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Future of optical glass education

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Abstract: In homage to the United Nations International Year of Glass 2022 (IYoG 2022), this article discusses the past, present, and future of glass education, with a focus on inorganic systems of value to optical and photonic applications.

1. Introduction

It is hard to imagine that over 150 years have passed since Ernst Abbe, Otto Schott (and Adolph Winkelmann), and Carl Zeiss first started laying the foundation for the glass science and engineering that is taken much for granted today [1]. A more recent, but now a decade old example depicting the *future of glass* was reported by Corning Incorporated in their (then) futuristic '***A Day Made of Glass'*** video [2], which conceptualized how 'highly engineered glass technology could deliver extraordinary benefits to everyday products'. While developed to highlight the challenges towards functional attributes of glass for the future, the Corning video also illuminates the exciting areas where new capabilities could be realized through tailoring of glass chemistry, properties, and manufacturing methodologies while keeping an eye towards aspects of sustainability, as container/flat silicate glasses are up to 100% recyclable. Many of the illustrated examples depicted glass' optical functionality while also pointing to its robust thermal and mechanical attributes quietly required to keep those optical functions intact.

In a series of subsequent papers, Corning and others summarized trends in glass research and, importantly, also described the present and future skills needed (from their perspective) for continued innovation in glass [3–9]. While representing the interests of but one, albeit major employer of graduates having experience in optical glass, the findings were broadly applicable across technical disciplines and geography. Such an articulation of workforce needs drives educators to envision those future skills, and the means to impart them, in the quest to support the growth opportunities in optics and photonics, as detailed by multiple US National Academy studies [10,11] that are dominantly reliant on glass.

Efforts to attract and excite students towards the study of glass science and engineering, as a prelude to a career which encapsulates the endless possibilities of this unique material, have always showcased the ubiquity of glass in Society and its endless possibilities for tailoring properties and performance towards future needs. This general approach remains true to this day, the vehicles for delivery of glass science and engineering education are changing. This article aims to highlight what the authors see as the future of optical glass education.

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2. Past and present of glass education

Before discussing present and future opportunities for glass science and engineering education, let us define what it means by "glass" in the context of this broader discussion. "Glass" is neither a single material nor a single-use material. While this statement might seem sufficiently known to be unnecessary, the authors can assure the reader that it needs to be stated since many scientists, especially in optics and photonics who use glass regularly, tend to believe that all "glass" is silica (or a silicate, defined as a high silica-content glass) and that its singular attribute is that one can see through it [12]. While on this topic of glass misconceptions, no, cathedral windows do not flow [13,14].

It is true that a great many commercial glass products, ranging from architectural windows to optical fibers, are silica-based and base much of their utility on transparency, glass is much more. One can argue that glass is itself a state of matter: typically considered a subset of solids but possessing the frozen-in structure of a liquid. Indeed, many of the original definitions of glass related to how it was made, e.g., "a solid cooled from the melt without crystallizing" was a common definition when the authors were students. Today, of course, there are many ways of obtaining a glass that do not involve melting (sputtering, sol-gel, chemical vapor deposition, etc.) and, so, glass is better defined in terms of structure and property: a non-crystalline (x-ray amorphous) solid which exhibits a glass transition, though more nuanced definitions have been proposed [15]. The "glass transition" is a temperature where the material transitions on heating from an elastic solid to a supercooled, visco-plastic liquid or vice versa on cooling; see Fig. 1. Unlike the well-defined melting point of a crystalline material, the glass transition is not a single temperature for a given composition but, instead, is a range of temperature which depends on cooling rate, i.e., glass is a kinetic creature.

