Reassessing Undergraduate Polymer Chemistry Laboratory Experiments for Virtual Learning Environments

Metin Karayilan,*§ Samantha M. McDonald,§ Alexander J. Bahnick,§ Kacey M. Godwin,§ Yin Mei Chan,§ and Matthew L. Becker*

Cite This: https://doi.org/10.1021/acs.jchemed.1c01259

ABSTRACT: Chemistry laboratory experiments are invaluable to students’ acquisition of necessary synthetic, analytical, and instrumental skills during their undergraduate studies. However, the COVID-19 pandemic rendered face-to-face (f2f), in-person teaching laboratory experiences impossible from late 2019−2020 and forced educators to rapidly develop new solutions to deliver chemistry laboratory education remotely. Unfortunately, achieving learning and teaching objectives to the same caliber of in-person experiments is very difficult through distance learning. To overcome these hurdles, educators have generated many virtual and remote learning options for not only foundational chemistry courses but also laboratory experiments. Although the pandemic challenged high-level chemistry education, it has also created an opportunity for both students and educators to be more cognizant of virtual learning opportunities and their potential benefits within chemistry curriculum. Irrespective of COVID-19, virtual learning techniques, especially virtual lab experiments, can complement f2f laboratories and offer a cost-efficient, safe, and environmentally sustainable alternative to their in-person counterparts. Implementation of virtual and distance learning techniques—including kitchen chemistry and at-home laboratories, prerecorded videos, live-stream video conferencing, digital lab environment, virtual and augmented reality, and others—can provide a wide-ranging venue to teach chemistry laboratories effectively and encourage diversity and inclusivity in the field. Despite their relevance to real-world applications and potential to expand upon fundamental chemical principles, polymer lab experiments are underrepresented in the virtual platform. Polymer chemistry education can help prepare students for industrial and academic positions. The impacts of polymers in our daily life can also promote students’ interests in science and scientific research. Hence, the translation of polymer lab experiments into virtual settings improves the accessibility of polymer chemistry education. Herein, we assess polymer experiments in the emergence of virtual learning environments and provide suggestions for further incorporation of effective polymer teaching and learning techniques into virtual settings.

KEYWORDS: First-Year Undergraduate/General, Second-Year Undergraduate, Upper-Division Undergraduate, Distance Learning/Self Instruction, Internet/Web-Based Learning, Computer-Based Learning, Laboratory Instruction, Organic Chemistry, Polymer Chemistry, Materials Science, Polymerization

1. INTRODUCTION

Laboratory experiments are a crucial component of the undergraduate chemistry curriculum. Currently, face-to-face (f2f) lab experiments are the university standard and most comprehensive way to teach students necessary synthetic methodology, instrumental lab techniques, and relevant safety precautions. However, the COVID-19 pandemic raised significant barriers for implementing these types of technical laboratories. As a result, notable attention shifted toward a new way of learning and teaching chemistry experiment: virtual learning, a topic heavily emphasized in this Journal’s special issue, “Teaching Chemistry in the Time of COVID-19”.

Virtual and remote learning spaces have been documented since the early 1960s but have been largely overlooked until recently. In the wake of the COVID-19 pandemic, there has been a substantial increase in the use of virtual learning techniques and an additional focus on gauging its effectiveness. For example, out of the distance learning papers published in this Journal between the years 1990 and 2021, approximately 38.4% (~185 papers) of the accepted virtual learning manuscripts were produced during the peak of the pandemic in 2020. Numerous new publications on distance learning
learning (~8.5% of the papers published from 1990 through 2021) were generated within the first eight months of 2021. Furthermore, 52.3% of the materials were published between the years of 2010 and 2019, while only 0.8% (four papers) of the total papers were produced in the two decades preceding 2010 (Figure 1). This data shows that the pandemic not only required educators to design new content for online teaching but also increased the awareness and importance of the benefits associated with virtual learning. Additionally, early and extended training in chemistry laboratories (e.g., course-based undergraduate research experiences, CUREs) that elevates student interest and skills in research, such as demonstrating scientific literacy, identifying a research question, designing an experimental plan, analyzing data, and communicating the results, can be accomplished by incorporating virtual learning components into teaching and research.

The pandemic is not the only driving force for enhancing virtual learning opportunities. Other potential issues that may necessitate virtual translation include limited resources (e.g., personnel, chemicals, equipment, lab space), safety concerns, and negative environmental impact. In addition, virtual laboratories can broaden accessibility. For example, students across different grade levels, institutions, and countries can benefit from the same virtual experiments that can be easily performed and reused in subsequent years. Educators can also design diverse virtual experiments to be more inclusive of students with learning disabilities or socioeconomic restrictions. For example, these virtual laboratories can promote greater inclusivity for students and instructors/teaching assistants (TAs) who cannot be in the lab due to physical challenges/disabilities, travel restrictions, health concerns, military deployment, and more. As such, virtual learning can allow for greater flexibility in chemistry laboratories and can foster a more equitable approach to chemical education. Nonetheless, virtual learning efforts assume students have access to certain levels of technology (e.g., a computer and reliable Internet connection) and an environment conducive to online learning (e.g., a quiet place to study). More robust strategies require advanced technology (e.g., virtual/augmented reality equipment and/or a smartphone), which further limits the feasibility of large-scale implementation. Existing electronic lending services and free Wi-Fi availability through universities can bridge this gap; however, particularly in the case of the COVID-19 pandemic, students may not always have access to public spaces and resources. Therefore, this is not a sufficient solution, and greater efforts will need to be made to address remote academic inclusivity.

In addition to these limitations of virtual learning efforts, certain fields have not been reflected enough in the virtual platform. Polymer chemistry laboratories, for example, are underrepresented in the virtual environment despite the fact that polymers are prominent within the chemical industry, manufacturing conglomerate (e.g., cosmetic, petroleum, food, automotive, aerospace, electronics, pharmaceutical, clothing, construction, packaging, and others), and academic research, which results in a growing demand for specialized polymer chemists. Students equipped with synthetic and instrumentation skills relevant to polymers will be better prepared

Figure 1. Breakdown of distance learning papers published in the Journal of Chemical Education between 1990 and 2021. The keywords “Internet/Web-Based Learning” and “Distance Learning/Self Instruction” were identified in papers by year. The 2021 dataset does not include work published after September 2021.

Figure 2. Laboratory experiments published in this Journal between 2010 and 2021 pertaining to polymer chemistry (front, red), organic chemistry (middle, green), and any (back, blue) topics. For the data labeled “Polymer Chemistry Lab Experiments”, the keywords “Polymerization” and “Polymer Chemistry” were identified in Laboratory Experiments or Articles with the keyword “Laboratory Instruction” for each year in data scraped from the Journal of Chemical Education website. For the data labeled “Organic Chemistry Lab Experiments”, the keywords “Synthesis” and “Organic Chemistry” were used. Papers that included both keywords were filtered as to not be counted twice. The 2021 dataset is current to mid-September 2021. Note that the overlap between synthesis and polymer topics was not eliminated.

https://doi.org/10.1021/acs.jchemed.1c01259
for these industrial and academic positions. However, comprehensive polymer chemistry education is often missing in the undergraduate curriculum, and polymer-focused lab experiments are generally not offered in undergraduate studies. Typically, students only get an opportunity to learn about basic principles and some practical applications of polymers when/if they join a research lab working in these areas.13 This matter was brought to attention in this Journal starting in the late 50s,14−16 and the 2015 ACS Guidelines for Bachelor’s Degree Programs recently necessitated the inclusion of polymers, macromolecules, and colloids systems in the undergraduate curriculum for certified degree programs.17,18 Uncoincidentally, this Journal highlighted polymer concepts across the curriculum even before the pandemic in the 2017 special issue.19

Although there has been a considerable effort to digitize aspects of chemistry within the virtual space, there remains an unmet need for polymer chemistry experiments. Compared to organic chemistry publications within this Journal, the number of works covering the topics of polymer chemistry falls considerably short (Figure 2).6 Virtual translations of existing polymer synthesis, characterization, and processing experiments would allow for a great opportunity to fill this gap. Herein, we highlight the strategies applied to distance learning lab experiments and explore their potential utilization for polymer chemistry undergraduate lab experiments in the future. First, we discuss the virtual learning techniques that have been developed for lab experiments prior to and during the pandemic. Then, we assess these techniques to suggest pertinent ways to digitize undergraduate polymer lab experiments.

