THE FIRST SCIENTIFIC REVOLUTION

As we shall see in a later chapter, without glass instruments, the famous scientific revolution, stretching from Galileo to Pasteur, that is roughly 1600-1860, could not have occurred. Glass played a central role in astronomy (Galileo, Kepler and all subsequent astronomers), in chemistry (Hooke, Boyle, Faraday onwards), in physics (Descartes, Newton and onwards), in medicine (Hooke to Pasteur). It seems reasonable to argue that the increasingly precise and reliable knowledge of the medieval period would have levelled off, just as knowledge levelled off in civilizations with little glass such as China, Japan and Islam after 1400. All of this is beyond contention. It is not widely known or thought about, but as soon as one points out the role of chemical apparatus (flasks, retorts, vacuum tubes, barometers etc.) or seeing apparatus (telescopes, microscopes etc.) an intelligent person will immediately concur. Glass was an absolutely necessary, if not sufficient, tool of thought. The links are above the surface and obvious.

What is less obvious and much more difficult both to discover and then to convince others of is the subterranean influences of glass in the centuries before Galileo. The role of glass in preparing the philosophical and practical foundations for the better known expansion of reliable knowledge from the time of Francis Bacon and Galileo is largely invisible. We need to understand something of what happened during that period for at least two reasons. The development of reliable knowledge in this period, what we loosely call 'science', is part of the context of the discussion of developments in the 'arts', which is an important feature of our argument. Art and science were not divided and I argue in the next chapter that the fifteenth century artistic Renaissance is only comprehensible if we see it as an application of the discoveries in medieval geometry and optics. Some account of those developments is needed. Furthermore, we cannot understand the burst of activity from about 1600 without seeing that it is really a later wave of the growth of reliable knowledge in the West, coming after earlier waves, in particular that which had started in the thirteenth century.[1]

By the time of Bacon and Galileo, there was already a four-fold foundation for science, without which the famous seventeenth century developments could not have occurred. There were a set of techniques, what we call the experimental method, which long preceded their supposed invention by Francis Bacon. There was a certain attitude of curiosity, a belief in the possibility of finding new things, a confidence that there were deeper laws to be discovered behind the surface of reality and that it was a person's task to task to discover these. Thirdly there was a set of mathematical tools, particularly geometrical and algebraic, and a large accumulated knowledge of the natural world and how it worked which would be essential for the new sciences. Finally there was already the concept of the laboratory, filled with tools of thought, many of them made of glass, but also others such as the astrolabe, for investigating and measuring nature with precision. Considerably influenced by alchemical experiments there was an array of retorts, flasks, jugs, mirrors, lenses, prisms, already being used in chemistry, physics and optics.[2] Let us now look briefly at these developments in science up to about

[1] See, for example, Crombie, Augustine, II, 110

[2] For the array of glass instruments used in sixteenth century science by investigators such as della Porta, Digges and Dee, before microscopes and telescopes were available, see Ludovici,

1600, posing as many questions as answers but also suggesting some hypotheses which those more expert in this period and topic may test.

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Einstein famously characterized science as the combination of two things; Greek geometry and the experimental method. He suggested that 'the discovery of the possibility of finding out causal relationships by systematic experiment' was discovered at the 'Renaissance'.[3] Many people believe this. Yet a great deal of work in the second half of the twentieth century, particularly the monumental work by A.C.Crombie, has shown that the experimental method is older than the fifteenth or sixteenth century (which is the period Einstein was thinking of).[4] Indeed, in one sense, the method is timeless. All animals, and consequently **homo sapiens** from the inception of the species, have used an experimental method, that is to say, hypotheses are formed and tested. A young child guesses something is hot, then lightly touches it to test out the hypothesis, then adds a piece of knowledge to strengthen the general law that things recently removed from the top of a hot stove maintain their heat for some time. Certainly all civilizations have used experiments, and not least amongst them the Greeks.

It would be more accurate to re-phrase Einstein as follows. We are talking about degree, rather than an absolute change. We are all experimentalists, but some are more experimental than others. While experiments abound in everyday life, it is undoubtedly true that in many civilizations, and often increasingly over time, it is thought that knowledge of the laws of nature is already sufficient. All that we need to know is known: the Buddha, Confucius, Mohammed, Aristotle, have already provided the answers. So why experiment? Indeed, many of those in power would contend that one should not do so, for it is a form of blasphemy or doubting. If this general disincentive is not enough in itself, it is strengthened by a further obstacle. The individual who experiments has little success or even chance of success. The tools and techniques for discovering new things are weak, the complex inter-play of causation too complex and concealed for the naked eye or the naked brain.

So we may ask, what is needed to make an experimental method not merely a private matter of individual survival but a widespread and accepted method of re-interpreting the received wisdom about the world? There are probably many things, only a few of which can be lightly passed over here. Some of them become obvious if we look at the two burst of experimentation which form the background to the era of Galileo.

