The Nature of Glass: Technologies of Transparency, Materials on the Move

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Abstract: Scientific instruments such as telescopes and distillation columns have played a prominent role in the history of science, but the key material of which these instruments were made has received scant attention. Focusing on the glass used to make scientific instruments and on the supply chains on which its production relied—allows us to see that "glass" covers a variety of materials and that the nature of glass depends on the material knowledge and environmental expertise invested in its manufacture. Between the seventeenth and the twentieth centuries, glassware moved back and forth between a dependence on processing locally sourced materials and reusing household items and a reliance on intraregional supply chains of specialty materials.

Galileo's telescope is an iconic scientific instrument, and the telescopic discoveries he published in *Sidereus Nuncius* are arguably among the most famous episodes in the history of science. Yet the material of which Galileo's telescope lenses were made has remained remarkably invisible to historians of science. To see this optical glass, and the materials and the knowledge invested in its production, we need to turn our attention from this epoch-making book to the astronomer's shopping list. (See Figure 1.)

In the autumn of 1609, Galileo jotted down on the back of a letter a list of items that he wished to buy on a shopping trip to Venice.[1] This list includes soap, oranges, sugar and spices, raisins, rice, slippers, and a small hat for his son Vincenzo, as well as more technical items such as German ground glass, pieces of mirror, and tripoli—and an address where these things might be found: the mirror-maker shop at the Sign of the King. Clearly, Galileo hoped to equip his optical workshop with the material substances, tools, and abrasives he needed to improve his telescope lenses. Venice was the ideal place to buy such things: the nearby island of Murano was home to the world's center of luxury glass production, and Venetian mirrors, made of *cristallo* glass, were widely acclaimed as the best. Galileo's shopping list reveals his knowledge of the quality of glass materials and the way in which mirrors were manufactured. Glass made according to the "German" method, which produced flat sheets by cutting and reheating a cylinder of glass, was preferable to glass made by the crown method, which resulted in much less even, irregular pieces. Galileo ground his lenses starting

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[1] Giorgio Strano, "Galileo's Shopping List: An Overlooked Document about Early Telescope Making," in *From Earth-Bound to Satellite: Telescopes, Skills, Networks*, ed. Alison Morrison-Low, Sven Dupré, Stephen Johnston, and Strano (Leiden: Brill, 2012), pp. 1–19.

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Figure 1. Galileo's telescope lens. Museo Galileo, Florence. Photographic inventory 20401. Photo by Franca Principe.

with pieces of flat mirror glass, and he polished them to perfection using tools and materials (e.g., the tripoli on the shopping list) that he adopted from mirror makers.

In the early modern period, the better clarity and transparency of Venetian-style glass became essential for fabricating telescopes and for use in alchemical laboratories. Scientific examination of the glassware from Oberstockstall, one of the most well-preserved alchemical laboratories from the period in Austria, shows that from the sixteenth century alchemists used *cristallo* glass in their laboratories, as it allowed them to observe the colorful transformations inside transparent glass vessels on which so much of their understanding of the material world was based.[2] The high clarity and transparency of Venetian glass allowed visual penetration without obstruction or tinting to observe visual effects. Yet while these scientific instruments play a prominent role in the history of science, the key material of which they were made has received scant attention. (See Figure 2.)

This essay studies the supply chains on which the production of *cristallo* glass depended, as well as the material knowledge and environmental expertise that went into its production. Glass production was shaped by processes of appropriating natural resources—both the raw materials and the energy and fuel for the furnaces. The essay shows that glass production was linked to several issues related to the management of nature and resources, colonial and environmental politics, and ideas regarding scarcity and sustainability. It begins by arguing that the transparent *cristallo* glass of which Galileo's telescope lens was made depended on intraregional supply chains and the sourcing of materials of a particular provenance, which made its production more vulnerable compared to that of other, more common, glass that depended on locally sourced materials.

GLASS ON THE MOVE

We have been living since the nineteenth century in an environment of mass transparency, yet transparent glass has not always been ubiquitous.[3] Window glass was first adopted in churches

[2] Umberto Veronesi and Marcos Martinón-Torres, "Glass and Alchemy in Early Modern Europe: An Analytical Study of Glassware from the Oberstockstall Laboratory in Austria," *Angewandte Chemie*, 2018, 57:7346–7350.

[3] Isobel Armstrong, *Victorian Glassworlds: Glass Culture and the Imagination, 1830–1880* (Oxford: Oxford Univ. Press, 2008).

