Science Education in Singapore: Where to Next?
A Science Research Seminar

by Dennis Kwek, Lee Yew Jin, Seah Lay Hoon, Subramaniam s/o Ramanathan, Michael Tan, Timothy Tan & Jennifer Yeo
Science Education in Singapore: Where to Next?

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**Acknowledgements**

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Core 3 Research Programme: Baseline Investigation of Science Pedagogy

By Dennis Kwek

Since independence in 1965, the emphasis on Science in Singapore has been unwavering. It has helped to build our rapidly expanding and changing economy—from engineering and computing to new scientific areas such as biosciences, environmental and energy sciences, to name a few. Our Prime Minister, at the opening of the Singapore University of Technology and Design in 2015, has re-emphasised that STEM (Science, Technology, Engineering and Math) skills will remain crucial to Singapore for the next 50 years (Lee, 2015). This is further cemented by the recommendations of the Committee on the Future Economy where the high demand areas for the future economy include data analytics, cybersecurity, data sciences, robotics, life sciences and artificial intelligence. There is therefore a strong need to create a cadre of STEM and information communication technology (ICT) professionals, and subsequently, a need to prepare our children in schools to be ready for a science-rich future with bountiful opportunities for them to embark on science-related careers.

This has to be seen in the broader contexts of the aims of science education. Osborne and Hennessey (2003, p.2, 11–14) point to four key purposes: 1) utilitarian (practical utility of science); 2) economic (for sustaining the economy); 3) cultural (recognising the scientific achievements of humans); and 4) democratic (participating in and debating on key political and moral dilemmas which are inherently scientific in nature, such as climate change).

In Singapore, the Core Research Programme—of which we are now at the third iteration (Core 3)—has been centrally focused on the questions of “How do teachers teach?” and “Why do they teach the way they do?”. The clear methodological focus and design philosophy of Core 3 is on “everyday classroom pedagogy, on the intellectual and discourse work of teachers and students in the classrooms” (Luke, Freebody, & Shun, 2005, p.9). We began to collect data on Science pedagogy in 2004, at the cusp of Thinking Schools, Learning Nation and Teach Less, Learn More reform initiatives. We collected data on Science pedagogy again in 2015.

We sampled a number of mainstream schools and teachers in average classrooms—1 teacher per school with a total of 10 schools—and collected 90 lessons in Primary 5 (P5) and Secondary 3 (S3) (Physics). We segmented the lessons into 5-minute phases and coded them for key pedagogical practices that we believe should be happening in classrooms, drawing from both the local curriculum intentions and international understandings of what science teaching and learning should be about. Interviews with teachers and students were also conducted.

In terms of Knowledge Focus, or what the knowledge emphasis is during that part of a lesson, we saw an emphasis on the following as shown in Table 1 on the left.

The chart above shows the trend of knowledge focus between 2004 and 2015. This can be attributed to the science curriculum reforms as well as an increased emphasis on scientific inquiry. The results are broadly comparable to the Singapore PISA 2015 findings, where Singapore Science shows a stronger emphasis on procedural and epistemic knowledge than content knowledge.
In terms of Epistemic Talk—the kinds of knowledge that is generated or discussed through talk—we see respectable proportions as shown in Table 2 below.

As such, there is definitely more room for Epistemic Virtues Talk in the classroom, where the talk focuses on the nature of science, justifying and arguing for scientific claims. Likewise, an average of 86 per cent of all phases in P5 and S3 had closed-ended questions with students required to respond with the correct answers, and 25 per cent with open-ended questions with multiple answers.

Such a proportion of closed-/open-ended question types is typical of Singapore classrooms. Based on our interviews with teachers, a key reason for this is time constraint—engaging in open-ended questioning requires time for active and engaging discussions, which comes into tension with the need to cover the necessary content students need to sit for examinations. A key strength of Singapore Science Pedagogy, we feel, is this balanced focus on factual, procedural and conceptual knowledge as teachers introduce and engage students in scientific concepts and procedures, while there is scope for improvement in increasing the focus on Epistemic and Metacognitive Knowledge.

In terms of the scientific skills that are exemplified in the Science syllabus, we find that observation, communicating in scientific terms, analysing patterns, compare and contrast, and inference to be respectable in P5 and S3 classrooms. However, we did not see a strong emphasis on skills such as evaluating reasonableness, accuracy and quality of information, predicting outcomes, generating possibilities, classifying objects of events, or formulating hypotheses. These latter skills are important scientific literacy skills, and areas that more innovations could be mounted on to help teachers improve the use of such skills in classrooms.

