21st Century Chemical Education

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Abstract

Chemical education is facing a number of significant challenges in the 21st Century. There are demands to include more online learning, new learning techniques, such as flipped classrooms and POGIL, to implement personal and institutional learning analytics, and, of course, to respond to problems with enrollment and funding. This paper focuses only one of those challenges, how technology is changing industrial chemistry and chemical education.

Introduction

Chemical education is facing a number of significant challenges in the 21st Century. There are demands to include more online learning, new learning techniques, such as flipped classrooms and POGIL, to implement personal and institutional learning analytics, and, of course, to respond to problems with enrollment and funding. George Whitesides even argues that in order to remain relevant chemical research must focus more on the crucial issues that currently face our society.[1] Presumably Whitesides' proposal would also affect chemical education. This paper will focus on only one of those challenges, how technology is changing industrial chemistry and chemical education.

How Technology is Affecting Industrial Chemistry and Research

After 50 years, Gordon E. Moore's prediction is still roughly accurate, that every two years the computer chip makers produce twice as much computing power for only slightly more money.[2] Similar trends are affecting digital communications and storage. The World Wide Web (WWW) is changing the way that chemists access information as well as creating new potential for their communication and collaboration. New types of digital tools continue to proliferate, especially mobile devices, like smartphones and tablets. The Internet of Things (IoT) and 3D printing seem poised to revolutionize the traditional methods of chemical research and production. The Internet is even changing the chemical literature and how people apply for scientific jobs.

Technology is significantly affecting the practice of chemistry in research and industry. Globalization of research and rapid communications by means of the Internet makes it possible scientists across the world to cooperate with each other. A job in biotechnology research may require a organic chemist in this country to plan the synthesis of a potential new drug which will be performed by a team of synthetic chemists in China who will actually do the synthesis. The work may be funded by a pharmaceutical company in Europe. Each of these participants must constantly share information by means of electronic laboratory notebooks or Laboratory Information Management Systems (LIMs) rather than the traditional hardcopy notebook.

Mobile devices are having a significant effect on the chemical industry. Nayak writes that, "Mobility solutions have changed the working environment of the chemical companies. It has improved the working style of the entire supply chain, procurement, and sales department.[3]" .Mobile devices are allowing organizations to stay connected in real time and become more productive. If this is the environment that young people will experience when they transition from the classroom to the workplace, they should experience s similar environment when they are trained in colleges and universities.

Whereas in the past, scientists could keep up with their research field by reading a few key journals, the proliferation of specialized scientific journals has changed the behavior necessary for current awareness. This deluge of data has affected the way scientists read journals.[4] It has become an essential skill to quickly browse an article to extract the crucial information as rapidly as possible. Another way that researchers also try to follow the latest news about a topic is by setting up some type of automated current awareness, like a RSS (Real Simple Syndication) feed.[5] This problem seems likely to become worse in the future as the amount of information available continues to expand. There is even software available, Quill, that claims it will summarize a set of scientific results and , ". . . create perfectly written narratives to convey meaning for any intended audience.[6]" If it becomes feasible for computers to create scientific articles with little or no human intervention, this will only increase the flood of information and make it more difficult to keep up.

When chemistry journals and databases first went online, many of them were subscription-only services that did not connect with each other. More recently, there has been a rapid development of online, open-access resources. The Directory of Open Access journals lists over 361 journals related to Chemistry,[7] and Apodaca has provided a listing of 64 large, open-access databases of chemical information.[8] These sources contain a wealth of information about hundreds of thousands of compounds. Many of these resources can be connected with each other by Application Programming Interfaces (APIs) to create a new way to work on the Internet.[9] Connecting multiple sources can give users a broader range of information about chemicals and their reactivity than is possible with any single source.[10]

Advances in digital technology have created small, inexpensive sensors that can be combined with data collection and communications software to create a new type of integration between the physical world and the computer. These systems are called the Internet of Things (IoT) or the Internet of Everything. As these types of systems are deployed, everyday objects ranging from cars to scientific instruments can constantly provide status updates to their owners. This information can be accessed through a smartphone or a similar device. The chemical industry is already looking to integrate the Internet of Things into their processes, and Guertzgen lists some examples of how IoT is being used.[11] Andrew Chatha, a consultant to the industry, recently said, "Our consumer smartphones represent the ultimate connected devices and now is the time to bring this type of technology to the industrial world.[12]" The same should be true for the world of education.

