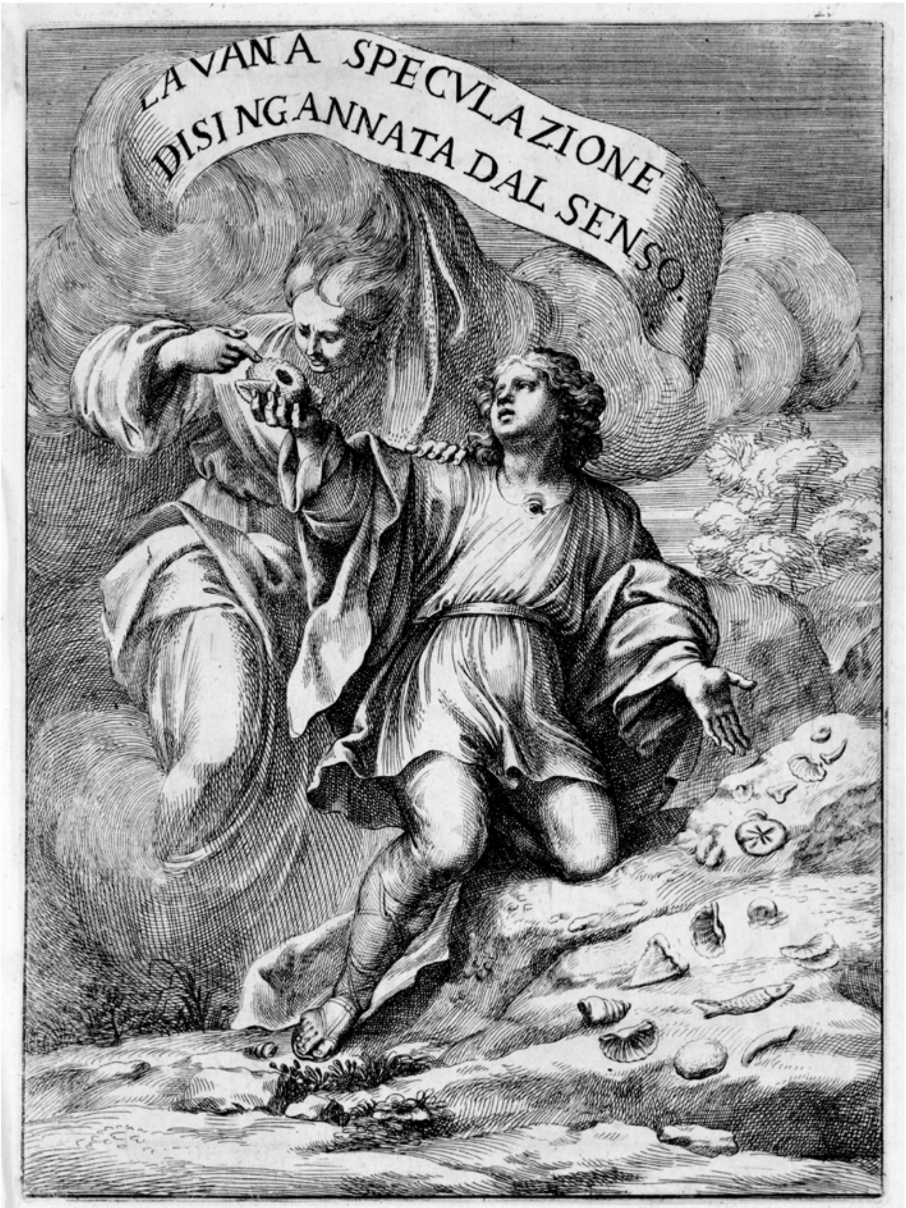

‘Vain speculation undeceived by the senses’. Engraving from *La Vana Speculazione Disingannata dal Senso* by Agostino Scilla, Napoli, 1670, page opposite p. 168. Used with permission of the Bodleian Library, University of Oxford (Shelfmark Lister C 101).

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PETER R. ANSTEY AND JOHN A. SCHUSTER

INTRODUCTION

One of the hallmarks of the modern world has been the stunning rise of the natural sciences. The exponential expansion of scientific knowledge and the accompanying technology that so impact on our daily lives are truly remarkable. But what is often taken for granted is the enviable epistemic-credit rating of scientific knowledge: science is authoritative, science inspires confidence, science is right. Yet it has not always been so. In the seventeenth century the situation was markedly different: competing sources of authority, shifting disciplinary boundaries, emerging modes of experimental practice and methodological reflection were some of the constituents in a quite different mélange in which knowledge of nature was by no means pre-eminent. It was the desire to probe the underlying causes of the shift from the early modern 'nature-knowledge' to modern science that was one of the stimuli for the 'Origins of Modernity: Early Modern Thought 1543–1789' conference held in Sydney in July 2002. How and why did modern science emerge from its early modern roots to the dominant position which it enjoys in today's post-modern world? Under the auspices of the International Society for Intellectual History, The University of New South Wales and The University of Sydney, a group of historians and philosophers of science gathered to discuss this issue. However, it soon became clear that a prior question needed to be settled first: the question as to the precise nature of the quest for knowledge of the natural realm in the seventeenth century. This collection is the product of the preliminary soundings made at the conference on that crucial prior question.[1]

The papers in this collection start from the premise that in the early modern period the central category for the study of nature was natural philosophy, or as Robert Hooke called it in his *Micrographia*, the Science of Nature. Any system of natural philosophy, whether a version of the hegemonic and institutionalised Scholastic Aristotelianism, or one of its challengers, concerned itself with a general theory of nature—that is, the nature of matter and cause, the cosmological structuring and functioning of matter and the proper method for acquiring or justifying knowledge of nature. To place the evolution of natural philosophy, and in particular the shifting patterns of its relations to other enterprises and disciplines, at the centre of one's conception of the Scientific Revolution is not novel, and more

[1] Six of the eight chapters in this volume ultimately derive from presentations at the Sydney Conference—those by John Schuster, Peter Dear, Helen Hattab, Peter Harrison, H. Floris Cohen and Stephen Gaukroger, the latter two having been plenary addresses. To these have been added related papers by Peter Anstey (who spoke in Sydney on another topic) and Luciano Boschiero.

