Coalescence of glass art and glass science

By Nadia A. Elbaar, Briana L. Bennett, Jane B. Cook, and John C. Mauro

Glass art and glass science often are viewed as dichotomies of the same material study. But these two areas complement each other in theory and utility—which makes promoting a dialogue between the two disciplines a fulfilling endeavor.

For millennia, glass has played an integral role in our daily lives.

People used glass to craft objects both functional and artistic dating as far back as 2000 BCE in Mesopotamia,[1] partially owing to its literal ubiquity—the most common silicate glasses consist primarily of sand. And the material's shape versatility—it can be molded, cast, blown, cut, and flameworked, among other techniques—makes it a highly appealing medium to artists today as it was to crafters in antiquity.

But since the latter part of the 19th century, glass found many uses beyond the artistic realm. Its structural strength and chemical versatility provided incentive to study glass and its properties through a scientific framework and to inculcate the term *glass science*. Through precise chemical modifications, common silicate glasses are enhanced and transformed to serve in a wide array of applications, from float glass panes used in building construction to mass-produced drink bottles to tactile devices used in today's cell phones and electronic screens. But the multitude of structure-property relationships in glass leaves much still to study, so glass science continues to be a prolific field with impact both ordinary and revolutionary.

After centuries of both artistic and scientific advancement, we notice a paradigm shift in today's world: the divergence of glass into glass art and glass science.

Glass art and glass science: A recent dichotomy

The divergence between glass art and glass science is interesting because society excels in working with glass as an artistic medium and as an engineering material—we can look easily to numerous glass sculptures and patents generated over the recent century as testimony. Yet, broadly defined, modern glass art and glass science are approached by many glass makers and researchers as dichotomies of the same material study.

Many glass artists discerningly select glass frits in a spectrum of colors and opacity, with less interest in the composition control of

Figure 1. Modern glass mosaic. Chris Wood's *Light Wall* at the National Convention and Exhibition Center in Taipei, Taiwan. Over 2,500 large "fins" made of glass and dichroic film are installed along the perimeter of the top floor. Done in collaboration with Hu's Art in 2019. From artist's website, with permission.[4]

Credit: Chris Wood

additive elements that made their creative palette. On the other hand, many glass scientists in their experiments narrow their focus on a single material parameter to control for a specific predetermined purpose, indifferent to or unaware of potential array of corollary applications that would delight the glass artist.

This dichotomy was not always the status quo and, indeed, only appeared relatively recently. At the end of the Renaissance period, i.e., Europe in the 1600s, glassworking was the domain of trained artisans engaged in the apprentice-journeyman-master craft structure and rarely documented on paper. In 1612, Florentine glassmaker, alchemist, and Catholic priest Antonio Neri published *L'Arte Vetraria (The Art of Glass)*, revealing in detail previously unwritten procedures for artistic and functional glass formulation we now attribute to Renaissance art.[2]

L'Arte Vetraria is more than a field manual of medieval glass how-tos; it is a detailed record of Neri's experiments and results in formulating glass—not unlike a lab notebook in research today. He was neither decisively glass artist nor glass scientist and yet, over 400 years ago, Neri created glass with the discipline of both. In Neri's time, glassworkers applied skill as well as an aesthetic flourish, much like today's artists. It also suggests a rigorous practical component, as well as a scholar-like intuition for formulation details, much like today's scientists.

We suggest that, by today's dichotomous view, Renaissance glassblowers all the way to their predecessors in antiquity were both glass artists and glass scientists. As to the present dichotomy, we might suppose that the invention of borosilicate glass by Otto Schott cemented the role of the material not merely as decorative luxury but as a means to technology and industry and furthermore to a scientific field of its own: the eventual conception of glass science.[3]

To help bridge this perceived dichotomy of fields, in this work we feature pieces from several exemplary contemporary glass artists with special focus on interplaying scientific concepts.