2. VIRTUAL LEARNING PARADIGM

“Virtual learning” broadly describes a learning process that utilizes technology as a substitute or complement to traditional f2f teaching.20 Under the virtual learning umbrella lies the term “distance/remote learning”, which pertains to the acquisition of knowledge outside of the institutional laboratory setting.8,21,22 The first reports of distance learning in this Journal appeared in the 1960s and described the use of "blackboard by wire" for remote instruction.2,23 Efforts to expand on distance learning continued throughout the 1980s and 1990s, including the development of “Take-Home Challenges” for at-home learning24 and remote lectures via two-way, synchronous audio-video networks.25

The COVID-19 pandemic has driven the need for new and engaging methods to teach chemistry remotely. As evidenced by this Journal’s Special Issue on “Insights Gained While Teaching Chemistry in the Time of COVID-19”, chemistry educators responded admirably to implement virtual teaching into their curricula, especially for lab experiments.1 Presently, we have observed that most approaches for virtual chemistry laboratories fall under the following categories: Kitchen Chemistry and At-Home Laboratories, Video-Based (prerecorded and live-stream), Data Analysis and Computational Chemistry, Digital Lab Environment (DLE), and Virtual Reality (VR) (Figure 3). Regardless of the approach, virtual translations of chemistry wet laboratories can demonstrate significant safety considerations without the risk associated

Figure 3. Virtual lab strategies for chemistry laboratories. Images reprinted with permission from refs 28−33. Copyright 2020 and 2021 American Chemical Society. The image for the Digital Lab Environment reprinted with permission from Labster ApS.34
Table 1. Virtual Lab Strategies with Associated Main Concepts Covered, Assessment Methods Used, and the Level and Domain$^a,b,c,d,e,f,g,h,i,j,k,l,m,n,o,p,q,r,s,t,u,v,w,x,y,z$.

| Entry | Strategy | Main Concept | Assessment Method(s) | Level, Domain | Year |
|-------|----------|--------------|----------------------|---------------|------|
| VL-1  | Kitchen/At-Home labs, virtual meeting, pre-lab discussion, quiz | Building a photometer using smartphones, dye-adsorption, UV-vis spectroscopy | Active participation | Lower, Physical | 2020$^{62}$ |
| VL-2  | Kitchen/At-Home labs, virtual meeting, synchronous experiment | Separation of the colors of ink markers and food coloring, column chromatography | Lab report | 2nd-year, Organic | 2020$^{59}$ |
| VL-3  | Kitchen/At-Home labs, synchronous (prelab lecture) and asynchronous (lecture videos, online problems, experiment) instructions | Separation of food coloring via liquid-liquid extraction using readily available materials | Pre-lab assignment, lab report | 2nd-year, Organic | 2021$^{68}$ |
| VL-4  | Kitchen/At-Home labs | Homemade kit for instrumental analysis: spectroscopy and chromatography | (Not performed by students, only described) | Upper, Analytical | 2020$^{59}$ |
| VL-5  | Kitchen/At-Home labs, virtual class meetings, collaborative learning | Several dry and wet-lab experiments (e.g., extraction, chromatography, modeling) | Lab assignments, online HW, parent feedback, instructor reflection | Lower, Organic | 2021$^{45}$ |
| VL-6  | Kitchen/At-Home labs, Data Analysis, video conferencing | Acid-base equilibrium, buffer capacity, titration | Image analysis, lab report | Lower, General | 2021$^{90}$ |
| VL-7  | Video-Based, synchronous lectures and lab sessions | Introduction to new instruments and experimental setup, data processing | Pre-lab assignment, synchronous in-lab questions | Upper, Physical | 2020$^{91}$ |
| VL-8  | Video-Based, pre-recorded experiments | Spectral and data analysis (IR, TLC), familiarization with standard procedures | Lab report, faculty reflection | 2nd-year, Organic | 2020$^{52}$ |
| VL-9  | Video-Based, remote-control experiment | Remote titration setup | (The titration unit described) | 1st-year, Analytical | 2021$^{93}$ |
| VL-10 | Video-Based, Data Analysis, virtual meeting | Acid dilution, filtration, UV-vis spectroscopy, electrochemistry, solution formation, titration | Pre-lab assignments, video quiz, data analysis, e-notebook | Lower, General/Organic | 2020$^{50}$ |
| VL-11 | Video-Based, Data Analysis, virtual meeting, small group discussion | Polymerization, kinetics, solubility, purification, UV-vis spectroscopy | Pre-lab assignment, lab report | Lower, General/Organic | 2021$^{94}$ |
| VL-12 | Data Analysis, Video-Based, asynchronous, virtual group meetings | Statistical analysis with previously collected data | Staff and student feedback survey | Lower, Analytical | 2020$^{96}$ |
| VL-13 | Computational, Video-Based, online computational teaching lab, pre-recorded videos, virtual meetings | Modeling software workshops and tutorial | (Not discussed) | Lower/Upper, Physical | 2021$^{53}$ |
| VL-14 | Computational, web-based simulation | Experimental design, enzymes, kinetics | Completion of simulation, data processing, post-lab report | 2nd-year/Upper, Biochemistry | 2020$^{96}$ |
| VL-15 | Video-Based, DLE, videos from JoVE, lab simulations from Beyond Labz | Several techniques and experiments | Quiz, lab report, student-recorded presentation | 2nd-year, Organic | 2020$^{97}$ |
| VL-16 | DLE, Video-Based, lab simulations, pre-recorded lectures, YouTube videos | Collecting experimental data and learning laboratory practices | Online quiz, pre- and post-lab assessments | Lower, General | 2020$^{96}$ |
| VL-17 | DLE, online choose-your-own-adventure activity | Electrochemistry, electrolytic cells | Pre-lab quiz and video, post-lab graded assignment | 1st-year, General | 2021$^{75}$ |
| VL-18 | VR, 3D contents | Collection and analysis of IR spectra | Online pre-lab assignment, lab worksheet, post-lab quiz | 2nd-year, Organic | 2020$^{92}$ |

$^a$Assessment methods for students’ performance. $^b$Lower level, first/second-year; upper level, third/fourth-year. $^c$DLE, digital lab environment; HW, homework; IR, infrared; TLC, thin layer chromatography; VL, virtual lab; VR, virtual reality.
with in-person laboratories (e.g., mixing incompatible chemical waste). In this section, we describe each of these virtual learning categories and highlight some representative works.

2.1. Kitchen Chemistry

Kitchen Chemistry and At-Home Laboratories utilize mostly common household materials and equipment to safely conduct hands-on experiments outside of conventional teaching laboratories. These strategies have been used to teach project design, scientific writing processes, and hands-on practical skills, such as experiment planning, attention to detail, and awareness of one’s workspace. Students can also benefit from this approach as a break from screen-based learning that is imperative for other distance learning strategies. Kitchen chemistry has become increasingly accessible and has been proven to reinforce fundamental concepts (e.g., spectroscopy, standard purification techniques) (see Table 1, VL-1-6). For example, several authors from the United States and Spain have reported the use of cell phones to aid kitchen chemistry experiments, namely, colorimetric and fluorescence analyses in high school and college (an R1 institute) chemistry courses. Furthermore, take-home chemistry kits for high school, two-year community college, and university students from Brazil and the United States address issues with student access to supplies and tools while offering a safe and often inexpensive alternative to traditional lab experiments. Overall, there is a consistent motif of kitchen chemistry in terms of learning objectives, such as the realistic learning experiences akin to hands-on laboratories, active engagement with small-scale experiments, and problem-solving during the experiment rather than reading from a recipe. Nevertheless, kitchen chemistry does not fully mimic a laboratory setting and associated safety considerations for laboratories whose objectives are primarily derived from the acquisition of technical skills (e.g., upper-level synthesis techniques).

2.2. Video-Based Laboratories

Video-Based Chemistry Laboratories encompass a variety of styles and delivery methodologies, including simple video recordings, narrative/voice-over lab recordings, and real-time delivery (see Table 1, VL-7-13, -15, and -16). Early renditions include the videotaping of experiments for students to watch later, often during lectures where demonstrations may not be suitable. Educators in universities from Australia, Canada, and the United States have utilized prerecorded videos as a tool for students to observe experimental protocols and chemical reactions outside of a lab environment. This method is favorable in its low cost and development requirements; however, students may not fully engage with these videos and miss valuable information. As supporting information to in-person laboratories, these videos can improve student comprehension of conceptual objectives (e.g., reactivity differences, kinetics), but stand-alone virtual laboratories require greater student input, which has inspired efforts to create active-learning video experiences. For example, in response to the COVID-19 pandemic, laboratory courses at the University of California, Irvine utilized prerecorded videos of lab experiments for synchronous class meetings. TAs and students met online to watch videos of the experiments together, and the TAs would pause periodically to discuss key steps and concepts. A similar synchronous approach conducted live-streamed, real-time demonstrations of scheduled laboratory experiments where students recorded their own observations and engaged in small-group discussions. Also, student-created videos have been used to supplement as well as test student understanding at NC State University and Florida International University. Overall, video-based remote learning can provide students the opportunity to experience experimental design, reaction setup, lab techniques, instrumentation, data collection, processing and analyzing samples/data/results, waste management, and safety precautions. Integration of these video-based laboratories into undergraduate curricula shows promise for emphasizing concepts within experimental observations but cannot replicate the hands-on aspects of in-person laboratories.

2.3. Computer-Based Learning: Data Analysis and Computational Chemistry

Computer-Based Learning has become a catch-all term to describe a wide array of learning methodologies. This learning method applies computers for chemical problems such as solving complex chemical equilibrium, nuclear magnetic resonance (NMR) spectroscopy simulations, reaction mechanism determination, kinetics calculations, and quantum mechanical problems. Today, chemistry courses still utilize computer-based learning; however, the definition has progressed to include simulations, software for data capture and analysis, programming-based tutorials, and coding and computational chemistry (see Table 1, VL-6, -10-14). Coding and modeling, for example, have also been used to showcase active-learning techniques in a computer-based undergraduate lab (University of Central Lancashire, UK). The key learning objectives aimed in these studies focused on simulations (e.g., thermodynamics of chemical reactions and chemical equilibria) and 3D model visualizations (e.g., target-drug interactions). In addition, Kobayashi et al. from the Australian National University demonstrated through a remote and hands-on computational chemistry course that virtual delivery of “dry” laboratories shows promise of effective engagement but is very technology-dependent. Another facet of computer-based learning is data analysis laboratories, which give students the opportunity to gain hands-on experience with characterization, data processing, and interpretation techniques. Data analysis can easily be completed at home by providing students with raw data; although in some cases, it requires an online training component to make students more familiar with the analysis software (e.g., MestReNova, ChemDraw), data interpretation, and/or structure elucidation. Ultimately, the scope of the raw data analysis is limited to instrumentation and characterization experiments in which instrument operation is not required, but in these cases, virtual translations show high fidelity to their f2f counterparts.