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The first wave is the work of the great Arabic scientists from the ninth to twelfth centuries, Al-Khind, Al-Hazen, Rhazes, Avicenna and others.[5] Three constituents of their world can be noticed here. There is the strong tide of new theoretical frameworks from other civilizations which need to be absorbed by way of testing and exploration. The recovery and absorption of Greek and to a lesser extent Roman discoveries, is but a part of it. They were also absorbing

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Seeing, 34-5

[3] Einstein, quoted in Crombie, Science, Optics, 41

[4] For example, Crombie, Robert Grossesteste, passim, and especially pp.1,290.

[5] For a useful overview, see Park, Light, 72-87; for a short account of Alhazen's optical works see Crombie, Science, Art, 304-315 and Crombie, Science, Optics.., 189-194.

ideas from the East, the mathematics of India and the enormous learning of China most notably. The great thinkers in this fertile area fed by so many streams of thought were faced with absorbing and developing some very high level theory into their philosophic systems. The powerful Islamic civilization that came to straddle much of Eur-Asia, placed at a perfect point between East and West, created a dynamic whirlpool propitious for experiment.[6] A sense of wonder, surprise, puzzlement, of new things emerging, all of which are essential for science, were there. Yet if this had been all, it is doubtful whether it would have led to much more than translations and annotations, and some developments in mathematics and general theory.

In order for there to be progressive experimentation, it is necessary for there to be technologies of knowledge, artefacts which allow one to do the testing of newly encountered or generated hypotheses. What was also special about the Arabic situation was that the arithmetic of India, the geometry of Greece, the medical knowledge of Rome, the practical discoveries of China, which had reached the limits of the greatest thinkers in those civilizations could now be put to the test. They could be taken on by a civilization which had a range of new tools of the mind which could allow investigators to look experimentally at the largely intuitive, deductive systems which had poured into the great cities of the middle east and southern Spain where Islam flourished.

In the area where glass blowing was invented, Syria and Iraq, glass making skills developed rapidly. After the collapse of the Roman Empire, this region was the glass-working centre of the world. By the time of the great Arabic scholars, the most exquisite glass of all shapes and sizes and colours was being made. If a thinker wanted a glass to test out chemical theories, there was no problem in making it. If glass to bend light in certain ways, or to break it up and examine its constituents, or to magnify the hitherto unseeeable, or to test whether sight came into or went out of the eye, all was available. It may be that there was still much frustration, that a good deal of time and effort was wasted, that many avenues were unexplored, that metal mirrors were still used rather than glass ones, that spectacles were surprisingly not invented, that legends of telescopes or binoculars being used against the Crusaders were untrue. Yet even when we take all this into consideration, it does not seem implausible to argue from what we do know, that glass provided, along with mathematical and logical tools from India and Greece, one device that made experiment possible.

That this seems likely, emerges if we look at those fields where the experimentation of the Arabic scientists made the greatest added contribution to what they had received from others. In medicine, the use of glass to see the minute or to test compounds is central. In chemistry, one of the greatest Arabic achievements, glass tubes, retorts and flasks are essential for the laboratory.[7] In astronomy, even before the telescope, mirrors and glass, combined with the marvellous astrolabe, are helpful. Above all in optics, which in turn deeply influences physics and geometry, we know of the role of prisms and mirrors in Arabic work. It is also seems that they used plano-convex lenses.[8]

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[6] For a brilliant older oveview of Islamic civilization see Marshall Hodgson, Venture, and in particular XXX. On Islamic science see Huff, Rise, ch.2, Lindberg, Beginnings, ch.8, Ronan, Cambridge History, ch.5.

[7] According to McGrath, Glass in Arch.,20, J.L.Myers suggested that 'the backwardness of the Greeks in chemistry was due to the lack of good glass...'

[8] See the discussion of lenses below.

A very brief sketch of optics is worth including.[9] The first major figure was Al-kindi (c.801-66) who perfected a theory of light and put some order into the chaos of observations and the relics of Greek science. In about 984 'a mathematician named Ibn Sahel attached to the court of Baghdad produced a treatise on burning mirrors and lenses that has recently been reconstructed and partially translated. It discusses the focal property of a paraboloid mirror and then goes from bronze to glass...'. The answer to his questions is a hyperboloid.' ' Ibn Sahel's proof shows that he had a mastery of geometrical reasoning and also a precious piece of knowledge that had to be rediscovered long afterwards: Snel's exact law that relates the angles of incidence and refraction when light passes from glass to air. He had everything that was needed to create a theory of optical instruments more than 725 years before Kepler - except, apparently, the concept of an optical instrument. He only wanted to light a fire.'[10]

This is a fragment of the background to the greatest of the Arabic philosophers of light. Alhazen (born c.965) worked at Alhazen mosque in Cairo (a theological university that still exists), making copies of Euclid and Ptolemy. He died in c. 1041 and published about 120 books. His work on optics was translated in about 1200 into Latin. 'On Vision' was printed in 1572 and dominated speculation until 1610 and Kepler. It was an empirical work, drawing conclusions from what he had observed. He argued that the incoming form was purely visual; recognition is the result of memory and inference. Things come into the eyes, rather than, as in the old theory, light travelling out of the eye and finding objects. He thus analysed an old subject in a new way and contributed to an understanding of the anatomy of the eye.