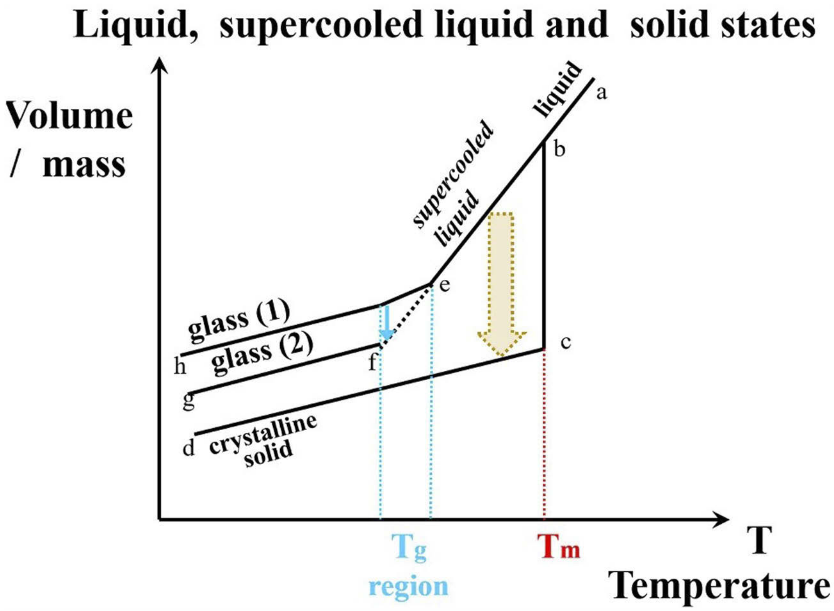


Fig. 1. Representative schematic of volume per unit mass (reciprocal density) versus temperature, showing the relationship between the glass, supercooled liquid, lying between the glass transition (T_g) and the liquidus (T_m), true thermodynamically stable liquid (above T_m) and crystalline states. Shaping of the supercooled liquid between T_g and T_m is retained in the glass cooled to ambient temperature. Note the material is defined as a glass below T_g (adapted from [16]).

Because glass is non-crystalline, it is not bound by stoichiometric demands on its composition. This, coupled with a continuously varying viscosity with temperature above the glass transition, means that glass possesses near infinite compositional and processing (shaping) possibilities. Further, since composition defines physiochemical, mechanical, thermal, and optical (!) properties, glass possesses equally broad functionalities. Glass is both beauty and eminently functional. A class of materials millennia old but each day being more deeply understood and practically applied. All the more reason that continued excitement exists for its study.

Turning now to glass education, it is illustrative to begin with its history as an underpinning for its future. Here, "education" will refer to formal, i.e., university-level, instruction and courses of study and not delve into the millennia-long history of training through apprenticeships, e.g., to glass-line operative, glassblower or gaffer.

As noted, the dawn of glass science begins with Abbe, Schott, and Winkelmann developing glasses and lenses for Zeiss' microscopes [1,17–22], so it is unsurprising that formal instruction followed relatively soon thereafter. To the best of the author's knowledge, the first University department in the world to study glass was established in 1915 at the University of Sheffield (England) under the guidance of Prof. W. E. S. Turner; see Fig. 2. Sheffield's "Department of Glass Technology" was well-aligned with the needs of the British glass industry, which largely was based around local coalfields, fuel to run glass furnaces, and was primarily focused on addressing raw material shortages for glassmaking during the 1st World War [23]. The establishment of academic programs often drives the establishment of associated professional societies. Here, after founding the Department of Glass Technology at the University of Sheffield in 1915, Prof. Turner establishes the *Society of Glass Technology* in 1916. Similarly, the *American Ceramic Society*, founded in 1898, established a *Glass Division* in 1930 in response to growth in the industry and in academic glass programs. That Glass Division is now the *Glass and Optical Materials Division*, a clear indication of the mutually enabling roles of glass and light in modern Society.

Fig. 2. A glass mosaic map at the Turner Museum of Glass at the University of Sheffield, UK, which shows important glass-making centers throughout the world [24]. Reproduced with permission from the Turner Museum of Glass (University of Sheffield).

Elsewhere, before and after, glass is being taught in ceramic science and engineering programs, which are often where glass science has been taught historically. Glass under the umbrella of ceramics (inorganic, crystalline, nonmetallic materials) in the US begins at the Ohio State University (1896, though their first course in ceramic engineering was offered in 1894 [25,26]), and thence Alfred University (1900), Rutgers University (1902), the University of Illinois (1905), Iowa State University (1906), Oregon State University (1914), the University of Washington (1918), and the University of Saskatchewan (1921), to name the first programs to be (or would have been) a century old.

Just as the history of glass education varies across the globe, so does the depth and breadth of its instruction. By the 1960s to 1980s, the undergraduate and postgraduate teaching on glass was based on physics (e.g., optics, lens-design by numerical calculation, performed, of course, by hand), chemistry (e.g., glass chemical durability, glass formulations and analysis, and chemistry of glass melting), and physical chemistry (e.g., studies of the glass transition, permanent and temporary glass stress, glass chemical and physical toughening, glass ceramics). For example, at the University of Sheffield, each of these topics had its own 10-lecture course.