Another potential game changer for research and industry is 3D printing (sometimes called additive manufacturing). Rick Smith predicts that soon customers will be able to create custom products on their personal 3D printers. These products might be medical devices made of human cells or micro and nano-sized objects, including batteries no bigger than a grain of sand.[13] Smith even predicts that the combination of 3D printing's unlimited shape and material customization with powerful computing will lead to the solution of design problems that are currently beyond human capabilities. According to a recent report on 2015 Chemical Trends, 3D printing is one of the digital transformations that will not only enable chemical manufacturers to make customized parts to better meet changing customer requirements but also require chemists to develope new materials with special properties designed for the printing process.[14]

Many chemical companies are at an early stage of implementing these new technologies, but that is no reason for complacency among chemical educators. Industrial firms can move relatively rapidly when confronted by the need to remain competitive; education moves much more slowly. It will be a long-term challenge to redesign the chemistry classroom environment to align with the changes that graduates will encounter when they enter the workplace of the 21st Century.

The job market is in flux in most fields, and Chemistry is no exception. It seems unlikely that computer automation and robotics will drastically affect the job market for chemists during the coming decade[15] , but the combination of off-shoring and consolidation of research laboratories due to mergers and acquisitions will probably mean that few chemists can assume their jobs are secure. Churning of the job market will change life-long learning from a platitude to a necessity. Students graduating today will face the challenge of continually retooling to maintain the up-to-date skills required to adapt to a rapidly changing work environment. Once in the workplace these students will find that the best way to maintain their skill levels while remaining on the job will be through online classes, MOOCs, and new forms of social networking. Today's graduates should have had some experience with these online training sites and be able to evaluate which are the best.

How Technology is Affecting Chemical Education

Today's chemical educator is faced with a plethora of new educational technologies. The challenge will be to identify and implement those technologies that will create the greatest improvement in learning. Humans tend to accept the devices they grew up with and not really think of them as technology. Thus, the classroom becomes a conflicted arena where the expectations of each new generation of students are disputed by older faculty who feel uncomfortable with the technology that the students routinely accept. Even younger teachers who have grown up since the computer revolution may find they sometimes have difficulty adjusting to a constantly changing technology environment.

For many teachers the most obvious concern about technology in their classrooms is the fear that their smartphone-using students will become wrapped up in a digital cocoon that pulls them away from the present reality towards relationships with a multitude of digital stimuli that can be more appealing than even the best lecture or activity. The worry is that a class may become just a collection of isolated and distracted individuals rather than a group focused on the lesson of the day. This concern has led some instructors to attempt to ban digital devices from the classroom.

Students today are becoming accustomed to a multiscreen world.[16] Three years ago a study by the Pew Research Center found that 52% of those who had smartphones used multiple screens when they watched television.[17] It seems inevitable that these practices will transfer to education. The arguments against multitasking are well known, but there is also some research suggesting that, ". . . those who frequently use different types of media at the same time appear to be better at integrating information from multiple senses when asked to perform a specific task.[18]" Kay summarizes his discussion of whether or not to multitask by saying, "Multitask where you can, task switch when you have to, and focus on the job at hand as much as possible for the best results." It would appear that a new type of educational environment is evolving, dictated more by student practices than by any traditional educational theory.

Student behavior in the classroom is being affected by both multitasking and multitooling. Some students attempt (or at least pretend) to listen to the lecture while checking social networks, playing online games, or listening to music. This form of multitasking does not work well. On the other hand, a few students are using note taking programs, like Evernote or Notability, to take pictures of the screens and/or blackboards, annotate the result with comments by the professor or their classmates, look up unfamiliar concepts or words on the World Wide Web, and even use Twitter to engage in backchat that is related to the material. This is a multitool approach to a single task. Thus far, multitooling has been limited by classroom policies intended to discourage multitasking, but more students are beginning to explore these possibilities in their everyday lives.

The smartphone is not just a source of distraction but also a versatile educational device. A smartphone user holds the equivalent of a major research library in the palm of her hand; teachers integrate this capability into classroom work. For many students the smartphone has partially or totally replaced their use of the library. The smartphone camera has become an important educational device, which students use to store classroom notes, capture interesting demonstrations, record experimental results, or obtain notes from a class that they missed. It is possible to convert a smartphone into a 375 power microscope,[19] or a useful colorimeter.[20]

The first generation of smartphone personal assistants, like Siri, Google Now, and Amazon Echo, is already widely accepted, and it seems probable that future iterations will become even more powerful. The next step may well be based on the combination of the smartphone with the semantic web[21] to create intelligent software agents that will serve as personal learning content mediators. These software agents will analyze the learning goals and abilities of the individual phone user and suggest content from the Web that is specifically designed to support his or her needs and interests. Sparrow *et. al.* have found that individuals already use a smartphone as an external memory that complements and expands the person's working memory.[22] Using a smartphone as a learning support is the next step beyond using a smartphone as an auxiliary memory.

