COVER STORY

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Student, Teach Thyself

Conceptual integration and application of science and the increasing sophistication of technological platforms are revolutionising science education. Learning is becoming more and more self directed. Here is how.

WHAT do Srinivasa Ramanujan, Karl Marx, Charles Darwin and Buckminster Fuller have in common? They were all autodidacts, self-taught thinkers with little schooling, learning on their own. Some ongoing innovations and trends in the practice of science and education suggest that we are entering an age where this type of learning will become more widespread and more valued than formal education.

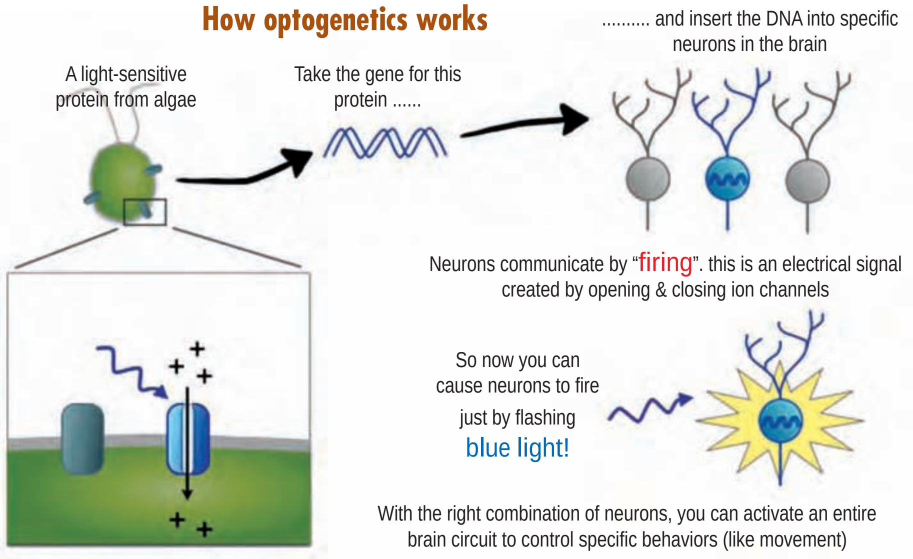
Let us take a look at some of these trends, and how each contributes to a shift to self-teaching.

Trends in Science Practice

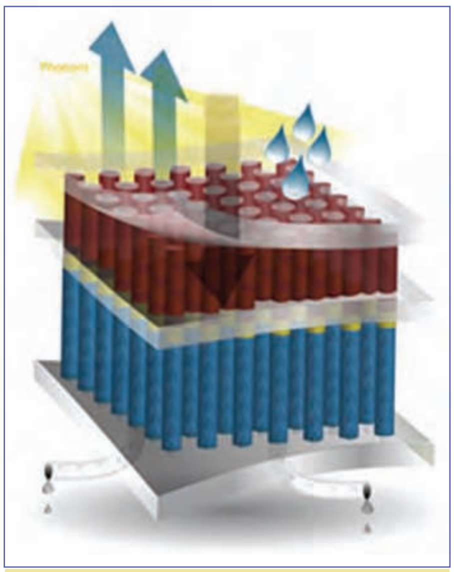
Interdisciplinary Problems: In many areas of current science a wide variety of techniques and methods, from many disciplines, are combined to attack problems that themselves span many disciplines. Examples include the application of control theory and graph theory to understand cell metabolism, statistical mechanics to understand computational complexity, tribology (the study of interacting surfaces in relative motion) to understand plant growth, the integration of optics and genetic techniques to understand the behaviour of neurons in real time (optogenetics), and the combination of electrical engineering, computer science, cognitive psychology, neuroscience, motor control and physiology to develop brain-computer interfaces that help stroke patients recover lost movements.

It is not possible for anyone to learn all these different disciplines and techniques in a classroom setting. Most students will learn one or two disciplines and their techniques, but based on this training, they will be expected to learn other techniques and disciplines on their own.