P. R. Anstey and J. A. Schuster (eds.), The Science of Nature in the Seventeenth Century, 1-7.

scholars are realising the value of such a perspective, but neither is it obvious or agreed upon in the scholarly community.

Many older discussions, and some contemporary ones, are marred by a tendency to lump the culture of natural philosophising under an anachronistic label of 'science',[2] thus obscuring the possibility of speaking convincingly about the internal texture and dynamics of the culture of natural philosophy and its patterns of change over the period. If such anachronism truncates historical analysis by making the object of study 'science' from the first, a more recent, sophisticated and, to many, convincing approach is to read natural philosophy entirely out of the story of 'modern science' and its early modern origins. This has been done by identifying the large and encompassing culture of 'natural philosophising' solely with its dominant, institutionalised form, neo-Scholastic Aristotelianism. Thus, some recent scholars have defined the Scientific Revolution in terms of the end or demise of 'natural philosophy', supposedly followed by an equally abrupt triumphant origin of something called 'experimental science' or 'modern science'.[3] Over against both these pitfalls, this volume assumes that natural philosophy, understood as a large and contested field of systematic natural inquiry, encompassed Aristotelianism and its various challengers, their evolution and conflict over time. It is precisely this sort of understanding that has allowed some scholars to view the Scientific Revolution, so-called, as a process of conflict, co-optation and displacement amongst different natural philosophical claims.

This volume aims to cast more light on this approach. But, the focal concern of the papers in the collection resides in the deeper question of how claims were constructed and located in the field of natural philosophising. This is where our central theme takes shape: the issue of how natural philosophical claims were positioned in relation to other enterprises and concerns, taken variously to be superior to natural philosophy (such as theology); or cognate with it (other branches of philosophy, such as ethics or mathematics); or subordinate to it (as in the dominant Aristotelian evaluation of the mixed mathematical sciences, such as astronomy, optics and mechanics); or simply of some claimed relevance to it, as for example pedagogy or various of the practical arts. Taking on board the assumptions of sociologists of science and social historians of science when working on similar issues in later periods, we may straightforwardly assume that the positioning of natural philosophical claims in relation to other enterprises and concerns always involved two routine manoeuvres: the drawing or enforcing of boundaries and the making or defending of particular linkages (including efforts to undermine others' attempts at bounding and linking). The description of concrete examples of such

[2] H. Floris Cohen's massive survey of Scientific Revolution historiography (Cohen 1994) illustrates that the term 'natural philosophy' has been endemically present in the literature, but not systematically theorised, often serving as a synonym for 'science' or (some of) the sciences. Recent attempts to delineate the category of natural philosophy and deploy it in Scientific Revolution historiography include, Schuster 1990, 1995; Schuster and Watchirs 1990; Cunningham 1988, 1991; Cunningham and Williams 1993; Dear 1991, 2001; Harrison 2000, 2002 and his chapter in this volume; and Henry 2002.

[3] Shapin 1994 and Dear 1995.

machinations is one aim of the papers in the collection; the articulation of better general models and conceptions of such dynamics is another.

In the time period addressed by the collection, it was of course the case that the dominant Scholastic Aristotelianism tended to provide all players with the fundamental grammar for how such boundaries and linkages were to be made, since many natural philosophers, including some of the most dedicated advocates of alternative systems, had originally been scholastically trained. But, even amongst Aristotelians the topography of boundaries and linkages was not overly rigid and could be contested; for example, in shifting evaluations of the natural philosophical import of the definitely 'subordinate' mixed mathematical sciences. Moreover, advocates of natural philosophical alternatives to Aristotelianism could and did propagate different patterns of bounding and linkage. That is why, arguably, the process of the Scientific Revolution can be mapped in terms of the larger secular trends in these moves, and the dynamics that governed them, and that is also why we can focus on these developments in the cases of major non-Aristotelian natural philosophers studied in this volume, amongst them, Bacon, Galileo, Descartes, Beeckman, Kepler, Huygens, Boyle, and Newton.

In sum, then, the volume aims to offer a set of interrelated but distinct studies motivated by these concerns. Hence it takes a position on the historiography of the Scientific Revolution, stressing patterns of change in the continuing culture of natural philosophising, and it offers various, related suggestions for improving the concepts and tools used to study natural philosophy and its dynamics.

In the first chapter, H. Floris Cohen examines the simultaneous emergence in the early seventeenth century and the ongoing impact of three different, yet mutually complementary modes of acquiring knowledge of nature. With broad historiographical brushstrokes, Cohen shows how the mathematisation of natural phenomena, the fact gathering experimentalism of Bacon and his heirs and the re-emergence of ancient (though rival) explanatory models in natural philosophising blended and interlocked throughout the seventeenth century, culminating in the achievement of Newton's *Principia* and *Opticks*. For Cohen, the emergence of these three modes of 'nature-knowledge' is constitutive of the Scientific Revolution, and, in the tradition of Koyré and Westfall, he claims that the mathematisation of natural knowledge was the most decisive. However, even though the mathematisation of nature was to yield more long-term fruit, it was the re-emergence of Classical and Hellenistic explanatory models of the functioning and structure of nature that proved to be the rallying points for allegiances and the basis of polemics amongst natural philosophers of the early modern period. And the dominant explanatory model to emerge was a form of kinetic corpuscularianism as found in the writings of Gassendi, Boyle and others.