Glass optics and *Light Wall*

Discussions of glass art often bring up the archetypal example of stained-glass windows in churches. Looking up at such stunning mosaics fills people with wonder—one persistently imprinted on our aesthetics since the Middle Ages, when crafters first used colored glass for this purpose. It affirms perhaps the most beloved property of glass in art: how beautifully light shines through the material. It is an essential quality that modern glass artists, such as Chris Wood (United Kingdom), continue to harness and elevate in their work today.

Visitors to Taiwan's National Convention and Exhibition Center can appreciate how Chris Wood harnesses light in his piece *Light Wall*, a large-scale installation spanning the perimeter of the building's top floor (Figure 1).[4] For this work, Wood arranged the placement of over 2,500 glass panels (affixed with dichroic film) that, together with ambient light, inspire moments of optical beauty with its surroundings. The result is a dynamic work of art that is constantly in movement, as sunlight is refracted in contrasting flickers of color: every moment brings an effervescence of chromatic beauty.

This visual pleasure is accomplished by optics, the physics governing light interaction with a material. What makes glass appealing, scientifically and artistically, is how easy it is to modify any desired optical property, such as reflection, transmission, and refraction. For example, color in glass can be created several ways, such as dissolution of transition metal ions into molten glass and precipitation of nanoparticles of gold, silver, and semiconducting chalcogenides. Each technique alters the range of wavelengths (colors) transmitted and absorbed. When natural light, which consists of not one but many colors (the visible spectrum of wavelengths), interacts with colored glass, the light is split into its different wavelengths

Figure 2. Flavie Audi's *Fluid Rocks* Series. (a) *Fluid Rock 26*, 2017, glass with fine gold; (b) *Fluid Rock 6*, 2016, glass with fine gold and silver. From artist's website, with permission.[5]

and provides unique ranges of hue and saturation. In this way optics makes an impressive artistic palette, in the very literal sense of the word, because artists have all the colors of the rainbow at their disposal.

Supercooled fluids and *Fluid Rocks*

Glass is a peculiar material, in its ability to appear fluid and yet firm and unyielding to the touch. Artist Flavie Audi plays with this paradoxical property in her series *Fluid Rocks* (Figure 2).[5] Each stone in *Fluid Rocks* artfully portrays glass as a noncrystalline "liquid-like" material, in the scientific definition as well as an aesthetic description.

From a materials science standpoint, a substance is noncrystalline when its atomic structure does not exhibit long-range order, in contrast to highly-ordered crystalline solids. Consider the simplest glass former, silicon dioxide (SiO_2), as an example. In its crystalline solid form, the bonding around every silicon atom is uniformly tetrahedral with an oxygen atom at the vertices, and periodic ordering of Si-O bonds is observed throughout the structure. As crystalline SiO_2 is heated close to its melting temperature, Si-O bonds that were previously rigid increasingly stretch and bend with disorder until it reaches beyond the melting point, where the arrangement of silicon and oxygen bonding is no longer uniform, and the structure thus loses the long-range order present in its crystalline phase. This disordered liquid configuration can be suspended in the material by supercooling, i.e., rapidly cooling the melt below its melting temperature (also its crystallization temperature), such that the disordered Si-O bonds become "frozen-in" and rigid at the lower temperature. The resulting solid-like material has a structural configuration that is like a liquid with no discernable long-range ordering.

