

Teaching with interactive simulations: One small contribution toward science education for all

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Abstract

Many of the greatest challenges facing humanity in coming decades have a scientific component: energy needs, disease pandemics, water and food security, climate change, machine intelligence and many not yet imagined. The tendency has been to assume that the solutions to these challenges will be developed by scientists, engineers and technologists, but it is increasingly important that all citizens have sufficient understanding of science to participate in the democratic processes that are necessary to address major issues. Enhancing the science education of all citizens is a huge challenge in itself, and will require a very wide range of strategies and approaches. One small contribution can come from teaching approaches using new technologies, including interactive simulations. This paper briefly describes interactive simulations and an approach to teaching using them, and addresses evidence of the effectiveness of this approach. Outcomes showed significant learning gains, relative to a control group, that were not differentiated by gender, or for students at different levels of academic achievement, suggesting that this approach may be effective as one contribution toward science education for all.

Introduction: Science education for all

All Australian students participate in science education until Year 10. Patterns of participation are similar in most developed countries in the region, and most countries aspire to this level of science education. Yet, in many ways the system from Year 10 on, and even before, is about 'filtering out'; the selecting and educating of the 10-15% of people who will take on careers related to science or engineering (Osborne, Simon & Collins, 2003). (A higher

proportion of students than this study science to Year 12 – perhaps 25-30% of students in most Australian states – but not all of these end up having careers in the sciences or engineering.) It's an unintended consequence, but a very real one, that this tends to leave the other 85-90% of citizens with the message that 'science is not for you'. Or, perhaps in some ways even more insidiously, 'you are not for science'.

At the same time, it is increasingly clear that a scientifically literate and educated populace is essential to facing the challenges posed by life in the 21st century. As just one example, most centuries have a major disease pandemic. We often think of the Black Plague in Europe in the 1300s, but, for example, the 1918 Spanish flu pandemic killed between 50 and 100 million people, 3-5% of the world's population at that time. More recently we have seen outbreaks of SARS, swine flu, bird flu and Ebola that have been controlled before becoming very large, but it is very likely that we still face significant challenges in addressing disease pandemics. Many other issues also have a social and scientific component – food and water security for a growing world population, climate change and energy policy, the increasing rate of automation and the threat/promise of machine intelligence, among a plethora of other issues. Beyond this, a high quality science education develops students' abilities to consider evidence and make decisions based upon that evidence, rather than on propaganda, misinformation or prejudice. It can protect them from charlatans selling useless or dangerous medical treatments or energy solutions. Scientific work is also inherently collaborative, and studying science helps students to develop skills in teamwork and collaboration that are important at work and home.

It is dangerous, in this context, where citizens need to both be able to vote in an informed manner, and also to take measures in their own lives such as making choices about vaccination, diet and lifestyle, to continue with a science education approach that tells 90% of citizens that science is not for them.

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It's important to note that I am *not* advocating for specific positions or policies on the various controversial issues previously raised. The goal of 'science education for all' is to allow all citizens to have *informed* views on the issues. There will naturally be a range of positions on social issues, but discussions and debates are more effective when informed by a good understanding of both the science and the values underlying particular positions.

Science education has always had the twin goals of 'science education for scientists' and 'science education for all'. This work is certainly not arguing that science education for all is a new notion. However, it would suggest that the balance has been shifted too far in the direction of science education for future scientists. It is possible to do both. Indeed, the authors would argue that ensuring that all members of society are well educated in science would do a better, not a worse, job of preparing those who do take up careers in science. Specialisation occurring in Years 11 and 12 and at university is still appropriate to the preparation of scientists but, the American 'liberal arts' tradition of college education in which Arts majors study at least one or two science courses, and vice versa, to ensure that citizens are broadly educated is asserted here as a model with advantages.

Solving the challenges of extending science education to all students—particularly those from disadvantaged backgrounds, those with special needs and those who are struggling with the concepts—will clearly require a very broad blend of approaches. It will need changes to policy and resourcing, to approaches to teaching and learning and science, and a variety of additional tools. This paper outlines one such tool: teaching an inquiry approach to science using interactive simulations.

Interactive simulations

The almost ubiquitous availability of computers (it's important to remember, though, that they may be less available in some schools and some homes) has offered a range of new 'affordances'—capabilities and possibilities—for learning. Some of these have been more effective than others. Our earlier study showed that teaching chemistry and physics using 'visualisations'—computer-based animations and simulations—was no more effective than teaching these subjects in more traditional ways (Fogarty, Geelan & Mukherjee, 2012; Geelan, Mahaffy & Mukherjee, 2014).