The most systematic and ambitious development of such an explanatory model of nature was René Descartes' and it is only fitting that his articulation of a cosmological system in terms of vortices should form the focal point of the next three chapters of the collection. Descartes' cosmology fulfilled the need for a credible mechanistic theory of the heavens on the demise of the Ptolemaic system and the modelling of his system on ancient hydrostatics and its relation to late

Renaissance work on mechanics provide central reference points for other contributions to this volume.

In chapter two John Schuster explores Descartes' often misunderstood concern with vortices; that is his vortex model for celestial motions and for light in the cosmological context. Schuster analyses the internal conceptual architecture of the vortical model, as well as its genesis out of Descartes' early attempts to construct a mechanical natural philosophy by both co-opting and in turn resynthesising the Scholastic 'mixed mathematical sciences' of mechanics, hydrostatics, optics and astronomy under the label of 'physico-mathematics'. He argues that whatever Descartes thought he was doing with vortices, it bears no relation to simplistic glosses routinely offered in the latter half of the seventeenth century and beyond, and that it constituted a serious and innovative, if ultimately flawed, cosmic hydraulics, or 'waterworld' for both light and celestial motion. In this way Schuster's chapter also illustrates some of the challenges, gambits and pitfalls that presented themselves to mathematically-oriented natural philosophical innovators of Descartes' generation. In particular, it exposes Descartes' complex debt to Beeckman, including Beeckman's own attempt, in the late 1620s, to produce a mechanist version of Kepler's radical program of a neo-Platonic synthesis of realist Copernicanism, with a new 'physics' of light and celestial motion.

Staying with Descartes' vortices, Peter Dear's chapter deals with the question of where, after all, did Descartes obtain his conception of vortical motion? Within what kind of textual, artisanal, or other context of practice (surely not that of 'mechanics' in its classical sense) did vortical motion appear as a topic for discussion? And how was the image or figure of the vortex supposed to clarify a new kind of physics for Descartes' readers? Dear discusses the most likely points of resonance that a philosophically-educated European of the period would have recognised in Descartes' use of vortical motion, and develops their implications for the disciplinary games that the 'mathematical' Descartes played in developing an alternative natural philosophy.

Yet despite the self-proclaimed novelty of his cosmological system, the causal explanations of Descartes' physics have affinities with the methods of the mixed mathematical science of mechanics. In her chapter, Helen Hattab explores the continuities and differences between the Aristotelian tradition in mechanics and Descartes' mechanistic view of causation and scientific explanation. She does this by focusing on the pseudo-Aristotelian *Quaestiones Mechanicae* (attributed to Aristotle, first printed in Latin in 1517) and a series of commentaries and other texts that took up its subject matter during the sixteenth century. These texts developed a form of explanation that, while not in contradiction with Aristotelian physics, nevertheless offered an alternative—one based on geometrical principles rather than the four causes. Her analysis provides then a basis for comparing the project of these Renaissance mathematical practitioners and humanists, who understood mechanics as the investigation into the causes of mechanical devices and wondrous effects, with Descartes' endeavour to apply the principles of mechanics to natural philosophy as a whole.

Thus it can be seen that Descartes' vortex theory provides an illuminating case study of the emergence of a new form of natural philosophising in the early to mid seventeenth century, and of some of the tactics he employed to exploit and transform the mixed mathematical sciences in the service of his natural philosophical gambits. Yet Descartes was not a lone player in these regards, nor were relations with mathematics and the mathematical sciences the only issues at stake. Stephen Gaukroger shows in his chapter on the autonomy of natural philosophy that some of the deep epistemological issues tied up with the emergence of natural philosophy as an autonomous discipline, and the concomitant realigning of disciplinary boundaries, can be best brought out by a comparison of some of the central players. To this end, Gaukroger provides parallel treatments of Galileo, Francis Bacon and Descartes to illustrate the protracted process by which natural philosophy extricated itself from a Christianised Aristotelianism and became established as a discipline in its own right. This process involved not only a rearticulation of the boundaries between natural philosophy and pre-established theological truths, but also careful manoeuvring by leading natural philosophers within their own intellectual and social milieux. It also involved deep epistemological issues concerning the relation between justification and truth as illustrated by the Renaissance debate over the immortality of the soul.

Gaukroger's concern with the relation between theology and natural philosophy becomes the focal point of the next chapter by Peter Harrison, who examines the origins and contours of the hybrid discipline of physico-theology in the seventeenth century. The early modern period witnessed the emergence of a number of hyphenated disciplines and modes of explanation. Physico-mathematics and physico-theology are perhaps the best known of these mixed disciplines, but in numerous works we also encounter physico-chemical, physico-medical, or physico-mechanical accounts of natural phenomena. All represent revisions of the traditional disciplinary boundaries inherited from the scholastics. Historians of the period have become increasingly aware of the significance of the introduction of mathematical principles into natural philosophy whether under the model of mixed mathematics or physico-mathematics. 'Physico-theology', however, is generally assumed to be simply a synonym for 'natural theology', and thus of marginal interest as a specific category in discussions of the identity of seventeenth-century natural philosophy. Harrison's chapter explores analogies between physico-mathematics and physico-theology, and suggests that the emergence of the latter discipline also sheds important light on the identity of early modern natural philosophy. In particular, he shows how some individuals dealt with the problematic issue of the extent to which theological concerns could have a legitimate place in natural philosophy. He therefore also addresses the broad question of the extent to which early modern natural philosophy was an inherently religious activity.

