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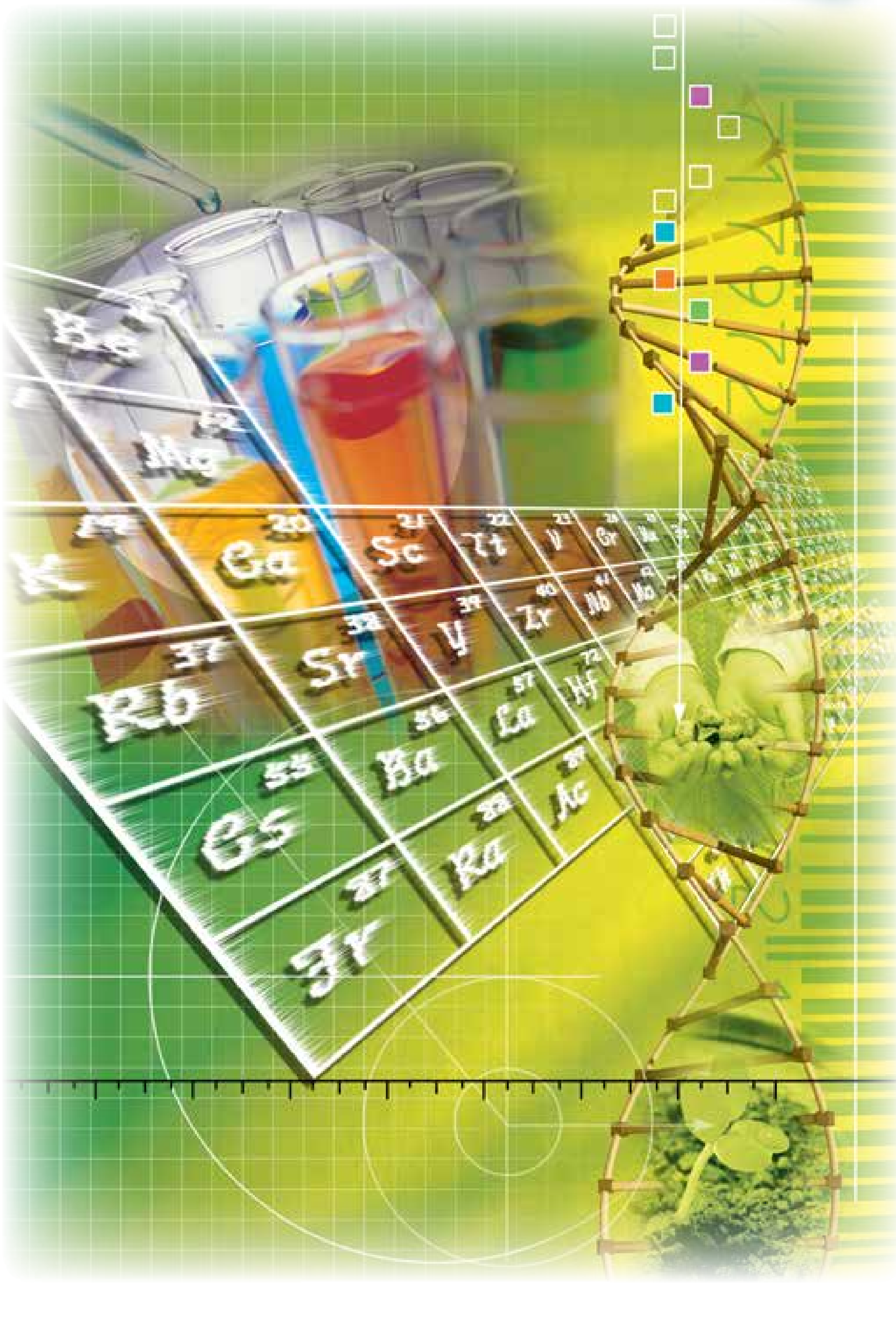

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ASEJ publishes scholarly work and strictly follows the blind review procedures and many other editorial policies described in the *Publication Manual of the American Psychological Association*, 5th edition (Washington, DC: American Psychological Association, 2001). Thus *ASEJ* is a refereed journal similar to most other scholarly periodicals published in Canada and the United States.

List of Contributors

Sue Arlidge, BSc (physical geography), BEd (secondary), has been an environmental educator for more than 30 years. A high school science teacher and hiking and snowshoe guide, Sue has held a number of positions in the nonformal education sector from park naturalist to family hiking guide to horticultural education coordinator at the Calgary Zoo. Sue's passion for engaging students and teachers in meaningful outdoor learning experiences has grown since coming to work with the University of Calgary's Biogeoscience (BGI) Institute's school ecology programs, 19 years ago.

Sandra Becker is a PhD candidate in the Learning Sciences, Werklund School of Education, University of Calgary. A former teacher-librarian, her doctoral research explores learning in unique environments, in particular makerspaces.

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Angie Chiang is a PhD candidate in communication, media and film at the University of Calgary and an instructor in communications, journalism and new media at Thompson Rivers University. Her research focuses on interactive and post-television audiences.

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Lisa Corbett, BSc (ecology), MSc (aquatic biology), BEd (secondary science), has been involved in environmental education for the past 10 years. She has worked as a naturalist, zoo interpreter, field station educator and high school science teacher. Her current role is as a junior high science teacher at Rundle College. She is passionate about science education and loves to find ways to get students to think like a scientist. She believes strongly in making learning authentic for the students and that part of that is to put them in the outdoor environment of study. Her passion was nurtured during her time as an educator at the University of Calgary's Biogeoscience Institute, and she continues to work there periodically for various feature workshops.

Luciano da Rosa dos Santos, PhD, is an assistant professor and faculty development consultant in the Academic Development Centre at Mount Royal University. His research interests include educational development in higher education, online teaching and learning, and alternative learning environments.

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Michele Jacobsen, PhD, is a professor in the Learning Sciences and the associate dean of Graduate Programs in Education with the Werklund School of Education, University of Calgary. She provides academic leadership for teaching faculty and graduate students in educational research and educational psychology. She uses action- and design-based approaches to research to understand technology-enabled learning in school and postsecondary classrooms, to study peer mentoring and research ethics, and to evaluate the design of participatory learning environments that sponsor knowledge building, intellectual engagement and assessment as learning.

Edward Johnson, PhD, is the director of the University of Calgary's Biogeoscience Institute. In addition to this position, he is a professor emeritus of biological sciences at the University of Calgary and involved with research programs at the Biogeoscience Institute. Dr. Johnson's research is directed at integrating natural disturbance into plant community organization and dynamics. His applied interests are in global climate change, biological conservation, and ecosystem and fire management.