More recently this research attention has turned to a specific class of computer-based visualisations described as 'interactive simulations'. These are typically 'virtual laboratories' in which students can manipulate variables and observe the results, either

qualitatively through colour changes or animations or quantitatively through generating result data in the form of numbers. An interactive simulation offers the capability for students to conduct a larger number of experiments more quickly than a 'real' laboratory experiment, which in turn allows students to test their developing concepts against these simulations of the world. Of course, there is an important step that needs to occur, where students develop confidence that the simulation does model the real world. One way of developing this confidence is to compare the results of the real laboratory experiment with the results obtained from the computer-based simulation, but there are also other approaches that can be used.

An interactive simulation also offers the ability to compare, for example, the 'physics world' in which we can assume that friction doesn't exist, some objects are mass-less and have no inertia and so on. Some of the best simulations allow these features like friction to be turned off and on, to compare the predictions of the simplified physics formulae students learn in high school with the complexities of the real world.

Many scientists and educators around the world, as well as some commercial companies, have developed interactive simulations for use in teaching, but the PhET project at the University of Colorado is perhaps the best-known source, and produces a very wide range of well-developed and supported simulations in a variety of scientific disciplines (<https://phet.colorado.edu/>). The central characteristic of PhET simulations is to support the implementation of inquiry learning. The design principles are based on research on how students learn (Bransford, 2000). PhET simulations have been used in a series of studies (Adams, Paulson & Wieman, 2009). Chinese translated versions of the physics simulations were used in the study described below.

One dimension of the research around computer-based tools has been largely neglected: the pedagogical (teaching) approaches used. Most often studies either have no comparative dimension—many studies in the field are of the form "I built this and used it in my class, it was great, students loved it and learned!" but without comparison or measurement—or else simply compare the results of students taught with the tool with those of students taught without it, with little attention to *how* the students were taught. As a consequence, Xinxin Fan and I (Geelan & Fan, 2014) developed a new teaching sequence for using interactive simulations in an inquiry approach to science teaching.

ISIS: An Instructional Sequence with Interactive Simulations for inquiry learning

The focus within 'Instructional Sequence with Interactive Simulations' (ISIS) is on an inquiry

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approach to learning (Bell, Smetana & Binns, 2005; Chiu, 2010) that focuses on students' construction of new scientific concepts and on challenging 'misconceptions' that no longer successfully explain their experiences. The teaching sequence is outlined in a 2014 book chapter (Geelan & Fan, 2014). It draws on Vygotsky's (1978) concept of the Zone of Proximal Development (ZPD) and on Posner, Strike, Hewson and Gertzog's (1982) 'conceptual change' teaching model. The work of Quintana et al. (2004) on scaffolding inquiry instruction using software was also influential. It has some similarities and differences with the 5Es model developed by the Biological Sciences Curriculum Study (BSCS) (Bybee et al., 2006).

Briefly, the steps are as follows.

Zeroth Step – Deciding whether an interactive simulation is the appropriate tool and ISIS is the appropriate sequence to support learning of this concept

This is, to us, a key step: is an interactive simulation even the best tool for the job? Given that science is about explaining our experience of the world, shouldn't we do 'real' experiments that have students test their ideas against the real world, rather than abstract simulations? Of course we should: but it needn't be either-or, it can be both-and. This is about enhancing the repertoire (to use a musical/theatrical metaphor) or toolbox (to use a more mechanical one) or toybox (our personal favourite) available to teachers. Making informed, thoughtful professional judgements about which is the best and most appropriate tool, the most suitable teaching approach for a particular concept, class and context, is a key part of being a professional teacher.

Assuming that the decision is made that interactive simulations are the appropriate tool and ISIS is the appropriate pedagogical model, teachers and their students can proceed through the remaining steps.

Step 1 – Eliciting and clarifying existing conceptions and the 'target' scientific conception

This approach is not a 'mystery novel' approach in which the scientific concept is held as a surprise twist at the end that students do not encounter until later. Rather, it is a very explicit approach, in which the teacher elicits from the class the concepts they are using to explain particular everyday phenomena. Some of these concepts will be amorphous and not fully formed, and the discussion may help to clarify them. Others will be fully formed but erroneous: these are often referred to in the science education literature as 'misconceptions'. Students may believe, for example, that the force acting on something is the

only relevant thing influencing its acceleration. This is a misconception: the mass of the accelerating object is also relevant.

During this step, it will become apparent whether or not there are clusters of student concepts: typically there will be more than one perspective on the part of students, but fewer than the number of students in the class. There may be two or three common misconceptions, and some students may also already hold the scientific conception.