Of Floris Cohen's three modes of acquiring knowledge of nature: the mathematisation of natural phenomena; the emergence of kinetic corpuscularianism; and the rise of Baconian experimentalism, it is the latter which receives detailed treatment in the final two chapters of this collection, in ways indicative of our focus on patterns of change in a wide culture of natural philosophy in the seventeenth century. First Luciano Boschiero offers a case study of experimental work at the Accademia del Cimento in Florence, the first of the new scientific institutions, along with the Royal Society of London and Parisian Académie des Sciences, to embrace

Baconianism as its public legitimatory rhetoric. Exploring the academicians' attempt to resolve debates about the rings of Saturn, Boschiero reinforces the importance of focusing upon natural philosophy as a wide, complex and evolving field of natural inquiry. He shows the continued existence within the Accademia of personal and group agendas in natural philosophy that framed experiments and the accounting of their results, thereby promoting competition and tension amongst the members. This contrasts with the strict maintenance by the Accademia's Medici patrons of a uniform public rhetoric of inductivist experimental methodology, supposedly issuing in a consensually agreed harvest of atheoretical matters of fact. Boschiero concludes that recent concentration by some historians on this rhetoric, whilst correct and useful, has had the unfortunate, if often unintended consequence of occluding the continued natural philosophical theorising and conflict that marked the actual knowledge making practices inside the Accademia.

In the final chapter Peter Anstey traces, in the case of England, some often overlooked elements in the growth and triumph of Baconian discourse in the self understandings and public representations of natural philosophers. He shows that references to 'experimental philosophy', 'observation and experiment' and a rejection of 'speculative hypotheses' were commonplace in early modern English natural philosophy. Yet what is invariably overlooked is that these terms mark a fundamental distinction in discussions about natural philosophical methodology from the 1650s on. This is the distinction between experimental and speculative natural philosophy. Anstey argues that the experimental/speculative distinction provides the basic terms of reference by which early modern English natural philosophers understood their practice and theoretical reflections on natural philosophy. Robert Hooke's comment, from which the title of this book derives, captures the sentiment nicely.

> The truth is, the Science of Nature has been already too long made only a work of the *Brain* and the *Fancy*: It is now high time that it should return to the plainness and soundness of *Observations* on *material* and *obvious* things.[4]

Anstey claims that this distinction transcended disciplinary boundaries within natural philosophy and beyond to medicine and that it appears to have been set in sharper focus in the 1690s when English anti-hypotheticalism reached new heights and when a 'dumbed down' version of the Cartesian vortex theory was paraded as the paradigm speculative hypothesis. Furthermore, the distinction provides us with a hitherto neglected methodological context for the interpretation of Newton's notorious comments on the value and role of hypotheses in natural philosophy.

The eight studies in this collection were inspired by a shared but not doctrinaire commitment to exploring problems about the Scientific Revolution from the perspective of continuity and change in the culture of natural philosophy, rather than within the more usual narratives of the origin of 'modern science', either by *de novo* discoveries of method or fact, or by heroic defeat of older regimes of knowledge. The cumulative effect of the studies presented here certainly is not intended to be the provision of a definitive analysis of the early modern discipline of natural

[4] Hooke 1665, The Preface, b1.

philosophy and its linkages and boundaries with other intellectual and artisanal pursuits. Rather, it is hoped that the present studies will inspire further research into that complex set of relations and the process of disciplinary definition that natural philosophy underwent in the seventeenth century.

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H. FLORIS COHEN

THE ONSET OF THE SCIENTIFIC REVOLUTION

Three Near-Simultaneous Transformations

This chapter deals with the radical transformation in modes of pursuing nature-knowledge that took place in Europe in course of a few decades around 1600.[1] My principal thesis is that this transformation involved three very different modes of acquiring knowledge about nature.

1. The mathematical, broadly 'Alexandrian' portion of the Greek legacy, after undergoing several centuries of reception and enrichment in Islamic civilization and then in Renaissance Europe, was turned, by Galileo and Kepler alone, into the beginnings of an ongoing process of mathematisation of nature, a process that was sustained and articulated through experimentation.
2. The broadly 'Athenian' portion of the Greek legacy, which consisted of four distinct, rival systems of natural philosophy with Aristotle's paramount, was replaced, at the instigation of Descartes and a range of other corpuscularian thinkers, by a natural philosophy of atomist provenance yet decisively enriched with a Galileo-like, mathematical conception of motion.
3. A quite specifically European-coloured mode of investigation bent upon accurate description and practical application that had started to emerge by the late fifteenth century began to consolidate around 1600, largely under the aegis of Francis Bacon's calls for a general reform of nature-knowledge, into an empiricist and practice-oriented form of experimental science.

What we are wont to call the Scientific Revolution consisted in these three by and large simultaneous transformations, plus an unprecedented amount of fruitful exchange amongst the resulting modes of investigation of nature over the remainder of the seventeenth century—a process leading up to and including Newton's *Principia* and *Opticks*. Thus, out of the revolution came three distinct modes of nature-knowledge of a kind the world had not seen before. Of these, the decisive mode was the program and practice of mathematisation of nature which was of universal import. Fact-finding experimentalism constituted a lesser mode, as yet very much coloured locally. Meanwhile the kinetic-corpuscularian mode of pursuit of nature was by far the most widely adopted at the time and certainly had more than local appeal, yet was of an essentially transient nature.