Jennifer Lock, PhD, is a professor and the associate dean of teaching and learning in the Werklund School of Education at the University of Calgary, Alberta, Canada. Her area of specialization is in online learning, ICT integration, change and innovation, educational development in higher education, and experiential learning through making and makerspaces.

Stephen A Martin, MSc (educational technology), is a technology/CTF learning leader and Grade 9 teacher of STEM and the performing arts with the Calgary Board of Education. He is a creative leader of exceptional drama productions; cofounder of ScratchEdYYC, a professional development community that works on finding ways to incorporate meaningful computation thinking and coding activities into our classrooms; and maker.

Savannah Poirier, BSc, uses her ecology background to inspire youth and teachers to poke a little deeper in the out of doors. She has been school program lead at the Biogeoscience Institute for three years.

Kenzie Rushton, MEd, is an educational consultant with the Galileo Educational Network at the Werklund School of Education, University of Calgary. He codesigns and presents professional learning for teachers with colleagues from the University of Calgary using a design-based approach. This work directly supports teachers in developing a greater understanding of effective teaching practices in relation to STEM task design.

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Marie-Claire Shanahan, PhD, is associate professor of learning sciences at the Werklund School of Education. Her research examines the roles of language and identity in participation and engaging in STEM knowledge communities.

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President's Message

Carryl Bennett-Brown

Welcome to our renewed *Alberta Science Education Journal*. The Alberta Teachers' Association's Science Council so appreciates having a professional journal in which research and articles, including sessions presented at the annual conference, are presented and celebrated. This journal allows for diverse topics to be investigated and contributions from a variety of educators to be shared. Thus, classroom teachers, university professors and PhD students are no longer stuck in silos or echo chambers. With such critical science education and knowledge to be shared, examining issues and burgeoning science topics, this journal allows us to support the values and beliefs of science. Further, it is essential for educators to be well versed in complex issues. With access to endless knowledge (that is not always based on research and sound practices) on the Internet, it is vital to have access to reliable data and strong facts.

Thank you for your contributions to education and to science!

2018 Science Council Executive

The ATA Science Council is an organization operated by science teachers for science teachers to promote, support and enhance the teaching of science in Alberta, Canada. The ATA Science Council executive is made up of a dedicated group of volunteers. Please meet your 2018 executive.

Carryl Bennett-Brown

President

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Carryl began teaching in 2001, in Ponoka, Alberta. This was the best way to start teaching—she was surrounded by a group of committed educators who cared deeply for children and were willing to share their time, their knowledge and their skills. Currently, she is teaching in St Albert at ESSMY, while also being very involved in ATA activities—president of Local 23, secretary of NCTCA and ATASC. She is pleased to become president of ATASC because it allows her science geekiness to thrive, while providing professional development for the science teachers of Alberta.

James Slattery

Vice President

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James comes from a family of teachers, and was born and raised in Fort McMurray. He graduated from the University of Alberta, has taught in Fort McMurray and now teaches in Edmonton. Involved in several capacities with the Alberta Teacher's Association, he joined the Science Council executive in 2017 with the hope of helping expand the council's work to provide support to science teachers across the province.

Kari Lagadyn

Treasurer

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Since 1998, Kari has taught in the same French immersion school in St Albert where she did her last round of student teaching. She has taught almost every science class from Grade 8 through Grade 12, except for Biology 20 and 30, and every junior high and senior high math course. For much of her time out of the classroom she is an energetic soccer mom.

Brenna Toblan

Secretary

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Brenna turned to an education degree after completing her degree in astrophysics and physics because she needed a way to pay off her student loans and continue to a graduate degree. Imagine her surprise when she not only enjoyed teaching, but seemed to be reasonably good at it.

Twenty-two years later, all but one spent teaching physics and chemistry at Central Memorial High School, in Calgary, she has developed a passion for getting students to think about how we know the things that we know, and to look at the world around them with a scientifically critical eye.

She spends her nonteaching time (yes, there really can be such a thing) involved in science fiction in all media, and assorted geekery such as potions classes for kids at the Calgary Comic Expo. At Science Council meetings she can be found behind her screen, typing up a storm and inserting assorted parenthetical comments into the minutes.

Tracy Onuczko
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Tracy has been teaching science, mainly biology and general science, in K–12 schools and to preservice teachers at the University of Alberta since 2005. She is currently completing her PhD in science education at the University of Alberta. Tracy is thrilled to be part of ATASC and is looking forward to the joint math and science conference this year when Geeks Unite 2.0!

Deepali Medhekar
Communication Director

Deepali started her teaching career as a science teacher and further as a teacher educator in Vadodara, India. Since moving to Canada in 2005, she has achieved her Alberta teacher certification. She has taught science in both countries in the formal school systems as well as in nonformal science education centres such as Eklavya and Telus World of Science. She is passionate about inquiry-based learning by doing in science and likes to infuse technology into her teaching practice. She believes in the power of volunteering as a means of feeling connected to her community.

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Trinity has been teaching with the Calgary Catholic School Board for 17 years—general elementary, and elementary and junior high science, art and technology. She joined the ATA Science Council first as an assistant conference director in 2012, then as conference director in 2013; she has been newsletter editor since 2015. She most enjoys hearing what other teachers are doing in their classroom and sharing teaching stories—not only in Alberta, but all across Canada.

Monica Chahal
Journal Editor

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Born and raised in Edmonton by hard-working, immigrant parents, Monica was encouraged to chase her dreams and passions, one of which is a love of science. While working full-time at an inner-city school in Westminster, London, she became inspired to want to make education more inclusive and accessible for marginalized youth and pursued graduate studies as a result. She is an avid science fiction fan and believes in the power of the Doctor. Bow ties are cool.

Peter Rehak
Elementary Director

Peter Rehak has been teaching Division II and III students for 21 years. He started in a rural school, teaching Grades 4 to 6 in the morning and junior high in the afternoon. Being flexible and proficient in multiple subject areas was a necessary talent. "Using and abusing" technology and science in the classroom has come naturally to him. Inspiring and promoting self-discovery have been mainstays of his lessons.

Amanda Joblinski
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Amanda began teaching in 1999 and has taught a variety of subjects over the years, primarily Grades 5 to 9 science. During this time, Amanda completed a diploma of education in curriculum studies (science and social studies) and a master of education in administration and leadership (policy studies). Travelling with students to explore science and being involved with different aspects of the science education community are both passions that take up all of her time that isn't spent in the classroom or with her two little boys.

Danika Richard
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Danika has been teaching for the past six years, primarily in high school biology, chemistry and general sciences. She is a certified yoga instructor and offers a yoga option for high school students as a locally developed course. As a former entomologist, she shares her love for insects with her students (and anybody else who is too polite to tell her to stop) and tries to incorporate this passion as much as she can into her lessons. She loves gardening and, despite her athletic abilities, enjoys playing on various recreational sports teams.