2.4. Digital Lab Environment

Digital Lab Environments (DLEs) consist of laboratory components that exist entirely in a virtual interface, which allows students to observe or perform experiments through software offline (e.g., ChemSense, LabVIEW) or online (e.g., Læbster, Beyond Labz, ChemCollective) with the goal of achieving cognitive and affective learning outcomes. Aljuhani et al. from Taibah University in Saudi Arabia, for example, demonstrated this ability with an interactive web-based platform for students to conduct chemistry experiments. Moore and co-workers from UC Boulder have produced a series of simulations that are readily accessible online and have been successfully integrated into
lectures and laboratories. Similarly, “Labventures” used at Rice University and Alfred University offer a creative alternative to virtual laboratories by adopting a Choose Your Own Adventure “click-through” format to test student decision-making in a laboratory context. Ali and Ullah from the University of Malakand in Pakistan thoroughly reviewed DLEs and analyzed both 2D and 3D virtual chemistry laboratories. This work found that virtual chemistry laboratories adequately familiarized students to chemistry experiments, though a lack of realism can impact student engagement, instructions may be insufficient for students to navigate the DLE, and many systems cannot be adjusted to account for students’ knowledge levels. While there are some examples of DLEs developed by the universities, this approach is dominated by corporate efforts that limit the available experiments and the ability of the instructors to create specific experiments for their course.

Commercially available DLEs also have costs associated with licensing and distribution, which hinder their accessibility within lower-income schools. However, some programs like ChemCollective do offer some creative flexibility, for example, furnishing digital laboratories with a customizable stockroom that can be modiﬁed by the instructor. In general, DLEs can help students develop a conceptual understanding of a scientiﬁc experimental design and provide engaging, dynamic, and visual feedback supports in a safe, cost-eﬀective, and repeatable lab simulation.

### 2.5. Virtual Reality

Popularized in the video-game sector, Virtual Reality (VR) has been translated to chemical education and serves as a powerful tool. However, VR has its own limitations and challenges. Some of the main challenges include the cost of hardware, the need for a high-speed internet connection, and the potential for motion sickness. Despite these challenges, VR has the potential to revolutionize chemical education, providing students with a more immersive and engaging learning experience.

| Table 2. Selection of Polymer Chemistry Laboratory Experiments |
|---------------------------------------------------------------|
| **Entry** | **Main Concept** | **Type** | **Year** |
| PL-1 | Polycondensation, interfacial polymerization, nylon rope trick | ✦ | 1959<sup>106</sup> |
| PL-2 | Microscale interfacial polymerization | ✦ | 1992<sup>108</sup> |
| PL-3 | Polycondensation, biobased polymers, crosslinking, degradation study | ✦ | 2019<sup>107</sup> |
| PL-4 | FRP, chain-growth and interfacial step-growth polymerization | ✦ | 2020<sup>108</sup> |
| PL-5 | Emulsion polymerization, size determination | ✦ | 2020<sup>109</sup> |
| PL-6 | Radical emulsion copolymerization, biobased monomers, organogels | ✦ | 2021<sup>110</sup> |
| PL-7 | ROP, renewable polymers | ✦ | 2014<sup>111</sup> |
| PL-8 | ROP, biodegradable polymers, organocatalysis | ✦ | 2015<sup>112</sup> |
| PL-9 | FRP, I'H NMR end-group analysis, M<sub>n</sub> calculation | ✦ | 2017<sup>113</sup> |
| PL-10 | Inverse vulcanization, radical polymerization, reaction kinetics, UV-vis spectroscopy | ▼ | 2021<sup>114</sup> |
| PL-11 | Photopolymerization, radical reactivity, structure-property relationship | ▼ | 2019<sup>115</sup> |
| PL-12 | CRP (ATRP), block and statistical copolymers | ▼ | 2001<sup>116</sup> |
| PL-13 | Clay nanocomposite hydrogels, stress testing | ▼ | 2017<sup>117</sup> |
| PL-14 | Oxidative chemical polymerizations, electrochemical properties | ▼ | 2016<sup>118</sup> |
| PL-15 | Epoxy adhesives, thermomechanical properties, contact angle | ▼ | 2021<sup>119</sup> |
| PL-16 | Impact of polymerization mechanism on properties of polyamides<sup>a</sup> | ▼ | 2019<sup>120</sup> |
| PL-17 | Rheology of polymer melts | ▼ | 1999<sup>11</sup> |

**Upper-Level Undergraduates, 3<sup>rd</sup>/4<sup>th</sup>-year**

| **Entry** | **Main Concept** | **Type** |
| PL-18 | Photo-crosslinked hydrogels, crosslinking density, fabrication | ✦ | 2020<sup>120</sup> |
| PL-19 | Step-growth polymerization, solid-state polyelectrolytes, crosslinked polymers | ▼ | 2020<sup>121</sup> |
| PL-20 | Step-growth polymerization, conductive polymers, structural characterization | ▼ | 2014<sup>122</sup> |
| PL-21 | Synthesis and investigation of conducting polymers, regionchemistry | ▼ | 2010<sup>123</sup> |
| PL-22 | Emulsion polymerization, redox initiation, colloidal and polymer characterization | ▼ | 2019<sup>124</sup> |
| PL-23 | FRP, anionic polymerization, tecticity, thermal properties | ▼ | 2006<sup>125</sup> |
| PL-24 | Hydrogels, swelling behavior, spectroscopy | ▼ | 2017<sup>126</sup> |
| PL-25 | FRP, hybrid hydrogels, mechanical properties | ▼ | 2020<sup>127</sup> |
| PL-26 | CRP (RAFT P.), polymerization kinetics | ▼ | 2008<sup>128</sup> |
| PL-27 | Oxygen-tolerant CRP (PET-RAFT P.), photopolymerization, reaction kinetics | ▼ | 2020<sup>129</sup> |
| PL-28 | CRP (ATRP), post-polymerization modiﬁcation, reaction kinetics | ▼ | 2016<sup>130</sup> |
| PL-29 | ROP, block copolymers, hydrogels | ▼ | 2020<sup>131</sup> |
| PL-30 | ROMP, monitoring reaction progress, NMR study | ▼ | 1999<sup>132</sup> |
| PL-31 | ROMP, telechelic polymers, conducting polymers | ▼ | 2009<sup>133</sup> |
| PL-32 | FTIR, thermal analysis, identiﬁcation of polymer samples | ▼ | 2017<sup>134</sup> |

*“Polymerization methods: melt-condensation, interfacial polymerization, and ROP. ATRP, atom transfer radical polymerization; CRP, controlled-radical polymerization; FRP, free-radical polymerization; FTIR, Fourier-transform infrared; M<sub>n</sub>, number-average molecular weight; NMR, nuclear magnetic resonance; PET, photoinduced electron/energy transfer; PL, polymer lab; RAFT, reversible addition-fragmentation chain-transfer; ROMP, ring-opening metathesis polymerization; ROP, ring-opening polymerization. ✦ for synthesis; ▼ for characterization; ● for virtual.”*
supplement and alternative setting for teaching students fundamental chemistry concepts, practical lab skills, and new instrumentation through “hands-on” activities (Table 1, VL-18). VR provides realistic interactions with customizable, computer-generated, 3D hologram-like learning environments. This approach has been most extensively explored as a forum for interactive molecule visualization, which has allowed students to interact with an otherwise inaccessible molecular world. Within a laboratory setting, VR has been applied to both instrumentation-based (e.g., IR spectroscopy and pH meter) at NC State University and Iowa State University and synthetic experiments (e.g., synthesis of gold nanocrystals) at the Chinese University of Hong Kong. The results from NC State University showed that there were no significant differences in learning outcomes between the group of students that experienced and performed the VR lab and the group that did the same experiment in a traditional lab. The recently developed Virtual Reality Remote Education for Experimental Chemistry (VRREC) system features both a digital interface and real-lab live-stream, which gives students control over the experiment and the opportunity to virtually observe an in-person experiment. Digitization of the lab environment and high interactivity that comes with it gives users a very close experience to in-person laboratories without the associated safety concerns. Overall, this translation allows for engagement with exploratory educational activities in chemistry that can enhance independent, discovery-based learning. This technology has also made improvements toward the inclusivity of chemistry laboratories, particularly for those who cannot physically participate in a lab experiment due to physical/attendance challenges or safety concerns. VR experiments are also more easily developed at the university level than other approaches with a similar level of interactivity (e.g., DLEs). Yet, their overall accessibility is limited by a greater upfront cost for both students and universities due to the required technology and software. In this respect, smartphone-based approaches minimize the associated costs, especially given many universities’ electronic lending services and affordable options for smartphone-compatible VR headsets like Google cardboard (~$9). However, smartphones are not ubiquitous to student populations and not all universities can supplement them, so this remains a significant barrier in the effort to develop equity-driven methods.

Overall, chemistry laboratories in particular present a challenge, as the learning objectives, such as hands-on skills, executing methodology, active learning, engagement, interpersonal interactions, and team building, that are assessed and gained in an in-person teaching lab cannot be identically translated to virtual learning platforms.