There is little likelihood that smartphones are going away; teachers must either integrate them or endure them. Attempts to play King Canute and push back against the rising tide of digital devices may become even more problematic if wearable technologies become popular. Several professors have already reported on interesting ways to make smartphones an integral part of the learning environment rather than a distraction. Rheingold has chosen to focus on ways to help students recognize and resist the temptation for continual partial attention.[23] Wijtmans *et. al*. have discussed using electronic devices to improve student's interest in lectures.[24] Libman and Huang have cataloged the various apps that can be useful in Chemistry classes.[25] A web site called Socrative allows students who have any web-enabled device to use their own device as a response system in lecture.

Personalization is often hyped as a benefit of digital technologies, but it also represents a potential problem. Technology now makes possible the personalization of everything from cars to dress shirts to handbags, and many companies are allowing consumers to design their own unique products.[26] For some time now, Google has been providing personalized search results that are based on the past behavior of an individual.[27] Individuals can personalize their information management tools to create Personal Learning Environments.[28] A quote from a recent advertisement summarizes the industrial response, "Businesses must now cater to a market of one, and each individual customer now needs to be understood and appreciated for their unique needs.[29]"

In education, the move towards personalization is reflected by proposals to use badges, certificates, or "nanodegrees" to recognize the mastery of specialized, narrow skills. Blumenstyk argues that these types of credentials may well be more useful to potential employers than traditional college degrees.[30] Nonprofits, corporate groups, and businesses are beginning to certify specialized student skills with badges or similar recognition, and some colleges are beginning to follow suit. The modern economy requires technical employees to constantly master new skills in order to remain employed. Alternative forms of certification are a potential way to represent these special talent s. So far, this development has been limited by the lack of a coordinated system to evaluate these providers, but this is changing rapidly.

It will be a challenge to introduce more personalization into college programs that were designed for the age of mass production. Educators like to view education in a holistic way, as consisting of a combination of courses in a major, augmented by a general education core to create breadth of knowledge. Even narrowly focused programs, like engineering or pharmacy, prefer to think of their programs as representing a set of courses that are designed to complement each other and create an integrated experience.

Some would argue that it is inappropriate for a liberal education to also provide specialized skills useful in the workplace. It would be better if higher education develops these specialized skill measures in combination with traditional liberal learning rather than leaving the field to organization s that are purely vocational. Even so, it will require a major shift in thinking for colleges to move from a funding model based on credit hours and seat time to giving credit for what were previously single courses or even partial components of courses. If higher educational is unable to meet these requests it is likely that less conventional educational groups will fill the void by becoming alternative forms of accreditation.

Digitization has given new life to an old instructional medium, video. Videos have always promised to add a visual component to teaching that allows students to see rather than just imagine the real world using demonstrations, simulations, and animations. Until recently, creation of effective videos required a well-staffed studio; the set-up in the classroom often consumed more time than the actual presentation; and students normally saw the presentation only once. Now, students can use their smartphones to access free, online sites, like the Kahn Academy and YouTube, which provide access to a multitude of instructional videos on almost every topic imaginable. In the past, videos often were reduced to somewhat boring talking heads. Now videos have become the central enabling tool for online classes, MOOCs, and flipped classes. Scientific journals have been somewhat slower to embrace video, but there is an entire science journal dedicated to video articles.[31]

It is probably still too early to predict the eventual impact of 3D printers on the classroom, but the price of these units is already low enough to allow them to be purchased by high schools and grade schools.[32] One obvious application is the creation of custom designed molecular models. Model kits are now commonly required in organic classes, but 3D printers allow students to inexpensively create accurate physical representations of not only molecular models but any three dimensional objects. Using recycled plastic from PET bottles and designs from sites like Thingiverse it is possible to make models ranging from laboratory equipment to complex crystal structure.[33] The National Institute of Health is developing a 3D print exchange, which will provide 3D printing files for free.[34] Since traditional chemical models commonly sell for hundreds of dollars each, it will only require making a few of these to justify the cost of a 3D printer. Rossi *et. al*. (and references therein) have described some uses of 3D printers in chemical education.[35] Once each student can make personal structures, it may also create news ways for them to visualize chemical reactions.