We also coded for when teachers explicitly mention or encourage students to embody scientific virtues such as curiosity, creativity, integrity, open-mindedness, perseverance and responsibility. In the 90 lessons we observed, we rarely saw or heard teachers talking about such virtues in the classrooms. Bearing in mind the caveats—these 90 lessons were observed during a specific time of the P5/S3 year, with only 10 teachers in mainstream schools teaching average P5/S3 Express classrooms. Most importantly, we also made the decision to only code when teachers explicitly mention or encourage such virtues. The rarity of encouraging such virtues through talk suggests an important area for improvement, especially given the significance of such scientific virtues. We also note that P5 and S3 students tend to engage in investigation far more than other scientific processes such as decision-making or creative problem-solving.

In terms of scientific inquiry, using the 5E model of inquiry, we observe largely teacher-directed inquiry rather than student-directed inquiry. Teachers tend to pose questions, provide materials, direct students to collect data, guide students in formulating explanations, provide possible knowledge connections, and give students steps and procedures for communication. We see strong emphasis on Engagement in Scientifically Oriented Questions, Evidence Management, and less for Explanation, Formulation, Elaboration and Evaluation. These findings again suggest that there is room for scientific classroom-based innovations on building capacities and opportunities for a more balanced and student-directed 5E inquiry pedagogy.

From our 2015 baseline study on Science P5/S3 Pedagogy, a number of recommendations can therefore be made as shown in the table on the following page.
Internationally, science education continues to emphasize the notion of science literacy. In a recent publication from the National Academies of Sciences, Engineering and Medicine in the USA, the authors argue for the need for teachers to engage in science literacy in classrooms: (a) Understanding scientific practices; (b) Content knowledge; and (c) Understanding science as a social process (Snow & Dibner, 2016). The notion of science as social process relates to the criteria of evaluating scientific expertise, the role of peer review, the accumulation of accepted findings, the existence of venues for discussion and critique, the nature of funding and conflicts of interest. The presence of websites such as Retraction Watch, which monitors scientific journal retractions due to irregular scientific methods, findings, replication issues, scientific misconduct (www.retractionwatch.com), signals a scientific world where science-literate citizens need to understand not only the content or nature of science, but also the social processes by which scientific knowledges are generated, shared, debated, refuted and retracted. Our students need to be prepared for such a future. As such, the work of science literacy, broadly envisaged by the National Academies, is perhaps one step towards that democratic purpose of science education.

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How to Cite
Students’ Learning and Views in the Sciences

By Subramaniam s/o Ramanathan

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In the research literature of Science Education, you’ll find that there has been a lot of research done about the different levels of student learning. However, this stratified view is complicated by the presence of learning difficulties and alternative conceptions. These conceptual misconceptions are more prevalent in physics especially. Students are not only asked to comprehend multiple representations of the same phenomenon but in physics, the concepts are often counterintuitive and run contrary to everyday experience.

This leads us to our first general difficulty in examining student understandings of science: just because a student answers a question correctly does not mean that they have a genuine or complete understanding of a particular physics concept. A student may stumble upon the correct answer by intelligent means of eliminating unlikely choices in multiple choice questions (MCQ) or simply by guessing intelligently based on some limited prior knowledge. We know that teaching in class does not equate to students learning. With the above in mind, I would like to share some of the work in which I am involved.

Question Tiers and Forms

In assessing student learning, MCQs are quite popular because they are easy to mark. In fact, with the rise of machine marking, there is often no need to mark at all. But while we are all used to simple-structured MCQs, there are a variety of ways to add complexity (see Image 1 below).

These sort of question forms help researchers form confidence ratings which subsequently help build psychometric indices such as the mean confidence for answer, (CF), mean confidence when correct (CFC), mean confidence when wrong (CFW), confidence discrimination quotient (CDQ), and confidence bias (CB). Generally speaking, if a student is more confident when the answer to the question is incorrect, then the student suffers from misconceptions in the topic. Overall, when students append a confidence scale to their questions as part of revision, they become aware of their own thinking processes. It is a good way for students to monitor their own learning.

Image 1. The different types of Multiple Choice Questions (MCQs).
Assessing Student Learning in the Sciences

Next, I would like to share some findings on student learning in specific science topics. On the topic of “transition metals chemistry”, we used 25 questions and found more than 20 misconceptions on the topic. Thermodynamics is a very difficult topic, as most would agree. Therefore, it was not surprising that we documented quite a number of misconceptions—about 25 misconceptions over 30 questions. Reaction kinetics was similar with close to 25 misconceptions over 11 questions. However, perhaps the most difficult single topic for students to understand correctly was “acid-base chemistry”, with more than 30 misconceptions documented over 25 questions.