[1] Several portions of the present paper overlap with passages in other publications of mine, all written with distinct, non-overlapping audiences in mind, to wit, Cohen 2001, 2004a and 2004b. Also, some are lifted more or less verbatim from the book mentioned in the text to note 3.

P. R. Anstey and J. A. Schuster (eds.), The Science of Nature in the Seventeenth Century, 9-33.

Given this sort of analytic framework, if we wish to understand how modern science could arrive in the world, we must ask how, around 1600, these three almost simultaneous transformations could come about. From that, a further question emerges—how did such kernels of 'recognisably modern science'[2] manage to stay in the world once they arrived there? To address that question we must examine the built-in dynamics of the three modes of thought and concomitant practice thus produced, and the nature of their interactions in the course of the seventeenth century, as well as their differential societal appeal and anchoring. In the present chapter the focus is very much on the former question. In seeking to explain, at least in rough outline, the arrival in the world of basic elements of recognisably modern science, I present here a range of salient points that I treat at much greater length in the first half of a forthcoming book, provisionally entitled 'How Modern Science Came Into the World: A Comparative History'.[3] Inevitably, the three transformations that stand at the centre of my present argument are being painted in very broad brushstrokes, with many an issue which here I dispose of in a few sentences (if at all) taken up there at section- or even chapter-length. Consideration of many possible objections also falls to the wayside — the reader is invited to read what follows as the kind of 'ideal type' argument needed to draw so big a picture in so limited an amount of space.

1.CAUSES OF WHAT? A COMPARATIVE APPROACH

So much by way of introduction. Now, our first substantive task is to examine the principal components of European nature-knowledge on the eve of their radical transformation. In doing so, we need to take into account the diverse, cultural constellations in which these components found themselves over their respective life-times in a variety of distinct civilizations, notably those of Hellenism, of Islamic civilization, and of medieval and of Renaissance Europe. For if we fail to do this, we sacrifice the most significant source for subsequent causal analysis. The point, therefore, is to make our search for causes of the Scientific Revolution a *comparative* one. This, in my view, is indispensable if the causal investigation of the past is to avoid the indiscriminate piling up of an, in principle, unending array of antecedent events and circumstances. What was unique about what happened in Europe in the early seventeenth century can be brought out best by comparing it to what happened in other civilizations than the one that, through a typical blend of coincidence and causally linked chains of events, was indeed to create 'recognisably modern science'. However much Islamic civilization and medieval and Renaissance Europe surely differed, one thing they did have in common was that their respective pursuits of nature-knowledge only burst into life after they had taken up and sought to master what the Greeks had previously achieved. Their achievement then, provides our point of departure.

[2] Stillman Drake frequently used this felicitous expression in his books and articles on Galileo.

[3] Since in that book I list the scholarly resources drawn upon in every successive chapter, in the notes for the present paper I refrain from indicating more than just provenance of literal quotations.

2.TWO MODES OF NATURE-KNOWLEDGE IN ANCIENT GREECE

The key point regarding nature-knowledge in the Greek tradition is that it was pursued in two fundamentally different modes. One was mathematical science, which had its centre in Alexandria and which we shall therefore label here by that city's name for short; the other was natural philosophy, which (in the original period of school formation certainly) was centred in Athens. Both certainly went back to identifiable strands in pre-Socratic thought, yet developed from there in quite distinct, indeed, in almost fully separate ways. I propose to outline in seven points the nature of the contrast between the Athenian and the Alexandrian modes of pursuing knowledge of nature, and in order to give the reader a 'feel' for our otherwise somewhat abstract, successive points of contrast, I shall illustrate these points by reference to issues about the properties of sound.

Questions about sound appeared in all four Athenian schools of natural philosophy. Leaving Platonism aside (where it played a very subordinate role), we find Aristotelianism most concerned with a qualitative account of the perception of sound (details of which we also leave aside here), whilst the Atomists, as well as Stoics, concentrated on its mode of propagation. Atomists, in the wake of Democritus taking the world as made up of particles moving through void space, consequently took sound to be produced when atoms, pressed out of our throat or other vessel, on their flight through empty space strike our eardrum. Stoics, taking the world as made up of *pneuma*, a material/spiritual, air/fire-like substance in dynamic equilibrium, consequently took sound to be a disturbance of such an equilibrium reaching our sense of hearing the way wavelets produced by a stone thrown in a quiet pond propagate. In Alexandria, meanwhile, neither the production, the propagation, nor the perception of sound received special attention, but rather (in the wake of the Pythagoreans) the phenomenon of consonant sound, or, to be more precise, the empirical fact that the very musical intervals which strike us as sounding well are produced by strings of lengths in ratios of the first few integers (the octave (C–c) 1:2; the fifth (C–G) 2:3, the fourth (C–F) 3:4). Upon this observation they erected a mathematical discipline called 'harmonics', in which they examined properties of the 'harmonic', i.e., consonance-generating numbers. In this regard it stood opposed to a much more directly empirical analysis of music, emerging from Aristotelianism, centred not on harmonic relations but on the flow of the melody.

From this brief example, our set of seven pertinent contrasts may be gleaned.