Figure 2. A distillation column (height: 41.8 cm) from the Oberstockstall laboratory. Photo by Marcos Martinón-Torres.

and cathedrals from around 1000 C.E., and larger clear glass windowpanes only arrived in houses owned by burghers from the seventeenth century. Transparency was made possible by the development of new glass technologies in the late medieval and early modern period.

Glass reliquaries and rock crystal flasks were among the most prized objects that Christian pilgrims brought back from the Holy Land. Their use by European Christians in a religious context that emphasized display caused their tactile sensation to be lost, and the material came to be appreciated primarily for its transparency. This traffic in reliquaries then shaped the way the Venetians harnessed raw materials and techniques imported from the Levant to make their city into a center of glassmaking. From the fourteenth century onward, the Venetians succeeded in making transparent glass, named *cristallo* because it was as transparent as rock crystal.[4]

Yet the specialty glass the Venetians exported participated in much larger and more substantial flows of glass objects that facilitated the spread of Venetian glassmaking knowledge to other centers of luxury *cristallo* glass production and were themselves embedded within global, colonial

[4] Avinoam Shalem, *Islam Christianized: Islamic Portable Objects in the Medieval Church Treasuries of the Latin West* (Frankfurt am Main: Lang, 1998); and W. Patrick McCray, *Glassmaking in Renaissance Venice* (Farnham: Ashgate, 1999).

flows of trade. In Antwerp, for instance, *cristallo* glass was produced by the Portuguese merchant-banker Emmanuel Ximenez, who collected enslaved people in Angola, shipped them to Brazil, returned to Europe with sugar and brazilwood, and delivered Venetian-style glass as well as colorful glass beads to Angola on the Atlantic coast of Africa, where the Ximenez family held a trade monopoly. Similarly, Louis XIV offered diplomatic gifts of glass to Siamese ambassadors—whom he received in the new Hall of Mirrors at Versailles—in hopes of obtaining access to Siamese tin, itself a crucial material for the production of mirrors and many other products. The Siamese began to decorate their own courts with Saint-Gobin mirrors, and Louis XIV got his tin.[5]

Despite its material fragility, then, glass has proven remarkably resilient given the variety of meanings that it has acquired for different audiences and contexts. Yet while scholars have widely noted the circulation of glass objects, it is equally important to observe that the production of Venetian-style glass also depended on shifts in the supply chains of resources required to make it. The material substances used for Venetian glass production are described in *L'arte vetraria*, the first printed book on the art of glass. Written by Antonio Neri, who experienced Venetian glassmaking at the Medici court in Florence and as a guest in the house of Emmanuel Ximenez in Antwerp, the book was translated into several languages and issued in editions with additional notes and commentary by Christoph Merrett and Johannes Kunckel; it remained the most important written source on the art of glass in the seventeenth century. The manufactured product it describes was a colorless *cristallo* glass that could be colored by adding pigments. And by looking at the four components that Neri identifies as required to make this glass, we can see how it depended on intraregional supply chains and the sourcing of materials (such as sand and manganese) of a given provenance.

The most important substance for the production of *cristallo* glass is sand, which artisans in Venice sourced from the Ticino River. The reason for this was purity. Sand was typically contaminated with metals, which tint the glass. In principle, one can make glass from every type of sand; depending on the presence of metallic contaminants, it will turn out to have different colors. The most important enemy of the seventeenth-century Venetian glassmaker was iron, which tints the glass greenish. Glassworkers preferred sand from the Ticino River because it was relatively free of iron, and thus they could avoid accidentally giving the glass a greenish tint. The second component of glass is soda. Sand only melts at temperatures of about 1750 degrees Celsius, too high for early modern glass furnaces. To lower the melting point, a flux is added. For Venetian-style glass the source of soda was coastal plant ashes. These were not locally sourced, but as a major trading center Venice was able to import them from the Levant. In Neri's time, the Venetian glass workshops used the ashes of the barilla plant found on the coasts of Spain and Sicily. The use of plant ashes was a major difference that set *à la façon de Venise* glass apart from Bohemian glass. The latter, known as *Waldglas*, was produced in glass workshops, which were often mobile, in the Bohemian woods. The ashes of burned local trees were used, typically resulting in glass with a greenish tint. Concerned with the purity of his materials, Neri advises the use of dry hardwood, preferably oak, for heating the furnaces to avoid contaminating the open pots of glass in the furnace with smoke or ashes from the fire.