Kerry Rose
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Kerry Rose was a high school science teacher in Sherwood Park for 30 years. She is presently completing her PhD in the Department of Secondary Education at the University of Alberta, where she teaches the introductory professional term (IPT) and advanced professional term (APT) science curriculum courses. She is also a project manager for the University's Centre for Mathematics, Science and Technology Education (CMASTE). At CMASTE, Kerry liaisons with schools, funding agencies, government departments and academics to coordinate science education projects locally, nationally and internationally. If you have ideas for projects or are interested in finding out more about CMASTE, please get in touch! Follow CMASTE on Facebook for upcoming projects, speakers and events.

Leon Lau
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Leon holds an MSc from the University of Alberta and has been a classroom teacher for 10 years. He is driven to promote science education and has volunteered with Science Council and ATA Local 38 for 7 years. Leon has also contributed to the Science 30 diploma exam and the current curriculum development process. Outside of school, he enjoys hiking, skiing, curling and social dancing.

Alicia Taylor
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Alicia has been teaching since 2004 and has had the opportunity to teach students both in the classroom and online. She now calls Calgary home and teaches chemistry, mathematics and science at Queen Elizabeth High School. She also has a role with her ATA local PD committee and serves on the local council of school representatives. After her work on the Science Council's 2017 conference, she is looking forward to providing support to the incoming conference director.

Sean Brown
Executive Staff Officer

Sean joined the Association's Teacher Welfare executive staff in 2015. He holds a BEd from the University of Alberta, a master of educational technology from the University of British Columbia and a graduate certificate in Catholic school administration from Newman Theological College. Sean began his teaching career with Grande Prairie and District Catholic Schools, where he taught for 5 years. He also taught for 16 years with the Greater St Albert Roman Catholic Schools, 5 of those years as a vice-principal.

In addition to acting as a representative of the bargaining agent, Sean acts as the Association's expert in the area of education finance and is the staff advisor for the Science Council. Provincially, Sean served as district representative for Edmonton District for two years and as an economic consultant for eight years. At the local level, he served as president, vice-president, EPC/NSC chair and several other positions with Greater St Albert Catholic Local no 23.

Wes Irwin
Alberta Education Representative

Wes Irwin has worked in the field of science education with diverse groups of students for over 30 years. Wes has worked as a junior/senior high school teacher, curriculum lead and, more recently, provincial curriculum manager. Over the years, Wes has been heavily involved with the executive of the ATA Science Council, including one term as council president. In his current role with Alberta Education, Wes is working with teachers from across the province on the development of the K–12 provincial science curriculum.

Editor's Message

Monica M Chahal

My students, past and present, influence all that I do and hope to do. While we celebrate the 100th year of the Alberta Teachers' Association, it is essential that we do not forget the history embedded in our subject—history that can be both disturbing and wondrous.

In the name of science, there was a justification for the eugenics movement, studies on human test subjects and much more. Yet it is also through science that DNA was discovered, a telescope highlighted that the world was round and we began travelling through the air. From Galileo and Bacon to Darwin, the push for metaphysics meant that the guiding epistemology of the "new" world was one of observation, dissection and analysis. During the 19th century, "primacy of scientific knowledge above other ways became a modern, public belief" (Blades 1997, 17), continuing into the modern day. During the 20th century, the world became engrossed in geopolitical competitions exemplified by the Great Space Race. In North America, a focus on science education ensued (Blades 1997). It was at this time that the importance of the science curricula was established, influenced by politicians, industrialists and scientific experts, and the "traditional" scientific method took precedence in schools. Through the processes of physical and intellectual colonization, Western notions of science education have been globalized and normalized (Nandy 1988; Shiza 2011). As we move into the next 100 years, we are beginning to understand that there are different ways of knowing our world beyond the Western notions of science. Nowhere is that shift more apparent than in our classrooms. As society continues to discover the incredible possibilities of science innovation in the 21st century, our classrooms are at the forefront.

Our curricula are changing, the introduction of Indigenous perspectives is forthcoming and innovation is everywhere. For example, as highlighted by our 2017 conference, Making Space for Science, Jennifer Lock and her coauthors' article, "It's More Than Just Making," highlights the growing trend of makerspaces in in our science classrooms as spaces for innovation and creativity. In the world of cross-curricular connections, Martin and Jacobsen's article, "Coding and Computational Thinking in Math and Science," discusses the benefits of a program like Scratch in today's classrooms. Building upon computational thinking, Pratim Sengupta and her coauthors' article, "Reframing Coding as 'Mathematization' in the K–12 Classroom: Views from Teacher Professional Learning," illustrates a pathway for integrating computational modelling and programming in the science classroom for teachers with little or no background in programming. Building upon Sengupta's STEM-based research, Man-Wai Chu and Angie Chiang's article, "Raging Skies: Development of a Digital Game-Based Science Assessment," discusses the development processes of interactive game-based assessment. With the focus being in the classroom, Lisa Corbett and her coauthors take us out of the classroom with their article, "Guiding Students Toward Open Inquiry in a Novel Outdoor Setting," discussing how the Biogeoscience Institute in the Alberta Rockies uses the outdoors to provide opportunities for scaffolded open-inquiry projects.

With innovation in science comes innovation in praxis, and it is essential that we do not forgot the history of science. So not only can we learn, build upon and go beyond, but we can also make sure that those we educate can go forth and truly understand the science that surrounds them every day in a critical, inventive and, hopefully, groundbreaking way. Who knows what the next 100 years will bring? Perhaps there is a future Darwin, Galileo, Marie Curie or Rosalind Franklin in your midst today.

May the students of today inspire you the way my students inspire me.

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It's More Than Just Making: Insights into Facilitating Learning Through Making

Jennifer Lock, Luciano da Rosa dos Santos, Paula Hollohan and Sandra Becker

Abstract

Makerspaces are a rapidly growing trend in education. Schools are incorporating makerspaces to provide students with experiential learning opportunities to be designers, innovators and makers. Attention must be given not only to the creation of such spaces but also, and more important, how to incorporate such activities in an environment that fosters deep learning. In this article, a team of researchers share their lived experience of implementing makerspace activities with students in a school of education. From reflecting on our experience designing and facilitating learning through making, we have identified three lessons learned: designing challenging learning tasks is not easy; facilitating learning through making is a delicate dance; and changing our dispositions through making changes our practice. Learning in makerspace environments is as challenging for teachers as it is for their students because it connects the development of iterative design provocations and a mindset that embraces failure.