1. In Athenian thought the central operation was explanation through the positing of first-principles; in Alexandrian thought, description in mathematical terms. First-principles of various kinds were put forward by a range of Athenian thinkers. What these first-principles held in common was, indeed, their being *posited*, with a blend of inner self-evidence and external, empirical illustration serving to underwrite their status as certain rather than probable knowledge. Such certainty was held to be both attainable and actually attained. Alexandrian thought had no use for any such first-principles. Its sole aim was to establish mathematical regularities without explanatory pretensions or underlying ontology; however, it did likewise lay claim to certain knowledge, with one of

the greatest representatives of Alexandrian thought, Ptolemy, deeming natural philosophical knowledge to be 'guesswork'.[4]

2. Athenian thought subsisted in four schools engaged in ongoing rivalry and (over time) alternating paramountcy. In addition another tradition, scepticism, opposed in principle the very possibility of the certain knowledge each claimed to have actually attained. Alexandrian thought appeared in one mode only, with the differences amongst its practitioners being solely over subjects examined and/or results arrived at.
3. In Athenian thought empirical phenomena appear as samples, chosen primarily in view of their capacity to illustrate the validity of the first-principles posited. In Alexandrian thought, empirical phenomena serve as individual points of departure for mathematical analysis. Each school of Athenian natural philosophy was ideally capable of explaining each and every natural phenomenon in terms of its own first-principles, which after all embrace the whole world, with no exceptions. In practice, however, empirical evidence served primarily to make the first-principles plausible (so, for example, in Stoicism empirical wavelets help us understand, by way of a profound analogy, what *pneuma* is, thus lending further credence to its existence and imputed properties). In Alexandrian thought, just as a vibrating string gave occasion to observe the numerical regularity of the consonances, other objects of sense, like beams in equilibrium or mirrors or lenses or planetary trajectories could give rise to mathematical analysis, provided they proved susceptible to such treatment.
4. In Athenian thought the aim, and the claim, was to gain a solid grasp of reality; in Alexandrian thought, real phenomena quickly vanished behind a process of ever increasing abstraction. The reality Athenian thought was seeking to grasp was our everyday reality, considered from a special point of view (this is true even of Platonism, so concerned to overcome everyday reality). By contrast, Alexandrian thought became ever more abstract the farther the process of mathematical idealisation went. Archimedes' proof of the law of the lever applies, not to real balance beams with real weights suspended, from which his analysis took its point of departure, but to straight lines to which numbers denoting weights have been assigned. Similarly, once the integer ratios for the consonances had been established, there was no trace of an inquiry into the nature of the vibrations produced by the string at its various lengths. In short, natural philosophy was about reality, grasped (with few exceptions) qualitatively; mathematical science about abstract entities treated with exactitude.
5. Athenian thought was comprehensive, Alexandrian piecemeal. The aim of Athenian thinkers was to grasp the whole; to explain the world or at the very least to understand that which gives the world the inner coherence they assumed identifiably to exist. The natural world was only a portion (in some cases, rather a subordinate portion) of all that had to be understood, in that the nature and mutual dealings of human beings, our place in the world, and how we can arrive at knowledge of all this in the first place, was likewise subject to the kind of

[4] Ptolemy 1984, Section I: 1.

understanding sought, called ‘philosophy’ for short. Alexandrian thought was none of these things. Investigators went about their researches one at a time, without positing or even seeking any necessary coherence between them, with the sole common thread being the mode of investigation applied, that is, the application of known mathematical theorems and properties.

6. Athenian thought spread out from four schools in Athens over the length and breadth of the Hellenistic, then the Roman world over a period of seven centuries, by means of coherent successions of teachers and disciples. Alexandrian thought, while fed from intellectual resources in a variety of Mediterranean cities (besides Alexandria also Rhodes, Perga, Syracuse), was and remained focused throughout on the Alexandrian centre and was cultivated on a more than individual scale for some two centuries; that is, by a few mostly isolated individuals, such as Ptolemy, for some two centuries more.
7. Any educated person could take part in philosophical debate, whereas to contribute to Alexandrian mathematical science required highly specialised skills. Philosophers in the Athenian mode filled an obvious social role in helping people make sense of the world at large; Alexandrian science could survive only for as long as the one powerful court that held a sustained interest in its doings persisted in its interest—which in antiquity was true only of the Hellenistic kings of Egypt, for reasons at which we can only guess.

3.MUTUAL ISOLATION

The next essential thing to grasp is how thoroughly the pursuit of these two distinct modes of nature-knowledge went ahead in mutual isolation. This applies both to practitioners (no philosopher was also a mathematical scientist or the other way round) and to contents. No Stoic or atomist thinker sought to link up his conception of sound with Euclid’s account of consonant sound; no mathematical scientist sought to enrich that account with a notion of sound propagating by way of either wave-like processes or the emission of particles. The separation was not, to be sure, entirely rigid. Both Athenian cosmology and Alexandrian mathematical astronomy took their point of departure in the self-evident conception of a fixed, central earth, and there were a few more overlaps. More than that, on two specific occasions attempts were undertaken at reconciliation or even fusion. Toward the end of the Golden Age of Alexandrian mathematical science some results of mathematical astronomy and elements of Aristotelian cosmology were jointly put into an astrological synthesis held together by the basic tenet ‘as above, thus below’. Further, Ptolemy’s overwhelmingly mathematical work in planetary theory, in optics, and in harmonics testifies to an awareness of the gap between the two modes in that in each case he sought to bridge it. For example, he sought to reconcile Euclid’s analysis of music in terms of the ratios of consonant intervals with Aristoxenos’ Aristotle-inspired, perception-based account in terms of melodic flow. Such attempts by Ptolemy to infuse abstract mathematical analysis with some greater degree of ‘reality content’ look hardly less misconceived from our modern point of view than the attempt at astrological synthesis. After all, that modern point of view has irredeemably been shaped by the kind of ‘mathematical realism’ introduced by Kepler and Galileo, and at bottom reconfirmed ever since (on which more below, of course). But this is not the main point of these mistaken efforts at synthesis. Their main point is rather that the very effort to overcome the gap is witness to its presence throughout antiquity (and way beyond), with Ptolemy’s very failure suggesting that there was no obvious or easy route toward doing a better job in this regard.