However, it is important that teachers keep these misconceptions in mind so that they can address them during their next teaching cycle. A good example might be from acid-base chemistry where one of the most pervasive alternative conceptions was that when an acid neutralises a base, there would be no H+ ions and no OH− ions present at the end point. This was a very persistent misconception because students did not realise that because of the dissociation of water, some residual H+ and OH− ions will remain in the reaction mixture.

In Biology, we took the opportunity to get our students study subjects through an open-ended question. We find that open-ended questions are great for deriving more insights into how students think and how they make use of concepts. The question that we posed was, “Scientists believe that humans and chimpanzees last shared a common ancestor from around 4–7 million years ago. How do you think the ancestors of humans looked like?” Such a question does not dictate that the students use any particular conceptual tool and thus we were able to generate a diversity of insights into students’ thinking about alternative conceptions and learning difficulties in evolution. One of the tools and alternative conception they most often made use of was transmutation, which denotes the ability of one species to evolve into another different species. Nevertheless, while open-ended questions produce rich findings, one problem is that a sufficiently broad coding scheme for classifying all the responses can be quite taxing to identify and record.

Students’ Views in the Sciences

I am also very much interested in students’ views in the sciences in order to, for instance, find out why student interest in Physics is declining in Singapore. As you might already know, the number of students taking A-Level Physics has declined quite significantly over the last 15 years. One of my PhD students took up this issue and together, we had some interesting findings. Centrally, we found that students shunned physics at O- and A-Level because they view Physics as a difficult subject and one that leads to limited employment opportunities.

Conclusion

A teacher practitioner had questioned me how teachers such as himself could develop these kinds of diagnostic questions. In actual fact, there are quite a number of online repositories for diagnostic questions, but I took the opportunity to also call upon teacher practitioners to approach and collaborate with academics. I think both parties can complement each other in generating effective diagnostic questions and instruments that can help tremendously in bridging the cognitive discrepancy between students’ understanding and the actual responses that they give.

How to Cite

As science teachers, we often find ourselves reading a variety of materials, whether they are textbooks from various publishers or websites. Reading helps to clarify and extend our understanding of the scientific contents that we teach in the classroom. Will our students also do the same should they encounter similar situations that require them to read to be able to understand certain scientific concepts?

While my research is not designed to provide a definitive answer to this question, it nonetheless suggests that the opportunities for students to do so can be quite limited in some classrooms. The same applies to the instruction provided for students that will allow them to engage in independent science reading. Within the classrooms that I have observed in both primary and secondary schools, support for reading science texts is often limited to just highlighting important information and clarifying key terms. Grammatical and structural language features distinctive to science are seldom unpacked for students. During science lessons, students are more often exposed to “truncated” texts—in which information are presented in point form or disparate short sentences in the form of PowerPoint slides or worksheets—than extended form of texts such as textbooks, magazines and articles—in which the scientific content are presented in a coherent and integrated manner. With limited support and opportunities provided for students, it comes with no surprise if their capacities to make sense of extended form of science texts are compromised.

The Role of Reading in Science Learning

Students’ limited capacity to make sense of scientific texts can be constraining to both their learning and performance in the science subject. Outside of classroom, students who have difficulties making sense of scientific texts lack the vital tool required for them to revise, refine and extend what they learn in class.

More importantly, science texts provide students with multiple exposures to academic language at their own individual pace. This is especially so for text structures that is less likely to be heard in conversational language (Zwiers, 2014). Indeed, spoken language and written language entail different language features. These differences relate to the different contexts in which they arise and purposes they serve. In fact, written language exists “because it fulfills functions and purposes that the oral mode cannot” (Hammond, 1990, p. 35).

In classroom contexts, teachers often engage in co-constructed discussion with students. The shared physical setting contributes to the meaning of the speech in the form of contextualisation cues (Gumperz, 1982) such as physical artefacts, gestures and intonation. By contrast, written texts including students’ writings are not supported by these cues. A common grammatical resource that is employed distinctly between spoken language and written language is pronouns (e.g., “it”, “this”). Use of pronouns is often taken for granted in speech as their meanings can often be easily derived from the contextualisation cues. But this is not the case in writings as the readers do not share the same space and time in which the writings are conducted (Hammond, 1990). Hence, pronouns have to be employed in writing in ways that “build coherence within the text” (Christie, 2005, p. 51). Unfortunately, science students are often found to use pronouns indiscriminately in their science writings making what they intend to construe unclear (Seah, 2013; 2015).

There is therefore a need for students to recognise the differences in the way language works in speech and in writing. Reading is an important means by which students can be exposed to how language is used differently in writings. Lacking the awareness of such differences can impede one’s ability to express intended meanings accurately in writing even if he or she is able to do so orally.