Now, more typically, glass is a single course offered within a traditional materials science and engineering or chemistry curriculum. Modules or lectures usually evaluate theory and experimental methods related to glass formation rules and composition-structure-property relationships for mostly inorganic glasses. While the definition for glass noted applied is equally applicable to organic (polymeric) or metallic (e.g., spin) glasses, the inorganic oxide or non-oxide families of glasses typically form the basis of most optical components. Such components can take on a wide variety of forms, ranging from bulk free-space optics (i.e., telescope mirror blanks to micro-lenses) to thin films (as anti-reflective coatings or filters and gratings) to fibers (that can be traditional core-clad, hollow core or filled with all sorts of other phases). Today, in-depth glass instruction resides solely in postgraduate courses on advanced materials.

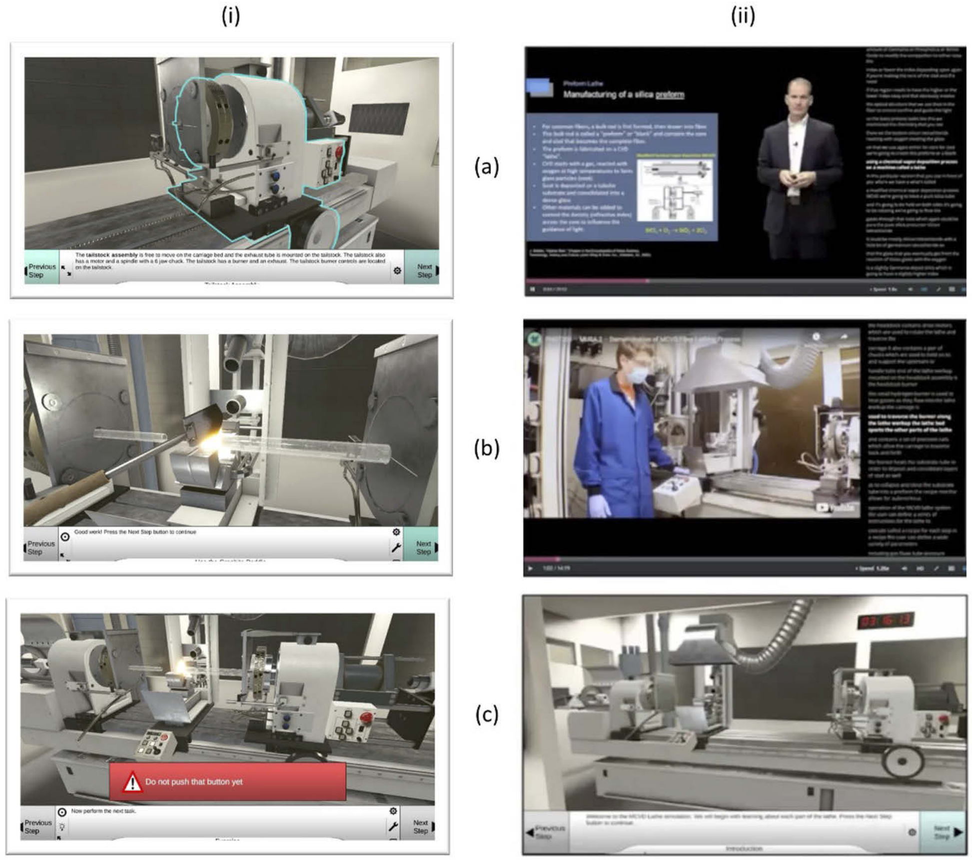
A subset of the educational and research activities in glass science revolves around optical and photonic glasses. As this is a naturally cross-disciplinary topic, cohorts often involve students from chemistry, physics, optics, materials science and other engineering majors. Such cohorts, however, come from very different educational backgrounds often making instruction in optical glass (optical materials broadly) challenging. The Sections that follow provide insights into potential ways to create excitement that drives learning in ways that bridges complementary disciplines and affords access.