Although he made enormous advances, there were two obstacles which stood in his way. He had no idea of the function of a double-convex lens and he did not perform a dissection of the eye (Islamic law forbade it), and hence had an erroneous picture of it. Nevertheless he made a most original contribution. He suggested that the surface of an object consisted of many different points or specks which we see and then re-arrange. He may have invented the **camera obscura**, and certainly used one.

In Book II of his 'Optics' he analysed the process of vision in a basically Aristotelian way. He provided a coherent picture of the entire process of vision. In Book III he treated of optical illusion and the next three books dealt with reflection from flat and curved surfaces and the distortions which they can produce. In the last, seventh, book he discussed refraction from plane and spherical surfaces. Park believes (quote? p.86) that Alhazen and Ptolemy were the only early students of light who thought in the ways we would now call scientific. They questioned Nature with experiments and tried to interpret its answers in ways that made sense. Park writes that 'Alhazen's greatest achievement was to get the image into the eye, impressed on the sensitive surface of the crystalline humor. He understood for the first time that one cannot stuff the whole image of something into the pupil...'[11] He realized that light is a substance that comes from the sun. Thus he laid the foundation for the laws of optics.

Yet despite the enormous advances made by Arabic theoreticians, it is generally agreed that they did not break through into that set of inter-connected practices which we call 'science'. For example, Crombie wrote that Arabic work 'for one reasons or another... failed to become

[9] This is based on the more detailed account in Park, Light, 72-87; see also Crombie, xxx and others.

[10] Reference XXX

[11] Park, Light, 86

thoroughly experimental in outlook'.[12] Those who have looked carefully at the achievements of Arabic scholars are agreed that, for some reason or another, they just fell short of that break-through that occurred in western Europe sometime after the thirteenth century. As Huff, for example, writes, 'The Arabs were perched on the forward edge of the greatest intellectual revolutions ever made, but they declined to make the grand transition "from the closed world to the infinite universe," to use Koyre's famous phrase.'[13] We therefore need to turn to the legacy of these developments in western Europe in order to pursue the argument further.

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In considering the nature of Islamic and medieval European science a good deal of the argument will hinge on the use of glass to bend light. One central aspect of this is the development of the lens. However, there is much dispute about the history of the lens which it is important to understand and resolve before we proceed further. Fortunately, it turns out that much of it can be resolved by looking at definitions. The Oxford English Dictionary defines a lens as '1. A piece of glass, or other transparent substance, with two curved surfaces, or one plane and one curved surface, serving to cause regular convergence or divergence of the rays of light passing through it.' A narrower definition of a lens is then quoted from Newton's optics, namely 'A Glass spherically Convex on both sides'. Much of the dispute about whether the Arabic and thirteenth century European philosophers had lenses or not revolves around this. Basically, those who say a lens must have two convex sides argue that there were no lenses manufactured until the late thirteenth century. Those who say that a plano-convex glass is a lens can show that from at least the ninth century Islamic thinkers were using lenses. We shall return to this.

There is an even earlier dispute. This is the question of whether the Greeks and Romans manufactured lenses. The question is discussed, for example, by Ludovici. He refers to the theory that certain objects in the British Museum might be plano-convex lenses. But he comes to the conclusion that 'the majority agree that these articles were not designed to magnify or help the vision in any way. They think the articles are ornaments... archaeologists have never yet unearthed the tools required to manufacture them.'[14] Even if there were lenses made in classical times, I know of no evidence of their use in the development of optics or geometry.[15]

The case of Arabic science is more complex. Ludovici claims that they had no lenses, stating that no lenses were manufactured until after 1270.[16] Lindberg also argues, by implication, that lenses were not known to Arabic philosophers for, as we shall see he argues that they were even unknown to Grosseteste and Bacon in the thirteenth century. On the other hand the equally knowledgeable Crombie frequently mentions that Arabic scholars knew about lenses. He states that Alhazen (c.965-1039) 'discussed, among other things, spherical and parabolic mirrors, the

[12] Crombie, Augustine, II, 10.

[13] Huff, Rise, 60; see ch.2, passim, for a discussion of the situation.

[14] Ludovici, Seeing, 26

[15] Gerry Martin has been through the whole of the British Museum stock of polished objects of quartz and glass. There are lenticular lenses, but they are not senses. They were decorations, jewels, not lenses, a polishe pebble like a mable.

[16] Ludovici, Seeing, 26

camera obscura, lenses and vision.'[17] Later he repeats that the 'Arabs had produced lenses as early as the 11th century...'[18] The difference here lies in whether one counts plano-convex glass used for studying vision as a lens. Crombie does count this, Lindberg not.

