THE CLASSIC SCIENTIFIC REVOLUTION AND GLASS

We have seen that the foundations for the classic scientific revolution had already been established by the later sixteenth century. With the help of glass instruments the experimental method, precision, pursuit of knowledge as a valued activity, abstraction and framing, the privileging of sight and many other central characteristics were already present. This chapter will concentrate fairly narrowly on the period when glass instruments of a more powerful and explicitly scientific nature were manufactured - microscopes, telescopes, barometers, thermometers, vacuum tubes and so on. We can obtain a preliminary glimpse of this increasingly glass-filled scientific world if we look at the work of the man who laid down the charter for the new experimental science, Francis Bacon.

Bacon imagined the kind of laboratories and their equipment needed for the effective interrogation of nature in his **New Atlantis**, written a few years after the discovery of the microscope and telescope. He outlined the necessary glass instruments which would be needed to generate reliable knowledge. Speaking through the keeper of 'Solomon's House' he wrote as follows.

Concerning the analysis of light, and foreshadowing Newton's work on optics: 'We have also perspective houses, where we make demonstrations of all lights and radiations; and of all colours; and out of things uncoloured and transparent, we can represent unto you all several colours: not in rainbows, as it is in gems and prisms, but of themselves single. We represent also all multiplications of light, which we carry to great distance; and make so sharp, as to discern small points and lines: also all colourations of light: all delusions and deceits of the sight, in figures, magnitudes, motions, colours: all demonstrations of shadows. We find also divers means yet unknown to you, of producing of light originally from divers bodies.' Furthermore 'We make artificial rainbows, halos, and circles about light. We represent also all manner of reflections, refractions, and multiplication of visual beams of objects.'

As far as telescopes, spectacles and microscopes were concerned, he explained that 'We procure means of seeing objects afar off; as in the heaven and remote places; and represent things near as far off; and things afar off as near; making feigned distances. We have also helps for the sight, far above spectacles and glasses in use. We also have glasses and means, to see small and minute bodies perfectly and distinctly; as the shapes and colours of small flies and worms, grains, and flaws in gems, which cannot otherwise to be seen; observations in urine and blood, not otherwise to be seen.'[1] The last points towards the work of Harvey on the circulation of the blood and work on the causes of disease. It is no surprise that among the statues of great explorers and inventors is that of 'the inventor of glass'. Nor is it surprising many of the experiments which Bacon described started with a phrase such as 'take a glass.

What Bacon fully realized, drawing on his experience from the later sixteenth century onwards, was the way in which glass had become the essential thinking tool for investigating the laws of nature. This connection, so often taken for granted and hence half-forgotten, was revived in the middle of the twentieth century by Lewis Mumford. In relation to space he wrote that the discovery of the telescope and microscope at the end of the sixteenth century or early in the seventeenth century had immense effects. 'One invention increased the scope of the

[1] Bacon, New Atlantis, 214

macrocosm; the other revealed the microcosm; between them, the naive conceptions of space that the ordinary man carried around were completely upset: one might say that these two inventions, in terms of the new perspective, extended the vanishing point toward infinity and increased almost infinitely the plane of the foreground from which those lines had their point of origin.'[2]

In a later work Mumford amplified the argument. 'The invention of the microscope and the telescope in the seventeenth century altered all the dimensions of the world: that which had been invisible heretofore, because it was either too small or too distant became visible under closer scanning. Thus these inventions opened up the new world both of micro-organisms and of distant stars and galaxies: a far greater New World than Columbus or Magellan explored. For the first time, to use a now overworked cliche, it was possible to see both the cosmos and the organic environment **in depth**. Without moving a foot from the microscope or the astronomical observatory, modern man could take into consciousness potentialities that had hitherto not been touched even in his most audacious dreams. This first transformation of spatial dimensions owed nothing to machines for instantaneous communication and rapid transportation, which came much later: the whole vast change was achieved by the glassmakers and lens grinders and optical scientists, with the aid of the simplest tools and utensils.'[3]

This reminds us of Dr Johnson's earlier way of putting it. The invention of glass would 'extend the sight of the philosopher to new ranges of existence, and charm him at one time with the unbounded extent of material creation, and at another with the endless subordination of animal life...enlarging the avenues of science... enabling the student to contemplate nature...' [4] Furthermore it reminds us that the effects of powerful glass tools acts at many deeper levels as well. Sight is one of humankind's strongest senses and by providing new tools with which to see an invisible world of tiny creatures, or to contemplate distant stars invisible to the naked eye, glass not only made possible particular scientific discoveries, but led to a growing confidence in a world of deeper truths to be discovered. It was clear that with this key one could unlock secret treasures of knowledge, below and above the surface of things, de-stabilize conventional views. The obvious was no longer necessarily true. Hidden connections and buried forces could be analysed.