Glass artists like Flavie Audi understand the "freezing-in" phenomenon in glass exceptionally well—they see it during glassblowing. Consider, for example, soda lime silicate, a common glass type. It has a liquidus temperature of 1,050°C and a glass transition temperature—the temperature where the transformation between liquid and glass is observed—of 570°C. Glassblowing this material involves melting sand inside a batch furnace at 1,100°C, at which point it is entirely liquid; it is then gathered, becomes glassy, flash-heated, and worked as it cools completely to a rock-like shape. Audi elaborates in an email that each piece in *Fluid Rocks* illustrates this process by "[appearing] like apparitions of the original form, returning to a rock-like physicality through a process of transformative material states; once rock, becoming sand into glass, appearing as rock once again."[6]

While individual glass artists may or may not know exactly the glass transition temperature of their creative medium (a value which varies based on numerous other factors), they are acutely and instinctively aware that glassworking affords a very hot, very narrow time window to do their work. Therefore, it would be categorically wrong to imply that a glass artist does not use glass science, but generally glass artists are disentangled from the myriad technicalities and terminologies of "supercooled liquids," "configurational entropy," "frustrated crystallization," and more that glass scientists routinely address in their study of the material.

Iridescent films: Kayleigh Young and cellulose nanocrystals

As previously suggested, an important aspect in appreciating glass art is through its interaction with light, i.e., its optical behavior. In the previous examples, this interaction mainly involved some wavelengths of light being absorbed (as light passes through glass, at the near-surface or in bulk) and refracted. Iridescence refers to the appearance of a surface to change color based on viewing angle or angle of incident light, a phenomenon that Kayleigh Young (West Midlands, U.K.) showcases in many of her works.

In Young's glass pieces (Figure 3), the striking iridescent shine plays with the viewer.[7] The glistening sheen of purples, blues, and greens that reflect off these sculptures can impel a second glance of disbelief and curiosity.

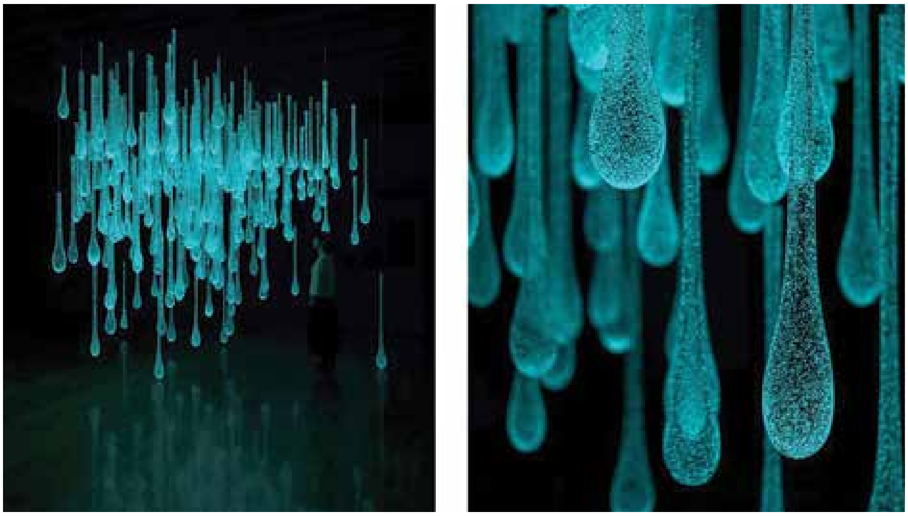
Iridescence in Young's glass art is due to light reflecting off metals on the glass surface. Silicate glasses and metals are materially totally distinct, as they have

Figure 3. Kayleigh Young's artwork catches the eye with beautiful metallic finish. The use of a chemical mixture sprayed onto a piece then placed into a reducing atmosphere allows these shimmering colors to be brought to life. From artist's website, with permission.[7]

different chemical bonding types. These metals are incorporated in the sculpture during the glassblowing process, slightly tweaked from a standard procedure to ensure the thin film dispersed on the surface imparts the desired iridescence. To finish the piece with a thin film exterior, Young sprays her shaped piece with a stannous chloride (or tin (II) chloride, $SnCl_2$) solution. Then the piece undergoes heat treatment in a reducing atmosphere. This process chemically reduces much of the tin to its metallic state, together with some transparent SnO_2 on the surface. Ultimately, the combination of transparent thin films of SnO_2 with an underlying metallic tin layer on the surface gives the piece its iridescent and reflecting qualities and the varying colors apparent with different viewing angles.