3. DIGITIZING POLYMER LABORATORIES FOR VIRTUAL ENVIRONMENT

Current virtual polymer laboratory experiments are predominated by characterization experiments and simulations. As such, to the best of our knowledge, the first virtual polymer synthesis experiment implemented by the authors of this work appeared only last year in this journal in a prerecorded video-based approach along with online collaborative learning. In this work, various high sulfur-content polymers were made using different styrenic comonomers through bulk free-radical polymerization. Short videos of polymerization reactions, polymer purification, and spectroscopic analysis were prepared for students to watch during the virtual lab meeting. The absence of virtual synthesis experiments, in general, indicates that conceptual learning objectives underpinning laboratories are more easily translated to a virtual environment, whereas objectives associated with reaction setup, acquiring technical skills, and understanding fundamental concepts derived from troubleshooting a laboratory experiment pose a greater challenge for virtual translation. For this reason, synthetic experiments are more difficult to adapt to a remote learning environment as a stronger emphasis is placed on hands-on techniques as well as safe lab habits—particularly for undergraduate students who are already familiar with fundamental concepts. Thus, digitization methods that allow students to make decisions about reaction conditions show the most potential for retaining the value of synthetic experiments (e.g., DLE, VR, and “labventures”) and offer some improvements toward safety education as well as material costs.

For more advanced, senior-level laboratories where the goal extends beyond concept familiarity, these options fall short and represent a critical need for future development—particularly in the case of upper-division synthetic experiments.

3.1. Polymer Synthesis

Existing undergraduate polymer synthesis experiments cover a diverse subset of methods predominated by FRP, controlled polymerization, ring-opening polymerization (ROP), condensation polymerization (see Table 2 for a selection of polymer chemistry laboratory experiments and see the papers for other polymer-related experiments that are not listed in the table). The first virtual translation of these experiments featured a prerecorded FRP reaction along with online discussions (see Table 2, PL-10). However, the prerecorded video approach lacks the student input critical to their acquisition of the experimental setup, active learning, and related troubleshooting skills. Combining the existing videos with an approach that allows for more student input (e.g., “labventure” approach and live stream) would allow the students to learn from incorrect decisions and build experimental intuition as they would in f2f laboratories. Ultimately, the existing video-based approach could be a valuable supplement to in-person laboratories to familiarize students with methodologies prior to performing the experiments themselves as they support the delivery of conceptual objectives (e.g., reactivity differences, kinetics). These prerecorded video-based approaches are also among the most accessible strategies; however, they struggle as a standalone replacement for in-person synthesis experiments as they are unable to provide hands-on technique acquisition—something particularly important for upper-level undergraduate students preparing for industry and graduate-level research.

Many key concepts in polymer synthesis are missing from the virtual landscape but could be adapted from existing experiments (see Table 2). For lower-level (1st/2nd-year) undergraduate students who have little to no background in polymer chemistry, understanding the nuances between polymerization mechanisms has been accomplished through experiments that feature multiple polymerization methods (Table 2, PL-4 and -16). These more fundamental objectives can be adapted to a virtual environment through modified video-based approaches that allow for more student input. In addition, polymerization methods with fast reaction times such as “nylon rope trick” lend themselves to live-streamed synthesis, which can also accommodate real-time questions and foster student engagement (Table 2, PL-7).
While the underlying concepts in these experiments can be adapted to a virtual environment using any of the previously discussed approaches, VR and DLE show the most promise for translating more tactile synthesis protocols such as air-free or Schlenk techniques for radical polymerizations for digital forum.

Fully virtual, upper-level polymer experiments regarding the synthesis of block copolymers, hydrogels, and polyelectrolytes would also require strategies that more closely approximate an in-person laboratory such as VR experiments and DLE (e.g., Labster, Beyond Labz). Both VR and DLE are more immersive and offer students a greater degree of control over the outcome of the reaction. However, many of these experiments feature application-specific objectives that equip students with property-directed polymer design fundamentals. This unique polymer synthesis technique would likely require heavy modification of existing DLE infrastructure. Thus, VR experiments might be more easily developed at a university level for upper-level polymer experiments. Overall, higher student involvement in these types of experiments promotes the development of technical and soft (e.g., problem solving) skills that will be critical in students’ success in their future graduate and industrial research.

### 3.2. Polymer Characterization

As components of synthesis laboratories and as stand-alone experiments, characterization experiments are critical to students’ ability to confirm polymer composition (e.g., using NMR, FTIR, UV–vis spectroscopies), elucidate properties (e.g., using thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and gel permeation chromatography (GPC)), and become more familiar with the instrumentation techniques (see Table 2). For lower-level undergraduates, kitchen chemistry can be an effective technique for providing students with a distanced but still hands-on experience. Kitchen chemistry can successfully introduce students to fundamental polymer concepts (e.g., thermomechanical properties), but it does not provide students an opportunity to do rigorous data analysis (Table 2, PL-15). Through data interpretation, students learn how to draw conclusions on the basis of gathered/generated datasets. The absence of data interpretation is a persistent challenge for student operation of such instruments can be sacrificed without much detriment. As such, many of the valuable characterization components of the aforementioned synthesis laboratories (e.g., molecular weight determination, composition verification, thermal analysis) and several characterization experiments covering more advanced topics (e.g., light-scattering electron microscopy, X-ray photoelectron spectroscopy) could be easily translated to a virtual setting by providing students with raw data. In cases where instrument-operation is more standardized (e.g., NMR spectroscopy) or is the focus of the experiment, upper-level synthesis strategies (e.g., video-based, live-stream, DLE, and VR experiments) can prove advantageous for teaching instrument operation alongside data interpretation. Additionally, there are existing simulations for kinetics, viscosity measurements, and thermal properties that can be used for students to generate raw data for analysis purposes and develop an intuition for structure–property relationships by generating data influenced by student inputs.

Regardless of the strategy and type of experiment, all the proposed distance learning approaches have the potential to improve students’ awareness and comprehension of safety considerations as individuals can make and observe unsafe choices without any of the associated risks.

### 4. CONCLUSION

The COVID-19 pandemic required educators to swiftly modify face-to-face chemistry lab experiments for virtual learning environments or develop new alternatives that are suitable for virtual settings. This sudden, involuntary shift also enabled an impromptu beta test of the rapid deployment of virtual lab experiments. Although the overall results and observations are very promising, further studies are needed to understand the actual effects of the current virtual lab experiments on students’ learning. We are all aware that in-person lab experiments are critical to teaching students synthetic and instrumental skills, fostering active learning, and maintaining human interaction and engagement. The recent studies indicated that virtual lab experiments can effectively complement these face-to-face lab experiments. In addition, the incorporation of virtual lab experiments into the undergraduate curriculum can be preferred in the postpandemic era due to their cost-effectiveness, safety, sustainability, and inclusivity.

With the spike in the number of virtual experiments in 2020 and 2021, some areas remain underrepresented, such as virtual polymer lab experiments. In this work, our objective was to introduce the readers to current virtual lab strategies and common polymer lab experiments and suggest how these strategies can be used to translate polymer lab experiments to the virtual environment. Richard Zare remarked in this journal more than 20 years ago: “Which is better: face-to-face learning or computer-aided instruction?” is the wrong question. The right question is “How do we best combine both approaches?” Here, we highlighted approaches for virtual laboratories that would be suitable for teaching and learning one of the most important fields of chemistry: polymers.
Authors

Samantha M. McDonald — Department of Chemistry, Duke University, Durham, North Carolina 27708, United States
Alexander J. Bahnick — Department of Chemistry, Duke University, Durham, North Carolina 27708, United States
Kacey M. Godwin — Department of Chemistry, Duke University, Durham, North Carolina 27708, United States
Yin Mei Chan — Department of Chemistry, Duke University, Durham, North Carolina 27708, United States

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.1c01259

Author Contributions

§M.K., S.M.M., A.J.B., K.M.G., and Y.M.C. contributed equally.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors are grateful for financial support from Duke University and thank Liam H. McDonald for generating the Journal of Chemical Education article data set used by the authors to make Figures 1 and 2.

ABBREVIATIONS USED

ATRP, atom transfer radical polymerization; CRP, controlled-radical polymerization; DLE, digital lab environment; DSC, differential scanning calorimetry; 2Df, face-to-face; FRP, free-radical polymerization; FTIR, Fourier-transform infrared; NMR, nuclear magnetic resonance; PET, photoinduced electron/energy transfer; PL, polymer lab; RAFT, reversible addition–fragmentation chain transfer; ROMP, ring-opening metathesis polymerization; SEC, size-exclusion chromatography; STEM, science, technology, engineering, and mathematics; TA, teaching assistant; TGA, thermogravimetric analysis; TLC, thin-layer chromatography; UV—vis, ultraviolet—visible; VL, virtual lab; VR, virtual reality; VR3E3C, virtual reality remote experiment for experiential chemistry