Introduction

Making and the makerspace movement is a fast-growing trend embraced by learning commons (Klipper 2014) and emerging in K–12 schools (Johnson et al 2014, 2015). A makerspace is a gathering space for inventors and innovative thinkers to access tools and technology to design, plan and produce solutions to problems (Bevan, Petrich and Wilkinson 2015). Students in makerspaces are able to design and build prototypes and create machines, games and/or solutions using a range of materials from low tech (eg, paper) all the way up to high tech (eg, 3-D printers). The addition of an array of digital technologies adds to the boundless potential for rapid prototyping. A makerspace in the K–12 setting is more than a resourced space where students can play with materials. Rather, it is a learning environment in which students are designers, innovators and makers.

The purpose of this article is to share reflections of our lived experience of designing and facilitating learning through making in an informal learning commons context. We begin by providing an overview of *making*, *maker* and *makerspace*, why they are emerging in school and the possible shift developing in education as a result of the maker movement. Next, we examine insights from a collaborative partnership with a library's technology instructor who is leading the maker movement in our higher education library and a team of researchers from a school of education, focused on learning through making. Finally, we share three lessons learned from our practice in designing and implementing a series of maker events. With each iteration of our work as facilitators and researchers, we are learning more about nurturing a maker mindset that needs to be grounded in curricular and pedagogical practice.

Maker, Making and Makerspaces

The terms *maker*, *making* and *makerspace* are often used without giving careful consideration to how they are defined. There is no agreed-upon definition for these terms (Martin 2015; Vossoughi and Bevan 2014). *Making* is considered a creative process (Willett 2016) and is sometimes associated with such terms as *tinkering*, *hacking* and *fabrication*, whereas makers design and build objects using physical and digital tools (Bevan et al 2015; Ryan et al 2016). While making involves creating and prototyping, a *maker* is an individual who engages in making in a highly personal way. A maker is "good at improvising: they are able to do things that have no instructions" (Dougherty and Conrad 2016, 144). Students in a maker environment participate in making by ideating and solving problems of interest to them; "[t]he process of realizing an idea and making it tangible is what defines a maker" (Dougherty and Conrad 2016, 144).

This work of making takes place in a *makerspace*, a participatory social environment in which people of different levels of skill and expertise work alongside each other to create and invent. Makerspaces are "constructivist spaces" (Fourie and Meyer 2015, 521)—flexible, community spaces, particularly well suited to libraries or learning commons, where groups and individuals can come together to hypothesize, explore and experiment as a means to deepen their own learning. As noted by Horvath and Cameron (2015), "making things allows students to try something, see what works, fix problems, and carry on" (p 60). In this physical space, there are tools and materials available for constructing, fabricating and testing. In an educational makerspace context that would be found in a school's learning commons, one would find boxes, buckets and baskets housing a variety of materials ranging from low technology (eg, wood blocks, Lego, paper, fabric, duct tape, and sets of scissors, pliers and screwdrivers) up to high-technology items such as digital kits, 3-D printers, and various digital devices (eg, Arduino, Makey Makey, Raspberry Pi). In their essence, makerspaces are places where tools are accessible for students to construct or deconstruct objects and projects, "embracing tinkering, or playing, in various forms of exploration, experimentation and engagement, and fostering peer interactions as well as the interests of a collective team" (Wong 2013, 35).

With the ongoing growth of the maker movement, terms such as *innovation lab*, *design lab*, *hackerspace*, *fab lab* and *science lab* (Peppler et al 2015) have been used to describe such spaces. Regardless of the specific term used, makerspaces tend to allow users to select their own activities in an environment that is supportive, playful and collaborative, and where trial and error is encouraged (Oliver 2016a).

A review of the literature indicates a prevalent focus on *what* makerspaces are and *how* such spaces are created (Good 2013; Haug 2014). In addition to that, we need to also uncover the educational benefits that may arise from makerspaces. The National Science Foundation, for instance, is funding research (Learning in the Making) to examine the educational benefits of makerspaces and the transference of this learning to improving skills in math and science (Johnson et al 2014). For example, Vanderbilt University and the University of Michigan's Center for Entrepreneurship are involved in work with makerspaces focused to foster experiential learning and student leadership (Johnson et al 2014). Over 50 per cent of those surveyed through Georgia Tech noted that their GPAs were positively affected by time spent at their makerspace innovation studio (Forest et al 2014, 21).

Traditional approaches to learning are "typically structured such that any failure would get a bad grade. Learning by making allows for experimentation in ways that are difficult to teach through books, lectures, papers and quizzes" (Horvath and Cameron 2015, 60). By allowing students a space to experiment with solutions—failing sometimes, succeeding at others—in order to construct their own knowledge about the situation, makerspaces may be one of the innovations that Papert (1991) envisioned that would "produce radical change in how children learn" (para 18). Within this shift from traditional learning to learning through making, "students can learn and create together, integrating content- and product-centered activities as part of their instruction" (Johnson et al 2014, 14). As such, educational makerspaces are prime opportunities to incorporate Papert's notion of constructionism (Kurti, Kurti and Fleming 2014a), where one could combine digital and physical artifacts or "objects to think with" (Papert 1980, 23) to elaborate new solutions to a given problem. However, for such benefits to be obtained, educational makerspaces need to be more than a resourced space that comes with the perspective of "have at it."

As more K–12 schools, along with their learning commons, are establishing physical spaces with tools and materials (eg, 3-D printers, digital kits), we also see a greater need for librarians and teachers to be able to scaffold and facilitate learning opportunities that foster creativity, where the students are encouraged to be innovators or makers. The complexity of this shift requires teachers and librarians to create maker tasks or offer opportunities for problems to be identified and/or solved through purposeful design, collaboration and risk taking that may include rapid prototyping. It is in these learning environments that we need to foster collaboration, creativity and iterative, creative solutions so that students can develop a maker mindset (Dougherty 2013; Paganelli et al 2017). A key challenge with makerspaces, according to Horvath and Cameron (2015), is the range of skills required by the teachers and/or librarian. No one person has the needed knowledge or skills to facilitate such learning. As Horvath and Cameron argued, "a combination of comfort with traditional shop class methods plus electronics plus competence in computer programming" (p 5) is what teachers need to facilitate learning through making. As such, within schools, it may require developing specifics skills but also working with others to support making. One approach to developing such skills, as noted by Horvath and Cameron, is to "gather a diverse group of colleagues to try out some joint interdisciplinary projects" (p 207). Experience and competence of a diverse group will help support the learning.

Fostering a Maker Mindset

The concept of a maker mindset originated from Dweck's (2006) work on growth mindsets, in which the iteration of ideas and embracing of failure is seen as an opportunity to learn. Scholars suggest that the maker mindset empowers students because it provides opportunities to develop perseverance, problem solving and thinking abilities (Cermak-Sassenrath and Møllenbach 2014; Oxman Ryan et al 2016). Some see the development of the maker identity or mindset being as important as the skills and knowledge (Chu et al 2015) acquired through making.

