Journal of Materials Education Vol. 37 (3-4): 139-154 (2015)

THROUGH GLASS, THE RISE OF MODERN SCIENCE

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ABSTRACT

Picture, if you can, a world without glass. There would be no microscopes or telescopes, *i.e.*, no sciences of microbiology or astronomy. Artists would draw without the benefits of a three-dimensional perspective, and ships would still guided by what stars navigators could see with their naked eye. People with poor vision would grope in the shadows, and planes, cars, and even the discovery of static electricity probably would not exist. For example, in this particular case, if one rubs a glass rod with a silk cloth, the glass will develop a static positive charge that can attract small bits of paper. We briefly review the history of glass science and technology and discuss some of the great challenges that contributed to modern science between 1600 and 1900. This discussion is based on *ten* key discoveries and experiments that illustrate how the use of glass evolved. These include: *i*) the discoveries of Jupiter's moons and sunspots by Galileo using glass lenses; *ii*) Torricelli's discovery of vacuum and atmospheric pressure by means of vertical glass tubes; *iii*) Hooke, van Leeuwenhoek and the creation of good microscopes using special glass lenses; *iv*) Newton, the decomposition of light and the reflecting telescope using glass mirrors; *v*) Thermoscope/thermometer glass experiments using sealed glass tubes; *vi*) The laws of gas experimentally tested using glass vessels (which are also chemically inert); *vii*) Germ theory using special *long* glass vessels; *viii*) Faraday, the light experiment through a glass bar and electromagnetism; *ix*) Thomas Edison and the glass light bulb; *x*) Thomson and the discovery of electrons using glass cathode ray tubes. As will be shown, glass is a material that has been central to many aspects of human history, especially in the developments of modern science and technology.

INTRODUCTION

Can you imagine a world without glass? There would be no windows to keep out the cold air, no televisions, no lenses, no light bulbs, no mirrors, no fiber optics, no glass vessels, and probably no *modern* science and technology. In other words most modern materials science and technology would not exist. But if this question would be difficult to answer, let us paraphrase it: where would science and technology be without glass? To answer this, let us point out the fact that many historically significant scientific experiments and discoveries from the 17^{th} to the

20th century were made essentially with the use of glass. In this work we briefly present *ten* fundamental discoveries related to experiments that contributed to modern science, which probably would not have been possible without the use of glass.

From 1600 to 1900, a revolution occurred not only in the world of art and architecture, but also in transport, housing, energy sources, agriculture and manufacturing [1]. However, in the last 200 years is it possible to say that there is a real glass science and technology [2], but to reach this *state*, there has been a long history. Historians of science have ascribed the causes of the emergence of modern science to factors as diverse as the invention of the printing press, the mechanical clock, the rise of the cities, and the creation of the medieval universities[1]. There is agreement that most of these have collaborated as main factors in the rise of modern science. However, there is a missing connection, namely the importance of glass in this period, as well as the rise of plastics in the 20th century and its influence in our modern life. As most plastics are *amorphous* and many of them are also *glassy*, this physical state of nature is important and it needs to be included in science classes, even at introductory levels.

Such a focus on the importance of glass in the history of science is recent, and was proposed by Macfarlane and Martin [1,3]. Consequently, it is significant to point out these scientific findings in some detail, and suggest that teachers use them in materials science classrooms.

A BRIEF HISTORY OF GLASS TECHNOLOGY

Among the disordered systems in nature, glasses belong to the most fascinating of materials. Natural glasses such as volcanic obsidian glass have been used by humans from the earliest times given archaeological evidence, *e.g.* for carving arrowheads, knives, and other things needed for daily survival [1].

The first glass objects produced by humankind date back to about 7,000 B.C. and were found in Egypt and Mesopotamia [1]. Glass was almost certainly discovered by accident — so the Roman historian Pliny the Elder (A.D. 23 – 79) tells us — by Phoenician traders, who apparently noticed that a clear liquid formed when blocks of natron (*i.e.* a mixture of sodium carbonate and sodium bicarbonate) on which they placed their cooking pots melted and mixed with sand from the beach [4]. (In particular, natron at the time was used as a cleaning product for both the home and body – blended with oil; it was an early form of soap). Egyptian craftsmen developed a method for producing glass vessels around 1,500 B.C., and the first manual of glassmaking appeared a millennia later [1]. Glass makers probably used a recipe similar to that found in the cuneiform library of the Assyrian king Assurbanipal (≈ 650 B.C.): Take 60 parts sand, 180 parts of ash of sea plants and 5 parts lime, and you obtain glass [5]. Add something absent in such a recipe' (mainly a furnace working at 1000-1200ºC), and most of our modern windows follow this starting raw materials composition: sand (silicon oxide), sodium, calcium and potassium carbonates.

Significant progress in glass technology came with the invention of glass blowing by Syrian craftsmen in the first century B.C. This new technique greatly increased the use of glass for practical purposes. Vessels and later windows were produced by glass blowing, which was brought near to perfection by the Romans, not only in Rome itself but also in their colonies. After the fall of the Roman Empire, glass manufacturing was dispersed to isolated sites in the West, and was continued in Byzantium and later in the Middle East by the Arabs. From about 1300 on, Venice became the centre of a resurgent glass industry in the West, and was able to produce first rate glasses needed for lenses and mirrors [6,7]. Figure 1 illustrates a glassmaking process in the 15th century, from a medieval book of Sir John Mandeville's supposed travels.