REFERENCES

(1) Holme, T. A. Introduction to the Journal of Chemical Education Special Issue on Insights Gained While Teaching Chemistry in the Time of COVID-19. J. Chem. Educ. 2020, 97 (9), 2375−2377.
(2) Meyers, E. A.; Hedges, R. M.; Zwolinski, B. J. Blackboard by wire and graduate instruction in chemistry. J. Chem. Educ. 1967, 44 (8), 452.
(3) Reeves, S. M.; Crippen, K. J. Virtual Laboratories in Undergraduate Science and Engineering Courses: A Systematic Review, 2009−2019. J. Sci. Educ. Technol. 2021, 30 (1), 16−30.
(4) Kelley, E. W. LAB Theory, HLAB Pedagogy, and Review of Laboratory Learning in Chemistry during the COVID-19 Pandemic. J. Chem. Educ. 2021, 98 (8), 2490−2517.
(5) Altwaijji, S.; Haddadin, R.; Campos, P.; Sorn, S.; Gonzalez, L.; Villafane, S. M.; Groves, M. N. Measuring the effectiveness of online preparation videos and questions in the second semester general chemistry laboratory. Chem. Educ. Res. Pract. 2021, 22 (3), 616−625.
(6) McDonald, L. H. ACS-Scraper, GitHub repository. https://github.com/ImLovenInTr/ACS-Scraper (accessed 2021-12).
(7) Dillner, D. K.; Ferrante, R. F.; Fitzgerald, J. P.; Schroeder, M. J. Integrated Laboratories: Laying the Foundation for Undergraduate Research Experiences. J. Chem. Educ. 2011, 88 (12), 1623−1629.
(8) Qiang, Z.; Obando, A. G.; Chen, Y.; Ye, C. Revisiting Distance Learning Resources for Undergraduate Research and Lab Activities during COVID-19 Pandemic. J. Chem. Educ. 2020, 97 (9), 3446−3449.
(9) Deveau, A. M.; Wang, Y.; Small, D. J. Reflections on Course-Based Research in Organic and Biochemistry during COVID-19. J. Chem. Educ. 2020, 97 (9), 3463−3469.
(10) Gallardo-Williams, M. T.; Dunnagan, C. L. Designing Diverse Virtual Reality Laboratories as a Vehicle for Inclusion of Underrepresented Minorities in Organic Chemistry. J. Chem. Educ. 2022, 99 (1), 500−503.
(11) Size and Impact of Plastics Industry on the U.S. Economy; Plastics Industry Association, 2021.
(12) Plastics - the Facts 2014/2015; An analysis of European plastics production, demand and waste data. www.plasticsindustry.org (accessed 2021-12).
(13) Mathias, L. J. The laboratory for introductory polymer courses. J. Chem. Educ. 1983, 60 (11), 990.
(14) Krigbaum, W. R. Instruction in polymer chemistry. J. Chem. Educ. 1959, 36 (4), 156.
(15) Salamone, J. C.; Deanin, R. D.; Young, M. G.; Pearce, E. M. Polymer science and engineering education in the United States. J. Chem. Educ. 1973, 50 (11), 768.
(16) Seymour, R. B. Recommended ACS syllabus for introductory courses in polymer chemistry. J. Chem. Educ. 1982, 59 (8), 652.
(17) Wenzel, T. J.; McCoy, A. B.; Landis, C. R. An Overview of the Changes in the 2015 ACS Guidelines for Bachelor’s Degree Programs. J. Chem. Educ. 2015, 92 (6), 965−968.
(18) Kosbar, L. L.; Wenzel, T. J. Inclusion of Synthetic Polymers within the Curriculum of the ACS Certified Undergraduate Degree. J. Chem. Educ. 2017, 94 (11), 1599−1602.
(19) Ford, W. T. Introducing the Journal of Chemical Education’s Special Issue: Polymer Concepts across the Curriculum. J. Chem. Educ. 2017, 94 (11), 1595−1598.
(20) Anohina, A. Analysis of the terminology used in the field of virtual learning. J. Educ. Techno. Soc. 2005, 8 (3), 91−102.
(21) Campbell, C. D.; Challen, B.; Turner, K. L.; Stewart, M. I. #DryLab20: A New Global Collaborative Network to Consider and Address the Challenges of Laboratory Teaching with the Challenges of COVID-19. J. Chem. Educ. 2020, 97 (9), 3023−3027.
(22) Grimminger, M. A.; Tracey, M. P.; Martinus, S. J. Colorful Approach to Teaching Extraction Using Azo Dyes and Comparison of Hands-On vs Distance Learning Assessment. J. Chem. Educ. 2021, 98 (11), 3509−3513.
(23) Levenson, R. A. Graduate instruction at a remote location. J. Chem. Educ. 1976, 53 (5), 300.
(24) Mason, P. K.; Sarquis, A. M.; Williams, J. P. Take-Home Challenges: Extending Discovery-Based Activities beyond the General Chemistry Classroom. J. Chem. Educ. 1996, 73 (4), 337.
(25) Burke, K. A.; Greenbowe, T. J. Collaborative Distance Education: The Iowa Chemistry Education Alliance. J. Chem. Educ. 1998, 75 (10), 1308.
(26) Jin, G.; Nakayama, S. Virtual reality game for safety education. 2014 International Conference on Audio, Language and Image Processing, Shanghai, China, July 7−9, 2014.
(27) Poyade, M.; Eaglesham, C.; Trench, J.; Reid, M. A Transferable Psychological Evaluation of Virtual Reality Applied to Safety Training in Chemical Manufacturing. ACS Chemical Health & Safety 2021, 28 (1), 55−65.
(28) Doughan, S.; Shahrouradyan, A. At-Home Real-Life Sample Preparation and Colorimetric-Based Analysis: A Practical Experience outside the Laboratory. J. Chem. Educ. 2021, 98 (3), 1031−1036.
(29) Ibarra-Rivera, T. R.; Delgado-Montemayor, C.; Oviedo-Garza, F.; Pérez-Meseguer, J.; Rivas-Galindo, V. M.; Waksman-Minsky, N.; Pérez-López, L. A. Setting Up an Educational Column Chromatography Experiment from Home. J. Chem. Educ. 2020, 97 (9), 3055−3059.
(30) Howitz, W. J.; Thane, T. A.; Frey, T. L.; Wang, X. S.; Gonzales, J. C.; Tretbar, C. A.; Seith, D. D.; Salaga, S. J.; Lam, S.; Nguyen, M. M.; Tieu, P.; Link, R. D.; Edwards, K. D. Online in No Time: Design and Implementation of a Remote Learning First Quarter General
Chemistry Laboratory and Second Quarter Organic Chemistry Laboratory. J. Chem. Educ. 2020, 97 (9), 2624−2634.
(31) Woelk, K.; Whitefield, P. D. As Close as It Might Get to the Real Lab Experience—Live-Streamed Laboratory Activities. J. Chem. Educ. 2020, 97 (9), 2996−3001.
(32) Dunnagan, C. L.; Dannenberg, D. A.; Cuales, M. P.; Earnest, A. D.; Gurnsey, R. M.; Gallardo-Williams, M. T. Production and Evaluation of a Realistic Immersive Virtual Reality Organic Chemistry Laboratory Experience: Infrared Spectroscopy. J. Chem. Educ. 2020, 97 (1), 258−262.
(33) Kobayashi, R.; Goumans, T. P. M.; Carstensen, N. O.; Soini, T. M.; Marzari, N.; Timrov, I.; Poncé, S.; Linscott, E. B.; Sewell, C. J.; Pizzi, G.; Ramirez, F.; Bercx, M.; Huber, S. P.; Adoré, C. S.; Talíř, L. Virtual Computational Chemistry Teaching Laboratories—Hands-On at a Distance. J. Chem. Educ. 2021, 98 (10), 3163−3171.
(34) Elimination Reaction: Use cyclohexanol to create polymers Virtual Lab. https://www.labster.com/simulations/elimination-reactions/ (accessed 2021-12).
(35) Whitmer, J. C. Kitchen chemistry. J. Chem. Educ. 1975, 52 (10), 665.
(36) Jones, C. D. The Kitchen Is Your Laboratory: A Research-Based Term-Paper Assignment in a Science Writing Course. J. Chem. Educ. 2011, 88 (8), 1062−1068.
(37) Meyers, J. K.; LeBaron, T. W.; Collins, D. C. The Journal of Kitchen Chemistry: A Tool for Instructing the Preparation of a Chemistry Journal Article. J. Chem. Educ. 2014, 91 (10), 1643−1648.
(38) Radzikowski, J. L.; Delmas, L. C.; Spivey, A. C.; Youssef, J.; Kneebone, R. The Chemical Kitchen: Toward Remote Delivery of an Interdisciplinary Practical Course. J. Chem. Educ. 2021, 98 (3), 710−713.
(39) Shultz, M.; Callahan, D. L.; Militadis, A. Development and Use of Kitchen Chemistry Home Practical Activities during Unanticipated Campus Closures. J. Chem. Educ. 2020, 97 (9), 2678−2684.
(40) Eason, J. Stay at Home Laboratories for Chemistry Courses. J. Chem. Educ. 2020, 97 (9), 3070−3073.
(41) Knutson, T. R.; Knutson, C. M.; Mozzetti, A. R.; Campos, A. R.; Haynes, C. L.; Penn, R. L. A Fresh Look at the Crystal Violet Lab at Brown University. J. Chem. Educ. 2019, 96 (9), 1692−1695.
(42) Al-Soufi, W.; Carrazza-Garcia, J.; Novo, M. When the Kitchen Turns into a Physical Chemistry Lab. J. Chem. Educ. 2020, 97 (9), 3090−3096.
(43) Toma, H. E. Microscale Educational Kits for Learning Chemistry at Home. J. Chem. Educ. 2021, 98 (12), 3841−3851.
(44) Burchett, S.; Hayes, J. L. Online Chemistry: The Development and Use of a Custom In-House Laboratory Kit. Online Approaches to Chemical Education; American Chemical Society, 2017; Vol. 1261, pp 57−70.
(45) Kelley, E. W. Sample Plan for Easy, Inexpensive, Safe, and Relevant Hands-On, At-Home Wet Organic Chemistry Laboratory Activities. J. Chem. Educ. 2021, 98 (5), 1622−1635.
(46) Haight, G. P.; Jones, L. L. Kinetics and mechanism of the iodine azide reaction: A videotaped experiment. J. Chem. Educ. 1987, 64 (3), 271.
(47) Cresswell, S. L.; Loughlin, W. A.; Coster, M. J.; Green, D. M. Development and Production of Interactive Videos for Teaching Chemical Techniques during Laboratory Sessions. J. Chem. Educ. 2019, 96 (5), 1033−1036.
(48) Tran, K.; Beshir, A.; Vaze, A. A Tale of Two Lab Courses: An Account and Reflection on the Teaching Challenges Experienced by Organic and Analytical Chemistry Laboratories During the COVID-19 Period. J. Chem. Educ. 2020, 97 (9), 3079−3084.
(49) Wang, L.-Q.; Ren, J. Strategies, Practice and Lessons Learned from Remote Teaching of the General Chemistry Laboratory Course at Brown University. J. Chem. Educ. 2020, 97 (9), 3002−3006.
(50) Wild, D. A.; Yeung, A.; Loedolff, M.; Spagnoli, D. Lessons Learned by Converting a First-Year Physical Chemistry Unit into an Online Course in 2 Weeks. J. Chem. Educ. 2020, 97 (9), 2389−2392.
(51) Davy, E. C.; Quane, S. L. Assessment of Technological Setup for Teaching Real-Time and Recorded Laboratories for Online Learning: Implications for the Return to In-Person Learning. J. Chem. Educ. 2021, 98 (7), 2221−2227.
(52) Box, M. C.; Dunnagan, C. L.; Hirsh, L. A. S.; Cherry, C. R.; Christianson, K. A.; Gibson, R. J.; Wolfe, M. I.; Gallardo-Williams, M. T. Qualitative and Quantitative Evaluation of Three Types of Student-Generated Videos as Instructional Support in Organic Chemistry Laboratories. J. Chem. Educ. 2017, 94 (2), 164−170.
(53) Nadelson, L. S.; Scaggs, J.; Sheffield, C.; McDougall, O. M. Integration of Video-Based Demonstrations to Prepare Students for the Organic Chemistry Laboratory. J. Sci. Educ. Technol. 2015, 24 (4), 476−483.
(54) Pulukuri, S.; Abrams, B. Incorporating an Online Interactive Video Platform to Optimize Active Learning and Improve Student Accountability through Educational Videos. J. Chem. Educ. 2020, 97 (12), 4505−4514.
(55) Brame, C. J. Effective Educational Videos: Principles and Guidelines for Maximizing Student Learning from Video Content. CBE-Life Sciences Education 2016, 15 (4), No. e66.
(56) Lichter, J. Using YouTube as a Platform for Teaching Learning Solubility Rules. J. Chem. Educ. 2012, 89 (9), 1133−1137.
(57) Gallardo-Williams, M.; Morsch, L. A.; Paye, C.; Seery, M. K. Student-generated video in chemistry education. Chem. Educ. Res. Pract. 2020, 21 (2), 488−495.
(58) Swinnerton, J. W.; Miller, W. W. Use of a Digital Computer for Solving a Complex Chemical Equilibrium. J. Chem. Educ. 1959, 36 (10), 485.
(59) Wilkins, C. L.; Klopfenstein, C. E. Simulation of NMR spectra: Computers as teaching devices. J. Chem. Educ. 1966, 43 (1), 10.
(60) DeTar, D. F. Simplified computer programs for treating complex reaction mechanisms. J. Chem. Educ. 1967, 44 (4), 191.
(61) Griswold, R. E.; Haugh, J. F. Analog computer simulation: An experiment in chemical kinetics. J. Chem. Educ. 1968, 45 (9), 576.
(62) Tabbutt, F. D. The use of analog computers for teaching chemistry. J. Chem. Educ. 1967, 44 (2), 64.
(63) Fisher, A. A. E. An Introduction to Coding with Matlab: Simulation of X-Ray Photoelectron Spectroscopy by Employing Slater’s Rules. J. Chem. Educ. 2019, 96 (7), 1502−1505.
(64) Tchoua, R. B.; Qin, J.; Audus, D. J.; Chard, K.; Foster, I. T.; de Pablo, J. Blending Education and Polymer Science: Semiautomated Creation of a Thermodynamic Property Database. J. Chem. Educ. 2019, 93 (9), 1561−1568.
(65) Marlowe, J.; Tsilomelekis, G. Accessible and Interactive Learning of Spectroscopic Parameterization through Computer-Aided Training. J. Chem. Educ. 2020, 97 (12), 4527−4532.
(66) Cahill, S. T.; Bergstrom Mann, P. E.; Worrall, A. F.; Stewart, M. I. Remote Teaching of Programming in Mathematica: Lessons Learned. J. Chem. Educ. 2020, 97 (9), 3085−3089.
(67) Lafuente, D.; Cohen, B.; Fiorini, G.; García, A. A.; Bringas, M.; Moran, E.; Onna, D. A Gentle Introduction to Machine Learning for Chemists: An Undergraduate Workshop Using Python Notebooks for Visualization, Data Processing, Analysis, and Modeling. J. Chem. Educ. 2021, 98 (9), 2892−2898.
(68) Xie, Q.; Tinker, R. Molecular Dynamics Simulations of Chemical Reactions for Use in Education. J. Chem. Educ. 2006, 83 (1), 77.
(69) Hayes, J. M. An Integrated Visualization and Basic Molecular Modeling Laboratory for First-Year Undergraduate Medicinal Chemistry. J. Chem. Educ. 2014, 91 (6), 919−923.
(70) Serafin, J. M.; Chabra, J. Using a Cooperative Hands-On General Chemistry Laboratory Framework for a Virtual General Chemistry Laboratory. J. Chem. Educ. 2020, 97 (9), 3007−3010.
(71) Belletti, A.; Borromei, R.; Ingletto, G. Teaching Physical Chemistry Experiments with a Computer Simulation by LabVIEW. J. Chem. Educ. 2006, 83 (9), 1353.
(72) Jones, E. V.; Shepler, C. G.; Evans, M. J. Synchronous Online-Delivery: A Novel Approach to Online Lab Instruction. J. Chem. Educ. 2021, 98 (3), 850−857.
(73) Aljubani, K.; Sonbul, M.; Alhabibi, M.; Meccawy, M. Creating a Virtual Science Lab (VSL): the adoption of virtual labs in Saudi schools. Smart Learn. Environ. 2018, 5 (1), 16.

