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How Should Chemistry Educators Respond to the Next Generation of Technology Change?

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Abstract: Chemical educators are facing a new generation of instructional technologies that impact classroom teaching. New technologies, like smartphones, cloud computing and artificial intelligence take learning beyond the classroom; 3D printing, virtual reality, and augmented reality provide new ways to teach the virtualization skills that are important for chemists. These technologies cause students to become more isolated, so students may not develop the social skills that they will need for today's workplace. Individualized learning may be beneficial to many students, but it will create challenges for faculty. Although this article focuses on chemistry education, it should be apparent that a similar argument could be made for other sciences, like physics and biology.

Keywords: augmented reality; artificial intelligence; badges; Big Data; blockchain; cloud computing; micro-credentials; microlearning; 3D printing; personalized learning; smartphones; virtual reality

1. Introduction

Chemical educators are facing a new generation of instructional technologies that impact classroom teaching. These technologies cause students to become more isolated, so students may not develop the social skills that they will need for today's workplace. Thus far, new computing technologies have had less effect on the college classroom than might have been expected. The types of technology that have been most widely adopted are those, like streaming lectures, PowerPoint and clickers, that fit best into the conventional lecture paradigm. Even Massive Open Online Courses (MOOCs) have often evolved towards a more lecture-like format (commonly called xMOOCS) than had been envisioned by Siemens and Downes when they created the first MOOC (now called cMOOCs) [1]. The lecture model persists, especially at the introductory level. By contrast, technology has dramatically changed the chemistry teaching laboratory. Much of the time that was formerly devoted to "wet labs" has now been taken over by instrumentation, and these instruments are often controlled by computers. Analytical techniques that were once found only in industrial labs, like NMR, mass spectroscopy, and gas chromatography, are now a standard feature of most college laboratories.

A new generation of instructional technologies is becoming available that focuses on individual student experiences. Each technology is being pursued separately, but there is a need to examine the aggregate effect. This may give fresh impetus to the use of cooperative learning and also require new forms of pedagogy. This article is not intended to be an in-depth review of these new classroom technologies. Rather it is hoped that by briefly examining them as a group it will be apparent that a new type of learning environment is emerging.

The thesis is that some new technologies focus on individual students and thus will probably require educators to place more emphasis on developing social skills. This discussion will emphasize technologies that satisfy two criteria, those that are mainly used by individual students rather than groups, and technologies that are already being discussed in the chemical literature. It should also be noted that although some of these technologies are still in the early stages of development, their eventual promise seems clear. Although this article focuses on chemistry education, it should be apparent that a similar argument could be made for other sciences, like physics and biology.

2. Smartphones in the Classroom

One of these new technologies that is already having a significant impact on most classrooms is the smartphone [2], although some faculty may argue that it has been more of a distraction than an asset. The modern smartphone is not only a powerful portable computer but also has become a personal assistant for communications and storing information. It can deliver personalized lessons, be the basis for student collaboration, be used to assess student learning, and give students access to the World Wide Web (WWW), where they can find information about almost any topic that interests them. Of course, not all of this information on the WWW may be accurate, so there is a need to balance ubiquitous learning with information literacy so the user can separate the wheat from the chaff. Many students use the smartphone camera to make videos of demonstrations, to copy complex diagrams from the blackboard or screen, and to copy notes from friends when they miss class. The main faculty complaint about smartphones in class is that some students are more likely to communicate with friends or play online games than to pay attention to the lecturer or the other students around them. Some teachers would argue that the current generation of students has a shorter attention span than was the case in the past. Watching a young person play a game on their computer or smartphone suggests that their attention span is adequate when there is sufficient stimulation. Integrating smart devices into the learning process seems more productive that a futile attempt to ban them.