(A note on the nature of science: I am being careful to use the language 'scientific conception' or 'canonical conception', not 'accurate' or 'correct' conception. Scientific knowledge is contingent and subject to challenge and change. The current best concept may in time be replaced by a more powerful and effective one. Science does not claim to have infallible knowledge of the real world—just concepts that have withstood the test of experiments without being falsified by the evidence.)

If the scientific concept is *not* elicited from the students, the teacher should outline it briefly and clearly. The ISIS approach differs from the Bybee et al. (2006) 5Es model and a number of other teaching models in this early explicitness.

Step 2 – Outlining the predictions and implications of students' existing conceptions and the scientific conception

Once the few 'candidate concepts' have been introduced, the teacher can introduce the context of the experiment to be simulated in the interactive simulation, and ask students to predict what will happen. This is linked with White and Gunstone's (1992) 'predict, observe, explain' sequence. It is also linked to an extended 'predict, explain, observe, explain' sequence: having students make their prediction, then explain why they have made it, is a further means of eliciting and clarifying the concepts they are using to make sense of their experiences.

In both these learning experiences using interactive simulations and in 'real' laboratory experiments, it is crucial that students understand what their observations mean in conceptual terms. Which concept is supported by the evidence, and which is falsified or challenged by it? If students simply complete Step Seven of the experiment 'recipe' and write down in their notebooks that the clear solution turned red, but without understanding what that observation means, it could be argued that they are not really learning science at all.

For this reason, it is important that the specific implications of each of the 'candidate concepts' are worked through and made explicit—ideally written down so that students must commit. If students hold the concept that the mass of the accelerating

“*[ISIS] focuses on students' construction of new scientific concepts and on challenging 'misconceptions'*”

object is irrelevant, for example, they will predict that the same force will cause the same acceleration, irrespective of the mass being accelerated. If they hold the conception that more mass will lead to greater acceleration when the same force is applied, they will predict that to be observed. The scientific concept is that the greater the mass being accelerated, with the same force, the less acceleration will be observed. Again, if students do not make this prediction, the teacher should, and should make it explicit that this is what the scientific conception predicts.

Step 3 – Testing predictions of competing conceptions using interactive simulations

Now the interactive simulation can be used to test the different predictions made. Since students understand that particular results support or challenge particular concepts, the results will be immediately meaningful to students. It will be obvious to many students immediately which concept has been successful in predicting the actual results and which concepts have been unsuccessful.

Step 4 – Clarifying findings and linking results to the scientific conception

Other students may require more discussion with peers and the teacher to make this connection, and Step 4 involves making the findings correct. If the experiments have been designed and conducted well, all 'candidate concepts', except the scientific concept, should be falsified by the evidence.

What *constitutes* a scientific theory is successfully predicting and explaining our experience and not being falsified by the evidence. Making it clear to the students that the scientific concept is uniquely capable of passing this test is the key to ensuring that students learn it. Further, that they learn it in ways that mean that they internalise the scientific concept and continue to use it as a 'tool to think with', rather than just memorising it undigested for regurgitation in assessment tasks, to be forgotten soon after they leave the class.

Step 5 – Further testing to develop and deepen understanding of the scientific conception

Additional experiences in which the newly developed (for these students) scientific concept is applied in new and different contexts, and continues to successfully predict results and avoid falsification, lead to enhanced student confidence in the concept, deeper understanding and engagement with it, consequently ensuring that learning is rich, powerful and transferable. This step and its effectiveness was relevant to the finding reported below that students' confidence in the correctness of their own answers

was enhanced by participating in this learning sequence.

The step sequence is an organising device: there is a logic to it in terms of developing students' concepts, but there is nothing sacred about the order of the steps, and it may be appropriate to, for example, skip the first step if prior discussion shows that students' concepts are already well defined, or the final step if the concepts are already strong and well-elaborated. It may be appropriate to cycle through steps 2 and 3 multiple times within a particular sequence. Like the initial selection of this approach, this is a professional decision that teachers make by drawing on all their experience, preparation and professional learning.

The sequence sounds plausible, but does it work? Is it actually effective for enhancing students' learning?

Evidence of effectiveness

Research methods

A preliminary research study was conducted in Beijing, China, by Xinxin Fan with two physics teachers. Each teacher taught Newton's Second Law to one 'experimental' class using ISIS and one 'control' class using his/her usual physics teaching approach. Over all, there were 62 students in the two classes that made up the control condition and 55 students in the two classes included in the experimental group. Students' conceptual understanding was tested before and after the teaching sequences using the relevant questions in the Force Concept Inventory (Hestenes, Wells & Swackhamer, 1992), which uses multiple choice questions in which the 'distracters' are common misconceptions about the key concept. This was complemented by asking students to explain their answers, and to indicate how confident they were about their answers.