(74) Moore, E. B.; Chamberlain, J. M.; Parson, R.; Perkins, K. K. PhET Interactive Simulations: Transformative Tools for Teaching Chemistry. J. Chem. Educ. 2014, 91 (8), 1191–1197.

(75) Warning, L. A.; Kobylanski, K. A. Choose-Your-Own-Adventure-Style Virtual Lab Activity. J. Chem. Educ. 2021, 98 (3), 924–929.

(76) D’Angelo, J. G. Choose Your Own “Labventure”: A Click-Through Story Approach to Online Laboratories during a Global Pandemic. J. Chem. Educ. 2020, 97 (9), 3064–3069.

(77) Ali, N.; Villah, S. Review to Analyze and Compare Virtual Chemistry Laboratories for Their Use in Education. J. Chem. Educ. 2020, 97 (10), 3563–3574.

(78) Resources to Teach and Learn Chemistry. http://chemcollective.org/ (accessed 2021-12).

(79) An, J.; Poly, L.-P.; Holme, T. A. Usability Testing and the Development of an Augmented Reality Application for Laboratory Learning. J. Chem. Educ. 2020, 97 (1), 97–105.

(80) Seritan, S.; Wang, Y.; Ford, J. E.; Valentin, A.; Gold, T.; Martínez, T. J. InteracChem: Virtual Reality Visualizer for Reactive Interactive Molecular Dynamics. J. Chem. Educ. 2021, 98 (11), 3486–3492.

(81) Qin, T.; Cook, M.; Courtney, M. Exploring Chemistry with Wireless, PC-Less Portable Virtual Reality Laboratories. J. Chem. Educ. 2021, 98 (2), S21–S29.

(82) Won, M.; Mocerino, M.; Tang, K.-S.; Treakgust, D. F.; Tasker, R. Interactive Immersive Virtual Reality to Enhance Students’ Visualisation of Complex Molecules. In Research and Practice in Chemistry Education: Advances from the 25th IUPAC International Conference on Chemistry Education 2018; Schultz, M., Schmid, S., Lawrie, G. A., Eds.; Springer Singapore: Singapore, 2019; pp 51–64.

(83) Ferrell, J. B.; Campbell, J. P.; McCarthy, D. R.; McKay, K. T.; Hensinger, M.; Srinivasan, R.; Zhao, X.; Wurthmann, A.; Li, J.; Schneebeli, S. T. Chemical Exploration with Virtual Reality in Organic Teaching Laboratories. J. Chem. Educ. 2019, 96 (9), 1961–1966.

(84) Limnioua, M.; Papadopoulosb, N.; Giannakoudakisb, A.; Roberts, D.; Ottoc, O. The integration of a viscosity simulator in a Virtual Reality Educational system for the Organic Chemistry Undergraduate Laboratory. J. Chem. Educ. 2020, 97 (9), 2971–2975.

(85) Orzolek, B. J.; Kozlowski, M. C. Separation of Food Colorings via Liquid-Liquid Extraction: An At-Home Organic Chemistry Lab. J. Chem. Educ. 2021, 98 (3), 951–957.

(86) Vass, D. T.; Wells, W. G. Lab-in-a-Box: A Guide for Remote Laboratory Instruction in an Instrumental Analysis Course. J. Chem. Educ. 2020, 97 (9), 3078.

