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PERSPECTIVE ARTICLE

Navigating the Future of Separation Science Education: A Perspective

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Abstract
A number of recommendations on how to improve the education and training of separation scientists were recently made by the National Academies of Sciences, Engineering, and Mathematics in their report, *A Research Agenda for Transforming Separation Science*. This perspective outlines how some of these recommendations may be fulfilled by examining trends in potential curriculum topics related to the field and new technological platforms for interactive content delivery. Identifying and adopting the best practices within these emerging educational directions will ensure the future success of the field.

Keywords Separation science · Education · Training · Pedagogy · Analytical chemistry

A Call to Action and an Opportunity for Change

In 2019, the National Academies of Sciences, Engineering, and Medicine (NASEM) published the consensus study report, *A Research Agenda for Transforming Separation Science* [1]. The report summarized the current state of the separation science field in the United States and proposed future research directions that could further advance the discipline [2]. To successfully implement the research agenda, it was recommended that "academic departments should provide high-quality training in separations" to fulfill the demand for separation scientists in a wide variety of industrial sectors [1]. Such training should combine "fundamental understanding and an awareness of the current state of knowledge" and strive to combine traditional analytical chemistry topics with separations-focused engineering curriculum as a first step in enhancing multidisciplinary collaborations [1]. To truly advance the field, expanding course content to include a wider variety of applications and strategies that can be used to design and characterize separation systems will be needed. This could be challenging, as many instructors already find it difficult to cover the existing curricular topics with sufficient detail in a set amount of time, let alone add more.

An unexpected transformative event in education, the COVID-19 pandemic, has provided an opportunity to rethink typical approaches to education that could make curricular re-design more feasible [3]. Although many of the technology platforms that are now common throughout higher education existed before 2020, the rapid pivot to remote learning in March 2020 greatly accelerated their adoption. However, separation science and the wider discipline of chemical analysis are often viewed as laboratory-focused areas that are difficult to fully grasp without hands-on experience. While this may be true, it may be necessary to investigate new ways of replicating that experience in a remote setting.

This perspective focuses on identifying potential future directions of separation science education (primarily at the undergraduate level), especially in areas where the "high-quality training" suggested in [1] may be facilitated by new pedagogical approaches that have recently emerged. Trends in how technology may be applied in separation science education are also discussed. Long-term planning focused on effective training of young scientists, especially with a focus on the needs of the wider scientific community, will ensure the future growth and advancement of chemical separations.

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Curriculum Design Combining Separation Fundamentals with Modern Needs

Most undergraduate chemistry students are introduced to the fundamentals of chromatography and electrophoresis at least once. These topics are usually covered in second-year analytical chemistry and upper-level instrumental analysis courses, although they can also be discussed in biochemistry courses within the context of biomolecular characterization. The idea of describing separation phenomena in the context of specific molecular classes can increase the breadth of separation modes that a student may learn about prior to a specialized, graduate-level course on the topic. Recent calls have been made to increase the coverage of macromolecular separations in the curriculum, both for biomolecules and polymers [4–6]. Because of the greater complexity of these molecules, and the wider variety of separation techniques that can be used to characterize specific properties of the molecules, understanding the nature of both the analyte and the analytical technique becomes especially critical relative to more basic, introductory examples (e.g. separation of a homologous series of alkanes by GC). Collaborating with industry partners to identify relevant analytical challenges, such as biopharmaceutical characterization under native conditions [7] or the analysis of synthetic polymers using hyphenated analytical techniques [8], can provide a framework for fundamental training [6]. Additionally, sample preparation techniques are often neglected, but these concepts play an important role in many analytical workflows. These topics can be used to reinforce fundamental mechanisms in separations, including kinetics, mass transfer, and equilibrium [9]. The NASEM report identifies these areas as core components of graduate-level separations courses in chemistry departments [1], but does not specify specific separation techniques that are required to explain each of them. This provides an opportunity to introduce techniques more commonly used for these macromolecules, including size exclusion chromatography and field-flow fractionation. This broader approach could also be designed to focus on applications that better bridge the analytical and engineering aspects of separation science [10]. Once identified, these examples could then be implemented into an integrated separations curriculum.