Reading is Disciplinary-Specific

Recent research has also shown that reading practices are distinctive across
disciplines. Shanahan, Shanahan & Misischia (2011) have shown that chemists, mathematicians and historians differ in the way they interpret, respond to, and make use of information presented in the written texts specific to their field. Imagine what our students can achieve through inquiry-based and self-directed learning if they are equipped with the skill-set that allows them to approach texts in ways that mirror how a scientist would. For a comprehensive review of the literature on disciplinary-specific reading, readers can refer to the Research Digest Vol 1, Issue 2 produced by the English Language Institute of Singapore.

**Implications for Science Instruction**

Given the many rationales for students to be able to read scientific texts effectively, there is thus an imperative to support students in science reading. Certainly, this does not involve reading line by line with students or simply highlighting important content in the relevant sections. Rather, it requires teachers to be knowledgeable about the distinctive features of scientific texts (see for example, Fang, 2005) and to provide contingent support to their students when such features are present and relevant to the topics being learnt. It also demands teachers to be aware of how scientists read differently from other disciplinary experts and to equip students with similar reading strategies.

Such reading support needs to be ongoing, progressive and started young. In recent years, there has also been an expansion in focus beyond single-text reading to multiple-text coordination. Within the context of inquiry-based learning, multiple-text reading involves coordinating “diverse—and sometimes contradictory—information and perspectives from multiple texts, accounting for authors’ intent, evaluating evidence presented in the text, and judging the relevance and usefulness of each text for the task at hand.” (Goldman et al., 2016, p. 222). In the Internet era where information are freely and widely available, the ability for such reading skills will only gain importance as students learn to tap on these resources to expand their understanding of the world around them.

**References**


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### How to Cite

Role of Representations in Producing Scientific Explanations in Physics

By Jennifer Yeo

Jennifer Yeo is Assistant Professor with the Natural Sciences & Science Education Academic Group at the National Institute of Education. Jennifer’s research interest is in understanding how people learn science, and designing learning environments to support students’ science learning.

The ability to produce scientific explanations is a key learning outcome of science learning. The production of scientific explanations is a multimodal process (Yeo & Gilbert, 2014) that entails the competent use of representations (Yeo & Gilbert, in-press). The aim of this article is to describe this competent orchestration of different modes of representations to produce two key types of scientific explanations in physics—the interpretive and causal explanations. Findings reported here are drawn mainly from the project “Developing a Framework for Assessing Students’ Construction of Scientific Explanations in Physics” (OER 13/13 JY).

Science can be characterised by the formulation of laws and theories to understand the world. As defined by National Research Council (2012), the production of scientific explanation necessarily entails the linking of these laws and theories to make sense of the events of the world. Explanations that rely on laws, commonly inscribed in the form of mathematical formulae and equations are described as interpretive, while those that make use of theories to account for the underlying mechanism of a phenomenon are referred to as causal (Gilbert, Boulter, & Rutherford, 2005). Findings from this study indicate that representations play different roles in the production of these explanations. The representational features and roles are summarised in Table 1 along with the three dimensions of scientific explanation as defined by Yeo and Gilbert (2014). These features and roles of different modes of representations and the competent orchestration of the representations to produce a successful explanation suggest that on top of conceptual understanding, students also need to develop representational competencies in order to interpret, construct, relate and transform representations to generate and extend meanings (Kozma & Russell, 2005). These competencies include the ability to:

- use representations for describing scientific concepts;
- construct and/or select a representation and explain its appropriateness for a specific purpose;
- use words to identify, describe, and analyze features of representations;
- compare and contrast different representations and their information content;
- connect across different representations and explain the relationship between them;
- realise that representations correspond to phenomena but are distinct from them; and
- use representations in discourse to support claims, draw inferences, and make predictions.

