12 Lionel Robbins, *The Nature and Significance of Economic Science*' (London 1932), p. 132.

13 A. Sen, *On Ethics and Economics*, (Blackwell, Oxford, 1987), pp. 1–2.

14 J. S. Mill confuses the two by defining wealth as 'all useful and agreeable things, which possess exchangeable value', *Principles of Political Economy* (New York, 1969), p. 9. W. S. Jevons wanted, confusedly, to turn usefulness from a qualitative concept into a quantitative one like exchange value, and he thought he found a way; *The Theory of Political Economy* (London, 1879), pp. vii–viii. Marshall simply says use value is of no importance and dismisses it out of hand; *Principles of Economics*' (London, 1898), p. 8.

15 *The Collected Writings of J. M. Keynes* (London, 1973), vol. 29, p. 81.

Styles of Scientific Thinking

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Science as we know it today has a long history stretching back to the Greeks and the Babylonians. It is essentially the results of our continuing attempts to understand the natural world, and as such it is conditioned by our culture, by our beliefs concerning what is important and what is not about the nature and purpose of knowledge, and about the structure of argument and the criteria of proof. These factors vary from one culture to another, and together they determine the style of scientific thinking.

It was very difficult to get started, and fatally easy to become trapped in a blind alley. Early civilisations amassed much natural lore, and extensive astronomical observations were made, notably by the Babylonians. But the chief credit for initiating the scientific enterprise belongs to the ancient Greeks.

The whole scientific enterprise, as Alistair Crombie points out in his magisterial treatise*, depends first of all on the underlying vision of

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reality, and then on the arguments used to support and verify that vision. The Greek philosophers provided both the vision and the argument. The first idea was that the vast complexity of the world can be understood in terms of simple elements; once we know these elements we can see how everything else follows from them, giving an integrated knowledge of the whole. The rules of rational inference were codified into the science of logic, and an outstanding example of the power of rational argument was provided by Euclid.

This immediately raises serious difficulties: how are we to find out about these elements, and how are we to connect them to the world of nature? The early Ionian philosophers simply postulated the elements: all is water (Thales) or all is composed of earth, air, fire and water (Anaximander).

It was Plato who realised that mathematics can be used to understand the world. He postulated a world of pure forms that are imperfectly realised in matter. The forms are mathematical, and thus we can understand the harmonies in nature, for example the simple numerical ratios between the musical harmonics.

A more extensive scheme, embracing all fields of knowledge, was elaborated by Aristotle. He saw the whole of nature as governed by laws; everything that happens has a cause, everything that moves has a mover. This implies that there must be a first cause or Prime Mover. All that we see is thus deducible from fundamental principles, and he tried to obtain these principles by rational argument. Thus for example he was impressed by the difference between the celestial world of the stars and the planets, where there seems to be no change, and the terrestrial world where things grow and decay. Everything is perfect in the celestial world, and so the planets must move in circular orbits, since the circle is the most perfect curve. The celestial world is eternal and incorruptible; the terrestrial world is changeable and corruptible.

Reacting against the materialism of the atomists Leucippus and Democritus, who maintained that all is atoms and the void, Aristotle tried to save purpose, and hence human freedom, by postulating that all material beings seek their natural place. Thus fire rises upwards whereas stones fall downwards towards the earth. In this way he was able to give a quantitative account of many natural phenomena.

This method of studying nature is too general and superficial; it fails to tell us exactly why things behave as they do, and so does not enable us to test whether the postulated principles are true. The intuitive approach is too simple and optimistic; the world is not open to our imagination and the truths of science are not so easily won. Aristotle indeed realised that the natural world must be carefully examined, and was himself an acute observer of biological phenomena. He failed however to observe inanimate phenomena with the same care; thus he attributed the Milky Way to mist from the marshes without noticing that it is unchangeable, and carelessly maintained that when things fall, their velocities are proportional to their masses. He thus failed to understand the importance of precise measurement, which was well understood by other Greeks such as Archimedes.