Within the context of instrumentation and method design, the core curricula of other disciplines, including electrical engineering and computer science, contain additional content relevant to separation scientists. Understanding the fundamental concepts of circuit design and how they apply to data acquisition and filtering is key to interpreting a transduced signal [11]. Instrument components, such as pneumatic controllers [12] and flame ionization detectors [13] in GC, can best be explained by combining thorough descriptions of the mechanical and electronic hardware with more typical aspects of GC method development. In addition to hardware updates over the years, software code is playing an increasingly large role in experimental design. Separation science is not exempt from this trend. One key area is artificial intelligence (AI)/machine learning (ML), which grows increasingly important in compound library matching, spectral interpretation, data analysis, retention time prediction, and method development [14]. In both instrument control and data processing, teaching the operating factors of a system and avoiding treating components as "black boxes" will ensure future separation scientists can effectively interpret the results of separations-based analyses, no matter how complex they may eventually become.

As curriculum evolves to better reflect the needs of modern separation science, there is an opportunity to increase the focus on diversity, equity, inclusion, and respect (DEIR) within the discipline [15]. Many instructors have updated their courses to focus on diverse scientists who have made important discoveries within a given field [16]. The authors of the widely used Quantitative Chemical Analysis textbook have developed a repository of such examples within analytical chemistry, including a large number of separation scientists [17]. The "DEI in Analytical Chemistry" organization facilitates real-time, virtual discussions where analytical chemists from diverse backgrounds share their work [18]. In terms of specific course concepts, the outcomes of sample measurements can be directly related to social justice. For example, the identification of lead in water samples related to the Flint water crisis can be used to demonstrate equilibrium concepts and heavy metal analysis, while also discussing equity and access in policymaking [19, 20]. Educational training can also be used to help serve communities in need of analytical testing, as students can analyze real-world samples for quality or safety purposes. The distributed pharmaceutical analysis laboratory (DPAL) project focuses on identifying medicine quality using HPLC in samples from low and middle-income countries in collaboration with 30 academic institutions [21]. Relatedly, topics of sustainability and environmental justice [22] can be connected to the reduction of solvent use and power consumption for chromatographic analysis [23], "greener" sample preparation [24], and the use of more environmentally-friendly mobile phases [25–27]. Equity in separation science education should also consider the cost of instrumentation, as this can be a barrier to hands-on learning in locations without access to large instrument budgets. Recently, relatively low-cost commercial ($<$\$3000) [28] and home-built ($<$\$100) [29, 30] GC systems have been reported and could be adopted as alternatives to traditional high-end instrument models. This integration of relevant societal issues with core discipline competencies puts the field in an appropriate context and can demonstrate typically overlooked ways in which chemical analysis connects to many aspects of our lives.

Finally, to keep students engaged during course instruction, active learning approaches that better represent real-world problem-solving using modern analytical techniques can be used to improve learning outcomes [31, 32]. One way to directly connect course topics to modern separation science is to rely upon examples directly from recent primary literature [33–35]. This approach adapts published data sets for mathematical data analysis exercises to directly show how fundamental separations theory can be applied to solve relevant analytical challenges. Rather than relying on single-week laboratory activities, other approaches to hands-on instruction can also be implemented. Shorter experiments can be combined into lecture periods [36]. These shorter experiential projects enable experience with a wider variety of instruments. Course-based research projects driven by students can be adopted to help teach project management, communication, and teamwork skills that are essential to success in today's chemical industry [37]. Student assessment should reflect the importance of these skills, as they are also abilities that will be critical in their future careers [38]. Aligning learning goals with the current needs of industry and leveraging research experiences and internships to give students direct hands-on experience with modern instrumentation can also be beneficial [39]. While the need for students to understand the fundamentals of separation science will not go away, the approaches that are used to introduce these topics can be updated to help improve the quality of training and broaden overall skill sets.