That this is the difference becomes plainer when we move on to the great thirteenth century western natural philosophers. Again Lindberg states that they were unaware of lenses. He writes, for example, that Roger Bacon 'had never heard of a lens'.[19] On the other hand Crombie writes that medieval natural philosophers made a number of advances 'in particular towards physical explanations of the propogation, reflection and refraction of light and in their work on lenses.'[20] He writes that Grosseteste and Bacon '...made academic natural philosophers familiar with the power of lenses to produce magnified or diminished images...'[21] In discussing where the sources of this knowledge had come from, Crombie makes it clear that he is talking of a plano-convex lens. 'Bacon... also developed Robert Grosseteste's conception of a magnifying glass by means of constructions based on those of Ptolemy for the plane and of Alhazen for curving refractive surfaces.'[22]

In fact the distinction is important, for clearly certain experiments (and development such as spectacles) depend on a double-sided lens. Yet it seems over-restrictive to argue that the lens was unknown, and it certainly gives a misleading impression when we consider the famous accounts of the effects of glass on magnification, which were to have such a profound influence. If, as we shall see later, one of the most revolutionary effects of glass was in telescopes and microscopes, the seeds of all this are to be found in Grosseteste and Bacon. It is worth quoting the famous accounts by these thinkers on the potentials of glass as a way of seeing new things.

Grosseteste wrote 'This part of **Perspectiva**, when well understood, shows us how we may make things a very long distance off appear as if placed very close, and larger near things appear very small, and how we may make small things placed at a distance appear any size we want, so that it may be possible for us to read the smallest letters at incredible distances, or to count sand, or grains, or seeds, or any sort of minute objects... It is obvious from geometrical reasons, given a transparent body (**diaphanum**) or known size and shape at a known distance from the eye... all visible objects may be made to appear to them in any position and of any size they like; and they can make very large objects appear very small, and contrariwise very small and remote objects as if they were large and easily discernible by sight.'[23]

Roger Bacon took these ideas further, for he now had available the work of Alhazen. He wrote that 'If the letters of a book or any minute objects be viewed through a lesser segment of a sphere of glass or crystal, whose plane base is laid upon them, they will appear far better and larger... And therefore this instrument is useful to old men and to those that have weak eyes.

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[17] Crombie, Augustine, I, 49

[18] Crombie, Augustine, I,221

[19] Lindberg, Bacon, xciv

[20] Crombie, Science, Optics, 196

[21] Crombie, Science, Optics... 262

[22] Crombie, Science, Art, 316-7

[23] Quoted in Crombie, Science, Optics... 198

For they may see the smallest letters sufficiently magnified... the greatest things may appear exceedingly small, and on the contrary; also that the most remote objects may appear just at hand, and on the contrary. For we can give such figures to transparent bodies, and dispose them in such order with respect to the eye and the objects, that the rays shall be refracted and bent towards any place we please; so that we may see the object near at hand or at a distance, under any angle we please. And thus from an incredible distance we may read the smallest letters, and may number the smallest particles of dust and sand, by reason of the greatness of the angle under which we may see them; and on the contrary we may not be able to see the greatest bodies just by us, by reason of the smalness of the angles under which they may appear. For distance does not affect this kind of vision, excepting by accident, but the quantity of the angle.'[24]

Although the application of this theory had to await the transformation of spectacle lenses into telescopes and microscopes, probably in the later sixteenth century, the idea was now established that glass could open up new realms of knowledge, the microscopic and macroscopic. The immense potential of lenses, partly developed by Arabic thinkers, was beginning to be realized.

Thus we have a preliminary model of how knowledge can progress. A rush of new knowledge which challenges human beings conventional assumptions at a high theoretical level sparks the curiosity and desire to experiment. Humans want to find out, to tinker with nature. Usually they are stuck here. Yet the Arabs were the first civilization who combined this with the potentials for good glass tools for seeing things in a new and clearer way. Let us test this simple hypothesis against the second case, that is medieval Europe from about 1150 to 1550.

The speed of the in-rush of new knowledge into medieval Europe is well known. Basically, almost all of the great tradition of Graeco-Roman science had been lost or garbled after the collapse of the Roman Empire. Although little pieces were retained, perhaps up to three-quarter or more had been lost. Crombie in a table provides a useful summary of the dates of the recovery of the major texts, many of them through translations of Arabic sources.[25] The great burst is in the twelfth and thirteenth centuries. Coincident with the founding of Universities and the flourishing of the Church and the economy, which in their different ways provided the institutional infrastructure for the new learning, reliable knowledge flooded in. For not only were the astonishing achievements of the Greeks and to a lesser extent the Romans, particularly in the latter case in natural history, engineering and medicine, made available, but what reached Europe was now given added force by the achievements in synthesis and extension achieved by the Arabic scholars. They had absorbed much of the accumulated knowledge of China and India as well, in particular in relation to a better mathematical system, and then added their own experimental and theoretical observations.[26]

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[24] Quoted in Crombie, Science, Optics... 201-2

[25] Crombie, **Augustine to Galileo**, vol.I, pp. 37-47

[26] Refs. to medieval European science

Within a period of about 150 years western Europeans moved from a world where they knew little about the principles of the natural world, just what had been preserved in a few monasteries plus some native ingenuity, to one where they had before them much of the accumulated reliable knowledge that had built up over most of Eur-Asia during three thousand years. The excitement, the stimulus to questioning, the wonder, the curiosity is palpable in the great thinkers of the time, and perhaps nowhere more so than in the works of Roger Bacon.[27]

This curiosity, impetus to test and speculate, the sense that there were expanding worlds of knowledge, that not all was known and there were new worlds to be discovered, must have been given a boost by the rapidly expanding wealth and technology of the period. The new burst of power through the intensive exploitation of wind, water and animal power, the growth of trade and cities, the expansion of religion are all part of the same story.[28] The symbol and expression of this expansion lies in religious buildings, in the magnificent development of the Gothic cathedrals. These very cathedrals also show us once again the necessary counterpart which allowed wonder and curiosity to be turned into progressive experiment.