Aristotle's philosophy had a great and enduring influence on subsequent thought because it provided an all-embracing framework for the analysis of human activities, rationally ordered and persuasively articulated. Most people were justly impressed by the profundity of his philosophy and were not so sensitive to the defects of his physics. The result of this was that further advances were inhibited and science was trapped in a blind alley for over a thousand years.

A new style of scientific thinking came from an unexpected quarter, from the Revelation given by God to the Hebrews. The God of Abraham, Isaac and Jacob was very different from the Prime Mover of Aristotle. God freely chooses whether to create or not, and what form His creation takes. The world is not a necessary world, like that of Plato and Aristotle, so it cannot be apprehended by pure thought. We have to examine it in detail to find out how God in fact made it. The world is not eternal; it was created in time. It reflects God's rationality and obeys His laws, and so there is no reason to distinguish between the celestial and the terrestrial bodies. God ordered everything in measure, number and weight, and so a precise quantitative study of the world is essential if that order is to be found.

The first attempts to confront Greek and Hebrew thought were made by the Jewish philosopher Philo Judeaus of Alexandria in the first century BC, and this was continued by Lactantius in the 3rd century AD, Augustine in the 5th and by John Philoponus in the 6th.The Incarnation of Christ strongly reinforced the Hebrew vision of the world as it enhanced the dignity of matter and destroyed the cyclic view of time that was such a debilitating feature of all ancient cultures.

The doctrine of creation was of particular importance for the development of modern science because of its influence on the philosophical discussions in the Middle Ages. The works of the Greek philosophers became known in the universities of Western Europe during the High Middle Ages, and it was soon realised that their sophistication and comprehensiveness provided the means to articulate the Christian Faith in a more profound way. Intense discussions took place, particularly in Paris, and eventually the bishop, Etienne

Tempier, found it necessary to condemn 217 propositions as contrary to the faith. Among these were many concerning creation, in particular several restricting God's power. The effect of this was to channel thought in fruitful directions, leading eventually to the rise of modern science.

The medieval philosophers greatly admired Aristotle but nevertheless did not hesitate to differ from him when he contradicted Christian doctrines such as the creation of the world in time. Thinking about creation Jean Buridan realised that when God created the world He gave an impetus to every material body that enabled it to continue in motion. He thus contradicted Aristotle's dictum that everything that moves is continually acted upon by a mover, and adumbrated the conservation of momentum, eventually to become Newton's first law of motion.

Experimental science was also developed in medieval times, following the logical methods of Aristotle that were designed to analyze the relations of cause and effect. In the hands of Robert Grosseteste and William of Ockham these were developed into systematic procedures by which hypotheses were tested by examining their consequences both logically and by comparison with experiment. Grosseteste based his physics on a theory of light, seen as the most fundamental form of energy, and thus paved the way to the mathematisation of nature. He saw light as an instrument used by God to produce all creation, from the celestial spheres to the human body, and thus it is the cause of all subsequent changes. He studied the reflection and refraction of light, and other optical phenomena such as the colours and geometry of the rainbow. This work was continued by Witelow, Pecham and Theodoric of Freiburg. Thomas Bradwardine was the first to try to quantify motion by connecting variables by algebraic functions. Further studies were made by William Heytesbury, Richard Swineshead and John of Dumbleton.

The extent and sophistication of medieval science, now very well-known through the work of Duhem, Crombie, Mayer, Grant and many others, is sufficient to refute the view, favoured by secularists and Protestants, that the Middle Ages were periods of intellectual stagnation and ignorance, and that science flowered only in the Renaissance when the domination of medieval theology was ended.

The medieval belief in the order of the universe encouraged accurate measurements that can be used to test general principles. Thus Kepler toiled for years to find the orbit of the planet Mars, believing it to be circular. He failed to fit the accurate data of Tycho Brahe, and eventually realised that the orbit is elliptical, thus contradicting Aristotle's a priori reasoning.