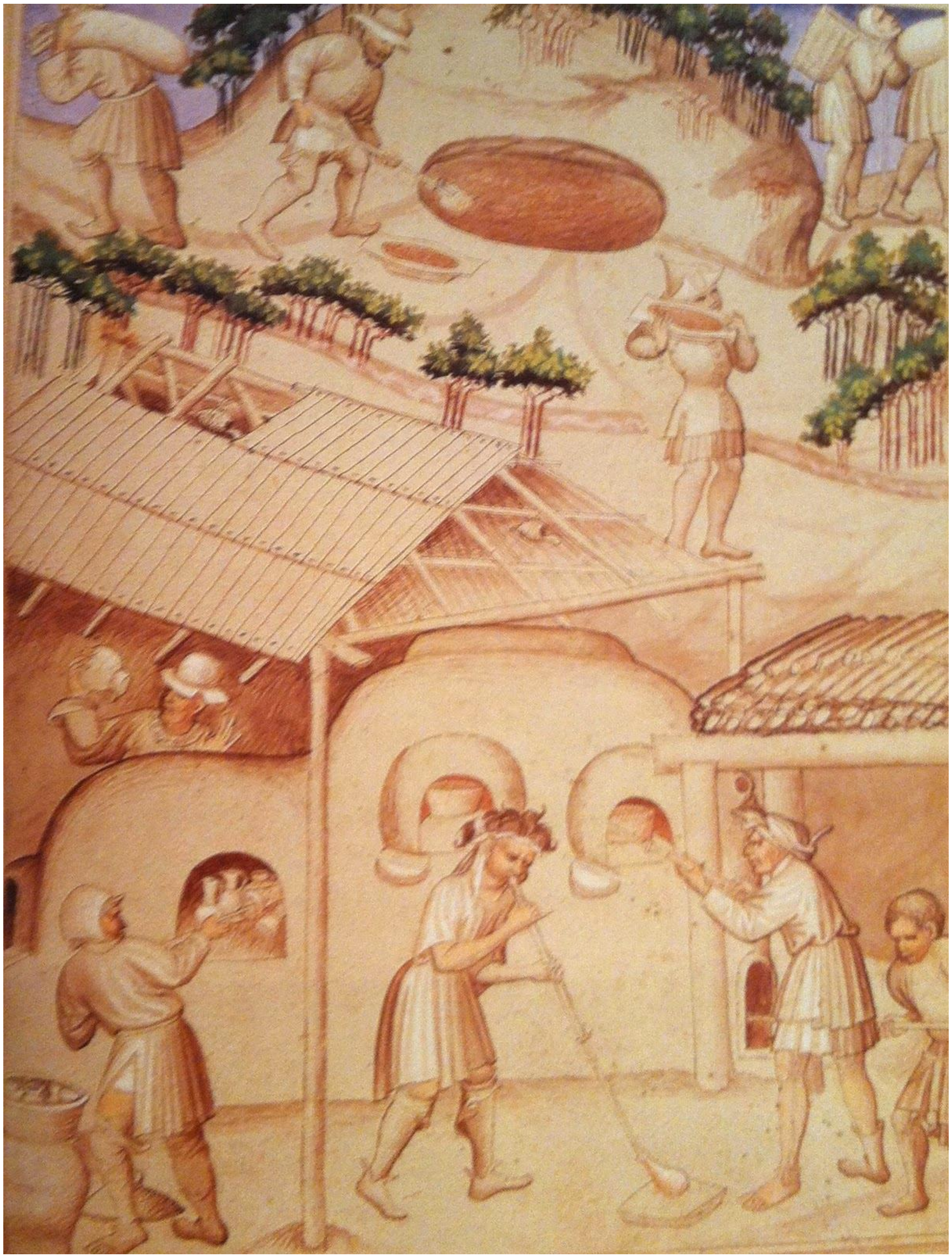


Figure 1. A glassmaking illustration at the Pit of Memnon, from the "Picture Book of Sir John Mandeville's Travels", *c*.1410, probably in Bohemia (British Library, London, UK). This painting shows a glass-house in operation and the whole glassmaking process. At bottom right, a boy either stokes the furnace with wood fuel, or rakes out ash, through an arch. To his left, a glassblower gathers glass from the crucible visible within the furnace, and to his left a blower blows glass on a 'mavering slab'. At bottom left another worker adds or removes vessels from an annealing kiln attached to the main furnace, while behind the furnace someone, perhaps the owner, exercises quality control. In the background workers may be digging sand that was probably added to plant ashes.

The art of glass making was summarized in 1612 by Antonio Neri in '*L'Arte Vetraria*'. At that time glassmakers had an extraordinarily high reputation, however, to keep their monopoly, they were strictly forbidden to leave the country. Many of those who left were assassinated by hired killers, among them two glassmakers who were hired by the French architect Colbert to make the mirrors for the famous Hall of the Mirrors in Versailles [8]. After this work, King Louis XIV founded the '*Manufacture Royale des Glaces de France*', now the Saint-Gobain factory [9].

By 1700 Venice had lost its dominant role in glass making. Glassmakers were now spread all over Europe, and glass products were becoming more and more popular. In 1918 Emile Fourcault in Belgium and, independently, Irving Colburn in the USA invented the technique of producing sheet glass. This, however, involved the glass being drawn through cooled rollers to produce a 'fire-finished' product [10]. The last great advance in the mass production of flat glass came in the 1960's with introduction of the float glass process [11] (G.B. patent 769,692), in which glass is floated out onto molten tin and high quality window glass is produced without the need for expensive grinding and polishing procedures.

The evolution of glassmaking, and the definition of a "Glass Science" only occurred, according to Zarzycki in the 1960's: "during this period the understanding of glass and the vitreous state experienced truly explosive growth similar to that in metallurgy few decades earlier", a Glass Golden Age [12]. Glass is no longer solely a material of primary technological value for construction / architecture, transport, chemical industry, lighting or chemical industry / packaging. New types of glass have been discovered and these play an increasing role in modern optics (lasers), opto-electronics (smart windows, fiber optics), energy conversion (solar window cells) and in medicine (bioglass materials). Thus, for Zarzycki [12], glass has been promoted to the rank of a noble material, not only for its "passive" but also for its "active" applications.

A BRIEF DEFINITION OF GLASS

The atoms and molecules that make up crystals are arranged in an ordered atomic structure while their corresponding glass form is not, see Figure 2: a crystal (*left*) and its glass counterpart (*right*). Such a picture was proposed by Zachariasen in 1932 [13], in the early period of modern glass science and technology. Tammann was the first to postulate the existence of a vitreous state in 1933 [14], and since then glass has assumed the significance of a *physical state of matter* [12]. Basically, a non-crystalline solid can be obtained in three different routes: by retaining the structural disorder of a liquid phase, by taking advantage of the disordered character of a gaseous phase, or by disrupting the order of a crystalline phase [12].

The classic way to produce glass consists of cooling a liquid so quickly that crystallization does not have time to occur. As the temperature decreases, the continuous increase in viscosity results in a progressive freezing of the liquid into its final solid form [15]. The working range of glass production depends on the glass chemistry which occurs in very diverse classes of materials such as [12]: *i*) the only elements able to vitrify alone are in groups V and VI of the Periodic Table: phosphorus, sulfur and selenium; *ii*) oxides such as SiO_2, GeO_2, B_2O_3, P_2O_5, As_2O_3 and Sb_2O_3 transform to the vitreous state – in fact, a great number of glasses can be made by mixing one or more of the above oxides in varying proportions; *iii*) chalcogenides, mainly in binary systems such as As-S, As-Se, P-Se, Ge-Se; *iv*) the only halides forming glasses alone are BeF_2 and $ZnCl_2$, but many fluorides can be combined with these two to form vitreous materials; *v*) some molten salts; *vi*) some aqueous solutions of salts, acids and bases; *vii*) organic compounds such as methanol, ethanol, glycerol, glucose, o-therpheyl, etc. to be cited; *viii*) many organic polymers; *ix*) many metals and metalloid alloys.