The third component of glass is lime. Mixtures of only sand and soda result in a glass that is not stable and dissolves in water. Neri was not aware of how lime worked (though he likely recognized that it was required), and it is highly probable that lime or calcium oxide was added to the

[5] Sven Dupré, "The Value of Glass and the Translation of Artisanal Knowledge in Early Modern Antwerp," *Netherlands Yearbook for Art History*, 2014, 64:138–161; and Meredith Martin, "Mirror Reflections: Louis XIV, Phra Narai, and the Material Culture of Kingship," *Art History*, 2015, 38:652–667.

glass composition unintentionally—for example, by contamination from shells that were present in the sand. This contamination contrasts with the intentional addition of a fourth component. This final component of Venetian *cristallo*, which set it apart from other types of glass, was manganese. Manganese was mined all over Italy, but Neri cautioned that only manganese from Piedmont was to be used, not that from Tuscany. Here, as in the case of the sand, Neri emphasizes the importance of the sourcing of materials of a particular provenance. Manganese gives the glass a violet tint, neutralizing the greenish hue that is imparted by contamination with iron. The result was the typical Venetian colorless glass that was as clear as natural rock crystal.

In sum, compared to the much more widely available and less transparent Bohemian *Waldglas*, which depended on local resources such as the wood that provided glassmakers with both ashes for their mixtures and fuel for their furnaces, Venetian-style glass depended on intraregional supply chains and the sourcing of materials of a particular provenance. This dependence made *cristallo* glass more vulnerable to scarcity; the wood needed as energy added to this vulnerability.

BROKEN GLASS AND THE SCARCITY OF RESOURCES

Venice was dependent on the mainland for its supplies of wood, and therefore it was also vulnerable to scarcity. With the growth of its manufacturing industries, such as glassmaking, Venice's requirements for firewood steadily increased beginning in the fifteenth century and continued to grow well into the eighteenth century. In 1531, a dearth of firewood was reported as making the work of glassmakers and other artisans such as dyers impossible. In following a strategy of large-scale forest conservation instead of colonial exploitation, Venice was unique in Europe—though we find comparable approaches in, for example, Tokugawa Japan. Yet fears regarding scarcity of wood were widespread throughout the early modern period, supported, for example, by the myth expressed in the first decades of the seventeenth century in England: that there had been many more woods in the recent past and that their depletion was in part due to the growth of the glass industry. The perception of accelerating scarcity fed into debates about woodlands in England and the passing of legislation to manage and regulate the supply of wood. Against this background, the Virginia Company established Jamestown in the hope of launching large-scale production of glass and escaping the restrictive forestry legislation in England.[6]

The establishment of a glass industry in colonial Jamestown went hand in hand with experiments in substituting locally available materials in glassmaking. Such experimentation was typically associated with the physical translation of glassmaking knowledge. In his translation of Neri's *L'arte vetraria*, prompted by his concern with developing a domestic industry, Merrett displayed an acute interest in locally available natural resources useful for coloring glass. To support his translation of glassmaking knowledge, he assembled a collection of vitreous materials used for multisensorial investigation. The collection consisted of shards of glass, much like the broken pieces of mirror glass from which Galileo's telescope lenses were made, which built on the age-old tradition of recycling cullet, as well as other materials such as potash and sand—in short, waste, failed, and intermediate materials and objects otherwise lost or rendered invisible by early

[6] On the 1531 firewood shortage see Karl Appuhn, *A Forest on the Sea: Environmental Expertise in Renaissance Venice* (Baltimore: Johns Hopkins Univ. Press, 2009), pp. 136–137. For the myth about the depletion of English woods see Paul Warde, *The Invention of Sustainability: Nature and Destiny, c. 1500–1870* (Cambridge: Cambridge Univ. Press, 2018), pp. 58–101. On the hope that Jamestown would become a glassmaking center see Umberto Veronesi, Thilo Rehren, Beverly Straube, and Marcos Martinón-Torres, "Testing the New World: Early Modern Chemistry and Mineral Prospection at Colonial Jamestown, 1607–1610," *Archaeological and Anthropological Sciences*, 2019, *11*:6851–6864.

modern recycling economies.[7] This practice of reuse and recycling was at odds with the emphasis on the sourcing of raw materials of a given provenance in Neri's branding of Venetian-style glass.

THE KITCHEN AND THE LABORATORY

The dependence of telescope lenses and alchemical laboratory equipment on Venetian-style transparent glass marked a shift away from the use and reuse of household glass for scientific purposes.[8] Yet in the early nineteenth century scientists returned to the use of home-blown glass. Catherine Jackson has shown that in this period "chemists began using glass in distinctly new ways and that their appropriation of glassblowing skill had profoundly important effects on the emerging discipline of chemistry."[9] This new practice of chemistry in glass—which Jackson calls "the glassware revolution"—transformed not merely the material culture of chemistry but also, as she argues, its geography and pedagogy. Central to this new practice of chemistry was the glass tube; chemists such as Michael Faraday advocated the use of small pieces of home-blown glassware, which enabled a greater number and variety of people to participate in the science of chemistry and even to challenge chemists working in Paris, the metropolitan center of chemistry in the early nineteenth century, where they had access to expensive equipment and specialized instrument dealers.