3. Cloud Computing and Artificial Intelligence

The usefulness of the smartphone is being enhanced by combination with two other new technologies, artificial intelligence and cloud computing. Artificial intelligence (AI) is the use of computer programs to perform tasks, like speech recognition and decision making that normally require human intelligence. The addition of AI programs, like Siri, to a smartphone creates a true personal assistant that can provide access to information whenever and wherever it is needed, maintain a personal calendar, and even create reminders of future events, like exams or meetings. Siri will already answer simple chemistry questions, and several companies are developing AI-based laboratory assistants that take hands-free notes or dictate laboratory procedures [3].

The combination of the portability of a smartphone with the processing power and data storage of the cloud is called mobile cloud computing (MCC). Cloud computing uses off-campus data centers to provide computing resources only as needed. This is financially advantageous because the campus no longer has to pay for and maintain expensive hardware on site. Using a cloud provider, like Amazon, Google, or Microsoft, means that when the computer access is no longer required the campus no longer needs to pay for it, and the staff who would normally maintain the on-campus systems can be reassigned to other tasks. The obvious use of cloud computing is data storage and sharing, which makes it an excellent platform for student and faculty collaboration in different departments or even different campuses [4]. Students can electronically submit assignments, have them graded, and returned using the cloud. Despite initial hesitation, even drug companies are moving to the cloud in order to deal with the large volume of data being produced and the need to share data among different locations [5].

Connecting a smartphone to the cloud gives students individual access to computer programs, like chemical simulations and molecular modelling, which require more processing power or memory than is available in a smartphone. An instructor can design a specific computing environment in the cloud with multiple pieces of software for a course, which means each student will only have to sign in once instead of accessing multiple separate programs. Cloud computing allows students to work on individual projects independently but report their results in a way that makes it easier for an instructor to keep track of them. Bennett and Pence have used the cloud in this way to manage the data from an undergraduate laboratory or research [6].

4. Learning Analytics

The extra storage made available by the cloud is useful in cases where the amount of data collected, the speed with which the data must be collected or processed, the need to do real-time monitoring of large sensor arrays, or the complexity of the data requires special handling [7]. This process, called Big Data, is made possible by the decreasing cost and increased availability of computer processing power and computer memory. On the college campus, Big Data is combined with artificial intelligence to create academic analytics, which mainly deals with administrative functions, and learning analytics, which uses educational data to support student learning. This discussion will focus mainly on learning analytics, since that directly affects students in the classroom.

Learning analytics is used to customize the student experience based on his or her abilities, interests, and goals. Artificial Intelligence (AI) tutoring systems can create an individualized course of instruction based on each student's abilities and interests and can monitor the emotional state of learners, changing the program if the students become bored or confused. AI assisted learning can give more challenging problems to students who have mastered the basic concepts but also offer more review for those who are having trouble with the material. Students can decide what courses to take, informed by the wealth of institutional information about how similar students have performed in courses being considered and what remedial work might be needed before attempting a particular course. Learning analytics makes it possible for students and professors to receive immediate feedback on progress and to suggest to students how they can improve their learning.

Maseleno writes that learning analytics can create a personalized learning environment, which allows students to design their own education program while making them more responsible for monitoring their own progress [8].

The combination of artificial intelligence with Big Data is becoming a critical tool for chemical research. Artificial intelligence uses Big Data sets to create computer algorithms to perform tasks that normally require human cognition. AI powered teaching assistants can answer many straight forward student questions, freeing the instructor to answer more complicated problems or give special help [9]. Cloud-based artificial intelligence programs can analyze scientific databases to find correlations that humans might not recognize. Peiretti and Brunel argue that AI is the future of organic chemistry [10] and Yang et al. have discussed the current status of the use of AI for drug design and discovery [11]. This technology shows great promise for chemical researchers and some educators are already introducing these techniques into undergraduate courses [12].