3. Future of glass science education

Today, new digital information technologies are poised to enhance and transform this pedagogical paradigm both in delivery and content. A prime example here are Massive Open Online Courses (MOOCs). An increasing number of educational institutions are introducing MOOCs to supplement or expand their curriculum [27] that also facilitates unconventional blended learning models such as "flipped classroom" [28]. Another potentially transformative technology is augmented/virtual reality (AR/VR), providing direct visualization and an interactive environment to help learners understand complex engineering designs or processes [29]. It is interesting to note that these technological innovations owe their existence to glass materials as well, with examples ranging from optical fibers enabling high-speed internet to holographic glass waveguides widely used in AR/VR displays.

Adapting these technologies to glass science education presents unique opportunities and challenges. While over 10,000 MOOCs are now available on platforms such as edX, Coursera, FutureLearn, Udacity, etc. and synchronous web-based topical short courses (e.g., on machine learning in glass engineering [30]) have been offered, we have not identified any MOOC dedicated to general glass science, other than online course material repositories [31]. This leaves an open gap yet to be filled. We note that the International Commission on Glass (ICG) has already established a tradition of hosting annual summer and winter schools on glass science – an international collaborative effort which has been continuing for over a decade [32]. Given the extensive breadth of modern glass science and technology, the development of MOOCs tailored for glass education will also benefit from a concerted initiative engaging the global glass research and education communities.

In addition to augmenting traditional classroom education, these new technologies further contribute to democratizing access to educational resources and expanding workforce training. This is of particular relevance to glass science education, since only a small fraction of universities offer classes focusing on glass materials, and even fewer of them can afford to house a full-fledged glass laboratory. MOOCs and virtual laboratories can help fill this gap by providing a scalable approach to workforce education and to reach a broad international audience. To name a particularly relevant example, AIM Photonics Academy (the education initiative of AIM Photonics, a Manufacturing USA Institute) has partnered with several US universities to roll out a series of synergistic MOOCs and interactive 3-D virtual laboratory modules to enable self-directed learning for the photonics workforce [33–36], which encompass several modules focusing on manufacturing of glass optical fibers; for example, see Fig. 3. A similar platform dedicated to glasses will broaden access to glass science education at a global scale.



The **tailstock assembly** is free to move on the carriage bed and the exhaust tube is mounted on the tailstock. The tailstock also has a motor and a spindle with a 6 jaw chuck. The tailstock has a burner and an exhaust. The tailstock burner controls are located on the tailstock.

Good work! Press the Next Step button to continue

Do not push that button yet

Now perform the next task.

Fig. 3. Column (i): Examples of MCVD (modified chemical vapor deposition) lathe desktop virtual reality (VR) simulation exercises: (a) terminology, (b) guided practice, and (c) open practice. Column (ii): Examples of 3-D virtual laboratory modules to enable self-directed learning: (a) lectures, (b) lecture and process, and (c) lecture and VR simulation.

The versatility and utility of glass has enabled its use in a wider and wider range of modern applications. However, this good fortune comes with a variety of equally heady issues, one being that the near-limitless possibilities for glass compositions that would conventionally need to be made, tested, and understood for a given purpose or theory. Despite millennia of glass making, nearly 150 years of "glass science" driving discovery and understanding, only a small fraction of possible compositions has been investigated. Glass development historically is an experimental exercise, meaning it is time consuming, costly, and sadly inefficient, all leading to a slow process in the development of novel glasses and glass processes.

Accurate physics-based modeling and atomistic simulation techniques have been used to predict the relation between glass composition and its properties [37–39]. However, these techniques come with their own challenges since the kinetic aspects of glass make them especially complex to model. Thus, the glass community has been moving slowly towards the use of artificial intelligence (AI) and machine learning (ML) approaches to predict glass properties. While in AI, machines perform actions based on stimuli, these tasks are usually without the added inputs associated with ML. ML includes, for example, regression algorithms used to predict properties as a function of glass composition. ML can be also used to label glasses within various categories (classification algorithms). Several recent studies that are instructive example of applying AI and ML to glass science include neural networks for 9 glass properties with up to 34 elements that has been developed through PyGGi Seer [40]. Using SciGlass database licensed under the ODC Open Database License (OdbL), *Cassar*, et al successfully predicted glass composition with desired properties such as glass transition temperature by combining data-driven predictive models and genetic algorithm [41]. Parameters such as Young Modulus [42] and viscosity [43], for example, were also successfully predicted. *Blanchard-Dionne*, et al., demonstrated an improvement of a factor of 20 in the prediction of the spectral response of an optical system from a neural network which integrates harmonic oscillator equations [44]. The inputs were the grating's parameters such as the period d and the slit width and the outputs the real and imaginary part of the transmission coefficient (Fig. 4). Finally, one should not forget the success in the development of the well-known Corning Gorilla glasses, which were obtained using ML. For a broader review of this topic, see also Ref. [39].