References


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<th>Causal Explanation</th>
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<td><strong>Function</strong></td>
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<tr>
<td>Makes use of a (mathematical) model, based on well-established pattern, to account for a specific event or observation.</td>
<td>Makes use of a theory to account for the underlying mechanism for the phenomenon.</td>
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<td><strong>Form</strong></td>
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<tr>
<td>Modeling and processing based on Redish and Kuo’s (2015) mathematical modeling framework.</td>
<td>Agent, instrument, target: structure of causality proposed by Lakoff and Johnson (1980). The “agent” and “target” are the theoretical entities, while the “instrument” is the actions of agent on target.</td>
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<td>Modeling involves the abstraction of the physical phenomenon into theoretical entities in the form of mathematical symbols.</td>
<td>The identification of agent and target involves identifying these inferred entities to be present in the phenomenon (e.g., sound waves) and representing them in a pictorial form.</td>
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<td>Processing involves the operationalising of mathematical representations to produce a quantitative outcome.</td>
<td>The instrument is a series of actions of agent on target and the effects produced.</td>
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<tr>
<td><strong>Level of Precision</strong></td>
<td></td>
</tr>
<tr>
<td>Typically laws (e.g., Newton’s laws and law of thermodynamics)</td>
<td>Typically theories (e.g., wave theory, field theory and kinetic theory)</td>
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<tr>
<td><strong>Level of Abstractness</strong></td>
<td></td>
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<tr>
<td>Mathematical representations used to relate theoretical entities</td>
<td>Pictorial (conventional) representations used to give form to the abstract entities</td>
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<tr>
<td><strong>Level of Complexity</strong></td>
<td></td>
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<td>Representational scheme: textual/pictorial representation naming and describing physical objects and actions → textual representation to identify theoretical entities → mathematical representations representing relations between theoretical entities</td>
<td>Representations scheme: textual/pictorial representation naming and describing physical objects and actions → textual representations to identify theoretical entities → pictorial representation to give form to the theoretical entities → textual/pictorial and gestural representation to describe interactions between entities over time and space.</td>
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Table 1. Representational features and roles.
The shift in science education towards the aim of developing broader scientific literacy is well underway. It is recognised that there is a need to integrate learning across the science, technology, engineering, and mathematics (STEM) domains in order to achieve this aim. There is also a need to equip our students with the skills necessary for the future and—for some—the eventual progression into these fields as technical or knowledge workers (PCAST, 2010; Honey, Pearson & Schweingruber, 2014).

Many argue we are faced with the looming difficulty in schools is in finding an approach to a time when such integration is inevitable given the inexorable changes in this VUCA world. What is much less clear is how we will get there (for example, English, 2016). Part of the difficulty is that integration is multi-faceted. It can merely be between subjects (e.g., biology and chemistry) or across the domains of science, engineering, technology, mathematics and beyond; there can be varying degrees of integration—interdisciplinary, multidisciplinary or transdisciplinary, in increasing order of interconnectedness (Drake, 2000). Another difficulty in schools is in finding appropriate contexts in which to craft learning experiences that naturally blend and encompass various disciplines. These issues potentially affect the value derived from such integration in schools.

Finding an Approach

In a transdisciplinary approach to learning, students learn and apply knowledge and skills to the task at hand, without discerning or distinguishing the disciplinary providence of that knowledge. This is by now, a familiar paradigm for educators, albeit better known in various guises as project- or problem-based learning, and the development of life skills and competencies. The difficulty in achieving true transdisciplinary integration in lessons begins with finding a context in which each domain has a key role to play, where learners have to find out, analyse, or apply knowledge or skills from that domain, whilst engaged in those lessons.

Design-based inquiry (DBI) is a lesser-known member of the inquiry-based pedagogies. DBI is characterised by a design-and-make approach to fulfil a specific task or objective. This can be couched as a challenge or goal, such as “build a paper airplane that can fly the furthest distance”. Additional or subsidiary challenges can also be given, such as longest time aloft, or accuracy in hitting a target. This type of activity thus affords a context in which broad-based knowledge of science, engineering, technology and mathematics can be applied in pursuit of the set challenge.

One key issue is that DBI activities tend to involve only the physical sciences, with very few that involve chemical or biological sciences, and none that incorporate all three. Leaving aside STEM integration for a moment, there are paltry examples of an integrated approach to the learning of science as a holistic discipline, or where all three of the natural sciences are seamlessly amalgamated. The learning of science in school is almost always segregated into its sub-disciplines. It’s either a life science topic, or a physical science topic.

The Microbial Fuel Cell

The microbial fuel cell (MFC) is a device that produces electricity through the biochemical life processes of microbes. It is capable of sustainably doing so, as long as there is a food source for the microbes, and typical applications for MFCs involve bacteria feeding on organic waste, such as sewage to generate municipal power. This incidentally affords a student-friendly introduction to the MFC as an environmentally-sustainable alternative energy source. Using the MFC as the context in science lessons with a DBI challenge in which secondary school students work in small groups to design and build their own improvised MFCs has been developed and found to be effective in achieving learning outcomes (Tan, Lee, Sam, & Lee, 2013; Tan, Toh, Teo, & Lee, 2017). Most of the students were in Secondary Two.

The MFC has a multitude of design parameters that influence its power output. For a start, we can simply focus on voltage output as a simple measure of the cell. Thus, building a working MFC is a basic task, but “building the MFC with the highest voltage” would be the DBI challenge. This friendly inter-group challenge serves well as motivation for students to seek ways to improve their MFC design in iterative cycles. Other measures such as current output, longevity of the cell, and the ability to...
power simple devices, such as LEDs and tiny motors serve as increasing levels of challenge.