The Islamic region was the centre of glass manufacture until about the twelfth century, but from then on, as I have shown above, a never-forgotten tradition of glass making in Europe blossomed. This development took place most famously in northern Italy, but also in most other parts of western Europe. The art of the glass-maker, in turn fed by the new knowledge in geometry and optics, flourished and was increasingly applied to uses of glass which were explicitly designed to improve the human eye and what it saw.

The Arabic scientists had used glass for chemistry and this tradition was used and expanded in west European chemistry and alchemy.[29] They had used glass prisms, and probably lenses, and this was greatly expended in the experiments of Grosseteste, Pecham, Bacon, Witelo and others to improve optics, geometry and physics.[30] They had used (mostly metal) mirrors of various shapes to test light; increasingly powerful glass mirrors were developed in the west and were used for the same purposes. To this western technology added spectacles and magnifying lenses of greater power.

One example of the inter-play between the new glass tools and abstract knowledge can be seen in the development of medieval mathematics. At first sight this seems quite distant from glass. After all Arabic mathematics, in particular arithmetic and algebra which had such an important influence, came from a more or less glassless civilization, India. What, one might put it, has the zero got to do with glass? Yet it is significant that Einstein singled out not mathematics

[27] See works on Bacon, especially those of Lindberg.

[28] refs. on medieval growth of technology, economy, society - e.g. Crosby, Mokyr, White et al.

[29] For a still-useful overview of medieval chemistry, see Crombie, From Galileo, I, 129-139

[30] On the use of lenses, see Park, Fire, xxx and Crombie, From Galileo, I, 99-113

but (Euclidian) geometry as the key tool in the 'scientific revolution'.[31] Perhaps geometry, in itself, is no more important than algebra or arithmetic. Yet other things are also true. Without geometry, much of the great developments in astronomy from Copernicus onwards would be inconceivable. Furthermore, it is well known that geometry was not greatly developed in China.[32] Likewise, while the Greeks had laid the foundations for geometry, the subject came alive again and was enriched first by the Islamic and then by the medieval mathematicians. This was not just a matter of recovering the lost Greek inheritance, difficult though this was. There was a conspicuous improvement in the understanding of space and light which lies at the heart of geometry.

These improvements were made possible by developments in optics and specifically the extensive work on bending and analysing light by Adelard, Grosseteste, Bacon and others.[33] For this they used glass tools, particularly mirrors, prisms, lenses. Now it might be that some of their discoveries could have been made by deduction or in other ways. Yet in order to sustain interest, to build up a community of inter-acting scholars, to have a sense of control and insight into hitherto intractable problems, it does not seem far-fetched to suggest that the glass tools used in geometry were very important. Their role has disappeared, for once the discoveries were made such tools seem unimportant. It may all seem easy, perhaps inevitable, after the event. But setting out to test and improve Greek geometry, it may well have been essential for the great mediaeval philosophers and mathematicians to have at hand the new tools not available to the Greeks, if only to give them strength in the task.

We are now in a better position to understand this, for in recent years there has been a growing realization of the sophistication and importance of medieval optics. This partly stems from the work of Crombie, who has shown the importance of medieval optics in general and, for example, the importance of mirrors in Robert Grossteste's theoretical work.[34] He shows the way in which research into the causes of the rainbow, using sunlight passing through a spherical glass flasks full of water, glass prisms, hexagonal crystals and so on begun by Grosseteste, carried on by Albertus Magnus, Roger Bacon and Witelo [give dates] was completed in the early fourteenth century by Theoderic of Frieburg.[35] For example Albertus Magnus used the flask 'as a model to show the action of a cloud acting as a single lens'.[36] The whole of this investigation using glass was crucial in the development of two of the most important methodological underpinnings of modern science, the experimental method and the principle of economy (that nature works by the shortest and simplest route - famously known as Ockham's razor).

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[31] Ref. to Einstein.

[32] On Chinese geometry, XXX

[33] For an excellent overview of medieval optics in the west, see Crombie, From Galileo, i, 99-113; more recently, see Lindberg XXX

[34] Crombie, Science, Art..., 44-5.