The development of the maker mindset is as critical for teachers as it is for students. Litts (2015) observed that "facilitators' ability to support making activities was severely limited by their own maker identity" (p 349). To gain the effects of makerspaces, teachers must take on the characteristics of the maker mindset, including persevering, problem solving and embracing failure as a part of learning. Whether for teachers or students, a "maker mindset is an expression of the growth mindset that is evident in a maker's willingness to learn new tools and methods as well as experiment without certainty of success" (Dougherty and Conrad 2016, 145).

One way in which the maker mindset is enacted during a pedagogical transaction is through a dynamic relationship in terms of the role of student and teacher. Maker education, whether in informal or formal environments, gives ownership of learning to students, but in a self-directed and participatory manner (Fleming 2015). During maker projects, learners follow their interests (Oliver 2016b), and different arrangements are constantly made between students, peers and instructors. As noted by Fleming (2015), at times students may be learning with and from colleagues and the instructor, yet at other times they may be in a teaching role with peers and with the instructor. Layering into this complexity is the changing role of the teacher. Working more in a fluid role as a facilitator in these maker environments requires teachers to be both risk-takers and learners. Further, Fleming (2015) found that, at times, the teacher's role may also be that of "an observer, intervening only when further rigor or the need to pass on a gem of wisdom from experience becomes necessary" (p 47). At the same time in this dynamic role, teachers and librarians are learning to navigate making in order to support deep learning. They become "spacemakers" (Kurti, Kurti and Fleming 2014b, 11), responsible for establishing the environment of discovery that is inherent to makerspaces.

Research Design

A design-based research (DBR) methodology is "a series of approaches, with the intent of producing new theories, artifacts, and practices that account for and potentially impact learning and teaching in naturalistic settings" (Barab and Squire 2004, 2). This flexible methodology is designed to "improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually-sensitive design principles and theories" (Wang and Hannafin 2005, 6–7). This design allows for the implementation of the innovation (makerspace) and the study of the iterations of the use of the makerspace over time. Through DBR, a collaborative approach has been used to study the design, implementation and facilitation processes for the creation of a series of makerspace initiatives. Two questions guided our DBR inquiry: (1) What are the essential conditions needed to build capacity of instructors who facilitate learning in makerspace environments? and (2) How does the design of a makerspace learning task influence teaching and learning practices?

Through the iterative process and the ongoing discussion of our research team in response to the various planned initiatives and data collected, we continue to learn of conditions and factors that influence the facilitation of learning using a maker approach. This article outlines reflections and insights from our lived experience with the initial year's collaborative work in terms of design, implementation and facilitation in support of learning through making.

Our Maker Team's Context

In 2015, the Education branch library at our university began to develop a makerspace environment. The library's technology instructor investigated the maker movement and engaged in various learning opportunities regarding makerspaces. Soon after, resources and materials were purchased. In order to prototype making for learning in a cost-effective and less obtrusive manner, the decision was made to house the resources and materials in a mobile makerspace, a large rolling tool chest purchased at a hardware store that could be moved to different locations as needed and tucked away when not in use.

We were curious about a variety of aspects such as task design, development of 21st-century skills through making, and the assessment of learning in this process. Through mutual interest in makerspaces, we formed our design-based research team: a librarian (specifically, the library's technology instructor), responsible for leading the making initiative; two doctoral students who actively engaged in supporting not only selected maker activities but also learning the research; and an academic charged with leading the study.

Over 12 months, we offered various maker activities to undergraduate and graduate students and faculty. This article highlights four of these initiatives, showcasing the range of work that occurred.

1. An event entitled Evil Genius was a three-part research series in which undergraduate students were involved in prototyping and testing with high- and low-tech tools. Each session of this series lasted 1.5 hours and was organized around challenges that needed to be solved in groups within the allotted time frame.
2. A series of half-hour workshops, entitled Black Chair Sessions, designed to be hands-on workshops focused on introducing undergraduate education students to makerspace tools and kits (eg, littleBits, Makey Makey).
3. Think. Design. Make was a three-part summer series providing participants with the experience of working through the design-thinking process, from identifying a problem all the way to prototyping a design.
4. A Spotlight area was established in the library that provided the testing of open-ended making opportunities (eg, knitting, marble runs, paper airplanes, paper design, bridge building, deconstruction).

The various offerings of maker activities have given the team an opportunity to reflect on our own learning and to use that to inform next steps. In particular, after maker events, the team met to debrief, reflect and develop a plan of action leading to the next iteration.

Lessons Learned

Through our ongoing team meetings and reflective process, three preliminary findings emerged from our work in terms of designing, implementing and facilitating learning through makerspaces:

- Designing challenging learning tasks is not as easy as one would expect.
- Facilitating learning through making is a delicate dance.
- Changing our dispositions through making changes our practice.

Designing Challenging Learning Tasks

In our first maker series, Evil Genius, we came to see that designing rich, relevant learning tasks is easier said than done. Part of the process was about giving ourselves permission to view each session as our own learning opportunity in terms of what and how we supported learning through the maker activity. We debriefed after each event and discussed what worked and what could be improved. With the Evil Genius series, we designed each task to be progressively more complex, moving from low-tech (eg, create a game using cards, dice and blocks) to a mix of low- and high-tech solutions (eg, littleBits and Makey Makey). We observed that the constraints built into the task design that fostered greater complexity in the work resulted in a less successful learning experience for some of the students. For example, one task involved the use of Makey Makey, an invention kit that allows students to use ordinary materials to create switches or controllers. In this task, groups were charged with using Makey

Makey to design a switch to time a toy car's speed. Students used the Scratch game on the Makey Makey site to guide the data collection without having to do the programming. As we observed two groups, we found it interesting to see how one group, when encountering difficulty, shut down, whereas the other group built on each other's ideas and appeared delighted when they accomplished the task. Observing how each group approached the task differently, we asked questions such as these:

- Why did one group give up?
- With the advancement of the complexity of tasks, was greater scaffolding required to support *how* and *why* to use the various tech-solutions?
- Was more time needed to lead into each making task?
- Were the students uncomfortable with being in this place of unknowing? and
- What did we need to explore in the task design that would make the work more fulfilling for *all* participants?

We grappled with these questions as a result of the experience. These questions helped us to rethink the design, and also the nature of our facilitation.