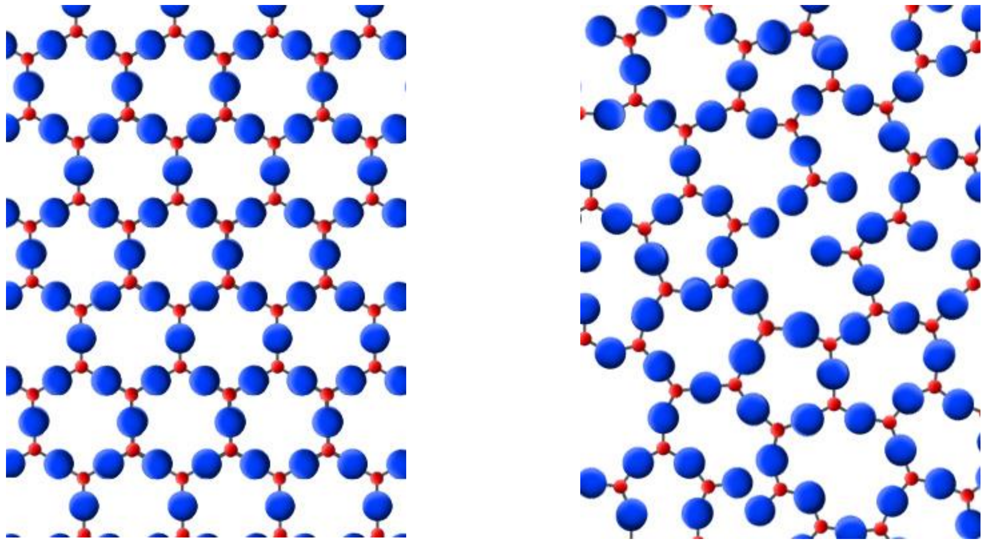


Figure 2. Schematics of a bidimensional molecular arrangement of a crystal structure similar to B_2O_3 [left - 2a] and its glass counterpart [right - 2b]. B represents the small and O the large atoms. Note that borons are coordinated to three oxygens, and each oxygen to two borons at crystal phase, but some oxygens could be linked to only one boron at glassy phase (a nonbridging oxygen). Charge compensations can occur for example with an addition of alkali metal ions (not shown in figure).

The preceding resumed enumeration shows that vitrification occurs in very diverse classes of substances, which do not display an obvious common relationship. Thus, the chemical nature of glass products should not only be taken into consideration, but also the rate at which the liquid is cooled, *i.e*. the quenching rate [12]. For example, to produce special materials such as metallic glasses, it is necessary to apply fast cooling rates, around 10^6 K/s [12].

To study the classic process in more depth, it is interesting to follow the evolution of volume (V) as a function of temperature (Figure 3), because one of the most important factors in the cooling rate is the volume of the sample. Starting with a liquid at an elevated temperature, the lowering of temperature first causes a contraction. When the point of solidification (or freezing) T_m is reached two phenomena may occur; either the liquid crystallizes (resulting in Figure 2*a*) and a discontinuity (generally a contraction) is introduced in the curve, or crystallization is avoided and the liquid passes to a 'supercooled' state. In the latter case, the representative point follows an extension of the liquid curve, which passes temperature T_m without discontinuity. It is as if the system "ignored" the melting point.

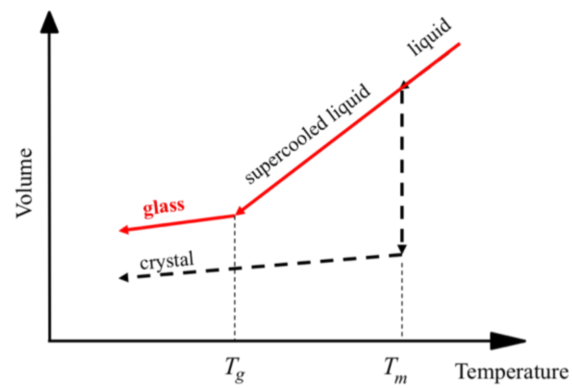


Figure 3. The volume-temperature diagram for a glass-forming liquid. Definition of the glass transition temperature T_g following the variation of the specific volume with temperature T. The melt temperature is T_m. Crystal has a schematic structure similar to Figure 2*a*, and glass to Figure 2*b*. The volume difference in such previous figures can be understood by this graph.

In the first case (Figure 2*a*), on completion of crystallization as the temperature decreases the crystalline solid contracts again and the slope of the curve is now less than that of the initial liquid. In the second case (Figure 2*b*), the decrease in the temperature at first causes a contraction of supercooled liquid with a coefficient of contraction identical to that of the original liquid. Then, starting at a certain temperature T_g, the slope of the curve decreases to approximate that of the crystalline solid. This break in the cooling curve marks the passage from a supercooled liquid to a glass (resulting in Figure 2*b*). The temperature T_g is called the *transition temperature* or the *glass transformation temperature* [12]. The viscosity of the liquid increases continuously from the melt. In the vicinity of T_m, it can be as low as 0.01 poise, which is the viscosity of water at ambient temperature. At the so-called working point, viscosity reaches the viscosity of honey, 10,000 poise, where it can be manipulated most efficiently by the glass blower. By further cooling the viscosity increases reaching at T_g as high as 10^{13} poise. Following this (thermo-dynamics) rule of the quenching rate, under an extremely slow cooling rate, no material will form a glass.

THE MANY USES OF GLASS

Historically, glass has been used in many different ways in many different places. Glass beads, counters, toys, and jewelry were produced almost universally throughout Europe and Asia before 1850 [6]. Glass was chiefly valued in its colored form as an imitation of precious stones. It is important to note that making reliable clear glasses was a major accomplishment in glassmaking chemistry. The great developers of glass vessels, vases, and containers as well as tableware were the Italians, first the Romans and later the Venetians. A major product was ‘glass for perfumes and cosmetics’ namely sprinklers, small flasks and boxes, small dishes for ointments and unguents, as well as scientific and medical items such as alembics for distilling and cupping glasses for the bleeding of patients [1].

Other crucial uses of glass were for making windows and mirrors. The use of silvered glasses spread throughout the whole of Western Europe, but it appeared rarely if at all in Islamic civilizations or in India, China, and Japan [3]. The resulting ‘specialization’ in the fabrication of window glass led to the development of two methods of producing a sheet of glass – the *cylinder* and the *crown* methods [12], the first related to a glass myth explained below. Another critical application of glass was in the production of lenses and prisms [1]. This led to the manufacture of spectacles to improve human eyesight. Eyeglasses first appeared in Europe during the 13th and 14th centuries. This coincides precisely with the surge in interest in optics and mathematics (especially in geometric perspective studies) during medieval times, which fed into other branches of learning, including architecture and painting. It is important to note that the development of glass through mirrors, lenses and spectacles depended entirely on the making of fine clear glass, a major technological step.