Not until the advent of scientific experimentation driven by epistemic values of precision and purity in the second half of the nineteenth century did the interaction between glass containers and substances in the laboratory come to be recognized and identified as a source of error, initiating a movement toward standardizing the material used for glass and developing more specialized glass for scientific purposes.[10] Around 1880, the best glassware was needed in the laboratory and was no longer found in the household. In response, in the late nineteenth century a sustainable method for testing the quality of glass was developed based on its "hygroscopicity"—that is, the discovery that the main culprit in the deterioration of glass was another seemingly neutral and invisible substance, water. The standardization of glass-testing methods eventually led to the development of the first standard of glass quality, the German industrial norm DIN Denog 62, in 1935. Another response was the development of specialty glassware for the laboratory in the 1880s by the Jena-based chemist and entrepreneur Otto Schott. This was Schott's famous borosilicate glass, which would dominate the global market for decades to come. It, too, was highly dependent on global supply chains, given that borax was a key ingredient determining its quality and that borax was not locally available. The interruption of the flow of borax to Jena in World War I marked the end of Schott's global market dominance. In 1915, Corning Glass Works presented its own borosilicate glass, branded as Pyrex, which soon became ubiquitous—even more in home kitchens than in scientific laboratories. After the end of the war, in response, the Schott company adapted its specialty glass and collaborated with Bauhaus and Werkbund designers to develop kitchen glassware.[11] Following the shift away from the use of household and home-blown glass in the

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[7] Ruth Ezra, "Deconstructing Glass and Building up Shards at the Early Royal Society," *Renaissance Quarterly*, 2022, 75:88–135; and Ian C. Freestone, "The Recycling and Reuse of Roman Glass: Analytical Approaches," *Journal of Glass Studies*, 2015, 57:29–40.

[8] Simon Werrett, *Thrifty Science: Making the Most of Materials in the History of Experiment* (Chicago: Univ. Chicago Press, 2019).

[9] Catherine M. Jackson, "The 'Wonderful Properties of Glass': Liebig's *Kaliapparat* and the Practice of Chemistry in Glass," *Isis*, 2015, *106*:43–69, on p. 43.

[10] Kijan Espahangizi, "From *Topos* to *Oikos*: The Standardization of Glass Containers as Epistemic Boundaries in Modern Laboratory Research (1850–1900)," *Science in Context*, 2015, 28:397–425.

[11] Kijan Espahangizi, "Stofftrajektorien: Die kriegswirtschaftliche Mobilmachung des Rohstoffs Bor, 1914–1919 (oder: was das Reagenzglas mit Sultan Tschair verbindet)," in *Stoffe in Bewegung: Beiträge zu einer Wissensgeschichte der materiellen Welt*, ed. Espahangizi and Barbara Orland (Zurich: Diaphanes, 2014), pp. 173–207; and Espahangizi, "Science in Glass: Material Pathologies

laboratory in the 1880s, then, the borosilicate glassware specifically developed for the laboratory flowed back to the household in the 1920s, turning the kitchen into the laboratory of the home.

In a *longue durée* perspective, scientific glassware moved back and forth between the kitchen and the laboratory, and between a dependence on processing locally sourced materials and reusing household items and a reliance on intraregional supply chains of specialty materials such as barilla plant ashes in the sixteenth and seventeenth centuries and borax in the nineteenth and twentieth centuries. While the nineteenth-century glassware revolution looks like a continuation of premodern and early modern recycling economies, the requirements of standardization later in the same century led to the production of a chemically durable glass that was as different from kitchen glassware as transparent Venetian-style *cristallo* was from ordinary household glass in the early modern period. Galileo's telescope depended on highly specialized glass, the production of which was vulnerable to scarcities of the materials and energy delivered by intraregional supply chains. Shifting our attention to the glass used to make scientific instruments, and to the supply chains on which its production relied, allows us to see that "glass" covers a variety of materials and that the very nature of glass depends on the material knowledge and environmental expertise invested in its manufacture.

in Laboratory Research, Glassware Standardization, and the (Un)Natural History of a Modern Material, 1900s–1930s," *Isis*, 2022, *113*:221–244.