The library's technology instructor, who participated in all makerspace activities, felt that the less structured design of the Black Chair sessions, as compared to Evil Genius, was more successful for the students. For example, during a littleBits half-hour hands-on learning session, the first part of the session was dedicated to discovery, with the second part connecting the use of the kit with curriculum outcomes. A possible explanation for the greater sense of success could be that the focus was on one technology, prompting participants to engage in rich discussions about the use of the particular tool in interdisciplinary curriculum settings. As a team, we did come to see that for student engagement, tasks needed to be authentic and student driven, and that documenting the process could serve as a reflection tool for prototyping enhanced session design solutions.

Facilitating Learning Through Making

Makerspace learning is messy but engaging. It is learner centred, inquiry based, interdisciplinary and technology enhanced for both students and instructors. It is implicitly creative, imaginative and process driven, allowing for differentiated problem solving that leads to more questions and deeper learning. It is in this space that the teacher plays a key role in helping students to make the curricular connections, to challenge their thinking and to guide the development of critical professional or 21st-century skills.

It is a delicate balance of knowing when to step in and when to step out, and of leading the learning. When will a demonstration or giving of guidance be helpful, in contrast to giving students more time to grapple with the learning? Along with the timing, we also found the need to be skilful in asking probing and/or linking questions to better scaffold the learning. The ability to observe and listen to the conversations occurring during the making and then to provide the necessary guidance and support by the instructor to foster the learning is a skilful art that needs to be developed in those who facilitate learning in makerspaces. For instance, in the first Evil Genius event, as facilitators we tended to stand back and let participants explore and engage in the task. Upon reflection, we felt that this particular group could have benefited from greater guidance. This made us realize that facilitating learning through making depends on our responsiveness in relation to learners and the learning task.

With makerspace learning, teachers must allow substantial time not only for their students but also, and just as importantly, for themselves to think, design, prototype, test and retest as part of the maker learning experience. Time provides opportunities for the exchange of collaborative peer feedback through multiple iterations, while embracing failure as fortuitous for rich learning, which turns the focus to process rather than a hurried, final solution. This means being aware of the fluidity of knowing and not knowing, of developing insights over time and iterations, and of learning not in scheduled time blocks but through ongoing experiences.

Changing Our Dispositions Through Making

The collaborative nature of making challenges teachers to let go of control and look beyond themselves for expertise. This can be done by encouraging all members of the immediate maker community to provide input and lead aspects of the design process, depending on their strengths and background knowledge. It allows teachers to see the possibilities for interdisciplinary connections across curricular areas and validates the complexity and "messiness" of rich teaching and learning, taking their own learning beyond the conventional notion of what it means to be literate. For example, Black Chair sessions allowed teachers to see the creative ways that participants used a photography app to capture artifacts while documenting the process with written comments. In a way, teachers need to embrace the spirit of making in their own preparation—tinkering, experimenting and designing solutions to the situations that arise.

Teachers who facilitate learning through making need to be confident and willing to ask for outside expertise when needed, and to create conditions so that students draw on the expertise within their own group. For example, in planning the Think. Design. Make session, the library's technology instructor called on 3-D printing experts to assist. Students in the Evil Genius session using Makey Makey declined the offer of a short video explaining the technology they were to use. Rather, they wanted time to mess around with the kit; they demonstrated a sense of pride and accomplishment when they were able to prototype a solution themselves. Teachers need to have the confidence to assess the situation and determine where and how expertise can be brought into the learning in a timely and appropriate manner.

Conclusion

As teachers embrace learning through making in the K–12 and postsecondary contexts, care needs to be taken that making is more than creating a space and resourcing it with various materials (eg, kits, computers). A critical factor for implementation is the willingness of teachers to take risks, accept failure, embrace the unknown and rely on the collaborative knowledge and expertise of all, while providing time for students and themselves to iterate solutions when designing and facilitating within a makerspace learning environment.

Taking time to reflect on our lived experience has helped us learn how to better facilitate learning through making. With the expansion of the maker movement, teachers need to become aware of and develop an appreciation for the intricacies of designing and facilitating learning through making. Through our own learning with designing and facilitating maker activities, we, too, are living the maker and making experience. After all, it is more than just making.

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Coding and Computational Thinking in Math and Science

Steve Martin and Michele Jacobsen

Introduction

Coding and computational thinking are generating renewed excitement among middle and high school teachers and students and are also gaining attention and momentum in schools and school jurisdictions across Canada. Unlike the command line interfaces of the past, contemporary coding software allows students and teachers to get started quickly with programming and the creation of games, simulations and other projects as part of a computational thinking curriculum. Coding and computational thinking build upon design and programming ideas developed by pioneers in the Media Lab at MIT (Seymour Papert, Yasmin Kafai, Mitchell Resnick, Idit Harel, Andreas diSessa and so on). Industry initiatives, like the hour of code, which is a global movement introducing computer science and computer programming to millions of students in 180+ countries during Computer Science Education Week, have been developed, in part, to address the identified and growing need for coding expertise across industries and organizational contexts.

The push to get students to work on coding and computer-based problem solving has resulted in some ministries of education across Canada adding coding to provincial programs of study (eg, Nova Scotia and British Columbia). While enrolment in postsecondary computer science programs grew in the 1980s and 1990s, it has levelled off at the same time that the need for programmers continues to grow. The number of people attracted to computer science is plateauing, so there is a call to engage K–12 students in coding and design experiences to help sponsor motivation for postsecondary study in computer science (Grover and Pea 2013; Information and Communication Technology Council 2016).

In this article, we provide a definition of coding and computational thinking as part of an explanation for why coding and computational thinking skills are important for all students to develop and learn as a part of their formal schooling experiences. We also provide three examples of computational thinking and design activities that have been successfully used in Alberta classrooms to illustrate teaching and learning experiences with coding, and to highlight how learning designs that promote computational thinking, and also allow students to express or develop their understandings of specific curriculum objectives, can create exciting and rich learning opportunities for learners.

What Is Computational Thinking and How Is It Different from Coding?

Coding is the creation of code—that is, the creation of a program or set of instructions that a computer executes in order to do a task. In order to create code, one needs to apply the skills that Wing (2006) identified as a new and necessary literacy: computational thinking. However, one cannot assume that computational thinking equals coding—one can engage students in computational thinking without requiring them to actively engage in coding. Wing (2006) argues that at its heart, computational thinking is about problem solving and understanding and designing systems. One can engage in computational thinking through coding, interface design, instructional design, the design of instructional software, video game design, the creation of simulations and so on. One can also engage in computational thinking by creating and building on ideas through hands-on and iterative problem-solving processes, such as the ones aligned with the Alberta elementary science curriculum—Problem Solving Through Technology activities in each grade (Alberta Education 1996). Challenges from the Problem Solving with Technology units, such as Building with a Variety of Materials, in Grade 3, or Flight, in

Grade 6, are examples of problem-solving processes that rely on students using trial and error to solve problems based on observation, adjustment, reflection and refinement, and, as such, provide important non-coding examples of students using and developing computational thinking skills without engaging in coding on a computer.