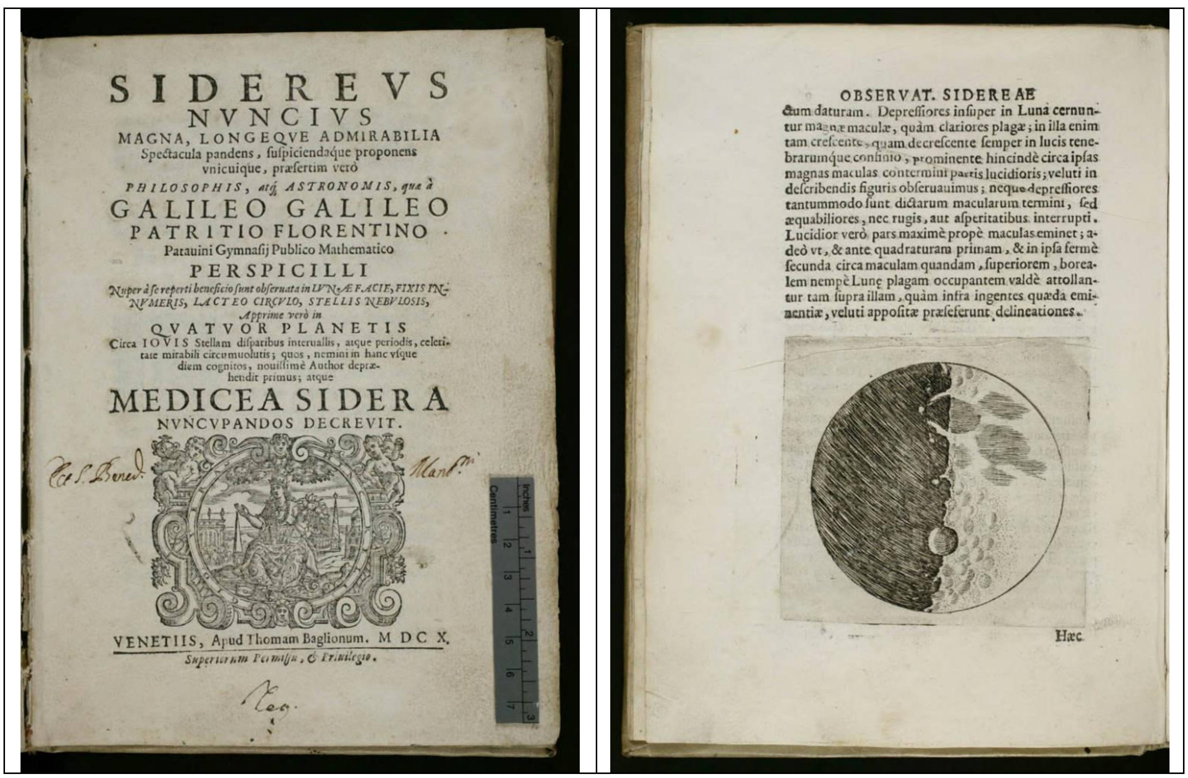
Improvements in glassmaking and the production of more sophisticated glass instru-ments yielded more accurate information about the natural and physical worlds, which fed back into refinements in glass manufacture and consequently glass quality. An interesting glass museum was set up by Corning [16], with exhibitions, videos and resources available online.

The reasons for the different uses of glass in different parts of the world may be largely accidental, reflecting variations in climate, drinking habits, availability of pottery, political events, and many other factors. Intent, planning, individual psychology, superior intellect, or better resources seem to have little to do with it [3].

TEN KEY DISCOVERIES / EXPERIMENTS USING GLASS

We have selected and present ten of the most famous discoveries or experiments that have changed our world and that could not have been performed without glass. Others could have been chosen. Without glass instruments, the scientific revolution, stretching from Galileo to Thomson, roughly covering the period 1600-1900, may not have occurred. Its use was made possible given the following characteristics of glass: it is transparent, inert during use with most liquids and gases, is non-porous, is re-sealable, resistant to low temperatures, can be pasteurized, sterilized, recycled and can improve magnification under certain conditions.

Figure 4 *a*). Portrait of Galileo Galilei (1564-1642) at National Maritime Museum, Greenwich, London by Giusto Sustermans (1597-1681) in 1636 (*www.rmg.co.uk/national-maritime-museum*). This is one of the last portraits of Galileo and several versions and/or copies were made. He is shown seated, with a telescope and the ring on his finger points to his membership of the *Accademia dei Lincei* in Rome.



SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
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PATRITIO FLORENTINO
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Apprime verò in
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Circa IOVIS Stellam disparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vsque diem cognitos, nouissimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
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OBSERVAT. SIDEREAE
dum daturam. Depressiores insuper in Luna cernuntur magnæ maculæ, quàm clariores plagæ; in illa enim tam crescente, quàm decrescente semper in lucis tenebrarumque confinio, prominente hincindè circa ipsas magnas maculas contermini partis lucidioris; veluti in describendis figuris obseruauimus; neque depressiores tantummodo sunt dictarum macularum termini, sed æquabiliores, nec rugis, aut asperitatibus interrupti. Lucidior verò pars maximè propè maculas eminet; adeò vt, & ante quadraturam primam, & in ipsa fermè secunda circa maculam quandam, superiorem, borealem nempè Lunæ plagam occupantem valdè attolluntur tam supra illam, quàm infra ingentes quædam eminentiæ, veluti appositæ præseferunt delineationes.

Hæc

Figure 4 *b*). Galileo's *Sidereus Nuncius* (Starry Messenger, 1610, showing moon's rugged surface) using a handy-made telescope. More details can be found at Galileo's Museum: *www.museogalileo.it* and at Linda Hall Library: *www.lindahall.org*.

1. The Moon's rugged surface, sunspots, and the discovery of Jupiter moons by Galileo (1610)

Glass lenses, originally developed for use in eyeglasses, were of critical importance in the development of the telescope with which Galileo observed the moons of Jupiter and the Moon's rugged surface (Figure 4). Galileo Galilei (1564 - 1642) was not the only observer of the Moon. Indeed, he was not the first. Thomas Harriot (1560 - 1621) drew the first telescopic representation of the Moon and observed our nearest neighbor for several years.

Based only on sketchy descriptions of the telescope, invented in the Netherlands in 1608, during that same year Galileo made some with up to about 32× magnification. With this improved device Galileo could see magnified, upright images on the earth. For a time he was one of very few that could construct telescopes well enough for this purpose. He published his initial telescopic astronomical observations in March 1610 in a short treatise entitled *Sidereus Nuncius* (Starry Messenger) [17]. In the week of January 7, 1610 Galileo discovered Jupiter's four largest satellites (moons): Io, Ganymede, Europa, and Callisto. He noted that the moons would appear and disappear periodically, an observation, which he attributed to their movement behind Jupiter, and concluded that they were orbiting the planet, thus confirming Copernican ideas.

Galileo observed the planet Saturn and was one of the first Europeans to observe sunspots and their dynamic behavior (moving, appearing and disappearing during the days of observation). Galileo was also the first to report lunar mountains and craters, whose existence he deduced from the patterns of light and shadow on the Moon's surface. He even estimated the mountains' heights from these observations. This led him to the conclusion that the Moon was 'rough and uneven, and just like the surface of the Earth itself', rather than a perfect sphere as Aristotle had claimed. Galileo observed the Milky Way, previously believed to be nebulous, and found it to be a multitude of stars packed so densely that they appeared to be clouds from Earth. He located many other stars too distant to be visible with the naked eye.

After many lunar missions we know today that much of the surface of the moon is covered by vitreous materials, either due to volcanic activity or meteoric bombardment [12].