Glass research more rigorously explores the property of iridescence, such as one study at the University of British Columbia. Scientists there fabricated iridescent glass films that reflect certain wavelengths (such as visible, infrared, or ultraviolet) by tuning the shape and length of pores within the material.[8] This tuning is achieved by mixing nanocrystals of cellulose (a versatile natural polymer commonly extracted from wood pulp) with a silica former in an initially wet mixture that is then dried.[8,9] Cellulose nanocrystals in the wet mixture tends to arrange into a helical (chiral nematic phase) structure, which can suspend with long-range order configuration as the mixture dries in a glass transition-like process.[9] After drying, the samples are heated to burn off (pyrolize) the cellulose leaving helical pores in the silica microstructure.

The apparent iridescence of these films is due to their reported submicron pitch measurement and has a potential (photonics band gap) for novel optical uses.[8] That is, this nanocrystal cellulose-silica system iridizes due to Bragg reflection of visible light, which is possible only if 1) the helical pitch measurement is on the order of hundreds of nanometers and 2) incident light occurs along, not normal to, the helix structural axis.[9] This seemingly simple condition in practice challenges with experimental constraints and questions for tuning



Credit: Rui Sasaki, Corning Museum of Glass

Figure 4. *Liquid Sunshine / I am a Pluviophile*, Rui Sasaki, Japan, Kanazawa, Ishikawa, 2018. Blown glass with phosphorescent material, broad spectrum UV lights, motion detector. 33rd Rakow Commission. Photo by Yasushi Ichikawa. From Corning Museum of Glass website, with artist permission.[10]

the process, including phenomenological explanations, relevant kinetic parameters, and considerations of best characterization methods.[9] Fortunately, this domain of experiments-and-results and sometimes-contradictions galvanizes scientific growth and drives the artist toward a deeper appreciation for the complex properties of the material.

Photosensitivity: Rui Sasaki and Don Stookey

In addition to the well-known optical properties on display in glass art, other properties can be showcased as well, such as phosphorescence.

Phosphorescence describes light emitted by a material without combustion or perceptible heat. The glass installation *Liquid Sunshine/I am a Pluviophile* (a Rakow Commission piece for Corning Museum of Glass) by Rui Sasaki (Japan) harnesses this property to create a truly interactive experience (Figure 4).

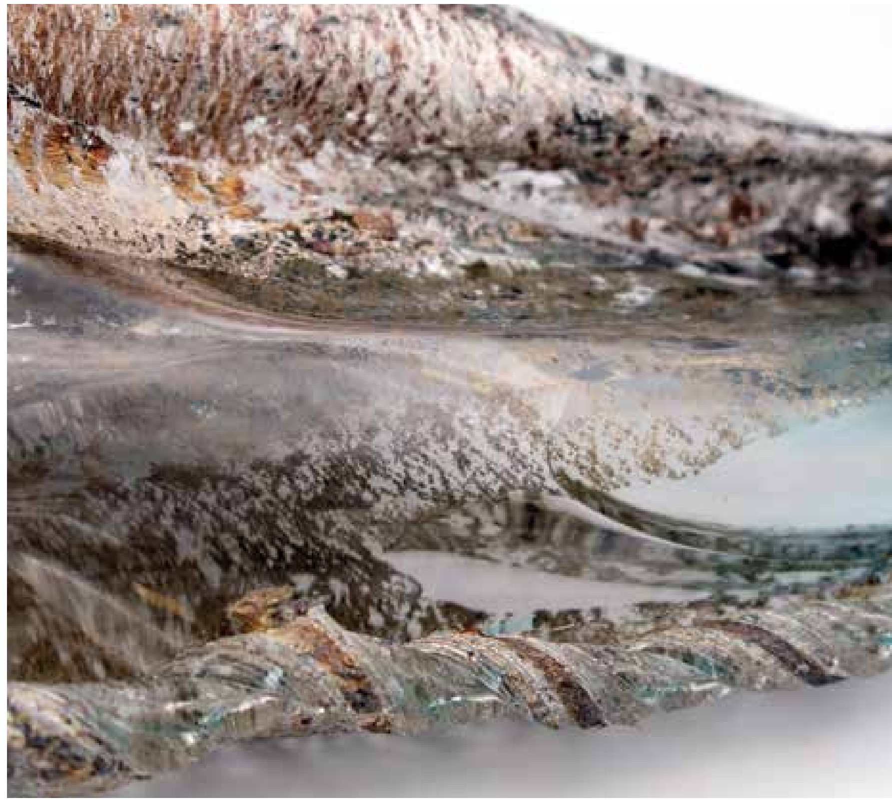
Sasaki's installation designs a small reality where the weather forecast is simultaneously sunny and rainy, bright and dark. Visitors step into a room to observe her glassblown "raindrops," each about 3 inches in diameter and 4 inches long. The over 200 droplets hang like stalactites in a roughly 13 square-foot area, in a room equipped with a motion sensor.[10,11]