5. Virtual Reality and Augmented Reality

Another group of technologies, virtual reality, augmented reality, and three-dimensional printing, is showing promise at helping individual students improve their visualization skills. One of the reasons students find chemistry to be a difficult subject is that it requires their thinking to shift rapidly among the macro level (experiments and experience), the sub-micro level (electrons, atoms, and molecules) and the symbolic level (formulas, equations, and computer models), Johnstone's famous chemical triplet. Although the triplet idea has generally been accepted, the specifics have been modified by various authors [13]. Trying to visualize three dimensional molecules and reactions can be difficult, but this skill is essential to understand stereochemistry, molecular structure, and reaction mechanisms. There are now new ways to teach students to visualize three-dimensional structures.

Virtual Reality (VR) uses computer technology to make an individual student feel that he or she is actually inside of a simulated environment. Virtual reality can be accomplished either by viewing on a computer screen, like the virtual world called Second Life [14], or with a heads-up display that can be as simple as a smartphone mounted on a cardboard support or a more expensive headset specifically designed for VR [15]. Either mode of virtual reality creates a sense of presence, the feeling that one is actually in the virtual space. Thus, virtual reality can give students a unique perspective on what the world looks like at the molecular level, but also tends to make the student less connected to the real world.

VR can also be used to have a student experience environments and instrumentation that would be too expensive or too dangerous to encounter in real life. A student can seem to be at the molecular size watching two molecules react, can appear to use research-grade instruments, or can perform a dangerous chemical reaction that is actually being done by a trained professional. For example, Bennie et al. found that a virtual reality program was a better learning environment for visualization than traditional approaches such as molecular models, textbook images, and the computer-screen to teach enzyme kinetics [16]. Virtual reality also offers a way to provide a form of laboratory experience for online courses [17], and Fung et al. found that using a virtual reality field trip for their environmental chemistry course was more convenient and less costly than its physical equivalent but produced comparable results [18].

Augmented reality (AR) consists of adding links to pictures, videos, or text onto the image of some real object on the screen of a computer or smartphone. There are various ways to trigger the augmented reality connection, but a QR (Quick Response) code is the simplest and probably the most often used. Smartphone-based AR systems can create computer simulations, games, models, and virtual objects that create learning environments in both formal and informal settings. AR is not as immersive as virtual reality, but it is much easier to introduce into the classroom. Photomath is an interesting example of augmented realty smartphone application that uses a photo of an algebraic equation to solve the equation and even shows each step in the process to help students learn algebra.

Simply adding a QR link to an object creates a smart object, which will display text and images to anyone with a smartphone that has a QR reader. For example, adding a QR code to a scientific instrument means that someone who wishes to use the instrument can view a video showing instructions for the instrument. A student can access this tutorial whenever he or she needs it instead of waiting for an instructor to gather the class for group instruction. Creating the videos and QR codes is so easy that students can do this with little supervision [19]. Augmented reality can also be used to link to simulations of laboratory experiments, such as a colorimetric titration [20], so this might be another way to provide the laboratory experience for online learning.

Both virtual reality and augmented reality will be greatly enhanced by the availability of 5G connectivity, which is becoming the new standard for mobile communication, and is the new level of mobile internet connectivity that is just now being implemented globally with speeds up to 20 times as fast as 4G systems, more stability, and greater bandwidth. The 5G systems will allow higher definition video and faster download speeds, which should give AR and VR faster refresh rates and a greater sense of the user actually being present in the environment.

6. Three-Dimensional Printing

It is now possible for an individual to create personal physical models with 3D printing. This is an additive manufacturing process in which an object is produced layer by layer from a digital description of the object to be modelled. Three-dimensional printers have become relatively inexpensive and atomic coordinates for many molecules are available from sources such as the Protein Data Bank. For example, Fourches and Feducia have successfully used 3D printing in organic chemistry lecture sections of at least 200 students to improve their students' ability to visualize molecules in three dimensions [21]. They had their students convert the chemical structure of a molecule of their choice into a three-dimensional object and then print it in the makerspace of their library. Even though this was the first time many of these students worked with 3D printing, the overall results were encouraging. Grumman and Carroll had their students use 3D printing to create space-filling models of electron-density iso-surface models and high-resolution molecular models [22] and Blauch and Carroll have used 3D printing to create potential energy surfaces for the teaching of structure-energy relationships [23]. Three-dimensional printing can help people who are blind or partially sighted to visualize three-dimensional objects, like complex molecules, by handling the models.