2. Torricelli, the discovery of vacuum and the atmospheric pressure (1643)

Glass vessels were crucial to the alchemical experimentation that preceded modern chemistry and to the Torricellian experiment and air pump that were fundamental for developing our understanding of atmospheric pressure (Figure 5). Pump makers of the Grand Duke of Tuscany attempted to raise water to a height of 12 meters or more, but found that 10 meters was the limit they could achieve with a suction pump. Evangelista Torricelli (1608 - 1647) succeeded Galileo as the grand-ducal mathematician and professor of mathematics at the University of Pisa. He thought of using mercury, fourteen times as dense as water, following Galileo's suggestion. In 1643 he created a 1 meter long glass tube, sealed at the top end, filled it with mercury, and set it vertically into a basin of mercury. The column of mercury fell to about 76 cm, leaving a vacuum above (the very first vacuum achieved). The mercury in the glass tube adjusts until the weight of the mercury column balances the atmospheric force exerted on the reservoir: this was the first *barometer*. High atmospheric pressure places more downward force on the reservoir, forcing mercury higher in the column. Low pressure allows the mercury to drop to a lower level in the column by lowering the downward force on the reservoir. This discovery, published as "*De Motu Aquarum*" ('On Movement in Water', as a part of "*Opera Geometrica*" [18]) has perpetuated his fame, and also shows the practical limit to the height of a column of water. The **torr**, a unit of pressure, was named in Torricelli's honor.

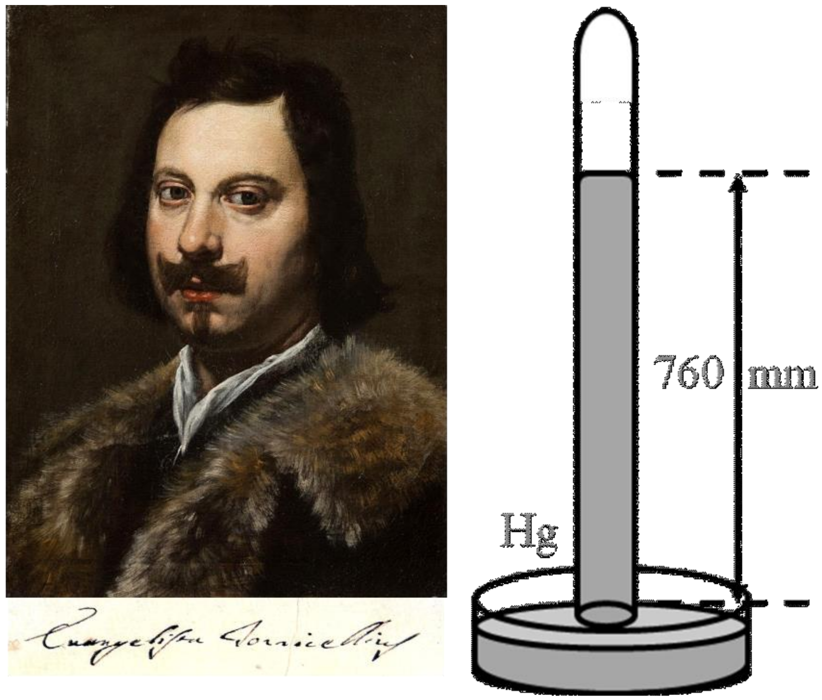

Figure 5. *Left*: Evangelista Torricelli (1608-1647) by Lorenzo Lippi (1606-1665), *circa* 1647, Galleria Silvano Lodi & Due (www.lodiedue.com). *Right*: Evangelista Torricelli's finding: the barometer and the discovery of the vacuum. The glass tube sits upside down in a container, called the reservoir, which also contains mercury. The barometer works by the mercury level in the glass tube falling due to its weight and it is equilibrated by the force of atmospheric pressure, creating thus a vacuum at the top.

3. Hooke, van Leeuwenhoek and the microscope (1665)

A magnifying glass is a two-sided convex (or biconvex) lens housed in a frame that may be attached to a handle, stand or platform for ease of use. If one looks through the glass lens at the object, an image that is right side up and larger than the original will be seen. This is because the simple lens of the magnifying glass is using the retina and lens of our eyes to create a virtual image, which appears to be closer to the convex lens of the magnifying glass. Lenses were also required for the development of the microscope, without which most modern biology would have been impossible. Robert Hooke (1635 - 1703) and Antoni van Leeuwenhoek (1632 - 1723) described the minute living world, which previously had been quite beyond comprehension (Figure 6). Early microscopes produced quite indistinct images - colored 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, as Pasteur and Koch later observed, and of the mechanism of dividing cells and of reproduction.

Robert Hooke was probably fascinated by the sciences, particularly biology from his early childhood. Born in Freshwater on the Isle of Wight in 1635, Hooke received his early education at Westminster School. In 1643, he secured a chorister's place at Christ Church, Oxford. Years later he met the chemist (and physicist) Robert Boyle, and became his assistant. It is possible that Hooke formally stated Boyle's Law, as Boyle was not a mathematician. In 1665 Hooke published a book entitled *Micrographia* [19], which contained a number of microscopic as well telescopic