Some of the effects of the microscope are well summarized by Ludovici. 'The microscope, it has been said, is supreme among modern optical instruments. Without it modern medicine would be unthinkable. So would allied sciences like histology (study of tissues), pathology (study of diseased tissues and generally of diseases), protozoology (study of animals of the simplest types), bacteriology, virology (study of viruses), and molecular biology (study of the interior workings of the cell). astronomy and the biological sciences have been the two main beneficiaries of improvements in lens-grinding and in other aspects of optics. Yet sciences like chemistry, physics, mineralogy/, and engineering equally find the microscope indispensable.'[5]

All this, of which a new conception of space was part, is supplemented by other glass instruments. Also fundamental, Mumford argued, was the effect on chemistry and related sciences. 'Chemistry would have been severely handicapped but for this development...For glass has unique properties: not merely can it be made transparent, but it is, for most elements

[2]Mumford, Technics, p.126.

[3] Mumford, Myth, 284-5

[4]McGrath, Glass in Architecture, 5

[5] Ludovici, **Seeing**, 162

and chemical compounds, resistant to chemical change: it has the great advantage of remaining neutral to the experiment itself, while it permits the observer to see what is going on in the vessel. Easy to clean, easy to seal, easy to transform in shape, strong enough so that fairly thin globes can withstand the pressure of the atmosphere when exhausted, glass has a combination of properties that no wood or metal or clay container can rival. In addition it can be subjected to relatively high heats and - what became important during the nineteenth century - it is an insulator. The retort, the distilling flask, the test-tube: the barometer, the thermometer, the lenses and the slide of the microscope, the electric light, the x-ray tube, the audion - all these are products of glass technics, and where would the sciences be without them?'[6]

One of the few subsequent historians to pick up Mumford's insights is Norman Davies in a general book on European history. He writes, for example, that 'The microscope (1590), telescope (1608), barometer (1644), and thermometer (1593), all glass-based, revolutionized our views of the world... whilst precision instruments encouraged a wide range of scientific disciplines, from astronomy to medicine.'[7] On the last of these he may be alluding to another point made by Mumford, namely that 'Even in medicine glass has its triumph: the first instrument of precision to be used in diagnosis was the modification of Galileo's thermometer that Sanctorius introduced.'[8] Furthermore, as Davies re-affirms, 'Transparent glass made possible the science of optics, and was crucial in the development of precision instruments... Glass flasks, retorts, and tubes facilitated the experiments of alchemy, later of chemistry.' [9]

These are views shared by some historians of science and technology. As Singer wrote some time ago, 'Lenses and lens-grinding have played a fundamental part in the history of technology. During their evolution from simple magnifying and diminishing glasses to their use as spectacles, to their combinations in telescopes and microscopes, and to still more complex uses, lenses have transformed some sciences and virtually created others.'[10] It is therefore no coincidence that the list of those who became lens grinders overlaps so closely with the great figures associated with the scientific revolution: 'many scientists, including Descartes, Newton, Huygens, and Leeuwenhoek were expert lens-workers. In Italy, Galileo and his pupil Torricelli had done much to develop the art of lens-grinding for scientific purposes.'[11]

Lenses, of course, are only part of the optical repertoire opened up by improved glass. Mirrors were also important, not only for their 'practical importance for use in instruments of survey and navigation'[12] but also for their use in other instruments, such as telescopes, and as aids in optical experiments. Furthermore there is the development of prisms, to experiment with light, with their immense consequences for Kepler, Descartes, Newton and others. Without these glass tools there could have been little deepening of knowledge of the properties and nature of light. And such knowledge, built back into improved lenses, led to new microscopes,

[6] Mumford, Technics, pp.127, 128; Crombie, Augustine, I, 213, 221, agrees with Mumford.