Engineering Sciences: The distinction between engineering and science is fast disappearing in some new areas of research, where interdisciplinary teams of engineers and scientists come together to tackle complex application problems. Many scientific discoveries are made in the process of trying to solve such application problems. This approach is very different from the traditional notion of engineering, where technology is built from translation of fundamental scientific research. The new



Left: (Source: http://www.rosslab.neurobio.pitt.edu/blog/optogenetics-mapping-neural-circuits/)



Conceptual drawing of an artificial photosynthetic system that uses only light, water, and carbon dioxide as inputs, and produces clean, renewable fuel.
(Source: http://solarfuelshub.org/research/)

problem-driven approach to science and scientific discovery is a common pattern in the new fields of bioengineering, neural engineering, systems biology and nano-engineering.

This way of combining science and engineering is encouraged by funding agencies as well. A good example is the Joint Centre for Artificial Photosynthesis, a $122 million project of the US Department of Energy, which seeks to "find a cost-effective method to produce fuels using only sunlight, water, and carbon-dioxide as inputs", bringing together scientists and technologists from a host of institutions (http://solarfuelshub.org/about-jcap).

Many of these new disciplines do not have basic textbooks, and it is difficult to write textbooks in these disciplines, as research in these areas spans many application problems. Since these are cutting-edge areas evolving very quickly, students trying to move into these new areas will need to be ready to do significant learning on their own.

Computational Modelling: Building and manipulating computational models is now a standard method in science, and this method plays many roles in scientific discovery. The following four factors have made the practice of building computational models more widespread, particularly in the biosciences and bioengineering.

1. The complex, non-linear, and dynamic nature of the problems in contemporary science, requires building computational models. For instance, in contemporary biology, it is almost impossible to develop detailed conceptual models of cellular and molecular-level interactions in your head, or using pencil and paper. This is because these processes: a) involve many levels of structure (organs to cells to molecules), b) occur across different time scales (cell signaling takes seconds, protein expression can take hours, circulation and organ growth takes days/weeks/years), c) evolve simultaneously, and d) involve many complex feedback loops.

2. Massive amounts of data are generated by experimental research work in many areas, such as high-throughput data in genetics, where thousands of measurements are made for a sample. The interactions among different variables are complex in such cases, and cannot be understood without modelling. Further, the technology that generates this data also relies heavily on embedded statistical models of the distribution of the data. Such large datasets, with embedded assumptions, usually require complex visualizations based on models, as they are difficult to represent, and understand, using simpler traditional representations such as graphs.

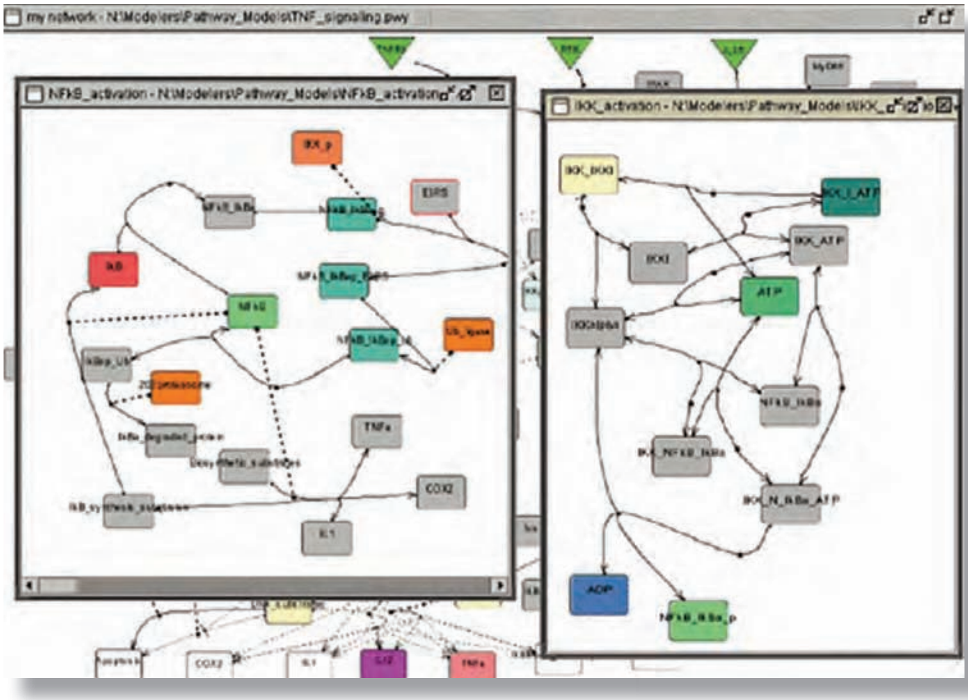
3. Data in biology are closely tied to context (e.g., specific cell lines, animals, diseases), and there is no theory that helps structure all these different and scattered types of data. Computational models bring these data together in a structured fashion, and help develop theory.