In sum, whereas in our modern era the big problem is to preserve quality in a world of quantity, in the intellectual legacy of the Greeks the issue—definable, obviously, only in retrospect—was quite the reverse. Not only in Greece, but everywhere humankind was living in what that most perceptive of historians of science, Alexandre Koyré, once called the ‘world of the more-or-less’.[5] In that world, so hard for us to recapture nowadays, the problem for the mathematical sciences was rather how to find a place for quantity in a world of quality. Recall how extremely tenuous the connection with reality actually was even in these few mathematised bits and pieces of science. With the fictitious and/or purely numerical handling of planetary trajectories, musical intervals, and the like, the only remaining, somewhat solid points of connection between the empirical world and its mathematical treatment were the mirror, the five simple machines known to obey the law of the lever, and regularly shaped bodies floating in water; and even these were treated in a thoroughly idealised manner. With so little quantity introduced into so relentlessly qualitative a world, it should not come as a big surprise that no breakthrough toward mentally conceiving a world of quantity occurred at this point (which is not to say that such an event would have been wholly impossible). With a bow to Koyré’s terminology once again, we might express the utterly marginal position of the mathematical branches of Greek nature-knowledge by stating that they formed little pockets of mathematical precision inside a world of the more-or-less, without there being any significant occasion to think that they might be turned into kernels of a new, entirely unheard-of ‘universe of mathematical precision’. We can say, guided by hindsight, that the Greek heritage was inherently capable of such an outcome; we cannot say that such an outcome was bound to occur *either then or at any later time*.

4.AGENTS OF ACTUALITY

What, then, was required to turn what was potentially there into actuality? The primary answer is that, due to a range of wholly unrelated, world-historical events—military conquests mostly—the Greek legacy became subject to a range of *cultural transplantations* and thus gained the very sort of opportunities for creative innovation that have so often in history gone with the meeting, or the clash, of cultures. That is to say, potentials inherent in the Greek legacy now got chances to unfold, and every subsequent feat of cultural transplantation entailed such chances afresh. From the perspective of the creator-civilization, once fresh developments

[5] See his ‘Du monde de l’“à-peu-près” à l’univers de la précision’ in Taton 1966.

turn into tradition, they tend to stifle and become routine. But, considered from the viewpoint of the receiver-civilization, the very effort required to master and appropriate a tradition foreign to one's own ways, may set free energies to go ahead and enrich or even, *under particularly propitious circumstances*, radically transform it.

5.THREE RECEPTIONS DISTINGUISHED

No such transformation did occur in the course of the *first* reception of the Greek legacy, which took place in Islamic civilization. In mathematical science as in natural philosophy, the legacy was adopted, expounded and creatively extended. In mathematical science it was enriched with new theorems here, new geometric tools there, and with syncretist efforts and shifts of emphasis in natural philosophy amidst their continuing rivalry. This process left intact not only these two overall frames and modes of thought as the Greeks had produced them, but also, once again with very few exceptions, the intellectual as well as social chasm between them.

Nor did any large-scale transformation occur in the course of the *second* and far less complete reception of the Greek legacy, which took place in medieval Europe. This reception was really an exception in so far as one of the four schools of natural philosophy (Aristotle's, of course), right from the start became so dominant that it either drove its three immediate rivals as well as the Alexandrian mode underground, or scholasticised portions of them to the point that they were almost unrecognisable.

Nor, during its earlier stages in the sixteenth century did any large-scale transformation occur in the *third* reception of the Greek legacy, which was overall a much more balanced one like its Islamic counterpart had been. In the first place, full rivalry in natural philosophy returned as Platonic, Stoic, and atomist conceptions along with their sceptical nemesis, were restored through textual transmission and in scholarly debates. Furthermore, mathematical scientists in the Alexandrian mode, by means of a similar restoration of texts and theorems and proofs, sought to regain, both intellectually and socially, such terrain as had been occupied by their counterparts in the worlds of Hellenism and Islam, but had been lost during the reign of the schoolmen. Thus in Renaissance Europe mathematical humanists like Regiomontanus or Maurolyco soon found themselves in a situation such as had confronted earlier Islamic mathematical scientists like Thabit ibn Qurrah or Ibn al-Haytham. They moved beyond the sheer recovery of proofs and theorems, through the hesitant reconstruction of some material, which over the centuries appeared to have gotten irretrievably lost, and eventually became involved in even more hesitant attempts at improvement of portions of the inherited archive.

It is important to realise that almost all this humanist activity was aimed at recovery of lost knowledge which was now about to be restored to its original integrity. What innovation actually took place in this regard was the unintended by-product of an essentially backward-looking business—the sense that all that could be known had once been known already was, if anything, more outspoken in Renaissance Europe than it had been in Islamic civilization. This is true of the modest extension of Archimedean theorems on equilibrium states accomplished by the end of the sixteenth century in Stevin's work, or in the school of Urbino that operated under Guidobaldo del Monte's patronage; it is no less true of the restoration on the grand scale of Ptolemaic planetary astronomy undertaken by Copernicus half a century earlier.