[7] Davies, Europe, 369

[8] Mumford, Technics, 128

[9] Davies, Europe, 369

[10] Singer, iii, 229

[11] Singer, iii, 234

[12] Derry and Williams, Technology, 111

telescopes, and finally into that great instrument of knowledge or extending of the eyes, the camera. Thus Singer is surely right in concluding that 'Glass has become one of the most important materials in the development of technology and experimental science, and is even now [1956] hardly replaceable by plastics..'[13]

The actual details of who discovered what, particularly in relation to such instruments as telescopes and microscopes, are not important for this argument. One early account of these by Singer will suffice here, though it no doubt needs modification. 'There are references as early as the mid-sixteenth century to reputedly successful attempts to devise optical instruments whereby distant objects could be seen more plainly, and enlarged. The English mathematicians Leonard Digges (1510-58) and John Dee (1527-1608) both made experiments to this end.'[14] Yet Singer accepts that it was probably at the end of the sixteenth century that the first real telescopes were made. Thus he writes that 'according to a reliable record of 1634 Johannes Janssen or Jansen, the son of the fortunate spectacle-maker, declared that his father "made the first telescope amongst us in 1604, after the model of an Italian one, on which was written **anno** 1590." Moreover, this record gives further significance to the description of Giambattista della Porta of Naples (1536-1605), in the second edition of his **Magiae naturalis** (1589), of ways to improve vision at a distance, including the combination of a convex and concave lens. His account is deliberately obscure.'[15]

Thus there are suggestions that the telescope originated in Italy and then went back there. Likewise there are disputes as to when and where the microscope was invented. 'Credit for the invention of the compound microscope has been variously assigned. della Porta again seems to have constructed a compound microscope, but the history of the instrument effectively begins with Galileo's use of what was actually a Galilean telescope with a very short working-distance to discern the organs of small creatures.'[16] Others suggest that the device was invented by Dutch spectacle makers in the 1590s. Whatever the true chronology, we can see that the fruitful inter-action between the various centres of experiment and technology in Italy, the Netherlands, England and elsewhere generated rapid advances in glass technology, and the new knowledge which improved instruments allowed then fed back into further technical advance.

This loop of improved knowledge, improved knowledge-generating artefact and so on is particularly important in relation to the one substance on this earth that extends human vision. A developing glass technology would have improved the precision of information, encouraged curiosity, broken down secrecy, and led to further artefacts which then in a circular way increased reliable knowledge. Glass is a perfect example of the circular nature of the process - some new knowledge, new artifacts, leading back to new knowledge.

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The way in which developments occurred as a result of a network of inter-acting knowledge and craft centres across the whole of Europe is well illustrated by the history of that key invention, the microscope. This account also shows the cumulative input of many minds into an artefact and the parallel development of glass and reliable knowledge.[17]

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[13] Singer, vol.I, 311 (Harden)

[14] Singer, iii, 231

[15] Singer, iii, 231

[16] Singer, iii, 232

[17] This is taken from Martin, 'Cultural diversity and Economic Growth', Munich, 1994

The story starts in the Low Countries in the early years of the 17th century, with the discovery, within a small group of opticians in Middleburg, of the microscope and of its close relation the telescope. Initial development was slow, but within a century some of the fine detail of the living world had been uncovered, and enough interest generated to ensure an ongoing process of discovery and exploration. Red blood cells were seen travelling through capillaries - first in Bologna in the mid 17th century, and equipment for seeing blood flow in the tails of small fish became part of the accessory kit of microscopes for over a hundred years.

Robert Hooke, working in London in 1665 and Anton van Leeuwenhoek, a draper and chamberlain to the Sherrifs in Delft in Holland, described a minute living world which previously had been quite beyond comprehension. Early microscopes produced quite indistinct images - coloured fringes, around the objects being observed and fuzziness at the edge of the picture. It took a period of 240 years to improve the microscope to a level of refinement at which it would display details of bacteria and of the mechanism of dividing cells and of reproduction.