4. The development and easy availability of new technology that supports modelling and rapid prototyping has made modelling more widespread.

These factors, together with the technological resource environment of contemporary science, are driving the practice of building computational models. Earlier resource environments, where the only cognitive tools available were pencil and paper and the brain, saw the development of methods such as thought experiments and static models drawn on paper. These methods have served science well, but they required idealizing the problems to a high degree, as both the cognitive and data-collection resources were limited.

Finer methods and representational modes are needed to provide insight into the complex, dynamic and non-linear phenomena investigated by contemporary science. Massive amounts of data are available and the details are critical, so idealizing them is not an option.

It is worth noting that the rise of computational models derives partly from the limitations of analytic mathematical methods in solving complex systems problems. Interestingly, most of the computational models of such systems are 'opaque', in the sense that they can help scientists make predictions about the systems they model, but the complexity of the model makes it almost impossible to specify the mechanisms in detail. This opaqueness, along with the approximate nature of the numerical solutions, suggests that this is a new way of doing science.



The screen shots in the image from software application PathwayPrism showing the representation of the signalling modules nuclear factor- B (NF- B) and inhibitor of NF- B kinase (IKK) within the larger pathway of the signal-transduction processes that are involved in stress signalling. This representation is converted into a set of mathematical relationships that can be simulated to understand complex cell behaviour.
(Source: http://www.nature.com/nrm/journal/v3/n6/box/nrm810_BX2.html)

The self-teaching component of science learning will surely rise, and people who excel at this type of learning will be valued, and remunerated, highly by society.

The interesting point is that this way is not an option, but a requirement, given the complexity of the problems and the nature and availability of big datasets.

The techniques used for computational modelling are specific to a problem, and these techniques can be very complex, depending on the problem that is modelled. Currently, most modellers come from an engineering or computer science background, and collaborate with experimentalists to develop models. But as the method spreads, everyone doing science will need to do, and understand, modelling. This requires focused study of many modelling practices, and a significant amount of this study would need to be done on one's own, as modelling courses are not taught at the undergraduate level.

Game Science: An interesting new technique to solve complex problems is coupling the computational simulations with the visuo-spatial skills of a large number

'Hole in the Wall' Experiment Points to Self-driven Learning

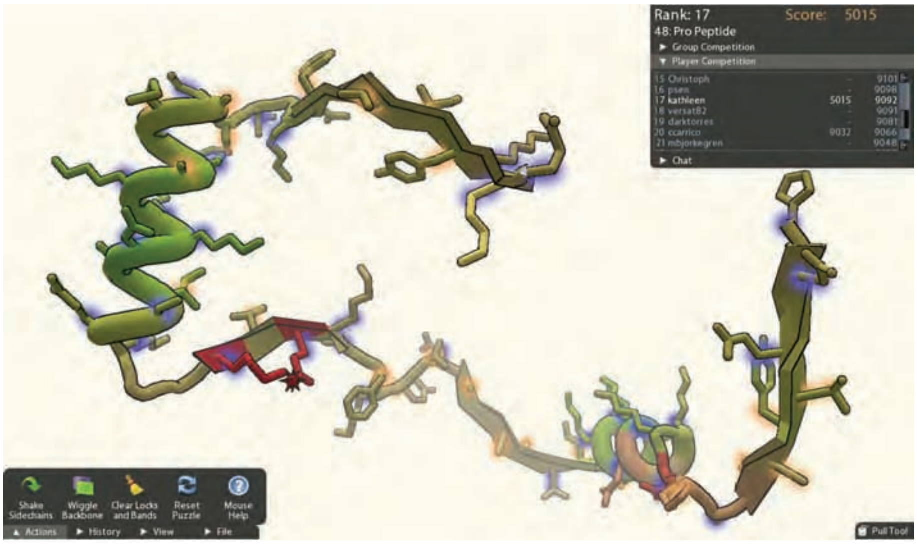
Dr Sugata Mitra, a Professor at the School of Education, Communication and Language Sciences at Newcastle University, UK, has been awarded with the first-ever TED prize in 2013. The TED Prize awards one million USD to an extraordinary individual with a creative and bold vision to spark global change. Dr. Mitra wishes to use his prize money to build a "School in the Cloud", a learning laboratory in India, where children can embark on intellectual adventures by engaging and connecting with information and mentoring through computers.