Wing (2006) proposed computational thinking as a necessary skill set, not just for computer scientists, but for everyone. Computational thinking includes analytical thinking skills that are common to computer science, and also have much broader applications to problem solving and system design problems outside the boundaries of computer science. Wing's (2006) key concepts of computational thinking include

- conceptualizing, not programming;
- fundamental, not rote, skills;
- solving problems, designing systems and understanding human behaviour through computer science concepts;
- a way that humans think, not a way computers think;
- complementing mathematical and engineering thinking; and
- working on ideas, not artifacts.

Grover and Pea's (2013) review of computational thinking in K–12 education identified the many simplified programming languages and computational thinking tools that have been developed and are being used for coding in schools, including Scratch, Alice 3D, Greenfoot, Game Maker, StarLogo and Kodu. Lye and Koh (2014) found that there are many different definitions of computational thinking and the specifics of what the literacy entails. Brennan and Resnick (2012) have defined key dimensions of computational thinking as the dimensions related to the Scratch programming language and student designers.

The field-tested classroom activities described in this paper use Scratch, a free programming language developed by the Lifelong Kindergarten Group at MIT. This programming language was designed to be easy to use and was specifically built to reduce the barriers of syntax. Scratch is a simple programming language, one in which commands are built visually, using an interface that is error resistant. Commands are built from creating stacks of interlocking pieces, much like building a puzzle. If two commands cannot work together, then they cannot be combined in Scratch, which reduces the number of errors a programmer can make (Utting et al 2010). The designers of Scratch describe it as having a low floor (easy to be successful right away), wide walls (it is a general programming language that can be used to make a wide range of programs) and a high ceiling (although simple to learn and use at the beginning, it also can create complex and robust projects as the user gains experience) (Scratch Team 2013). Figure 1 shows the Scratch online programming environment, with its simple-to-use drag-and-drop interface and interlocking puzzle-piece commands.

The two of us have adopted Brennan and Resnick's (2012) definition of computational thinking, given that the classroom projects discussed later in this paper have all been created using Scratch.

Contemporary software, like Scratch, LOGO and Boxer, makes coding and programming easier and more accessible to students than earlier programming environments; importantly, newer programs make coding and programming more accessible to classroom teachers. Through the prototyping and design of games, simulations and models using general programming languages such as Scratch, students and teachers can engage deeply with computational thinking concepts and practices at the same time that they are engaging in science and math concepts, ideas and challenges.

Why Is Learning Coding and Computational Thinking Skills Important?

One of the strengths of modern educational programming languages is that they are agent-based languages. In an agent-based programming language, a system can be broken down into individual elements, whereby each "agent" can be programmed separately. In the Scratch programming language, for example, the agents are the sprites and the stage, which students can program independently. Agent-based programing languages have evolved into languages with multiple agents, which can all be programmed separately but can also execute code simultaneously (Sengupta et al 2013). Teachers and researchers have found that embodied modelling allows the student programmer to think like an agent, because the student needs to understand the relationship between the code they create and the output of the agent, as well as the relationships that exist between agents (Sengupta et al 2015).

Coding and computational thinking are directly related to constructionism and design thinking.

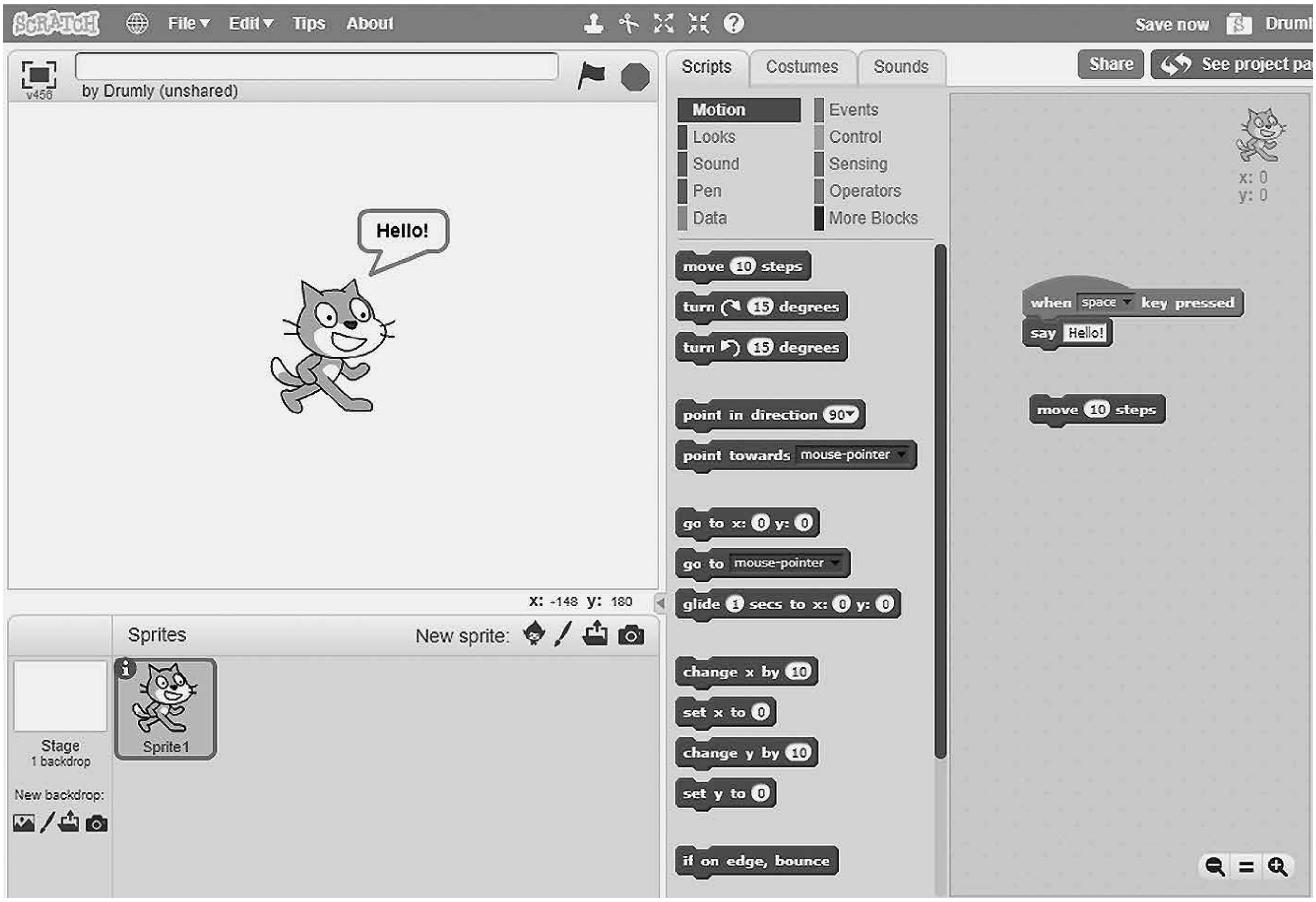

Figure 1. *The Scratch programming language's drag-and-drop coding environment*[1]

Building upon seminal work by Seymour Papert, Mitchell Resnick, Idit Harel, Yasmin Kafai and Andrea diSessi from the MIT Media Lab, researchers have found that programming in agent-based languages, like Scratch and others, can be effective in helping students to learn science and math concepts that are otherwise abstract and challenging to understand (Martin 2016; Sengupta and Farris 2012).