Content Delivery Approaches Utilizing Advanced Technology

As instrumental analysis is commonly taught using hands-on laboratory activities, transitioning to remote learning at the outset of the COVID-19 pandemic required innovative content delivery methods to teach the fundamentals of chemical separations [40]. A recent survey of analytical chemistry instructors found that chromatographic theory, HPLC instrumentation, and GC instrumentation were rated as some of the most important topics in the curriculum (Fig. 1) [41]. In virtual learning environments, hybrid approaches that combine synchronous, real-time instruction with asynchronous, on-demand content access have been widely adopted [42, 43]. However, use of asynchronous delivery to add content to existing material must be carefully balanced with not overloading learners with an ever-expanding set of assignments. In terms of discussions on general theory, students appreciate the flexibility that asynchronous delivery provides [44], which may have additional benefits in increasing equitable access to scientific content delivered at professional conferences [45]. However, for the instruction of laboratory techniques, many students report a desire for hands-on activities to truly master the learning outcomes [46, 47]. One of the simplest approaches to blend remote activity with instrument operation is through the use of online simulators [48]. There are several chromatography-related simulators that are freely available online and can be used for these types of activities [49], including the 'Practical HPLC Simulator' (Fig. 2) [50, 51]. Best practices for adopting these simulators include providing clear instructions for use and assigning activities that encourage exploration of system variables to teach specific topics that would be similarly performed in the lab [52]. Another approach to remote instruction of these techniques is re-designing experiments so that they can safely be performed in non-laboratory settings, including at home [53]. Separations-related examples of this strategy include the separation of dyes in powdered drink mixes [54, 55] and in ink [56]. As many of these activities are relatively low-cost, they can be used for hands-on learning in settings where the purchase of a full instrument may be cost-prohibitive.

In addition to remote activities that mimic instrument operation, developments in additive manufacturing and human–computer interactions have created new opportunities to re-think how students interact with instruments. Low-cost 3D printers can generate replicate instrument components out of plastic, giving students a hands-on model of a part that may typically only be viewed as a static textbook figure [57]. A model of a six-port HPLC injector valve is shown in Fig. 3A. Augmented reality blends interactive digital overlays with real-world locations. In a general example, labels of specific instrument components were overlaid on a real-world chromatograph through a smartphone interface; these labels hyperlink to pages that described the operation of each component (Fig. 3B) [58]. This interaction can be streamlined through the use of smart glasses, which allows hands-free operation and can be utilized during technical training, routine laboratory procedures, and instrument maintenance and troubleshooting [59]. More immersive experiences use virtual reality to take place completely within a digital environment [60] and entire laboratory settings can be recreated using this approach [61]. A completely digital HPLC instrument that can be opened, closed, and partially manipulated in a 3D space can be used for training purposes has also been demonstrated (Fig. 3C) [62]. These interactive platforms provide a unique space between textbook learning and direct instrument operation that could be used to enhance the training of the next generation of separation scientists by combining the positives of each individual approach.