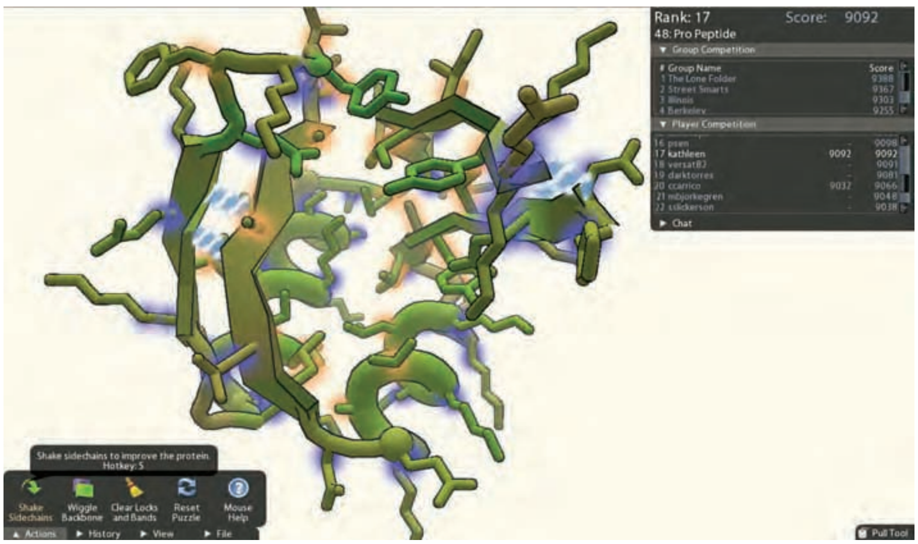
Dr. Mitra's research bolsters the main point of this article: learning is a self-driven phenomenon. As he puts in a succinct quote: "Education is a self-organizing system, where learning is an emergent phenomenon." This insight arises from the 'hole in a wall' experiments that Dr. Mitra has conducted around the world.

Dr. Mitra thought of his first 'hole in a wall' experiment when he used to teach people to write computer programs in New Delhi fourteen years ago. As the institute where he worked was located right next to a slum, he wondered if and how children living in the slum could learn to write computer programs. To answer the question, Dr. Mitra made a hole in the boundary wall separating his office from the slum and placed a computer there. About eight hours later, he found slum children browsing and teaching each other how to browse. This experiment was an eye-opener as it demonstrated that children could learn computer browsing even though they did not own a computer, know English or Internet browsing. Dr. Mitra repeated this experiment in a rural setting, only to be told by the slum children, "We want a faster processor and a better mouse"!

Based on several kinds of 'hole in a wall' experiments over the years (including ones that have taught slum children about DNA replication), Dr. Mitra contends that the present educational system is obsolete. Schools in India were set up by the British Empire in order to train people to become a part of their administrative machine. However, jobs of the future require the development of completely different skills, salient among which is the ability to teach oneself. In a computer-based environment, teachers play the indispensable role of encouragement and facilitation to train students in self-directed learning.

Learners around a "Hole in wall" computer. (Source: http://www.fastcoexist.com/1681483/ted-prize-winner-sugata-mitra-to-create-a-school-in-the-cloud)





Left: Unfolded (and unstable) Puzzle 48 (Source: http://fold.it/portal/info/about)
Left Below: Solved Puzzle 48 (Source: http://fold.it/portal/info/about)

The rise of citizen science, where the design of new media helps recruit large numbers of non-scientists to solve complex research problems, will accelerate this process.

of people. The modelling problem can be re-represented as a competitive video game that can be played by a large number of people over the Internet. The best example is the protein-folding video game called Foldit, which is played by around 200,000 people over the Web.