Galileo adopted the medieval idea of studying concomitant variables and relating them algebraically. He saw that the way ahead was not through general speculations but by careful and detailed analysis of specific well-defined problems. Thus he measured the time taken by balls to roll down inclined planes and found that the distance travelled is proportional to the square of the time taken. He made the first telescope and immediately observed the satellites of Jupiter, which tended to support the Copernican heliocentric system. He also observed sunspots, which were seen as a blemish on the perfect celestial realm.

Galileo's discoveries offended the Aristotelian establishment, and soon he was in trouble for his support of Copernicus. They asked how he could explain the passage in Scripture where it is said that the sun stood still; implying that normally it is in motion. He was told by his friend Cardinal Bellarmine that there would be no difficulty if he simply said that heliocentrism was a mere calculational device, with no pretence to represent reality. He admitted that if definite proofs of the earth's motion were found, then the question of the interpretation should be looked at again. This did not satisfy Galileo, who said that the Scriptures were given to teach us the way to salvation, not to provide us with information about the world that we could find out about by reason and experiment. At that time, however, a definitive proof of heliocentrism was not known; this came years later with the work of Foucault and Bradley. Nevertheless, Galileo vigorously propagated his views with more skill than tact, with well-known consequences.

Subsequently, Newton postulated his laws of motion, and showed that they account for the elliptical orbits of the planets as well as the observations of Galileo, thus unifying celestial and terrestrial dynamics. The demolition of Aristotelian physics was complete and modern science was established in a state of unending growth.

From the sixteenth century onwards there was great interest in the historical development of mankind, the goal being the identification of the causes of change The method consisted in trying to find a common origin of a class of phenomena. It was first applied to the comparative study of languages in order to establish how they are related to each other and how they have diversified from a single postulated source. Matthew Hale saw an analogy between the development of languages from a common origin and the development of living things, and Leibniz established the comparative method as a systematic discipline.

Francis Bacon believed that the goal of history is the discovery of causes and saw the history of thought as central to any account of mankind. He saw himself as the inaugurator of a new scientific epoch, and tried to specify the scientific method in a way that would guarantee progress. He hoped that from the increased understanding of nature would come the improvement of man's estate. He believed that he had succeeded in firmly linking the empirical and the rational. His role was more that of a philosopher of history than of science, and he believed that the true purpose of knowledge is not for pleasure or for profit but for the benefit and the use of life.

It was increasingly realised that science is a co-operative endeavour, and groups of scientists banded together to form national academies that provided opportunities for discussion and facilitated exchange of news about the latest discoveries.

In the eighteenth century there was increasing emphasis on the history of science and of mankind in general, with emphasis on explanation through a search for origins. This was partly and in different ways the legacy of Descartes and Locke. The philosophical histories often relied more on imaginative reconstruction than on established facts, which were in short supply for the earliest times. The need for more facts stimulated extensive anthropological studies of primitive societies and languages in order to obtain some insight into the development of our own. Herder insisted on the need for careful observations of man in all his aspects, and offered 'a philosophical history of humanity within a Leibnizian history of nature. He saw in the whole history of nature and mankind a providential teleology designed to generate in succession first the general structure of the universe and then, within the special conditions of the solar system, the Earth and on it the sequence leading from inanimate materials up through plants and animals to man. Each stage was designed to prepare for the next, all leading to humanity, to man with his rational and moral capacities as the final product'.

There was intense debate between philosophers like Maupertuis, Buffon and Herder who insisted on an unbridgeable gap between man and the nearest animal and those like La Mettrie and Rousseau who argued for a real affinity between them. La Mettrie tried to prove that man and animals are both machines, with different organisations, whereas Rousseau saw apes not as machines, but as men in a natural state. This discussion stimulated further interest in the evolution of languages, and attempts were made to educate apes, without much success.