[35] Crombie, Science, Optics... 120ff

[36] Crombie, Science, Optics, 123

Particularly important was the work of Roger Bacon, studied in immense detail and recently made available in English by David Lindberg. Two of Bacon's most important works dealt with optical matters, '**De multiplication specierum** by developing a philosophy of natural causation on an optical model, **De speculis comburentibus** by investigating the modes of propogation of light and applying them to the analysis of the burning mirror'.[37] The former is 'one of Bacon's most successful and interesting attempts to carry through a sustained analysis of a broad physical (or philosophical) topic', while the latter is 'clearly Bacon's best and most sophisticated treatment of a narrow mathematical question; indeed, it contains possibly the most incisive and original piece of geometrical optics produced in the West during the entire Middle Ages.'[38] All of this work depended on optical tools, most of them made out of glass. 'He takes a mathematical look at incidence on curved surfaces - spherical, pyramidal, columnar, oval, annular, and lenticular - and extends the principles of refraction to such surfaces'. He later 'returns to the mathematics of reflection to explore reflection at equal angles in concave and convex mirrors, and to analyse hemispherical, oval, and annular burning mirrors.' He 'considers the uniformity of surface that produces clear mirror images, and argues that reflection does not involve the impression of an image in the mirror.'[39] Mirrors, prisms, lenses allowed the new mathematics and geometry to occur, and without them, as we shall see later, it is inconceivable that either the Renaissance or the seventeenth century scientific revolution could have occurred.

So we can see that what had been a rapid expansion of knowledge in the Islamic world, combined with a limited use of glass thinking tools, was repeated in western Europe. There are, however, a number of reasons why the expansion of reliable knowledge in medieval Europe took earlier ideas on to a further stage. There was more knowledge available to the earlier European scientists than to the earlier Arabic thinkers, for on top of the revived Greek knowledge there was the added component of the completed Arabic synthesis and re-working. The backdrop of ignorance in western Europe was probably greater than it had been in Islamic civilization, for Byzantine traditions and contacts had kept much more Greek and Roman knowledge alive in the Arabic lands. The speed of the in-rush of new thought was far greater in western Europe. Spread over half a millenium in the Arabic world, it occurred in a third of that time in Europe. So the propulsion towards wonder and curiosity was greater. The shock of vast realms of new knowledge surfacing and flooding in must have been immense.

Likewise the level of the practical tools available for experimentation, the laboratory glass as it were, was noticeably higher. The mirrors were increasingly made of glass, which gives a more detailed reflection of depth and colour, the lenses which began to be used were able to provide hints of a world below the level of normal vision, the prisms were more sophisticated, the chemical apparatus improving as glass technology rapidly developed.

[37] Lindberg, Roger Bacon's Philosophy, lxxi

[38] Lindberg, R.B., lxxi

[39] Lindberg, Roger Bacon's Philosophy, lxv

In fact, the 'laboratory' without glass is impossible to conceive of; what would be in it (apart from books and a few measuring tools), without the retorts, flasks, containers, mirrors, lenses, prisms and so on? When we look at medieval illustrations of the working places of medieval scientists in the west, they are often filled with glass devices. We are beginning to appreciate the extent of these glass instruments as one of the fruits of medieval archaeology. For instance we are told that recovered medieval English glass includes 'a variety of chemical equipment. Fragments of tubing, alembics, cucurbitis and receivers, presumably intended for monastic pharmacies or laboratories, have also been found.'[40] [Insert an analysis of Roger Bacon's laboratory; analyse illustration of the huge number of different glass tools in the Breughel print]. How far, one might wonder, did the laboratory develop outside western Europe and, to a certain extent, the Islamic world?

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One of the rapid developments in glass technology was the making of panes of glass, plain and coloured, a development that was particularly noticeable in the northern half of Europe. One very practical effect of this was on the working condition of thinkers. In the cold and dark northern half of Europe, people could now work for longer hours and with more precision because they were shielded from the elements. The light poured in, in the summer into the evenings, yet the cold was kept out. Of course this can be achieved in other ways, as with Japanese paper screens. But before the advent of windows on a large scale, there had been no really effective substitutes in the west.

Somewhat more abstractly, one should also consider in a preliminary way how windows altered thought at a deeper level. The question here is the way in which glass, whether in a mirror, window, or through a particular sized lens, tends to concentrate and frame thought by bounding vision, and at the same time leads to abstraction and attention to the details of nature. As with a camera, early glass artifacts such as the window, mirror and lens focused attention and made the observer look in a different way at the external world, a sort of positive blinker. It puts the world in a frame, divides up external reality into a set of bounded and hence manageable problems. In some ways it is the mental equivalent of the famous division of labour in economics, or the Cartesian method of breaking down a problem into small bits so that it can be solved. This was pointed out long ago by Mumford. Speaking of the new colourless glass of Murano, Mumford wrote: 'Glass helped put the world in a frame: it made it possible to see certain elements of reality more clearly: and it focused attention on a sharply defined field - namely, that which was bounded by the frame.'[41]

The glass window may have played a particularly important part here, changing the whole aspect of the outside world.[Certainly I have read something to this effect in relation to China, where there was an enormous reverberation when glass windows replaced the view-obstructing

[40] Klein and Lloyd, Glass, 49

[41] Mumford, Technics, p.125.

windows made of paper or other substances.(cf. the evidence XXX)] But there is more to this shift than just glass. Atkinson and Bagenal discuss the contemplative use of the window: 'This contemplative use of the window meant a high stage of culture; it meant that man having originally built his house in order to shelter or separate himself from the universe, now opens it out to look again upon nature from quite a new point of view.......To enjoy a prospect from a window two things are necessary; first the leisurely appreciation of nature for its own sake and quite apart from its elemental associations, and second, either an unobstructed opening or clear, colourless glazing'"[42]