This process of improvement was driven almost entirely by curiosity - there was no economic use for the microscope until 1840. Crucial contributions to improvement came from all around Europe. Great improvements in the glass for the lenses was made by Pierre Guinand, a Swiss working with Joseph Fraunhofer at Benediktbeuern and by Otto Schott in the Carl Zeiss Company at Jena. To correct the coloured images produced by simple lenses, which limit the magnification and clarity which can be obtained, two differently shaped lenses made of two different types of glass are needed. Newton, trying to eliminate colour fringes by combining lenses of different shapes, but made of the same type of glass, had not succeeded and had concluded that the task was impossible.

Before 1670 only one type of glass had been available, but a second type, lead glass, was developed by Italian glassworkers working in London, for an English entrepreneur, George Ravenscroft. Ravenscroft had been importing large quantities of wine glasses from Venice and he wanted to set up manufacture in England, using a strong and more brilliant type of glass.

He succeeded in producing this new type of glass, but he had no thought of its use in telescopes or microscopes. Ravenscroft had developed it for use in wine glasses, jugs and bowls. It was 70 years before it was used in telescopes by John Dolland, in London. Dolland was the son of a French Huguenot refugee, who came to England after the revocation of the Edict of Nantes in 1685 - just one hundred years after Flemish opticians were fleeing Antwerp and seeking to establish themselves in their new lives.

The theoretical development of the new lens, central to the improvement of the microscope, had important inputs from Klingenstierna, Professor of Mathematics at Upsala and from Leonard Euler, a Swiss mathematician working at St. Petersburg. Further improvements to the theory of the microscope were made by Joseph Lister, a London wine merchant encouraged by David Brewster, a Scottish scientist.

Ernst Abbe, a German physicist working in the Zeiss company at Jena with Schott, the glassmaker, refined the optical theory, and the practices of manufacture, to a standard at which the microscope could open the door to our new understanding of the world. The microscope was crucial to Pasteur, the French chemist and microbiologist in his work on the germ theory of disease and in his proof that life did not spontaneously generate. Later, the microscope would be the foundation of an even greater break-through. Our new understanding of genetics springs from the discovery of DNA and the double helix, which in turn rests on the discovery of the chromosome and the processes of cell division. This relied entirely on the steady improvement in the resolving power (the ability to see fine detail) of the light microscope which has been briefly sketched in above.

The story as related above is misleading in its simplicity. Many more individuals were involved, each situated in a complex network essential to their contribution. Nevertheless the tale is typical of any of the stories of product development, that is the inter-action between ideas and things over long periods of time, which collectively make up our modern world.

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Although it is not too difficult to see a general connection between scientific tools of glass and increased reliable knowledge, the subtler connections are so much more complex that they often escape us. In most major scientific discoveries there is a long chain of causation which, if broken at one point, cannot be completed. Often we find that glass in some form, whether as container or lens is one vital link. Thus while it is not the proximate cause, it is an essential one.

We have looked at the twenty great scientific experiments selected by Rom Harre for description and analysis.[18] The result of asking whether they could have occurred without the development of glass are laid out in the following table.

TABLE OF TWENTY EXPERIMENTS AND THE NECESSITY OF GLASS IN THEM.

(see table, appendix xerox at the end)

In order to see the complex way in which glass can form an essential chain in an apparently unconnected but important development, we can look at the relationship between glass and the history of the steam engine. At first sight the connection is not obvious. Steam engines do not seem to have any glass in their manufacture, so why would it have been impossible to build a steam engine without widespread use of scientific glass?

There can be no doubt of the importance of the steam engine. It is the symbolic and actual tool of the change from an agrarian to an industrial world. The speed of travel, the speed of weaving and many other things were transformed by this device. It allowed civilizations to move from the current use of energy from plants and animals, to have access to the massive deposits of millions of years of carbon energy. It was made into an effective invention in north-western Europe as the result of a chain of causation that directly ran through glass.