7. Micro-Learning

Another way to introduce new technologies into existing courses is by a technique called micro-learning. Micro-learning consists of relatively narrowly focused learning units on a single topic that are short-term activities (5 to 15 min) often presented on personal devices, like smartphones or tablets. These learning units can be inserted into a traditional course format or assigned for out-of-class work. In either case, there should be a social component where students share what they have learned with each other. Micro-learning is based on the idea that students remember information better when it is presented in small chunks, especially when it is followed by reinforcement.

Some educators are already experimenting with micro-credentialing using badges or certificates to supplement traditional academic transcripts. These types of credentials give potential employers a more granular understanding of what prospective employees know. Townes et al. used badges in the analytical chemistry course to identify the mastery of basic laboratory skills, such as pipetting, reading a burette, or making solutions with a volumetric flask [24]/ Mellor *et al.*, used badges in the green chemistry course to teach chemical safety [25].

8. Personalized Learning

Taken together, this group of learning technologies creates a level of personalized learning that would be difficult to achieve even with one-on-one tutoring. Personalized learning, defined here as providing a learning environment that is designed to support the aptitudes, interests, and goals of each student, has become the current buzz word in instructional technology. Some educators argue that personalized learning will improve student learning and retention because it adapts to the needs and abilities of each student. Student retention is a critical issue on many campuses, and any change that promises to improve this measure will be seriously considered. Technology usually plays a major role in personalization, and technology leaders, like Bill Gates and Mark Zuckerberg, are providing millions of dollars to support this movement. Many states are adopting personalized instruction at the K-12 level, and it is often cited as an advantage of virtual schools and on-line learning programs.

Personalized learning will be difficult to evaluate using the traditional course transcript taken as the official record of a student's accomplishments. Each of the technologies described above allows students to create a unique set of learning goals. This means that all of the students completing a course may not have been taught the same skills. In addition, some colleges are supplementing their classroom activities with MOOCs that are available for free on topics ranging from atmospheric chemistry to nanotechnology. Three students may have taken the same instrumental analysis course, but one has completed a MOOC about instrument electronics, another has worked on a VR simulation of a type of instrument that is not physically present on the campus, and a third may have done only the minimum work required. This can represent a problem for the instructor if he or she is expected to be an expert in everything that the students are learning.

The available research about the effectiveness of personalized learning is ambiguous, so the effectiveness of personalized learning is still being debated [26]. In addition, personalized learning often consists of students working alone on computers. This ignores the need for social development. Chemical research and industrial chemistry today are often collaborative efforts, and so chemical education must include opportunities, like cooperative learning, for students to develop the social skills necessary for working with a group. Many educators fear that the push towards personalized learning is really an effort by technology firms to conduct a data mining project on young people.

9. Conclusions

There is clearly a need to prepare for change. The new learning technologies described above focus more on the individual experience than on group activities. These technologies make it all too easy for a student to become socially isolated even though in the midst of his or her peers. Educators will need to integrate social constructivism with these types of technological advances. Just as was the case with electronic calculators and smartphones, the immediate tendency for some may be to ban new technologies from the classroom. This will be even more difficult than was the case with these new technologies. Each new generation of students is becoming more technologically sophisticated, and they will expect their undergraduate courses to reflect the world they encounter every day. It will be a challenge to create teaching strategies that will use these technologies but also encourage the interpersonal involvement that will prepare students for the collaborative work environments that they will encounter in the modern workplace.

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