The game involves building novel protein structures, by pulling and pushing and turning the different strands of a protein model on the screen. In 2010, the builders of this game and the players together published a paper in *Nature*, where they argued that such "gamification" could help solve complex scientific problems. Some of the successes of Foldit include:

1. The emergence of a 13-year-old folding prodigy, Aristides Poehlman. The structures that Aristides created using Foldit were judged better than professional biochemists' structures, in an international protein folding competition, in the hardest category!

2. The Foldit gamers identified the three-dimensional structure of an AIDS-causing virus in ten days; scientists had been trying to identify this structure for nearly fifteen years. This result was published in *Nature Structural and Molecular Biology*.

3. The game is now being redesigned for developing possible drug molecules.

4. It has led to some spin offs. EteRNA is a game where players propose RNA folds, and every week the most promising folds from the gamers are synthesised by a Stanford laboratory, and the results fed back to the gamers, who use these results to improve the folds. They have made some fundamental discoveries on RNA folding this way. Phylo is another game that tries to solve the problem of optimising DNA sequences. EyeWire is a game from MIT where users propose how neurons are wired. Astronomy has a similar crowd-sourcing effort for classifying data from Hubble and other probes, named Galaxy Zoo.

5. The University of Washington, where Foldit was created, has opened a Centre for Game Science, which seeks to develop video games for both scientific discovery and science learning.

Such games give students an early entry into cutting edge science, and their contributions to the domain would be recognised through the game. Such games also present a participatory way to learn advanced concepts, as the community of players is very helpful, and include people with advanced degrees and knowledge of the area.

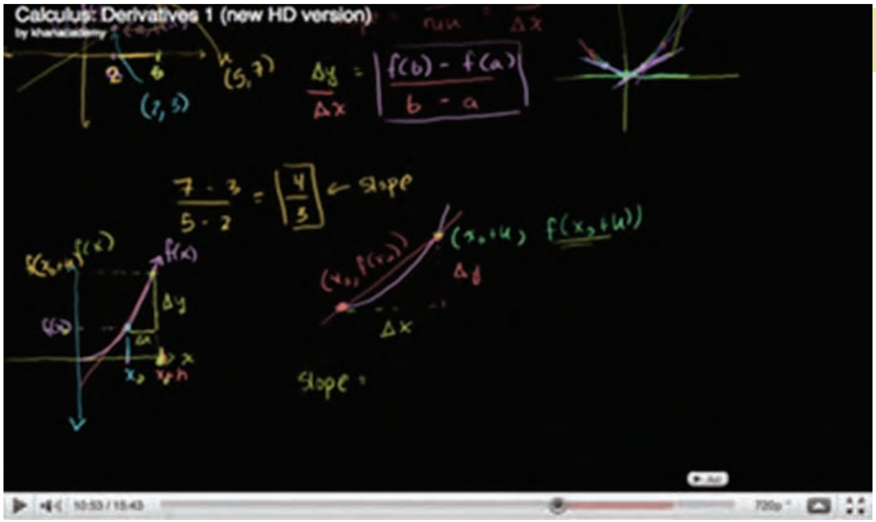
Biology as Paradigm Science: Biology is also increasingly studied as a source for ideas to develop technological solutions, an influential design approach known as biomimicry (http://en.wikipedia.org/wiki/Biomimicry). This trend (biological problems inspiring new methods, technologies, and institutional mechanisms, and biological phenomena generating new designs) suggests that biology is replacing physics as the paradigm science, a trend captured by the slogan "century of biology".

This shift suggests that everyone will need to access and understand biology knowledge, even engineers and scientists not trained in biology. Much of this understanding will need to come from self-learning, at least until biology becomes a required discipline like mathematics in engineering and science.

Trends in Education

Quality Content for Free: There is an explosion of high quality content online, particularly videos clearly explaining many, if not most, science and mathematics concepts students find difficult. The leading provider and standard-setter in this domain is Khan Academy, but there are also courses from universities and teachers.

The Khan Academy videos, lasting 10-15 minutes for a concept, have been used



A Khan Academy video
(Source: https://www.khanacademy.org/about)

to successfully 'flip' the structure of a class. Students listen to the Khan Academy video at home, and then do problem solving in class, supervised by the teacher. Essentially, the teacher's lecturing function is now shifted in large part to the video, and the teacher can now focus on ensuring the practice required to learn the concept. Students have the advantage of playing the video as many times as they want to better understand the concept. They can also go and revise component concepts using previous videos.