In fact, the steam engine was only one of the converters which has enabled mankind to release absorbed sunlight and accelerate matter, later giving way to internal combustion engines, gas turbines and so on.[19] All these devices worked by deriving useful mechanical work from expanding gas. An understanding of the properties of gases - the gas laws, the relationship between the volume of a gas and it's pressure and temperature was advanced greatly during the seventeenth century by experiments with the newly invented air pump in Germany, England and Holland, following the invention of the barometer, and the demonstration of the existence of the

[18] Rom Harre, Great Scientific Experiments, OUP, 1983

[19] These paragraphs I owe to Gerry Martin.

vacuum in Italy in the 1640s.

Some of the foundational experiments are as follows. In the 1640s Berti in Rome, and a little later Torricelli in Florence, performed experiments which strongly suggested the existence of space empty of matter - what we would call a vacuum. Each performed the experiment with a long vertical tube initially filled with a fluid (Berti - water; Torricelli - mercury). Berti's tube was made of lead, around 30ft tall and supported on the side of his house. On the top was cemented a flask made of glass 'rather large but very solid'.[20]

Torricelli, using mercury, used a much shorter tube, entirely of glass and sealed at the top end. The tube would have been around 3ft long. In each case, when the fluid in the tube was allowed to flow out, leaving a space at the top. The nature of the space and the reason for a constant and fairly reproducible height of remaining fluid stimulated a huge amount of subsequent experimental work.

The prior existence of clear glass, and of quite sophisticated glass working skills, were essential to each enterprise. If we marked on a map of the world the sites in 1640 where these experiments could be performed, we would find them to be both rather concentrated and rather limited in number - none at all in China, India, Japan, Africa or the America's.

Torricelli's experiment provides an interesting event to consider the selectionist, as against the deterministic or teleological aspects of innovation. In the absence of glass, Torricelli could not, realistically, have said 'I need a material which I can see through, in the form of a tube of indeterminate length' (for to arrive at the correct length already required a number of exploratory experiments) and closed at one end. Strong enough to support itself and a heavy column of mercury. Unaffected by mercury or water, which he also used.[21] A would-be experimental philosopher in the majority of the world, where sophisticated glass making was absent, would have had to compress the skills, knowledge and experience embodied into three thousand years of glass making into an exercise before he could perform his experiment. This would have been physically impossible.

If we consider the next stage, and assume the existence, in Italy in the 1640s of a competent glass industry used to producing clear glass, and making blown bottles or decorative ware or blowing large bubbles of glass as a stage in the production of sheet - and all of these techniques were available in North Italy in the 17th century, then Torricelli could pay a glassworker to draw out one of his large bubbles of glass into a long tube. This would be an innovation, but one well within the capabilities of the time.

The final state of manufacture, the closing off of one end of the tube, sometimes with a simple melted seal, sometimes with a glass bubble blown at the melted end, could have been performed either by the skilled glassworker or by Torricelli or an assistant, if they procured a small furnace. Thus, the process is a mixture of selection and determinism with selectionism, the selection from already existing variation playing a major, but not exclusive part.

This shows the way in which if one moves back along the chain of causation, one finds that you can not have barometers or air pumps and gas laws without clear glass, as Robert Boyle knew so well. If you use metal or pottery or porcelain containers or tubes you simply cannot see

[20] Middleton, 11

[21] see Middleton, 23

what is going on. Thus glass was an essential link in the chain which lay behind towards the major power sources of the industrial revolution, by way of more accurate knowledge of the laws of nature.

These developments rest firmly on the availability of clear glass and the skills to manipulate it. They are good examples of chains of causation in which glass is a crucial link. So we can conclude by noting how much of our world would not now exist without the wonderful material glass. Without clear glass we can have no gas laws, no steam engine, no internal combustion engine. Without clear glass we can have no visualisation of bacteria, no understanding of infectious disease and the whole medical revolution since Pasteur and Koch. Without the chemistry which depended crucially on glass instruments we can have no recognition of nitrogen and so no artificial nitrogenous fertilisers and hence much of the agricultural advance of the nineteenth century onwards is lost. Without clear glass there can be no telescopes. Astronomy would be limited to visual observation. There would be no knowledge of the moons of Jupiter, no obvious way to prove that Copernicus and Galileo were right. Without glass we would have no understanding of cell division (or of cells) and thus no micro-biology and no detailed understanding of genetics, certainly no discovery of DNA. Also, of course, without spectacles, a majority of the population over the age of fifty would have very great difficulties in reading this or any other book.