Digitization is also affecting traditional journals and books. Digital information is not fixed by a physical medium and may change at any time. The classic example is, of course, Wikipedia, the encyclopedic information source that seems to be in a continuing state of transition. Traditional educators are unaccustomed to the idea that information may change while one is looking at it. The activity of creating and sharing new knowledge is no longer limited to those with specialized training. Increasingly, faculty, students, and even non-professionals are contributing to blogs and online databases, like PubMed and Chemspider, that depend upon the crowdsourcing of information to keep the site current.[36] New knowledge is being disseminated at a pace that is breathtaking compared to the tempo of traditional publishing. The resulting democratization of knowledge creates new opportunities for students to be not just consumers but also creators of knowledge. Young people are not only willing to apply their talents to create educational sources but often seem enthusiastic to be asked.[37]

One educational medium that is still in the early stages of development is virtual space. For example, some chemists have created laboratory teaching spaces in the virtual world called Second Life.[38] Despite this, truly virtual worlds do not seem to have become popular with most educators. The use of augmented reality seems more successful, perhaps because the user remains grounded in the real world, and this makes it seem more familiar. For example, QR codes and augmented reality can be combined to create smart instruments that will provide video instructions to a potential user without the need for a physical instructor.[37] Instruction in a virtual space can be both inexpensive and convenient, especially for adult learning, and so it will not be surprising if these initial exploratory efforts are expanded, perhaps in combination with the badge and certification programs mentioned earlier.

As the above discussion indicates, a profusion of new technologies is becoming available for chemical education. Some offer valuable educational benefits; some should be implemented to align academic chemistry with industrial practice; and all of them require a re-examination of the way that chemistry is taught. Normally, education changes very slowly. It is a significant challenge to respond to all of these changes arriving at the same time, especially since there are also many non-technological developments that are also demanding attention. It would be difficult for chemical educators to adequately respond to any single one of the changes described above, but everything seems to be happening simultaneously. The future is arriving faster than expected and often faster than teachers can adapt.

Future Shock

It has been over three decades since Alvin Toffler coined the term Future Shock to describe the stress and disorientation that people encounter when technological change occurs too fast for humans to adjust.[39] In his book, Toffler discusses how education should respond during a time of rapid technological change (pgs. 398-427). He argues that as long as the future is going to be similar to the present, the structure of education can be more oriented to the past and present, but in order to prepare for a world that will be much different than the present, education must focus more on the future. He suggested that teams of men and women (including students and advisors currently in the workplace) should develop "assumed futures" that can serve as a basis for identifying possible new directions for education. Even if these predictions are not totally accurate, Toffler suggests that teaching students to "think in the future tense" will make graduates better prepared to adjust to whatever the future may actually bring.

Today's young people are probably better prepared to think in the future tense than the youth of Toffler's time. Today's youth culture requires them to constantly master new technologies. They must learn to be continuous learners. Not all young people are facile with all technologies, but when a group of them encounter a new device or software there are always pathfinders who lead the way and then show the rest how to catch up. Many of today's students would probably welcome an opportunity to explore what the world of the future might bring.

Officials from State and National governments often argue that colleges and universities should prepare students for the jobs of the future. Unfortunately, they provide few suggestions (or governmental examples) about how institutions can accurately predict the future. Toffler would argue that the prime objective of education should be to 'increase the individual's 'cope-ability' - the speed and economy with which he or she can adapt to continual change. A more recent article by Slaughter agrees that Toffler's ideas had some impact at the time but that this response has now been largely dissipated.[40] Slaughter concludes that, "To read Future Shock 30 years on is to be struck by the disjuncture between the power of the vision and the poverty of means. Perhaps this disconnect is inevitable. Few people like to really think deeply about the future, and the current system is too deeply entrenched to happily accept change." The most important skill to teach students is the ability to adapt to an environment that is constantly changing. Living in the 21st Century will require one to not only continuously learn new ideas but also to unlearn those that previously been generally accepted.

A Modest Proposal

Suppose that each professor took five minutes during a semester to talk in class about some very recent development might be important in the coming decade. This discussion might focus on some specific topic in one of the chemical sub-disciplines, organic, biochemistry, etc. or it might deal with the disruption caused by one of the new technologies that have been discussed previously. Perhaps the teacher could hand out copies of an article from C&E News or some similar general science journal for students to think about. The goal would not be to accurately predict the future; few of us have the time or inclination to become Futurists. Rather the purpose would be to shift the students' horizons beyond the next test or even graduation day to help them think about what adjustments they are going to have to make as their careers progress.

Conclusion

Technology is by no means the only challenge that chemical education will face in the 21st Century. There may be so much political pressure connected to areas like employment training and online learning that the temptation will be to set technology aside for later consideration. That would be a mistake. It would be a disservice to our students and also a missed opportunity. The chemical industry will need the next generation of graduates to be prepared for a new and changing technological workplace. The real world is changing; education must also change. The purpose of this paper is to focus on only one of the challenges that is ahead and to initiate a discussion of how chemical educators might best respond to new situations.

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