Clear glass windows were only one side of the effects of glass on thought. It is rather noticeable that all of the greatest of the medieval scientists in the west were church men, Adelard of Bath, Pecham, Grosseteste, Bacon, ?Witelo. Although this may be due to the fact that only ordained clerics had access to the time and learning to make a high level contribution at this time, it still remains interesting that they should have turned their attention so strongly to optics and related subjects. Is it just a coincidence that they were living at a time when the new cathedrals of light were being developed? It seems very probable that they were influenced by the light that flooded in through the magnificent stained glass windows. No wonder that optics became the central field of medieval science in the West, the counterpart of astronomy and physics in later centuries.[43] The metaphysics of light, its symbolic importance both in Greek neo-Platonic thought, and in Christian thought, is a rich theme with enormous consequences. It is also immensely complex. Styles of thought were inherited, but given a new impetus by the expanding world of light through the new windows in churches and private houses.[44] Thus light and knowledge became fused and glass played a crucial role in this.[45] So there was a combination of the impetus to explore combined with a developing set of glass artefacts. This made that exploration possible and became part of what we call the experimental method.

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What is very difficult to judge is the way in which glass in all its manifestations, its making, its illumination, its bending, influenced perception. It had so many different paths into human activity, many of them related to the conditions of what we can call reliable knowledge. One of these was in relation to the way in which it increased precision and attention to detail.

It is well known that grinding glass to make into tools is about the most precise craft skill in the world. As Simon Schaffer puts it, it is several orders of magnitude more exact than anything

[42] Quoted in McGrath, Glass in Arch., 111

[43] On optics and the study of light as the pinnacle of medieval science, see Crombie, Augustine, II, p.118

[44] See the marvellous account of the effect of windows on the metaphysics of light in XXX

[45] On the metaphysics of light in medieval natural philosophy, see Crombie, Grosseteste, ch.6, esp. 128; Crombie, Science, Nature.. esp. p.41; Lindberg, Roger Bacon's, xli, xlix.

else western craftsmen were doing.[46] Is it any coincidence that so many great scientists (Spinoza, Descartes, Hooke, Huygens, Newton, van Leeuwenhoek) were also glass grinders?[47] Even if not grinding glass themselves, they were well aware, from using precise glass instruments, what a huge difference tiny differences in space could make, just as mechanical clocks were making the same message obvious in relation to time. Precision, accuracy, exactness, focusing down on the particular problem, all are deeply affected by mirrors, lenses, prisms, spectacles.

The scientific revolution is basically about the increase in precision, and glass made a great difference, both in more precise making, and precise seeing. An interesting sidelight on this is thrown by the experiences of an opthamologist who worked in China in the 1930's. Rasmussen early notes that his workmen, though adaptable and quick, 'had, in common with other Chinese craftsmen, a convenient and somewhat irresponsible slogan, "Tso pu do" - or as we might say, "Not far out" - but their idea of the amount of tolerance and ours were very far apart.' As a result, after a series of good lenses, the next lot would be useless. He returns to this theme and expands it later. 'Native workmen' he said are 'notoriously inexact when left to their own discretion', for the 'majority of them do not understand accuracy, and the small minority who do, hold it in lofty contempt as an exaggerated punctiliousness. Indifference to precision is the result of lazy mental habits and one of the gravest disabilities confronting Chinese progress in exact science and mechanics.'[48]

Rasmussen does not enquire into the reasons for this at all, but it might be surmised that this was somehow related to glass. Glass leads to precision in various ways. The making of glass instruments requires precise knowledge and precise workmanship. Furthermore, the observation of things is given extra precision if they are seen through glass, either at a distance, in a mirror, in a test tube, through a microscope. Precision pays off and is the essence of experimentation. Working with glass, an external mind and eye, reveals all the lack of precision of the human mind. Things are made crystal clear, and clarity and precision are close partners. Grubby, cracked, badly ground glass is of little use; and more obviously so than its equivalent in poor eye-sight or shoddy thought.

Of course, in all of this discussion it is important not to fall into the trap of believing that glass always led to a closer approximation of what finally turned out to be correct knowledge as we conceive of it. There were many fruitful errors on the way. One of the most important roles of glass was in 'natural magic', especially in alchemy and astrology. Alongside the curiosity and desire to understand God's laws on the part of a man like Roger Bacon, there were numerous people who desired power through the making of wealth (alchemy - the search for gold) or foreknowledge of the future (astrology and sooth-saying). For them glass was a powerful tool and retorts, mirrors and lenses were developed in this fermenting no-man's land, one of whose

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46 Schaffer ref. xxx - World

47 See Ludovici, Seeing, 71

48 Rasmussen, Spectacles, 2,46

last great Magi was Newton. For example the extensive use of mirrors in magic, from the early fourteenth to the works of Dr John Dee, is alluded to in many places in the work of G.L.Kittredge.[49] The story of the work of Giordano Bruno and the Hermetical Tradition, the Rosicrucians, Della Porta and John Dee, all would have to be unravelled if we were to travel down this path, with the help of the likes of Frances Yates.[50] Work in this field shows that the old opposition between 'science' and 'magic' needs to be re-thought.