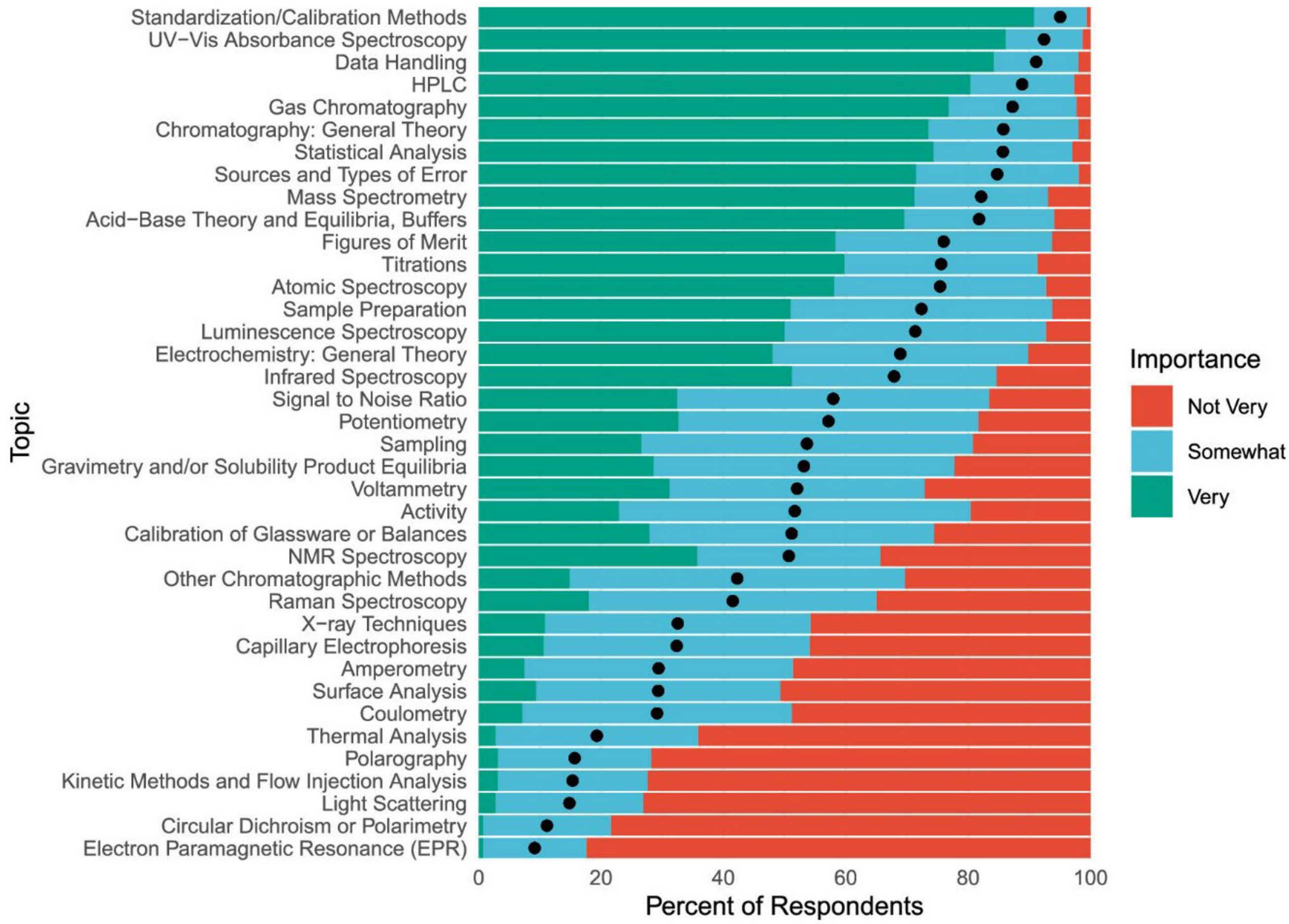

Fig. 1 General results of survey of analytical chemistry instructors on topics covered in their courses organized by average rating of importance. Reprinted with permission from [41] (Copyright 2022 American Chemical Society)

Conclusions

The recommendations in *A Research Agenda for Transforming Separation Science* guide instructors on how the next generation of separation scientists may best be trained for the future of the field. Expanding the applications and molecular classes that can be probed by separations-based analysis, especially if introduced in the context of real-world examples as part of active learning activities, can highlight the importance of these techniques within science and industry. Effectively preparing students for future changes in the field requires introducing instrument circuitry and data analysis topics from electrical engineering and computer science, while discussing the role of chemical separations in social and environmental justice can instill a deeper connection of laboratory work to the general public. As these changes are made, new technological tools like online simulators, augmented reality, and virtual reality will provide new ways of introducing these topics and may revamp how we successfully achieve training-related learning outcomes. This transformation of the field will require extensive effort from many of its members, and there is perhaps no better time to work towards these goals than during this current era of massive change within education.