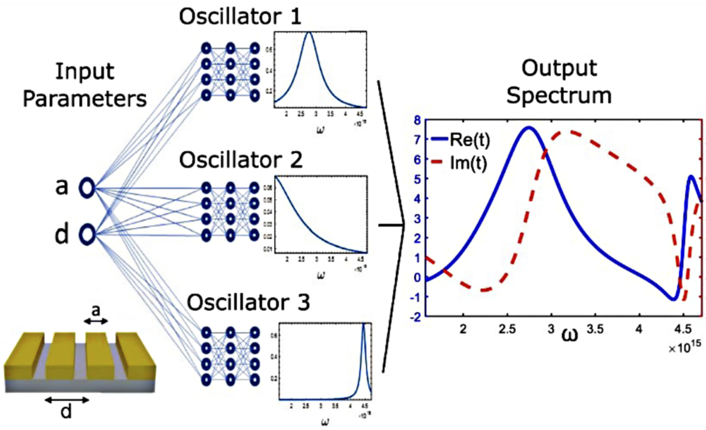


Fig. 4. Schematic of a neural network approach to Lachie learning of optics. Reprinted with permission from [44] © Optica.

AI and ML approaches are now of great interest for industrial production, as noted in [45]. They have been used for automated scheduling of activities and for manufacturing. For example, AI can monitor and tune process parameters such as temperature of the furnaces reducing the energy and cost related to the fabrication of glass. AI also can be trained to detect flaws automatically allowing the optimization of the production line. ML approaches can monitor production equipment and predict accidents which can strongly impact productivity. CFD (computer fluid dynamics) modelling of glass-melt flow predicts the geometry of co-extrudates [46], with potential for wider glass-processing applicability.

Although Al and ML approaches offer the opportunity to speed the development of novel glasses, they face multiples challenges, some of them being discussed in Ref. [43]. AI has been developed to automate the extraction of data from published documents (publications, patents, etc.) allowing the collection of a large quantity of data. However, to be useful, these data need to be accessible, complete, accurate and consistent just to cite a few of the requirements for the AI approach. For example, one of the challenges related to glass science is related to the representation of the glass composition which differs in the published documents depending on the authors (e.g., $Na_2O{\cdot}SiO_2$ versus $50Na_2O{\cdot}50SiO_2$ versus $(Na_2O)_{50}{\cdot}(SiO_2)_{50}$, all of which are compositionally equivalent if molar compositions- but sometimes are stated in weight%). Another example is where latent reactivity takes place such as the formation of $AlPO_4$ in optical fiber when the original glass composition is doped separately with Al_2O_3 and P_2O_5. Glass being a non-equilibrium system is also a challenge, as the final structure of the glass not only depends on the glass composition but also on the synthesis procedure and thermal history. Additionally, some glass properties can vary linearly while others may vary nonlinearly. Thus, an automated and smart system suggesting the best learning algorithm for a given dataset while following the physics of glasses need to further advances, while not, of course, violating the laws of physics and chemistry.

The promising results obtained worldwide have clearly demonstrated that AI and ML approaches can lead to robust prediction of properties as a function of glass composition and to expedite a glasses manufacturing. Efforts should be continued to accelerate the discovery of novel glass compositions with tailored properties. This will be achieved only through closed-loop approach: experiments (synthesis and characterization of glasses including data analysis), theory, and simulations.

4. Conclusions

As Society and technology have advanced over the past millennia, so too has the enabling role of glass. Glass remains a central player in future commercial and industrial products, especially those that are light-based. It then goes without saying that education in optical glass science and engineering must also evolve from more classical forms of classroom and laboratory instruction to take advantage of new tools, such as machine learning, artificial intelligence, and virtual and augmented reality to capture the richness of glass composition, structure, properties, and applications while conveying in a more straight-forward, engaging, and accessible ways.

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Data availability. Data underlying the results presented in this paper are available in the associated References or are available upon reasonable request of the authors.

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