Khan Academy now also provides analysis tools for teachers, which allows them to track how students work with the videos and practice problems, particularly the points where they get stuck. There is also a massive initiative to translate the videos into different languages, including Hindi. At the university level, similar quality content is provided free through the massively open online courses offered by groups of universities, where enrolment is in the tens of thousands.

This move to free content allows complex concepts from many domains to be learned through self-study. This possibility will be pursued by many motivated people, and this will raise the expectation of employers and institutions, that such self-study will be pursued by everyone.

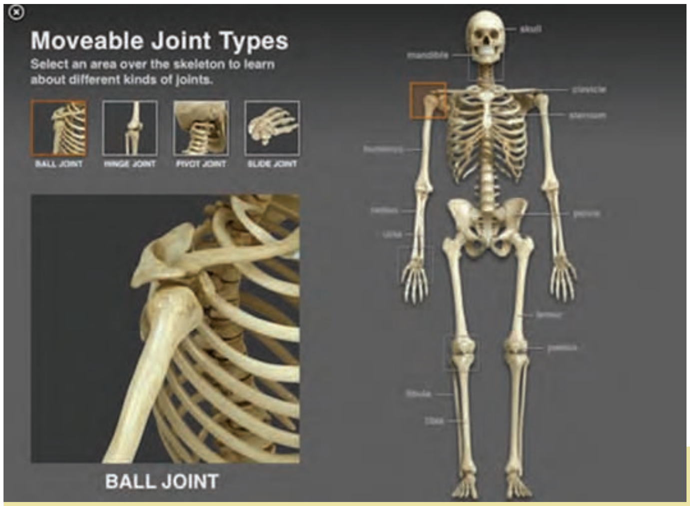
Interactive Textbooks: Apple has created a platform for the creation of interactive textbooks, where dynamic content such as animations, videos and manipulable figures and simulations can be embedded in the textbook.

An impressive sample textbook (two chapters free for download) built using this platform is E.O. Wilson's *Life on Earth*, created for the iPad tablet computer. The book illustrates the power of providing interactive media in conjunction with text in a book format. The ability to see, and manipulate, biological structures in three dimensions, allows addressing many misconceptions related to biology, such as the flat-cell and two-dimensional DNA.

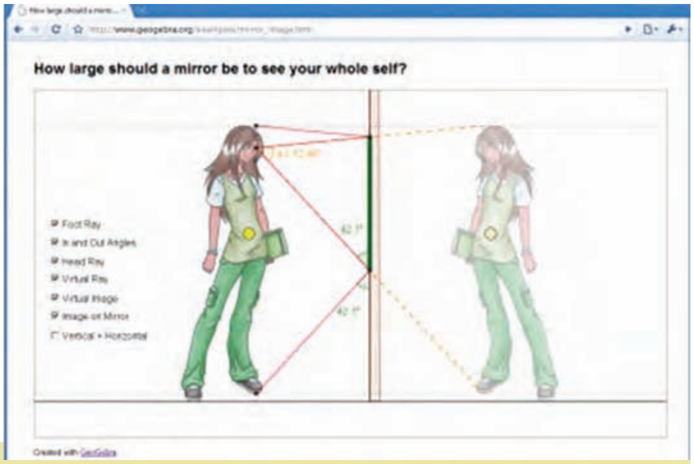
Apple is targeting education as a big market, and has set up the iTunes U, where users can download lectures as well as textbooks developed using the Apple authoring platform. The two platforms (content-building tool and store) together are considered an effort to replicate in the education domain Apple's iTunes Store and its phenomenal success in selling music (15 billion songs sold by June 2012) and mobile applications (25 billion apps downloaded). The iTunes store is the world's largest online music store, and accounts for 64% of music sold online and 30% of all music sales worldwide.

Such textbooks make the learning of complex concepts easier, and the content-generation platform will see textbooks being written by practitioners for many new and complex subjects for which textbooks and courses do not exist currently, as there is no big market for such books and courses. This will allow almost any new topic or technique to be learned through such media.