Complementing these studies of the history of man were parallel studies of the history of nature, from the origin of the world until the present time. Until the seventeenth century most philosophers were more concerned with nature as it is now, rather than with how it came to be. At first the discussion centred on the complex interaction between the revelation in Genesis and the ancient Greek cosmogonies, particularly that in the *Timaeus*. Twelfth century philosophers like Thierry of Chartres looked for natural causes as well as divine reasons,and much later Descartes tried to reduce the laws of nature to those of matter in motion. He suggested that the existing universe could have been generated by the operation of purely physical laws on the primal chaos created by God. This was highly speculative, but the subsequent detailed studies of geology and biology provided a vast body of empirical evidence to be explained by evolutionary theory. Fossils looking like fish skeletons were found high in the mountains, suggesting a long process of geological change. Early estimates of the time taken for such changes expanded the time scale of the earth's history far beyond the 6000 years apparently implied by Scripture.

The study of fossils suggested that species have changed in the past,and this idea was supported by the success of breeders of new plants and animals. Extensive studies were made of the structure of plants and the anatomy of animals, and the many similarities were classified by Linnaeus. Buffon saw that this could imply a common origin, and conjectured how species developed from simple molecules. Lamarck improved Linnaeus' classification of the animal kingdom, basing it on fundamental anatomy, and proposed that species are gradually transformed by the inheritance of acquired characteristics. Cuvier on the other hand stressed the effects of the surroundings and attributed the similarity of living organisms to a common response to functional needs.

These descriptions of the development of species left open the question of the effective agent. Paley saw the intricate organisations of plant and animal forms as evidence of design, and considered it incredible that it could all have come about by chance. Lyall used such theological ideas to guide his research into the ecology and geology of creation, following unchanging laws. Inspired by Malthus, Darwin and Wallace found in natural selection, acting on chance variations, the agent of evolution. Their achievement was to develop a new vision and to provide massive evidence in its support. They were able to explain, in broad outline, how species could change and adapt themselves to new environments. Darwin saw in this a nobler conception of design than that afforded by a series of individual creations, but did not see the process of change as leading in any particular direction; it is simply a series of progressive adaptations made in order to survive. The idea of evolution had been around for a long time, but Darwin and Wallace showed that effective originality required not only ideas but also the detailed painstaking work necessary to reveal their consequences.

These brief reflections on the effects of styles of scientific thinking on the development of science give scant indication of the vast scope and massive scholarship of Alistair Crombie's three-volume work. There are extensive references to the literature, and the notes, bibliography and index alone run to nearly a thousand pages.

In all, he identifies six styles of scientific thinking, each of them identified by the object of enquiry, the questions posed and the answers accepted. These styles are firstly *postulation,* exemplified by the Greek realisation that mathematics could account for some of the simple regularities of nature. Then there is *the experimental argument,* a way to search for principles in more complicated phenomena, as exemplified by the medieval logic of experiment and also the rational artists of the Renaissance. This led to *hypothetical modelling* comprising the imitation of nature by analogical models, giving insight into the working of nature. The studies in the 17th and 18th centuries of the *taxonomy* of living things, the logic of ordering by agreement and difference, provides a fourth style. Studies of the random processes underlying change required the development of *probabilistic and statistical analysis* allowing probability to be quantified. Finally there is *historical derivation.* whereby the diversity of existing things, from languages to living organisms, are traced to a common origin. This style is found throughout history, from the ancient Greeks to more recent times, when it is applied to the history of the human mind and to the cosmological, geological and biological history of nature, culminating in the theory of organic evolution by natural selection.

It is of particular interest to see how at each stage theological ideas have inspired the growth of science, and how the resulting scientific discoveries have in turn influenced theology. Any serious study of these interactions will be greatly indebted to Alistair Crombie for this culmination of his life's work, which puts us all once again immeasurably in his debt.