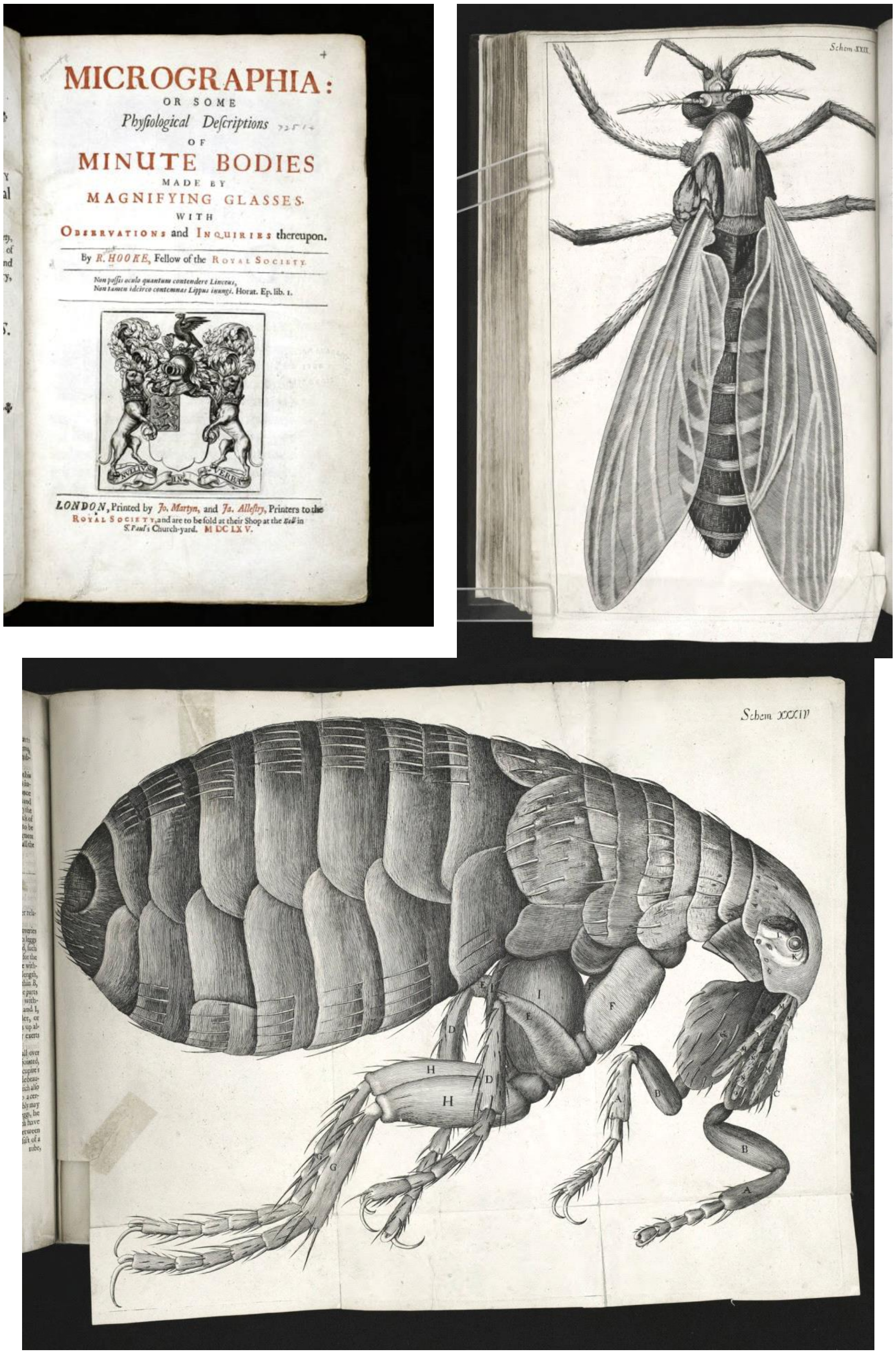

Figure 6. Robert Hooke's original findings using the microscope. At right and below, Hooke's drawing of a gnat and a flea, respectively. Full digital facsimile can be accessed at Linda Hall Library: *www.lindahall.org*.

original observations. Hooke coined the biological term cell, so called because his observations of plant cells reminded him of monks' cells, which were called "*cellula*". *Micrographia* is a historical book detailing the then twenty-eight year-old's observations through various lenses. This book was an immediate best seller.

Leeuwenhoek was a Dutch tradesman and scientist from Delft, The Netherlands. He is best known for his work on the improvement of the microscope and for his contributions towards the establishment of microbiology. Using his handcrafted microscopes he was the first to observe and describe single-celled organisms, which we now refer to as microorganisms. He was also the first to record microscopic observations of muscle fibers; bacteria, spermatozoa and blood flow in capillaries (small blood vessels).

It is believed that soon after 1665 he read *Micrographia*. Leeuwenhoek's interest in microscopes and his familiarity with glass processing led to one of the most significant, and simultaneously well-hidden technical insights in the history of science. By placing the middle of a small rod of lime glass in a hot flame, Leeuwenhoek could pull the hot section apart like taffy to create two long whiskers of glass. By then reinserting the end of one whisker into the flame, he could create a very small, high-quality glass sphere. These spheres became the lenses of his microscopes with the smallest spheres providing the highest magnifications.

4. Newton, light decomposition and the reflecting telescope (1704)

Galileo is generally credited with being the first to use a telescope for astronomical purposes and named it "telescopio" in Italian, from which the English word derives. But Newton improved it by creating the *reflector* telescope, which uses basically glass mirrors to construct the image. From his optics works Newton concluded that any telescope at that time would suffer from the dispersion of light into colors. He invented a new one, today known as a *Newtonian telescope* [20] to bypass this problem. By grinding his own glass mirrors, using Newton's rings to judge the quality of the optics for his telescopes, he was able to produce a superior instrument to the refracting telescope, due primarily to the wider diameter of the mirror. In 1671 the Royal Society asked for a demonstration of his reflecting telescope. Their interest encouraged him to publish his notes *On Colour* (written in the same year [21]), which he later expanded into his *Opticks*. When Robert Hooke criticized some of Newton's ideas, Newton was so offended that he withdrew from public debate. The two men remained enemies until Hooke's death. He also investigated the refraction of light, demonstrating that a glass prism could decompose white light into a spectrum of colors, and that a glass lens and a second prism could recompose the multicolored spectrum into white light.

5. Thermoscope and Thermometer glass experiments

Thermometers measure temperature. The first glass thermometer was a *thermoscope*, which is made of a glass tube and small sealed glass cylinders. Different versions of the thermoscope were invented by several inventors around the same time. The first to put a numerical scale on the thermoscope for use in medicine was the Italian inventor Santorio Santorio (1561 - 1636). In 1593, Galileo invented his own thermoscope, which was made of sealed glass cylinders containing a clear liquid immersed in another sealed glass tube. Suspended in the liquid there are a number of weights for each small sealed cylinder. Usually these weights are themselves sealed glass containers with colored liquid (*e.g.* alcohol) for an attractive effect. As the liquid changes temperature it changes density (another Galileo finding) and the suspended weights rise and fall to stay at the position where their density is equal to that of the surrounding liquid. If the weights differ in density by a very small amount and are ordered such that the least dense is at the top and denser at the bottom, they can form a temperature scale. In 1714, Daniel Gabriel Fahrenheit (1686 - 1736) invented the first mercury thermometer (also using a tiny glass tube), and published his results ten years later [22].

6. The gas laws under glass vessels

Glass has unique properties, it cannot only be made transparent, but it is resistant to chemical change when in contact with most elements and chemical compounds. 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. It is also easy to clean, to seal, 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 temperatures and it is also an insulator. Boyle's, Charles's, and Gay-Lussac's laws form the combined gas law. None of them could have been perceived without the use of glass apparatus: tubes, flasks, containers, vessels and retorts, all essential for laboratory research.

a) ***Boyle's law:*** for a fixed mass of ideal gas at a fixed temperature, the product of pressure and volume is a constant.

Boyle's Law [23] is named after the Irish natural philosopher Robert Boyle (1627 - 1691) who was the first to publish it in 1662. It is possible that Boyle's assistant Robert Hooke, who built the experimental apparatus, may well have helped to quantify the law. Hooke also developed the improved vacuum pumps necessary for the experiments. The French physicist Edme Mariotte (1620-1684) discovered the same law independently of Boyle in 1676, so this law can be referred to as Mariotte's or the Mariotte-Boyle law.

b) ***Charles' Law***: at a constant pressure, the volume of a given mass of an ideal gas increases or decreases by the same factor as its temperature increases or decreases.

This law was first published by Joseph Louis Gay-Lussac (1778 - 1850) in 1802 [24], but he referenced unpublished work by Jacques Charles (1746 - 1823) from around 1787. This reference has led to the law being attributed to Charles. Charles was born in Beaugency-sur-Loire, and made the first flight of a hydrogen balloon on August 27, 1783. On December 1, 1783, a mere ten days after the manned flight of the Montgolfier hot-air balloon, Charles with Ainé Roberts ascended to a height of about 550 meters in his balloon – "La Charlière". The balloon was destroyed by terrified peasants when he landed outside Paris. He developed several useful inventions, including a valve to let hydrogen out of the balloon and other devices, such as the hydrometer and reflecting goniometer. In addition he confirmed Benjamin Franklin's electrical experiments.

c) ***Gay-Lussac's Law:*** The pressure of a fixed amount of gas at a fixed volume is directly proportional to its temperature [24].