Here is an example of an item from the questionnaire:

Two metal balls are the same size but one weighs twice as much as the other. The balls are dropped from the roof of a single story building at the same instant. The time it takes the balls to reach the ground below will be:

- A. About half as long for the heavier ball as for the lighter one.
- B. About half as long for the lighter ball as for the heavier one.
- C. About the same for both balls.
- D. Considerably less for the heavier ball, but not necessarily half as long.
- E. Considerably less for the lighter ball, but not necessarily half as long.

“that they internalise the scientific concept and continue to use it as a 'tool to think with', rather than just memorising it undigested”

Could you please explain why you choose this answer? You can use your physics knowledge or your own words to write down your understanding.

How sure are you of your answer to the question?

A. Very sure; B. Sure; C. Neutral; D. Unsure; E. Very unsure.

Students' inquiry skills were tested before and after the teaching sequences using a 13 question survey based on work by White and Frederiksen (1998). Students rated their inquiry skills on a 5 point Likert scale.

Results

The statistics for the analysis of the student responses on items related to conceptual understanding, inquiry skills and confidence follow.

Conceptual understanding

Comparing the gains in conceptual understanding, measured using the Force Concept Inventory, between the experimental and control classes, the effect size, η^2 , was .18 ($p = .000$). This effect size is considered large (Cohen, 1988, suggests that η^2 of .01 represents a small effect, .06 a medium effect and .14 and above is a large effect). That is, students who learned the concepts about the ways in which forces work that are summarised in Newton's Second Law of Motion using the ISIS teaching approach understood the concepts significantly better than those who learned it using the more 'traditional' approaches used by these teachers. It is worth noting that both the participating teachers were effective and successful teachers. Their 'usual' teaching was not of poor quality, but this approach to inquiry learning through interactive simulations—the combination of the computer-based tool and the pedagogical approach—was significantly better for students' learning.

Inquiry skills

Students' perception of their own skills in inquiry learning, measured using the 13 item test, differed even more markedly between the experimental and control groups, with $\eta^2 = .38$ ($p = .000$). Students perceived themselves as being more capable of learning science through inquiry—using their own minds and their skills in thinking, communicating and experimenting to develop concepts. This occurred within the context of a Chinese physics education system, which is typically much more teacher-centred and transmissive in approach.

Confidence

Students' confidence in their own answers to the Force Concept Inventory Items, when the experimental group was compared to the control group, showed a high medium effect size, $\eta^2 = .12$ ($p = .000$). That is, students who had learned using the ISIS approach were more confident that their answers were correct. They had developed the new concepts through intensive thinking and scaffolded discussion, and felt more secure in their understanding.

On each of the three sets of findings, analyses were also conducted to determine whether boys or girls received more benefit, and whether the lowest, middle or highest group of students ranked by academic achievement received more benefit, but in no case were there statistically significant differences. This means that the educational benefits from ISIS seem to support the learning of all students similarly.

This is perhaps the most significant finding of the study for the purposes of this paper, which is focused on 'science for all'. Some of our earlier studies (Fogarty, Geelan & Mukherjee, 2012; Geelan, Mahaffy & Mukherjee, 2014) seemed to suggest (not always at statistically significant levels, so not always reported in the papers coming out of the studies) that scientific visualisations may be more effective for the learning of boys and of the most academically capable students. That would be a case, in physics education, of giving more to those already doing best, increasing the gaps between the highest and lowest achieving students. These effects were not observed in this study—overall students of both sexes and at all academic levels received a significant increase in knowledge, skill and confidence.

Conclusion

Clearly it is important to replicate the Beijing study in Australian schools, in other schools around the region and internationally to ensure that the results are generalisable, and in addition to repeat the study with much larger groups of students and teachers to enhance our confidence in the statistical power of the results seen, but the preliminary results reported above are very encouraging. These effect sizes are seldom seen for educational innovations, particularly those involving relatively brief interventions, so there seems to be considerable potential. Expanding the context to the teaching of chemistry concepts seems likely to be appropriate, however, there are interesting theoretical questions about whether there are concepts in biology that would be susceptible to this approach. Similarly, it is possible that some mathematical or economic concepts could be interactively simulated and that students could learn them using the ISIS approach, or an adapted sequence.

“[All] students ... using the ISIS teaching approach understood the concepts significantly better than those ... using the more 'traditional' approaches”

Research & Scholarship

While this evidence of learning effectiveness is gratifying for science education researchers, as noted above, one important facet of interest is in 'science education for all' and ensuring that, as far as possible, all members of society develop an understanding of science sufficient to allow them to participate in finding solutions to the significant challenges facing humanity. There are many facets to an approach to broadening the appeal and effectiveness of science education, and it is hoped that this research program is making some small contribution. **TEACH**

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