(87) Caraballo, R. M.; Saleh Medina, L. M.; Gomez, S. G. J.; Vessaps, P.; Hamer, M. Turmeric and RGB Analysis: A Low-Cost Experiment for Teaching Acid-Base Equilibria at Home. J. Chem. Educ. 2021, 98 (3), 958–965.

(88) Anzovino, M. E.; Mallia, V. A.; Morton, M. S.; Barker Paredes, J. E.; Pennington, R.; Pursell, D. P.; Rudd, G. E. A.; Shepler, B.; Villanueva, O.; Lee, S. Insights and Initiatives While Teaching Organic Chemistry I and II with Laboratory Courses in the Time of COVID-19. J. Chem. Educ. 2020, 97 (9), 3240–3245.

(89) Soong, R.; Jenne, A.; Lysak, D. H.; Ghosh Biswas, R.; Adamo, A.; Kim, K. S.; Simpson, A. Titrate over the Internet: An Open-Source Remote-Control Titration Unit for All Students. J. Chem. Educ. 2021, 98 (3), 1037–1042.

(90) Karayilan, M.; Vakil, J.; Fowler, D.; Becker, M. L.; Cox, C. T. Zooming in on Polymer Chemistry and Designing Synthesis of High Sulfur-Content Polymers for Virtual Undergraduate Laboratory Experiment. J. Chem. Educ. 2021, 98 (6), 2062–2073.

(91) Buchberger, A. R.; Evans, T.; Doolittle, P. Analytical Chemistry Online? Lessons Learned from Transitioning a Project Lab Online Due to COVID-19. J. Chem. Educ. 2020, 97 (9), 2976–2980.

(92) Worrall, A. F.; Bergstrom Mann, P. E.; Young, D.; Wormald, M. R.; Cahill, S. T.; Stewart, M. I. Benefits of Simulations as Remote Exercises During the COVID-19 Pandemic: An Enzyme Kinetics Case Study. J. Chem. Educ. 2020, 97 (9), 2733–2737.

(93) Ali, N.; Ullah, S. Review to Analyze and Compare Virtual Chemistry Laboratories for Their Use in Education. J. Chem. Educ. 2021, 98 (10), 3153–3162.

(94) Al-Maameri, H. H.; Jaf, L. A.; Suppes, G. J. Simulation Approach to Learning Polymer Science. J. Chem. Educ. 2018, 95 (9), 1554–1561.

(95) Schmidt, S.; Wright, Z. M.; Eckhart, K. E.; Staraggi, F.; Vicker, W.; Wolf, M. E.; Pitts, M.; Warner, T.; Taofik, T.; Ng, M.; Collier, C.; Sydlik, S. A. Hands-On Laboratory Experiment Using Adhesives for Remote Learning of Polymer Chemistry. J. Chem. Educ. 2021, 98 (10), S317–S317.

(96) Qin, T.; Cook, M.; Courtney, M. Exploring Chemistry with Wireless, PC-Less Portable Virtual Reality Laboratories. J. Chem. Educ. 2021, 98 (2), S21–S29.

(97) Limnioua, M.; Papadopoulosb, N.; Giannakoudakisb, A.; Roberts, D.; Ottoc, O. The integration of a viscosity simulator in a chemistry laboratory. Chem. Educ. Res. Pract. 2007, 8, 220–231.

(98) Kim, A.; Musfeldt, J. L. Understanding Chemical Structure/Physical Property Relationships in Polymers through Molecular Modeling and Traditional Analysis Techniques. J. Chem. Educ. 1998, 75 (7), 808–812.

(99) Morgan, P. W.; Kwolek, S. L. The nylon rope trick: Demonstration of condensation polymerization. J. Chem. Educ. 1959, 36 (4), 182.

(100) Lewis, R. G.; Choquette, M.; Darden, E. H.; Gilbert, M. P.; Martinez, D.; Myhaver, C.; Schlichter, K.; Woudenberg, R.; Zawistowski, K. Interfacial polymerizations. Microscale polymer laboratory experiments for undergraduate students. J. Chem. Educ. 1992, 69 (8), No. A215.

(101) Knudson, C. M.; Hiller, A. P.; Tolsbyka, Z. P.; Anderson, C. B.; Wilson, P. A.; Mathers, R. T.; Wentzel, M. T.; Perkins, A. L.; Wissinger, J. E. Dyeing to Degrade: A Bioplastics Experiment for College and High School Classrooms. J. Chem. Educ. 2019, 96 (11), 2565–2573.

(102) Allred, A.; Holland, J. S.; Shupert, A. G.; Konzelman, J.; Huddleston, N. E. Synthesis, Modification, and Application of Sulfonylated Poly(styrene-co-maleic anhydride) as a Stain Blocker for Polymides: Polymer Chemistry for the Undergraduate Organic Laboratory. J. Chem. Educ. 2020, 97 (7), 2001–2005.

(103) Lisensky, G.; Dauzvardis, F.; Luo, J.; Horger, J.; Koening, E. Emulsion Polymerization, Size Determination, and Self-Assembly of Monodispersed Poly(methyl methacrylate) Nanospheres for Photonics. J. Chem. Educ. 2020, 97 (3), 813–819.