This law holds true because temperature is a measure of the average kinetic energy of a substance; as the kinetic energy of a gas increases, its particles collide with the container walls more rapidly, thereby exerting increased pressure. Simply put, if you increase the temperature you increase the pressure. Gay-Lussac was born at Saint-Léonard-de-Noblat, in the department of Haute-Vienne. He received his early education at home and in 1794 was sent to Paris to prepare for the École Polytechnique into which he was admitted at the end of 1797. In 1808, he was the co-discoverer of boron. In 1824 he developed an improved version of the burette that included a side arm, and coined the terms "pipette" and "burette".

7. The Germ theory, by Pasteur and Koch

The germ theory is an assumption that microorganisms are the cause of many diseases. Although highly controversial when first proposed, it is now a cornerstone of modern medicine and clinical microbiology, leading to important innovations such as the development and use of anti-microbial and antibiotic drugs, vaccines after the empirically derived one for smallpox, hygienic practices in hospitals, and public sanitation. Louis Pasteur (1822 - 1895) further demonstrated that fermentation and the growth of microorganisms in nutrient broths did not occur by spontaneous generation [25]. He exposed freshly boiled broths to air in glass vessels that contained a filter to stop all particles passing through to the growth medium: and even with no filter at all, with air being admitted via a *long* tortuous glass tube that would not allow dust particles to pass. Nothing grew in the broths, therefore the living organisms that grew in such broths came from outside, such as spores on dust, rather than being generated within the broth.

Robert Koch (1843 - 1910) was the first scientist to devise a series of proofs used to verify the Germ Theory of Disease. Koch's Postulates were first used in 1875 to demonstrate that anthrax was caused by the bacterium *Bacillus anthrasis* [26]. These postulates are still used today to help determine if a newly discovered disease is caused by a microorganism. For his discoveries, in particular to tuberculosis, he received the Nobel Prize for Physiology or Medicine in 1905.

The microscope was also crucial to Pasteur and Koch in their work on the germ theory of disease and in their proofs that life did not spontaneously generate. Later, the microscope would be the foundation of an even greater break-through. Our new understanding of genetics which sprang 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.

8. Faraday, light through a glass bar and electromagnetism

In physics, the Faraday Effect is an interaction between light and a magnetic field, which was discovered by Michael Faraday (1791 - 1867) in 1845 [27]. It provided the first experimental evidence that light and magnetism were related. The rotation of the plane of polarization is proportional to the intensity of the component of the magnetic field in the direction of the beam of light that passes through a glass bar. The basis of this, now called electromagnetic radiation, was developed by James Clerk Maxwell (1831 - 1879) in the 1860's. This effect occurs in most optically transparent dielectric materials (including liquids) when they are subject to strong magnetic fields. Faraday wrote in his notebook, "I have at last succeeded in illuminating a magnetic curve or line of force and in magnetizing a ray of light". Briefly speaking, the angle of rotation β of the polarization is proportional to the magnetic flux density B and the length d. Some applications of the Faraday Effect include its use to measure optical rotatory power through a glass bar, for amplitude modulation of light, and for remote sensing of magnetic fields. It is important also to note that Faraday published some of the earliest studies on glass technology in 1900's.

9. Thomas Edison and the glass light bulb (1879)

The glass light bulb works by incandescence. An electrical current passes through a thin filament; heating it and causing it to release thermally equilibrated photons in the process. The enclosing glass bulb prevents the oxygen in the air from reaching the hot filament, which otherwise would be destroyed rapidly by oxidation. To achieve this technological improvement, many studies were carried out by many people. In fact, it was not Thomas Alva Edison (1847 - 1931) who invented the first electric glass light bulb, but rather he invented the first commercially practical incandescent light bulb (Figure 7).

In 1878, Edison applied the term filament to the element of glowing wire carrying the current, although English inventor Joseph Swan (1828 - 1914) had used the term prior to this. Edison took the features of these earlier designs and set

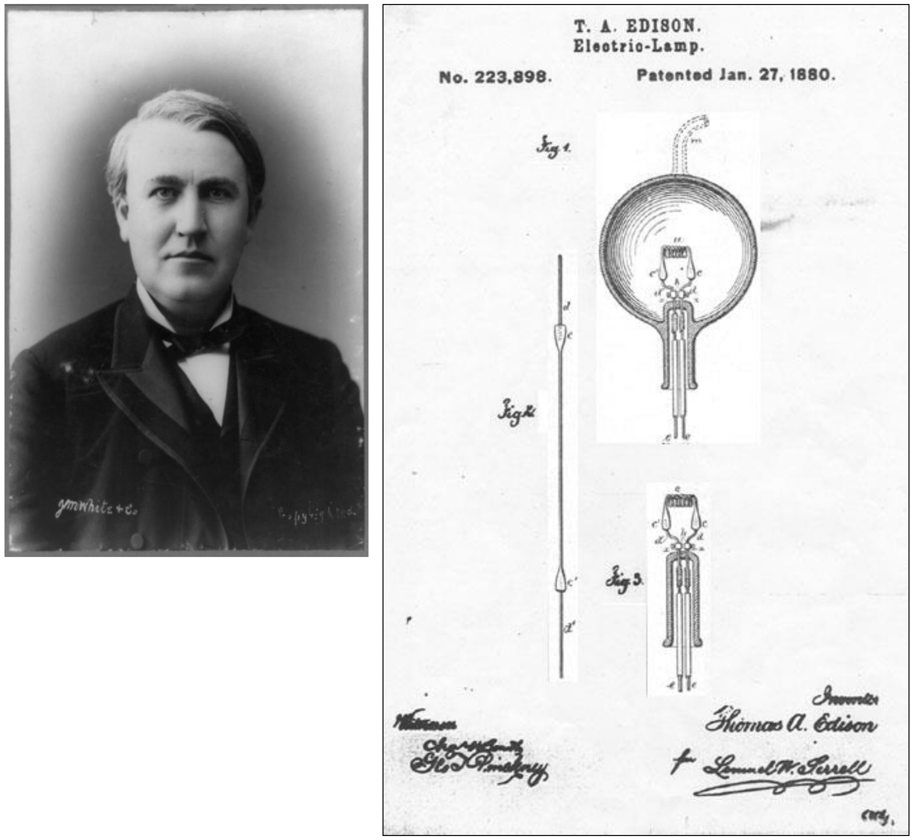

Figure 7. Thomas Alva Edison (1847-1931) and his electrical lamp patent (U. S. 223,898), related to the first successful light bulb model, used in public demonstration at Menlo Park, December 1879. Interesting details can be found at the Museum of Electric Lamp Technology: *www.lamptech.co.uk*.

his workers the task of creating longer lasting glass bulbs. By 1879, he had produced a new concept: a high resistance lamp in a very high vacuum, which would burn for hundreds of hours. While the earlier inventors had produced electric lighting in laboratory conditions dating back to a demonstration of a glowing wire by Alessandro Volta in 1800's, Edison concentrated on the commercial application and was able to sell the concept to homes and businesses by mass-producing relatively long-lasting light bulbs and creating a complete system for the generation and distribution of electricity [28].