**School Science Reimagined**

Learning about the MFC inherently involves acquiring and applying knowledge from across biological, chemical and physical subject areas, most of which are already standard topics in school science. A substantial proportion involves topical areas that are already familiar transdisciplinary fields, such as the biochemistry of respiration and the electrochemistry of fuel cells. Unlike the typical learning of science, each discipline in isolation, each topic ordered by thematic similarity, this type of problem-based science lesson centres learning in the task or goal at hand, with what needs to be learnt brought up in an as-needed and a just-in-time basis. This is perhaps the core idea in finding an approach to reengineering school science in order to integrate STEM in a way that is not only pedagogically appropriate, but also serves to prepare students for the future workplace.

This of course, would involve a sea change in the teaching and learning of science—not one to be taken lightly nor hastily. But the MFC programme does offer opportunities to tackle current shortcomings in more manageable portions. The MFC programme can help in the near-term to address long-standing problems with school science practical work. For example, it is an inherently hands-on programme, but it also excels as one which forces a minds-on engagement as well. Building a functional MFC requires the application of scientific knowledge. A pour-it-all-in approach will not work, nor would random trial-and-error. Furthermore, in investigating the parameters that influence voltage output, experimentation has to be sequential and iterative; the results of one experiment informs and guides the conduct of the next, and ultimately underpins the design decisions students have to make.

Traditional school science practicals have been carefully crafted to direct students to observe or measure the change in one dependent variable, as one independent variable is manipulated, while everything else remainsunchanging controlled variables. The real world rarely ever works that way. Being an actual device that students have to grapple with hands-on, they also come up against real-world interactions. Just as one example, changing the concentration of one reagent, not only influences the reactions that reagent is involved in, but changes parameters such as the salinity and osmolality of the MFC, thus influencing the biological functions of the microbes within, with concomitant changes to the microbes’ ability to provide the energy needed. With the MFC, such complex interactions result in a system where there is no “model answer”, and in trying to build your own improvised MFC, there are no ready references on the internet.

Thus, learners are presented with a situation in which they have to invoke their own critical and inventive thinking, work collaboratively in conducting authentic experiments to investigate various properties of the MFC, actually measure the effect of individual design decisions made, and then use all that to engineer a winning MFC that outperforms the rest. And that they do, with the best designs so far from secondary two students producing a voltage approximately 75 per cent higher than the reference MFC design.

**Issues and Challenges**

The MFC programme described above presents a multitude of issues for school science. While it may incorporate the desired transdisciplinary STEM integration with inquiry-driven approaches to broad-based learning, it is this very nature that gives rise to significant difficulties in teacher-readiness, curriculum integration, assessment and so on.

The author has conducted teacher professional development workshops for over a decade on the MFC, and many teachers find the material challenging, baffled by the simplicity of the paradigm, but facing the complexity of explaining the MFC in the light of their own extant, but sometimes distant, knowledge. As nearly all teachers are subject specialists by training and/or practice, and the need to apply integrated science knowledge from across disciplines tends to perplex and unsettle. On the other hand, the school students were far less intimidated by the material and approach the programme with enthusiasm and were much less concerned with the disciplinary boundaries they were blithely traversing.

At present, these issues and more have limited the programme to be employed as a niche enrichment programme for higher-progress students. However, it is hoped that it provides a working model to serve as a basis for future approaches to, and a small step towards, integrating STEM in schools.

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**How to Cite**

Science Education, Innovation and Makerspaces: Educating in a Post-Google World

By Michael Tan

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In considering how science instruction in Singaporean classrooms ought to be in the coming years, a prime concern will be the advent of contemporary technologies. It is sufficient to simply point out the well-worn clichés of “unprecedented”, “VUCA”, “21CC”, or some manner of anxiety causing terms to indicate that we cannot continue the status quo. While tempting, I would rather put a spotlight on the simple observation that the practices of science have not received as much attention as the products of scientific investigation. What gets lost in this approach has been the creative nature of science: how scientists approach the difficult problem of creating new knowledge through empirical investigations; and the relationship between abstract knowledge claims, and the practical investigations that need to be done to advance knowledge claims. In this regard, the widely touted need for innovative dispositions for economistic reasons could be satisfied by merely communicating a more accurate picture of science to students.

How are Scientists Innovative?