Once more, then, just as had happened in Islam, just so in late Renaissance Europe some increasingly creative yet retrospectively modest enrichment took place, while leaving both the overall frames of the Athenian and Alexandrian legacies and the chasm between them fully intact. The number of practitioners was quite considerably larger and a narrower geographical scope, the printing press, religious controversies, and a proliferation of princely courts gave a certain increased speed and urgency to ongoing debates. Yet by the turn of the seventeenth century, there was little reason to anticipate any major break in a by now familiar, perhaps already somewhat worn-out pattern of such a 'renaissance' of Athenian natural philosophy and of Alexandrian mathematical science. Or, was there not, in fact, something more going on, something that portended a break in that pattern?

Note here that not all pursuit of nature-knowledge in Renaissance Europe was aimed at restoration. A great number of books appeared at the time with the word 'new' in their lengthy titles (written mostly in the vernacular). It can safely be said that they had nothing to do with this recovery-oriented movement of Greek or Latin writing humanists, but tended rather to be contemptuously dismissed by them. Instead, works advertising their novelty, like a Spanish book on American herbs typically translated as *Joyfull Newes of the Newe Found World* (1565/1577) belong to another mode of pursuit of nature-knowledge altogether. Their programmatic insistence on novelty, to be sure, stood for a confidently future-oriented, dynamic approach to things much more than for unalloyed, fully genuine originality. This vigorous current of thought of a novel kind had begun to manifest itself by the mid-fifteenth century, along with the humanist replay of the Greek performance, yet separated from that movement by a considerable intellectual and also social chasm. Here, one does not see the mathematical handling of a restricted set of geometric or numerical figures thoroughly abstracted away from selected pickings of natural reality, as in Alexandrian science. Nor is one presented with assorted pieces of real-life evidence adduced to shore up empirically a set of comprehensive principles established beforehand, as in Athenian natural philosophy. Rather, one finds here a dedicated striving for life-likeness, for factual accuracy and for exhaustive description. This is what came to mark domains as varied as anatomy (Vesalius), plant description (the three German herbalists, Garcia de Orta), the cataloguing of planets and stars (Tycho), or geography (Pedro Nunes, an assortment of scholarly and/or commercial mapmakers). This thirst for facts accurately rendered, as strongly exemplified in the work of Leonardo da Vinci, was accompanied by a strongly practical orientation. Paracelsian iatrochemistry and other currents of natural magic under the banner of Hermes Trismegistos offer the most spectacular examples of this action-directed aspect of Europe's third mode of nature-knowledge. But, the linking of the pursuit of nature-knowledge to matters of current concern was equally exemplified in the widely expressed aspiration to apply mathematics to practical problems in perspective, fortification, and navigation. Thus arose a new kind of knowledge intermediate between the artisans' design of ingenious devices for practical use and the lofty abstractions of Greek provenance taught (albeit in a simplified manner) in all of the universities of Europe.

6.EUROPE'S COERCIVE EMPIRICISM

It is now time to make a distinction between the culture-transcending nature of both the Alexandrian and the Athenian modes of pursuit of nature-knowledge, and the much more locally determined nature of the motley of activities just surveyed—locally determined, in that our third mode can be seen to reflect certain specifically European values. What, then, was so specifically European about hosts of accurate descriptions, the application of some mathematics to artists' problems, the emergence of several other possible interfaces between nature-knowledge and the crafts, the universal claims raised for chemistry, and a magical philosophy bent on the conquest of nature?

The answer is, in the first place, that several other long-term processes going on at the same time in Europe stand clearly reflected in those activities. Artists were similarly concerned with finding new modes of naturalist representation, and it is not by chance that we find Vesalius' atlas or Brunfels' and Bock's herbals illustrated by contemporary men of art, or Leonardo even blurring any distinction whatever between art and the pursuit of nature-knowledge. The voyages of discovery, too, shine through our third mode at many a spot, as in Orta's extensive descriptions of herbs and plants in India or in Nunes' pioneering work on navigation, with the whole enterprise as such turning into a powerful symbol of a forward-looking stance generally. An ongoing concern with machine tools and their labour-saving capacities can further be seen at work behind the scenes of the ongoing *rapprochement* between the pursuit of nature-knowledge and the crafts. For example, they are behind Leonardo's painstaking analyses of how machine tools work so as to optimise their effective power, and they are behind Agricola's creative survey of current mining practice.

Modes of naturalist depiction; explorations of foreign lands and peoples, and the invention, importation, and employment of machine tools, were surely not absent from other civilizations at the time. European uniqueness does not of course rest in that; it was of a more *restricted* kind in that what happened elsewhere in fits and fashions turned into far more sustained enterprises in Europe. What began as a comparably limited exercise in naturalist depiction by men like Giotto and Duccio turned in the end into a sustained, and by and large desacralised art no longer bound up with stereotyped modes of depiction. Vasco da Gama's voyage to India did not remain what it originally appeared to be—the regional counterpart to incidental voyages like Ibn Battuta's or even to far-flung expeditions like those under Chêng Ho—rather it turned into an early link in a chain essentially unbroken until the last blank spot on the map of the earth had been filled in. Similarly, in Europe the invention and/or importation of machine tools did not remain a matter of sporadic and incidental activity, but came to display a dynamic characterised by unusually eager reception, very quick spread, and a comparatively huge impact upon daily life,