The raindrops contain crystalline phosphorescent sand-sized grains of europium-doped strontium aluminate, which Sasaki incorporated into the glass during the glassblowing process. When the room lights with an invisible UV component are on, the raindrops absorb this surrounding light, which excites the phosphorescent materials into a higher-energy state. When visitors enter and the room goes dark, the raindrops release the absorbed energy as light and relax back into their favored low-energy state. The emitted light outlines the raindrops' shapes for a few minutes before fading, leaving the viewer in darkness.[11]

Sasaki infused this subtle light into exaggerated raindrops in reference to the showery weather of her hometown, projecting that the constant precipitation would not be so unappreciated if sunshine can also be recorded in drops.[11] These large, glass-blown, candescent raindrops convey the metaphors in the artist's message: changes in weather and seasons greatly affecting us all, the stark capture of something shining when the lights go out, the persistent promise of sunshine after rain, and the feeling of peace in the dark amidst the lambent raindrops.[11]

Phosphorescence is a subset of photosensitivity. Photosensitive glasses are important for a wide variety of commercial and research applications today, including construction of buildings, electronics fabrication, and consumer eyeglasses, to name a few.

Glass scientist S. Donald Stookey pioneered research on photosensitive glasses,



Credit: Jane Cook

Figure 5. Glass elementals in Vermaids by Jane Cook. Blown soda lime silicate glass with incorporation of aluminum foil and copper blue glass. Image courtesy of artist.

producing colors and effects caused by selection and tuning of elements precipitating out or changing redox states. Stookey invented various forms of photosensitive glasses, from copper and gold ruby glasses to photosensitive opalescent glasses. It is understood that sufficient amounts of oxidized metal (e.g., copper, gold) in the presence of tin and antimony oxides in the glass can reduce upon heating and impart color to the glass.[12] Stookey's photosensitive glasses remained transparent after this heating, yet the ruby effect could be precisely tuned with heat treatment and subsequent exposure to UV light. Masking areas of the glass during UV exposure limits development of the ruby effect to only the unmasked areas.[12]

Studies of this controlled process led to Stookey's invention of his first commercial success—Fotalite—in 1949, wherein cerium oxide in gold- and silver-containing glasses created nucleation sites (after heat treatment and UV exposure) for large NaF crystal growth, which was then used in industrial lighting applications.[12, 13] A prolific scientist, Stookey's later discoveries of glass-ceramics and Fotoceram also carved new pathways and applications for glass research.[3]

Jane Cook and glass expression

For any of its widespread applications, including art and science, it is highly critical to have stable glass recipes, i.e., pieces that remain functional and durable within utility specifications. And in order to create stable glass, an optimal combination of network formers (the chemicals composing the structural backbone of the network) and network modifiers (property enhancers) must be selected.