In the natural sciences, knowledge is generated in empirical interactions. Knowledge is not simply “out there” awaiting discovery but rather, is created and validated within the scientific community, with empirical interactions as neutral arbiter of correctness. Scientists witness events discrepant within their current framework of understanding, propose candidate explanations then test predictions of their explanations against reality. This approach utilises abductive reasoning, where guesses are made based on a combination of prior knowledge and an initial evaluation of the circumstances. These guesses are necessarily prone to error and the inevitable disappointment of “failure” when best efforts are met with empirical evidence of mismatch between theory and reality. Scientists need to learn from these failures and continue refining their guesses for better fit. This reasoning process incidentally occurs in other fields, notably in design, or practical professions such as engineering, medicine, or education.

Several outstanding examples include Einstein’s gedankenexperiment, which was essentially “what-if” suppositions that took years between proposal and empirical verification; the discovery of Neptune based on observations of the irregular orbit of Uranus; Watson and Crick’s superior method of discerning the DNA double helix structure based on modelling proposed chemical structures and then working out the expected empirical findings; and many others.

Classroom Science

While it may seem most efficient to consider talking as teaching and listening as learning, contemporary evidence has shown that such forms of learning provide little else beyond utility in direct recall for standardised testing. If we consider alternative curriculum goals such as innovativeness to be important for science classrooms to achieve, conventional approaches need to be considered as inadequate. Even if these alternative goals are considered to be temporarily beyond the reach of the immediate classroom context, it is important to consider an appropriate relationship to the nature of science as a core curriculum goal for schooling. In this regard, understanding the practices of science must be considered as the “missing link” preventing conventional classrooms from accurately communicating science to learners. The stakes here are high. Given that scientific and technological issues bear upon almost every aspect of our contemporary lives, miscommunication could lead to citizens having unreasonable expectations and to seek inappropriate kinds of solutions. The perspective here is that science education cannot be merely thought of as a means for preparing “human resources” for the economy. Instead, science needs to contribute to citizens’ widened possibilities for understanding and decision making in futures that have never been, or unlikely to be, certain and predictable.

Makerspaces

To attend to these concerns, makerspaces need to be considered as an interesting context for the pursuit of these goals. While recent excitement surrounds technological innovations such as digital design and fabrication tools, it is easy to lose sight of the purpose of these makerspaces. They should not be
used as interactive museums or training spaces for these technologies, but rather, as collaborative experimental spaces in support of student initiated goals. Seeking to learn from the mistakes of past technological deployments, it is important not to simply immerse students in the emblematic project forms *du jour.* Instead, a key feature of makerspaces that needs to be exploited are the tools’ capacity for the fabrication of a wide range of possible “inventions”. Whereas in the past, students imaginations had to be limited to what could be fabricated by hand, the contemporary makerspace affords its users a wide range of possibilities for exploration. Nonetheless, as with any technological innovation, there is probably no implementation that can succeed without effective human interaction. Here, teachers still play the most significant role in the success of makerspaces or otherwise. Teachers need to depart from the role of epistemic authority in the classroom, the final arbiter of truth, and become mentors, coaches, and facilitators of inquiry. This position can be profoundly unsettling to teachers accustomed to classroom management strategies based on centralised control of knowledge. Also challenging will be the abilities of teachers to provide just in time instruction; such an approach is foreign to the dominant industrial paradigm of the last century but unfortunately still commands attention in our time.

We return once again to thinking about the shape of schools in relation to societies. That schools are conservative organisations bears no need for repetition. Yet, despite changes in the way industrial production is organised, not to mention the kinds of individuals needed for the democratic and equitable functioning of society, schools still operate as they did; if not in form, at least in intent. The future for science education needs to seriously take into account these changes, and paradoxically attend to classical problems so as to better prepare for uncertain futures.

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**How to Cite**

For many, the strongest memories of school science involved doing “stuff” in the laboratory that were filled with noxious liquids, explosive gases, swinging pendulums, or perhaps even a trembling attempt at dissecting a frog! All these activities (and various forms of field-trips cum social excursions) were definitely unforgetable and formed what many would consider as their favorite bits of receiving an education in science. But are these all that there is to it?

Others less charitable would immediately cry foul; much of the time it is claimed was instead spent memorising definitions or solving written problems with abstract concepts that bore little resemblance with the concerns of daily life. Indeed, it seemed as though one’s competence in science was judged by the singular outcome often did not ring true. Worse, these facts were quickly forgotten or rendered irrelevant the minute these school examinations were over. This perspective both acknowledges and considers knowing as an active “verb” form too. Therefore, when pupils investigate and discuss whether certain data/ideas/claims are trustworthy and how we might we explain them, this encourages a robust, dynamic form of understanding that transcends learning science as a body of received textbook truths.