Manipulation - based Mathematics Learning: Geogebra is an open-source learning platform for learning mathematics concepts, particularly geometry, by manipulating visual and algebraic elements on screen. This manipulation model has been extended to complex concepts such



A screenshot from iTunes interactive textbook on E.O Wilson's Life on Earth
(Source:https://itunes.apple.com/us/book/e.-o.-wilsons-life-on-earth/id529004239?mt=13)



A screenshot from an interactive Geogebra problem in which students can manipulate images and measure geometrical parameters to solve a problem.
(Source: http://www.geogebra.org/cms//images/stories/screenshots/graphics-view-mirror.png)

as differential equations by the interface designer Bret Victor, who argues that the static representation of mathematical concepts using text and pictures is not user-friendly, and limits thinking the way Roman numerals limited calculations. In this view, a shift to dynamic and manipulable representations of mathematical concepts would be as significant as the shift to the place value notation.

Such interfaces allow students with no knowledge to collaborate with students who are experts, and learn new topics, particularly mathematical techniques, through exploration. This type of interactive software would allow anyone with good knowledge of concepts to become a teacher, thus accelerating the trend of gaining knowledge outside school.

Broader Impact

There are many possible ways these innovations and trends could come together. The possible impact of their confluence on the learning of science and science education is difficult to predict. But the following three broad patterns relevant to science education can be seen to be emerging, which also reinforce each other:

1. Integration: The focus on interdisciplinary inquiry and the engineering sciences will lead to more rapid integration across disciplines, particularly engineering and science, and smooth movement of people, practices and resources across disciplines. Such movement is possible now, but it is not easy, with much of it based on motivated individuals' interests and learning across disciplines. This shift would also be closely tied to the rise of computational modeling, as it provides a very good platform to integrate different types of data and methods. Since biology is a domain that requires high levels of integration and modeling skills, training in biology, particularly quantitative biology and modeling, would become more valuable, and central to science education.

2. Apprenticeship: Given the variety of the problems tackled and the methods applied in this type of integrated inquiry, it is not possible to train large number of students in a classroom on all aspects of the problem and all the methods used. This suggests there will be more apprenticeship in research labs, possibly starting at the high school level. Outside labs, game environments such as Foldit

Galaxy zoo website (Source: http://www.wired.com/images_blogs/wiredscience/2010/11/galaxy-zoo-supernovae.jpg)

The best example is the protein-folding video game called Foldit, which is played by around 200,000 people over the Web.

and EteRNA, and the free online content, would contribute to such learning, and this type of learning would become trackable, certifiable and valuable. As more such content becomes available, the chances of students getting serious science exposure outside the classroom will go up significantly, which would change the nature of learning as well as teaching and career paths. A good analogy would be participation in open-source projects, which now gets serious attention in hiring for software and graduate school positions. It is also possible that some trajectories to research would be independent of exam scores, and even university-based learning.

3. Media Design: Computing can no longer be seen as a tool that just improves productivity. It is better to view the rise of computing as the emergence of a powerful new media system, similar to the emergence of written text and graphics, which are at the core of most of our current educational and institutional mechanisms. Computing brings a shift to dynamic and interactive media, which provide a manipulable model of the dynamic phenomena science investigates. This is a radical shift from the static text and graphical representation of phenomena, which only describe the systems investigated, and that too in an indirect and approximate fashion.

Much of teaching now involves using the textual and graphic media as a starting point, and using the interaction in class to overcome the limitations of the representational material. The shift to exemplifying media changes the teaching and learning dynamic significantly, particularly by moving the focus away from lectures to activities, and forcing an augmenting of text-based evaluations with interaction-based tests of understanding.

The rise of citizen science, where the design of new media helps recruit large numbers of non-scientists to solve complex research problems, will accelerate this process. The design of such new media, and also new teaching, learning and collaboration systems based on dynamic media, is already a significant area of research and development in computer science and biology, and this will be a leading employment generator in the future.

The following statement, made by one of my students in a leading research university in the US, captures the flavour of the coming change:

"Now companies say, 'hey, you are from Famous University, let me interview you'. Fifteen years down the line, they will say, 'you had to go to Famous University to learn that? Let me go talk to some people who can learn by themselves.'"

This is an overstatement, and it is unlikely that formal education provided by universities and schools would be completely replaced by online videos, games, wikipedia and other sources. However, the self-teaching component of science learning will surely rise, and people who excel at this type of learning will be valued, and remunerated, highly by society. The coming age is of the autodidact. Student, teach thyself.

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