(104) Gormong, E. A.; Wentzel, M. T.; Cao, B.; Kundel, L. N.; Reineke, T. M.; Wissinger, J. E. Exploring Divergent Green Reaction Media for the Copolymerization of Biobased Monomers in the Teaching Laboratory. J. Chem. Educ. 2021, 98 (2), S59–S66.
(110) Schneiderman, D. K.; Gilmer, C.; Wentzel, M. T.; Martello, M. T.; Kubo, T.; Wissinger, J. E. Sustainable Polymers in the Organic Chemistry Laboratory: Synthesis and Characterization of a Renewable Polymer from δ-Decalcate and L-Lactide. J. Chem. Educ. 2014, 91 (1), 131−135.
(111) Chan, J. M. W.; Zhang, X.; Brennan, M. K.; Sardon, H.; Engler, A. C.; Fox, C. H.; Frank, C. W.; Waymouth, R. M.; Hedrick, J. L. Organocatalytic Ring-Opening Polymerization of Trimethylene Carbonate To Yield a Biodegradable Polycarbonate. J. Chem. Educ. 2015, 92 (4), 708−713.
(112) Wackerly, J. W.; Dunne, J. F. Synthesis of Polystyrene and Molecular Weight Determination by IH NMR End-Group Analysis. J. Chem. Educ. 2017, 94 (11), 1790−1793.
(113) Croissant, M.; Breit, S. L.; Konkolewicz, D. Investigating Radical Reactivity and Structure-Property Relationships through Photopolymerization. J. Chem. Educ. 2019, 96 (2), 348−353.
(114) Beens, K. L.; Matyjaszewski, K.; Woodward, B. Controlled/Living Radical Polymerization in the Undergraduate Laboratories. I. Using ATRP to Prepare Block and Statistical Copolymers of n-Butyl Acrylate and Styrene. J. Chem. Educ. 2001, 78 (4), 544.
(115) Warren, D. S.; Sutherland, S. P. H.; Kao, J. Y.; Weal, G. R.; Mackay, S. M. The Preparation and Simple Analysis of a Clay Nanoparticle Composite Hydrogel. J. Chem. Educ. 2017, 94 (11), 1772−1779.
(116) Abu-Thabit, N. Y. Chemical Oxidative Polymerization of Poly(α-linolenic acid): A Practical Approach for Preparation of Smart Conductive Textiles. J. Chem. Educ. 2016, 93 (9), 1606−1611.
(117) Sterner, E. S. Three Ways to Polyamides: The Impact of Polymerization Mechanism on Polymer Properties. J. Chem. Educ. 2019, 96 (9), 2003−2008.
(118) Commeruccio, S. Basic Rheology of Polymer Melts. An Introductory Polymer Science Experiment. J. Chem. Educ. 1999, 76 (11), 1528.
(119) Alfoid, A.; Caviedes, R.; Kharlampieva, E. Photo-Clicking Hydrogel Replication of Small Objects: A Multistep Final Project for Undergraduate Polymer Laboratories. J. Chem. Educ. 2020, 97 (6), 1637−1643.
(120) Yang, Y.; Li, W.; Zhou, N.; Shen, J. Design and Construction of Cross-Linked PEO with the Integration of Helical Polypolyurethane as an Advanced All-Solid-State Polymer Electrolyte for Lithium Batteries. J. Chem. Educ. 2020, 97 (10), 3758−3765.
(121) Knoerer, T. A.; Balaich, G. J.; Miller, H. A.; Iacono, S. T. An Integrated Laboratory Approach toward the Preparation of Conductive Poly(phenyleinevinylene) Polymers. J. Chem. Educ. 2014, 91 (11), 1976−1980.
(122) Pappinen, T. M.; Hermansson, D. L.; Kohl, S. G.; Melby, J. H.; Thoma, L. M.; Carpenter, N. E.; da Silva Filho, D. A.; Bredas, J.-L. Regiochemistry of Poly(3-hexylthiophene): Synthesis and Investigation of a Conducting Polymer. J. Chem. Educ. 2010, 87 (5), 522−525.
(123) Murshid, N.; Cathcart, N.; Kitaev, V. Room-Temperature Synthesis of Size-Uniform Polystyrene Latex and Characterization of Its Properties: Third-Year Undergraduate Teaching Lab. J. Chem. Educ. 2019, 96 (7), 1479−1485.
(124) Duval-Tétreau, C.; Lebrun, L. Polymerization and Characterization of PMMA. Polymer Chemistry Laboratory Experiments for Undergraduate Students. J. Chem. Educ. 2006, 83 (3), 443.
(125) Hurst, G. A. Green and Smart: Hydrogels To Facilitate Independent Practical Learning. J. Chem. Educ. 2017, 94 (11), 1766−1771.
(126) Houben, S.; Quintens, G.; Pitet, L. M. Tough Hybrid Hydrogels Adapted to the Undergraduate Laboratory. J. Chem. Educ. 2020, 97 (7), 2006−2013.
(127) Nguyen, T. L. U.; Bennet, F.; Stenzel, M. H.; Barner-Kowollik, C. Reversible Addition Fragmentation Chain Transfer (RAFT) Polymerization in Undergraduate Polymer Science Lab. J. Chem. Educ. 2008, 85 (1), 97.
(128) Li, Z.; Ganda, S.; Melodia, D.; Boyer, C.; Chapman, R. Well-Defined Polymers for Nonchemistry Laboratories using Oxygen Tolerant Controlled Radical Polymerization. J. Chem. Educ. 2020, 97 (2), 549−556.
(129) Tsarevsky, N. V.; Woodruff, S. R.; Wisian-Neilson, P. J. An Undergraduate Chemistry Laboratory: Synthesis of Well-Defined Polymers by Low-Catalyst-Concentration ATRP and Postpolymerization Modification to Fluorescent Materials. J. Chem. Educ. 2016, 93 (8), 1452−1459.
(130) Wu, K.; Yu, L.; Ding, J. Synthesis of PCL-PEG-PCL Triblock Copolymer via Organocatalytic Ring-Opening Polymerization and Its Application as an Injectable Hydrogel—An Interdisciplinary Learning Trial. J. Chem. Educ. 2020, 97 (11), 4158−4165.
(131) France, M. B.; Uffelman, E. S. Ring-Opening Metathesis Polymerization with a Well-Defined Ruthenium Carbene Complex: An Experiment for the Undergraduate Inorganic or Polymer Laboratory. J. Chem. Educ. 1999, 76 (5), 661.
(132) Moorhead, E. J.; Wenzel, A. G. Two Undergraduate Experiments in Organic Polymers: The Preparation of Polycyanocrylate and Telechelic Polycyanocrylate via Ring-Opening Metathesis Polymerization. J. Chem. Educ. 2009, 86 (8), 973.
(133) Dickson-Karn, N. M. The Use of ATR-FTIR in Conjunction with Thermal Analysis Methods for Efficient Identification of Polymer Samples: A Qualitative Multi-instrument Instrumental Analysis Laboratory Experiment. J. Chem. Educ. 2017, 94 (11), 1780−1783.
(134) Zhang, H.; Bai, Y.; Zhao, J.; Shi, Q.; Zang, Y.; Wu, J. Designing, Synthesizing, and Analyzing a Comb-like Polymeric Surfactant, Poly(acrylic acid-co-octadecyl acrylate), in a Multidisciplinary Laboratory Experiment. J. Chem. Educ. 2021, 98 (6), 2074−2082.
(135) Chen, Q.; Yang, Y.; Yu, Y.; Xu, H. Reprocessable Thermostets*: Synthesis and Characterization of Vitrimer in the Undergraduate Lab Course. J. Chem. Educ. 2021, 98 (4), 1429−1435.
(136) Schwinefus, J. J.; Checkal; C.; Saksa, B.; Baka, N.; Modi, K.; Rivera, C. Molar Mass and Second Virial Coefficient of Polyethylene Glycol by Vapor Pressure Osmometry. J. Chem. Educ. 2015, 92 (12), 2157−2160.
(137) Erk, K. A.; Rhein, M.; Krafick, M. J.; Ydstie, S. Demonstrating the Effects of Processing on the Structure and Physical Properties of Plastic Using Disposable PETE Cups. J. Chem. Educ. 2015, 92 (11), 1876−1881.
(138) Makó, T.; Levine, M. Synthesis of a Fluorescent Conjugated Polymer in the Undergraduate Organic Teaching Laboratory. J. Chem. Educ. 2013, 90 (10), 1376−1379.
(139) Vasanthan, N. Crystallinity Determination of Nylon 66 by Density Measurement and Fourier Transform Infrared (FTIR) Spectroscopy. J. Chem. Educ. 2012, 89 (3), 387−390.
(140) Mc Ilrath, S. P.; Robertson, N. J.; Kuchta, R. J. Bustin Bunnies: An Adaptable Inquiry-Based Approach Introducing Molecular Weight and Polymer Properties. J. Chem. Educ. 2012, 89 (7), 928−932.
(141) Weizman, H.; Nielsen, C.; Weizman, O. S.; Nemat-Nasser, S. Synthesis of a Self-Healing Polymer Based on Reversible Diels-Alder Reaction: An Advanced Undergraduate Laboratory at the Interface of Organic Chemistry and Materials Science. J. Chem. Educ. 2011, 88 (11), 1317−1340.
(142) Kamber, N. E.; Tsujii, Y.; Keets, K.; Waymouth, R. M.; Pratt, R. C.; Nyce, G. W.; Hedrick, J. L. The Depolymerization of Poly(ethylene terephthalate) (PET) Using N-Heterocyclic Carbenes from Ionic Liquids. J. Chem. Educ. 2010, 87 (5), 519−521.
(143) Tillman, E. S.; Contrella, N. D.; Leasure, J. G. Monitoring the Nitroxide-Mediated Polymerization of Styrene Using Gel Permeation Chromatography and Proton NMR. J. Chem. Educ. 2009, 86 (12), 1424.
(144) Robert, J. L.; Aubrecht, K. B. Ring-Opening Polymerization of Lactide To Form a Biodegradable Polymer. J. Chem. Educ. 2008, 85 (2), 258.
(145) Tillman, E. S.; Roof, A. C.; Palmer, S. M.; Zarko, B. A.; Goodman, C. C.; Roland, A. M. Synthesis of Chromophore-Labeled Polymers and Their Molecular Weight Determination Using UV-Vis Spectroscopy. J. Chem. Educ. 2006, 83 (8), 1215.
(146) Iler, H. D.; Rutt, E.; Althoff, S. An Introduction to Polymer Processing, Morphology, and Property Relationships through Thermal Analysis of Plastic PET Bottles. Exercises Designed to Introduce Students to Polymer Physical Properties. *J. Chem. Educ.* 2006, 83 (3), 439.

(147) Chen, Y.-H.; Yaung, J.-F. A Polymer in Everyday Life: The Isolation of Poly(vinyl alcohol) from Aqueous PVA Glues. An Undergraduate Chemistry Experiment. *J. Chem. Educ.* 2006, 83 (10), 1534.

(148) Donahue, C. J.; Exline, J. A.; Warner, C. Chemical Recycling of Pop Bottles: The Synthesis of Dibenzyl Terephthalate from the Plastic Polyethylene Terephthalate. *J. Chem. Educ.* 2003, 80 (1), 79.

(149) Matyjaszewski, K.; Beers, K. L.; Metzner, Z.; Woodworth, B. Controlled/Living Radical Polymerization in the Undergraduate Laboratories. 2. Using ATRP in Limited Amounts of Air to Prepare Block and Statistical Copolymers of n-Butyl Acrylate and Styrene. *J. Chem. Educ.* 2001, 78 (4), 547.

(150) Williams, K. R.; Bernier, U. R. The Determination of Number-Average Molecular Weight: A Polymer Experiment for Lower-Division Chemistry Students. *J. Chem. Educ.* 1994, 71 (3), 265.

(151) Dunnagan, C. L.; Gallardo-Williams, M. T. Overcoming Physical Separation During COVID-19 Using Virtual Reality in Organic Chemistry Laboratories. *J. Chem. Educ.* 2020, 97 (9), 3060−3063.

(152) Destino, J. F.; Cunningham, K. At-Home Colorimetric and Absorbance-Based Analyses: An Opportunity for Inquiry-Based, Laboratory-Style Learning. *J. Chem. Educ.* 2020, 97 (9), 2960−2966.

(153) Lopez-Ruiz, N.; Curto, V. F.; Erenas, M. M.; Benito-Lopez, F.; Diamond, D.; Palma, A. J.; Capitan-Vallvey, L. F. Smartphone-based simultaneous pH and nitrite colorimetric determination for paper microfluidic devices. *Anal. Chem.* 2014, 86 (19), 9554−62.

(154) Koshut, W. J.; Arnold, A. M.; Smith, Z. C.; Wright, Z. M.; Sydlik, S. A. Teaching Polymer Theory through the Living Polymerization and Characterization of Poly(methyl methacrylate) and Poly(butyl methacrylate) Homo- and Copolymers. *J. Chem. Educ.* 2019, 96 (5), 895−904.

(155) Poche, D. S.; Russo, P. S.; Fong, B.; Temyanko, E.; Ricks, H. Teaching Light Scattering to Reinforce Basic Principles. *J. Chem. Educ.* 1999, 76 (11), 1534.

(156) Matthews, G. P. Light scattering by polymers: Two experiments for advanced undergraduates. *J. Chem. Educ.* 1984, 61 (6), 552.

(157) Izutani, C.; Fukagawa, D.; Miyasita, M.; Ito, M.; Sugimura, N.; Aoyama, R.; Gotoh, T.; Shibue, T.; Igarashi, Y.; Oshio, H. The Materials Characterization Central Laboratory: An Open-Ended Laboratory Program for Fourth-Year Undergraduate and Graduate Students. *J. Chem. Educ.* 2016, 93 (9), 1667−1670.

(158) Zare, R. N. On the Love of Teaching and the Challenge of Online Learning: A Few Reflections. *J. Chem. Educ.* 2000, 77 (9), 1106.