Yet if we try the thought experiment of wishing away glass in Islamic and medieval Christian civilization, it is not difficult to see how reliable knowledge would probably have come to a halt. Any child will tell you that an exciting science book is not enough, even when it sets out all sorts of possible connections and theories. Only when equipped with jam jar, magnifying glass and, later, test tubes and microscopes, will the amazing world of nature's secrets be unlocked. Obviously glass, on its own, is not enough. Without the burst of curiosity and new knowledge from ancient and Asian civilizations, all the glass in the world would probably have had little influence on thought. It is the combination of curiosity and tools that is important. And, of course, there were many other factors which have often been pointed to. The growing explorations along the land routes to Asia, the demands of competition and war, the growth of cosmopolitan cities, the rise in wealth, the development of Universities in the west and so on. Yet glass, it seems to me, is a **sine qua non** of the experimental method, a method which has always existed, but was given a large impetus by the Arabic scientists, an even greater one by the medieval west European thinkers and finally flourished in the world of the Royal Society, of Boyle, Hooke and Newton and later of Lavoisier, Faraday, Pasteur and many others. It is worth examining the role of glass in some detail because it has largely been overlooked as a central feature of what has happened.

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Science consists of verifiability, repeatability, openness to refutation. Now the pure speculations of many thought systems were not open to such checks. Plato or Confucius or the Buddha set up systems which were internally consistent, coherent, closed, as Popper, among others, demonstrated. They could not be challenged from within nor destroyed by 'evidence'. Nor could their parts be checked by the casual observer. The logical experiments could not be done again - they were in one man's mind - the setting up of a system. It would be as meaningful to 'test' them with experiment as it would be to 'test' the Mona Lisa, Chartres cathedral, Handel's Messiah or Hamlet. They were statements which could not be repeated or verified. Modern science, however, depends on the formulation of laws based on experiments which can be repeated by others. Ultimately it depends on the human eye to check whether the procedures work.

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[49] Kittredge, Old and New, pp. 180-191, 503; for mirrors and trick glasses, see Scott, Discovery, 265

[50] Works of Frances Yates on... XXX

Glass shifts authority from the word, from the ear and the mind and writing, to external visual evidence. The authority of elders is challenged, the test is the individual eye, the authority of the doubt-filled and sceptical individual. The primacy of demonstration through showing something happening became obvious. 'Glasses not merely opened people's eyes but their minds: seeing was believing. In the more primitive stages of thought the intuitions and ratiocinations of authority were sacrosanct and the person who insisted on seeing proof of imagined events was reviled as the famous disciple had been: he was a doubting thomas. Now the eye became the most respected organ. Roger Bacon refuted the superstition that diamonds could not be broken except by using goat's blood by resorting to experiment: he fractured the stones without using blood and reported: "I have seen this work with my own eyes." .The use of glasses in the following centuries magnified the authority of the eye.'[51] Seeing is believing; what is seen is more important than what is asserted by authority (the word).

Thus it could be argued that glass helped change the balance of power from the brain to the eye; the odd empiricism and positivism of the west, where only seeing is believing, demonstration to others is essential, became a distinguishing feature of the new cosmology. Every time the technology of seeing was improved it lent more authority to the experimental method.[52] It confirmed the view that God had created a mysterious, little known, world, yet one which contained clues to certain general rules or principles which could be known and once established could be used to base other findings on. There was no fixed and known pattern in the mind, just divinely inspired curiosity for which the new tools, including glass and mathematics, provided the data. No longer reliant on thought experiments, one looked at nature, from every angle, at the minute and macro levels, sideways and upside down, with mirrors, lenses and prisms, under various conditions of heat and cold and in various mixes in glass tubes, to torture her to see what she was. Such experimentation, without glass tools, would quickly have run out of energy, if it had started at all. Mathematics would have had little on which to bite and become arid as it seems to have become in India. The limits of practical reason, common sense and ordinary observation would quickly have been reached. There are no grounds for thinking that western thought would have got beyond that barrier which halted Indian, Greek, Arabic and Chinese science. Yet the magical properties of glass, combined with the wealth of previous logic and thought, produced new conditions out of which occurred the largest increase in reliable knowledge of man and nature in the history of this planet.

This shift from the authority of texts, and of received wisdom, to the authority of the eye and the perception of each observer, is one of the most intriguing aspects of what happened. It is possible to wonder about the role of glass in giving authority to the experimenter or author and his vision. For instance, in the book by David Park, we are shown how Aristotelian philosophy was finally overthrown by the products of a new knowledge fundamentally based on glass. It is argued that in order for science to emerge required the ultimate subsuming and overthrow of

[51] Mumford, Technics, p.127.

[52] For an overview of the development of the experimental method in the medieval west, see Crombie, From Augustine, I, 11-24

Greek science.[53] It does not seem implausible to argue that this massive task could not have been achieved without the confidence which glass produced. The evidence lies in the war between the Aristotelians and what they considered to be the lies and deceits and false knowledge created by glass. It can also be studied in the next great shift in self-confidence and endorsement of the authority of the individual and of vision, which we call the Renaissance.

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[53] Park, Fire, passim, esp.ch.5