After many experiments with platinum and other metal filaments, Edison returned to a carbon filament. The first successful test was on October 22, 1879, and lasted 13.5 hours. Edison continued to improve this design and by November 4, 1879, filed for U.S. patent 223,898 (granted on January 27, 1880) for an electric glass lamp using "a carbon filament or strip coiled and connected ... to platina contact wires". Although the patent described several ways of creating the carbon filament including "cotton and linen thread, wood splints, papers coiled in various ways", it was not until several months after the patent was granted that Edison and his team discovered a carbonized bamboo filament that could last over 1200 hours.

10. Thomson and the discovery of electrons by glass cathode ray tubes (1897)

Sir Joseph John Thomson (1856 - 1940) was a British scientist who conducted a series of experiments with glass cathode ray tubes. These led him to the discovery of electrons and subatomic particles by using glass apparatus [29]. In his first experiment, he investigated whether or not the negative charge could be separated from the cathode rays by means of magnetism. He constructed a cathode ray tube ending in a pair of cylinders with slits in them. These slits were in turn connected to an electrometer. Thomson found that if the rays were magnetically bent such that they could not enter the slit, the electrometer registered little charge. Thomson concluded that the negative charge was inseparable from the rays.

In his second experiment, he investigated whether or not the rays could be deflected by an electric field (something that is characteristic of charged particles). Previous experimenters had failed to observe this, but Thomson believed their experiments were flawed because they contained trace amounts of gas. Thomson constructed a cathode ray tube with a practically perfect vacuum, and coated one end with phosphorescent paint. Thomson found that the rays did indeed bend under the influence of an electric field.

In his third experiment, Thomson measured the charge-to-mass ratio of the cathode rays by measuring how much they were deflected by a magnetic field and how much energy they carried. He found that the charge to mass ratio was over a thousand times higher than that of a proton, suggesting either that the particles were very light or very highly charged.

Thomson concluded that cathode rays were indeed made of particles which he called "corpuscles" (in fact *electrons*), and these corpuscles came from within the atoms of the electrodes themselves, meaning they were in fact divisible. He was awarded the 1906 Nobel Prize in Physics for the discovery of the electron and for his work on the conduction of electricity in gases. Using similar equipment, also based on glass tube, Roentgen discovered the X rays in a series of simple experiments [30].

GLASS IN EVERYDAY LIFE AND USES IN NEAR FUTURE

Glass is one of the most used materials, and certainly one of the most versatile, adaptable, showing considerable chemical durability. Transparency is its best quality and brittleness its worst defect. Glass also has the advantage of being impermeable, easily cleaned and reusable. However, nowadays it is possible to create non-transparent or even tough glasses for specific purposes, such as metallic glasses [31] or bioglasses [32] respectively. There are other useful applications of glass widely used in everyday life. To cite a few: self-cleaning glass [9]; controlled dissolution glasses [33], photochromic glasses and vitrification of radioactive wastes.

Glass is in modern life no longer solely a transparent material of primary technological value that has widespread practical, technological, and decorative use for lighting, windowpanes, tableware, transport and packing [12] among others. As said previously, new types of glass have been discovered and these play an increasing role in modern optics, electronics, opto-electronics [34], information and energy conversion. Very recent and interesting examples can be viewed at "A Day Made of Glass", where it is possible to look at Corning's vision for the future with specialty glass at the heart of it [16].

The field of modern glass science and technology has a remarkable history spanning about two centuries of research [2], certainly due to some of the discoveries and experiments presented in this work. Undoubtedly, advances in glass science and technology have served as essential ingredients for modern day society, in areas including architecture, transportation, medicine, energy, science exploration, and communication and the display of information. Mauro and Zanotto [2] noted that modern glass science and technology publication rates have increased exponentially since 1945. While the United States is the most prolific country overall, within the most recent decade, China has become the clear dominant player in the global glass research community in the beginning of XXI century, while the publication rate has declined in many of the historically most prolific countries. Oxide glasses, metallic glasses, amorphous carbon, and amorphous silicon have drawn the most research attention overall and are still given the greatest focus today. Optical and mechanical properties have received the most attention overall, with mechanical properties gaining visibility in recent years. Thermal and rheological properties have also received considerable attention from researchers, both historically and today. Unfortunately, according to Mauro and Zanotto, the level of published (fundamental) glass research from industrial laboratories has dropped significantly in recent years. However, the number of patents issued worldwide has surpassed the number of published scientific articles surprisingly, indicating a very high level of activity in technological research [2].

CONCLUSIONS

To the layman, glass is a transparent solid with good chemical durability that breaks easily [1]. We delve deeper showing that glass constitutes a fascinating group of materials both from fundamental and applied standpoints. They are among the most ancient materials in human history and it seems paradoxical that our knowledge of their structure is far from complete, as well as its importance in history of science. We have discussed the contributions of glass from the scientific perspective. Nevertheless from 1600 onwards, knowledge became interconnected. Without mirrors, lenses, and glass panes, the startling changes that marked the Renaissance would not have taken place.

Glass helped to accelerate the amazing acquisition of knowledge about the natural and physical worlds. Without clear glass, the gas laws would not have been discovered and so there would have been no steam engine, no internal combustion engine, no discovery of static electricity, no light bulbs, no cameras, and no television. Chemistry depends heavily on glass instrumentation. Thanks to glass, European scientists elucidated the chemistry of nitrogen and learned to fix this gas in the form of ammonia to produce artificial nitrogenous fertilizers, a huge step forward in 19th and 20th century agriculture. Without glass, there would have been no means of demonstrating the structure of the solar system, no measurement of stellar parallax, no way of substantiating the conjectures of Copernicus and Galileo. The application of glass instruments revolutionized our understanding of the universe and deep space, completely altering our whole concept of cosmology. The list of scientific fields of enquiry that could not have existed without glass instrumentation is legion: histology, pathology, protozoology, bacteriology, and molecular biology to name but a few. Astronomy, more general biological sciences, physics, mineralogy, engineering, paleontology, vulcanology and geology would have emerged much more slowly and in a very different form without the help of glass instruments. Glass literally opened people's eyes and minds to new possibilities and turned western civilization from an aural to a visual mode of interpreting experience.

Such brief experiments suggest that glass was the key factor involved in the emergence of Western science and technology. Unfortunately, little attention is given to the rise of this technology in science classrooms, and that glass has a major contribution in this field.

The different applications of glass are all interconnected — windows improved working conditions, spectacles lengthened working life, stained glass added to the fascination and mystery of light and, hence, a desire to study optics. The rich set of interconnections of this largely invisible substance has made glass both fascinating and powerful, and as cited by Macfarlane and Martin – a molten liquid that has shaped our world [3].

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