This need to interrogate and explain applies even during laboratory work. Too often, students miss out on numerous opportunities to critique their findings or methods of analysis due to the stepwise nature of so-called experiments. Nor have there been sufficient opportunities for students to seek answers to their own questions or hypotheses. Educators have instead been more successful in providing for the hands-on learning of science than allowing learners to participate in its more intimidating although extremely crucial counterpart—minds-on science. Using more technical language, there are ample benefits in helping learners grapple with the epistemic and ontological aspects of science (i.e., evaluating why or what something is) compared to piling up more and more content knowledge (i.e., facts, theories).

It has further been said that while scientists have taken many years to establish their claims through cycles of experimentation (and failure) as well as through bitter disputes among expert peers, teachers are able to rapidly cover these very same concepts in the classroom with little trouble: “Read this, study that, bring home worksheet 6” and the lesson is completed! No wonder students miss out on the intellectual excitement of learning the subject as well as fail to appreciate the difficult process of establishing a theory as true in science. It may come as a surprise that the real achievement of science consists not so much in making new discoveries important thought it may be, but the peer review process where colleagues debate new evidence and act as impartial gatekeepers. Modern science has indeed blossomed through this manner; it is utterly dependent on peer-critique and healthy skepticism for what is the point of increasing the height of a skyscraper when its foundations have been built on quicksand?

We are thankful that we do not need to force young people to retrace the historical trajectory of all scientific concepts although this might be a useful teaching method. What will be more productive is to help students learn how we arrive at reliable knowledge in science or in any other school subject. These skills of critical thinking—argumentation/explaining are current buzzwords—are obligatory given the amount of partial truths, unwarranted inferences, and outright lies in circulation. Above all, this way of teaching has been found to increase deep understanding as students practice alternating in their roles as consumer, producer, and critiquer of science. Such a vision neither mitigates keeping learning fun and relevant nor forgets to uphold an ethics of care and responsibility: We simply underscore how young people are best served when they perform knowledge work by working through knowledge.

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Knowledge Work in Science
By Lee Yew Jin

Factory Reset or Update?

One contemporary understanding of powerful science instruction has been to reconsider the nature of scientific knowing. This perspective both acknowledges and yet is skeptical of the collection-of-facts type of schooling, which was the bane of science education ver1.0 described previously. While a content-rich curriculum is necessary within reasonable limits, knowledge should not be merely regarded as a noun. We really ought to consider knowing as an active verb form too. Therefore, when pupils investigate and discuss whether certain data/ideas/claims are trustworthy and how we might we explain them, this encourages a robust, dynamic form of understanding that transcends learning science as a body of received textbook truths.

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### Fostering Innovative and Inquiring Students

- **Consider how to balance all aspects of scientific inquiry, as teachers generally do not attend equally to the 5Es.**
  - Teachers in Singapore, according to a large-scale study, tend to ask more closed- than open-ended questions, and emphasise the first 3Es in the 5Es of scientific inquiry.

- **Emphasise that the activity of science is a messy and social process.**
  - For instance, this can be done by drawing attention to discrepant data and the role of peer review.

- **Makerspaces and “design and build” activities that integrate STEM could serve to develop innovativeness and “street smarts”.**
  - It is not clear yet what a comprehensive model of integrated STEM may look like, but as a start, educators can try to implement small programmes in selected streams. Teacher-readiness is needed to teach various disciplines; support could be potentially needed from more than one teacher.

- **Reserve time for reflection when facilitating student-directed inquiry.**
  - It is valuable to leave time at the end of a lesson to recap what has happened through the inquiry process.

### Helping Students Understand, Analyse and Explain

- **Take into consideration whether the role of scientific texts is overlooked in the classroom, and whether students have adequate reading support to access such texts on their own.**
  - When it comes to teaching how to read science texts, research suggests that teachers may emphasise scientific vocabulary at the expense of grammar.
  - Encouraging students to read the textbook prior to a lesson could help foster self-directed learning which can be further enhanced with suitable scaffolding that alerts students to features of scientific language.

- **Believe in your students’ abilities to handle questions of science inference in addition to more straightforward types of questions.**
  - A large-scale assessment of Normal-track students’ science inference abilities offered some encouraging findings.

- **Address potentially weak aspects of science inference.**
  - This can be done by emphasising:
    - Strategies for interpreting diagrams and tables
    - Learning to infer from given information
    - Problem-solving by logical elimination

- **Consider the representational competencies and challenges faced by students in producing successful scientific explanations.**
  - For example, students may be challenged in choosing a suitably precise model of representation from different options (e.g., graphs vs equations vs pictures).

- **To shed light on students’ thinking, multiple-tier MCQs could be an effective tool.**
  - For example, in addition to providing the answer, students can be asked to rate their level of confidence in the answer and/or provide the reason for the answer.