Silicate glasses comprise a predominant network of tetrahedral Si-O bonding, with elemental additives randomly situated within this network that can be engineered for certain material properties (e.g., metals and oxides to modify optics, ions to increase toughness, dopant elements to deter crystallization). A combination of covalent and ionic bonds joins this network together, stabilizing the glass throughout.

Working with glass (technically or otherwise) demands balancing contraposing physical principles: of crystallization versus noncrystallization, of highly rigid to highly fluid behavior, of heating and cooling, of oxidized then reduced states, just to name a few. Glass scientists hold this knowledge explicitly. We emphasize that glass artists also subscribe to this knowledge, perhaps with less precision but with no less empiricism, with their own creations to testify.

Vermaids, a sculpture by artist-scientist Jane Cook (Pennsylvania, U.S.), demonstrates the balance (Figure 5).[14] A piece made with copper blue glass and aluminum foil on and in transparent soda lime glass, *Vermaids* connects these counterbalances into a cycle of mending and disruption—of the glass shape as well as structural composition—in the glassblowing process.

When describing the process of *Vermaids*, Cook says she considers the glass "personality" as inhabited by its "elementals" (i.e., creatures inhabiting and made of molten glass).[14] As she works her piece, these elementals require sometimes coaxing, sometimes soothing, sometimes mediating between each other—each translating to a different handling technique. At the end of this process, Cook allows the glass to present as-is, to flow and harden and express itself as its captured form outside of the "melting pot" (batch furnace) suspended into finished *Vermaids*.

While this anthropomorphizing of glass reveals her artistic liberty with the material, Cook's materials science expertise guides her artistic creations. A glass scientist herself (she helped develop the glass in flat screen displays, cell phone screens, and more), Cook recognizes familiar glass processing challenges in her glass elementals in *Vermaids*, albeit with more scientific nomenclature.

For instance, Cook anticipates the general mismatch of bonding types between the silicate glass network and pure metal that leads to other mismatches, such as the coefficient of thermal expansion. As she picks up and rolls aluminum foil to incorporate it into hot glass, Cook is aware the pure metal disrupts the surface of her glass and generates a multilayer metal/metal oxide/glass interface, a sandwich of clashing thermal, chemical, and mechanical properties that alters the behavior of her workpiece. Copper ions present in the glass impart color dependent on oxidation state (Cook notes that the appearance of blue corresponds to its nominally +2 state and red to its metallic 0 state). Cognizant that the metals copper and aluminum can alloy with each other in a manner they do not with glass, Cook consults a Cu-Al binary phase diagram when preparing works like *Vermaids*.

Using her scientific savvy, Cook reins in glass properties, interfaces, and "elementals" with persuading approaches of twisting, pulling, and heating while still allowing the material to represent itself in its own way of cooling and remembering in *Vermaids*.

Conclusions

The field of glass has advanced considerably over millennia since ancient Mesopotamia and the centuries since the Middle Ages. From inventing and engineering sophisticated properties in glass to effortless infusion of color, iridescence, and phosphorescence in art, the tools we now possess to work and create with glass are impressive. Still, it is interesting that today this glass knowledge is too often further split into glass art and glass science.

Using glass science concepts (such as iridizing films, phosphorescent ceramics, and metallic coatings and inclusions), glass artists create masterpieces that not only inspire awe but also express the material behavior of their chosen media. This spotlight on glass and its technical properties is also fundamental to the work of glass scientists and drives them also to create functional and often aesthetic new glasses.

Glass art and glass science complement each other in theory and utility. Coalescing glass art and glass science is a celebration of glass. Glass art celebrates the material—its apparent utility and behavior—while glass science celebrates its accompanying knowledge—its potential applications and answers to empirical questions. Regardless of the origin of this dichotomy, glass art and glass science are very much coterminous.

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