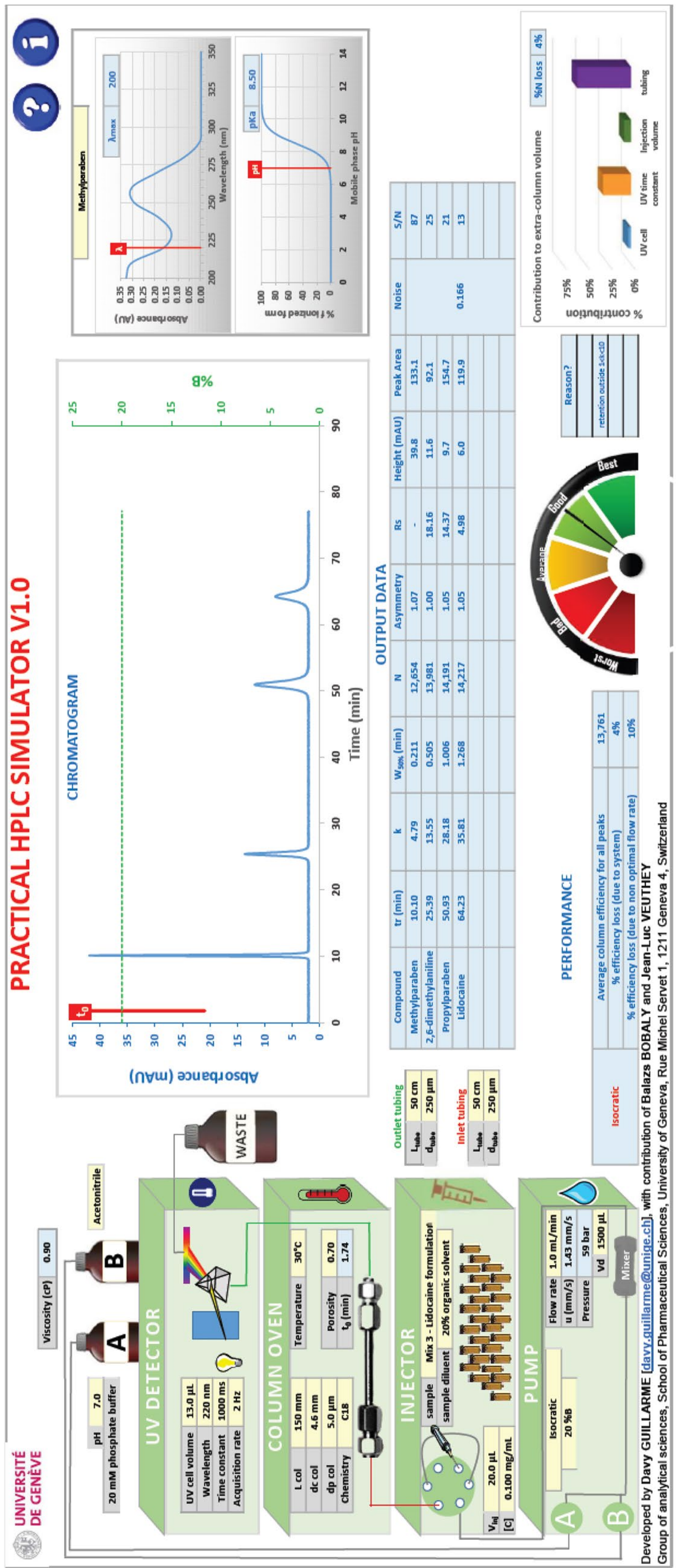

Fig. 2 Primary user interface of the 'Practical HPLC Simulator' program. Adapted from freeware available from [50]

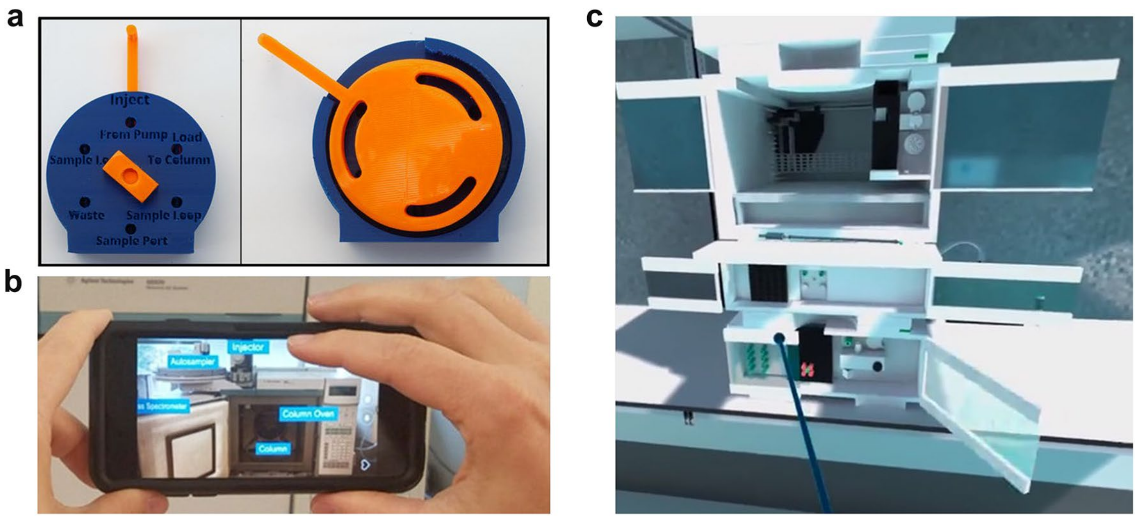

Fig. 3 **A** 3D printed version of an HPLC six-port injection valve. Reprinted with permission from Springer Nature from [57] (Copyright 2021). **B** Augmented reality overlays of instrument component labels on a gas chromatograph. Reprinted with permission from [58] (Copyright 2019 American Chemical Society). **C** Virtual reality digital reconstruction of an HPLC instrument. Reprinted with permission from [62]

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Declarations

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Human and Animal Rights This article does not contain any studies with human participants or animals performed by the author.

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