What Are Effective Ways of Teaching Computational Thinking to Students?

Teachers can adopt signature pedagogies, which reflect "what counts as knowledge in a field and how things become known" (Shulman 2005, 54), to promote design thinking, inquiry-based learning and problem-based learning and to create flexible boundaries for coding and computational thinking work by students. During the first author's thesis research (Martin 2016), the two of us found that when a thoughtful and purposeful task is created for students, students can be successful at using the Scratch programming language to create scientific models. The early solutions that students create to solve problems may not always be the most elegant; however, as students engage in the iterative design process and the debugging process over time (both of which are key ideas in computational thinking), students begin to see more efficient and elegant solutions, especially if, as an intentional part of the learning process, they are allowed to share and demonstrate their solutions with peers.

[1]All images from the Scratch website used in this paper are reused here under the Creative Commons Attribution-ShareAlike license. Scratch is developed by the Lifelong Kindergarten Group at the MIT Media Lab. See http://scratch.mit.edu.

Table 1
Summary of Computational Thinking Framework (Brennan and Resnick 2012)

Computational Thinking Key Dimension	Concept	Definition of Key Understanding
Concepts found in Scratch that can be used to design.	Sequence	A sequence contains a set of steps that a computer executes in order.
	Loop	A sequence can be repeated in a loop. This can be an iteration of a particular number of times or an infinite number of times.
	Events	Something that happens on the computer can cause something else to happen.
	Parallelism	Multiple sequences can happen and run at the same time.
	Conditionals	A program can be written that allows for multiple outcomes, often based on a test using the word *if*.
	Operators	Functions in a programming language that use mathematics, logic and/or strings (text based).
	Data	Information can be stored, retrieved and updated.
Practices used by Scratchers in designing.	Incremental and iterative	Designing a program is a process that involves adapting and changing. A plan may change as ideas are developed.
	Testing and debugging	A program often does not work as intended right away. Finding errors in logic, mistakes in the code are part of developing a program.
	Reusing and remixing	Building on other peoples' work. Sharing your work with others.
	Abstracting and modularizing	Building something larger by working first with smaller parts.
Perspectives of students involved in design	Expressing	Designing is about creating something and sharing it.
	Connecting	Designing is a social experience; working with others enriches the experience.
	Questioning	Wondering about how design is used in other situations.

We found that students find the most success with programming when the tasks

- are based on a problem that can be broken down into smaller tasks (key computational thinking understanding),
- showcase or build on previous core curricular understandings and extend that learning through further inquiry questions,
- have flexible boundaries (and there are multiple solutions) and can be differentiated based on student experience, and
- incorporate an explicit design thinking process, and students use that process when generating their ideas and solutions.

What follows are some field-tested classroom examples of science and mathematics curriculum projects, using the Scratch programming language, that involve students in computational thinking and coding. The examples are discussed in the context of both Alberta Education's programs of study and Wing's (2006) ideas about computational thinking.

Classroom Examples of Coding/ Computational Thinking Projects

Grade 6—Model of the Earth/Moon/Sun System (Science)

(seven hours of class time)

One of Wing's (2006) key ideas in computational thinking is that students need to look at designing systems as a problem-solving exercise. Martin (2016) reports on a mixed-methods descriptive and exploratory case study that examined coding and computational thinking in two Grade 6 classes in an elementary school (39 students) where the students were designing a simulation of a system. Over 85 per cent of the students in the study were new to computer programming, and their classroom teacher had not worked with computer programming as part of her program.

After the students had completed their Sky Science unit with their teacher, and after four 45minute lessons using the Scratch Challenge Cards (Rusk 2011) and the Scratch Curriculum Guide (Brennan, Chung and Hawson 2011), the teacher and researcher gave students a design task linked to the Sky Science unit in the Alberta elementary science curriculum (Alberta Education 1996). The design task was to create, in Scratch, a working model of the Sun–Earth–Moon system to demonstrate how the positions of those three bodies were related to the phases of the Moon as seen from Earth.

The design task was created in collaboration between the classroom teacher and the researcher, and then broken down into the seven main components that would be required to simulate the Sun–Earth–Moon system (Table 2).

Table 2

Student Task and Related Alberta Elementary Science Program of Studies Objectives (Martin 2016)

Tasks for Student-Designed Simulation/ Models as Presented to Students	**Alberta Elementary Science Program of Study Objectives, Topic C: Sky Science** **General Learner Expectations (GLEs)** **(Alberta Education 1996, 32)**
1. The Earth revolves once per day.	GLE 6-7.3 Recognize that the apparent movement of objects in the night sky is regular and predictable, and explain how this apparent movement is related to Earth's rotation.
2. The Earth has night and day represented.	Not explicitly mentioned in curriculum, although it is generally taught as part of the Earth–Moon system.
3. There is a sprite that shows a picture of the Moon phases for each of the 28 days of the lunar cycle.	GLE 6-7.8 Illustrate the phases of the Moon in drawings and by using improvised models.
4. There is a label or text somewhere on the screen that names each phase as it occurs in your simulation.	GLE 6-7.7 Recognize that the Moon's phases are regular and predictable, and describe the cycle of its phases.
5. The Moon orbits the Earth in 28 days.	GLE 6-7.7 Recognize that the apparent movement of objects in the night sky is regular and predictable, and explain how this apparent movement is related to Earth's rotation.
6. There is an arrow on the provided sprite of the Moon that always points at Earth.	Not explicitly mentioned, but generally taught as part of the Earth–Moon system.
7. The Moon Needs to have night and Day	GLE 6-7.1 Recognize that the Sun and stars emit the light by which they are seen and that most other bodies in space, including Earth's Moon, planets and their Moons, comets, and asteroids, are seen by reflected light.

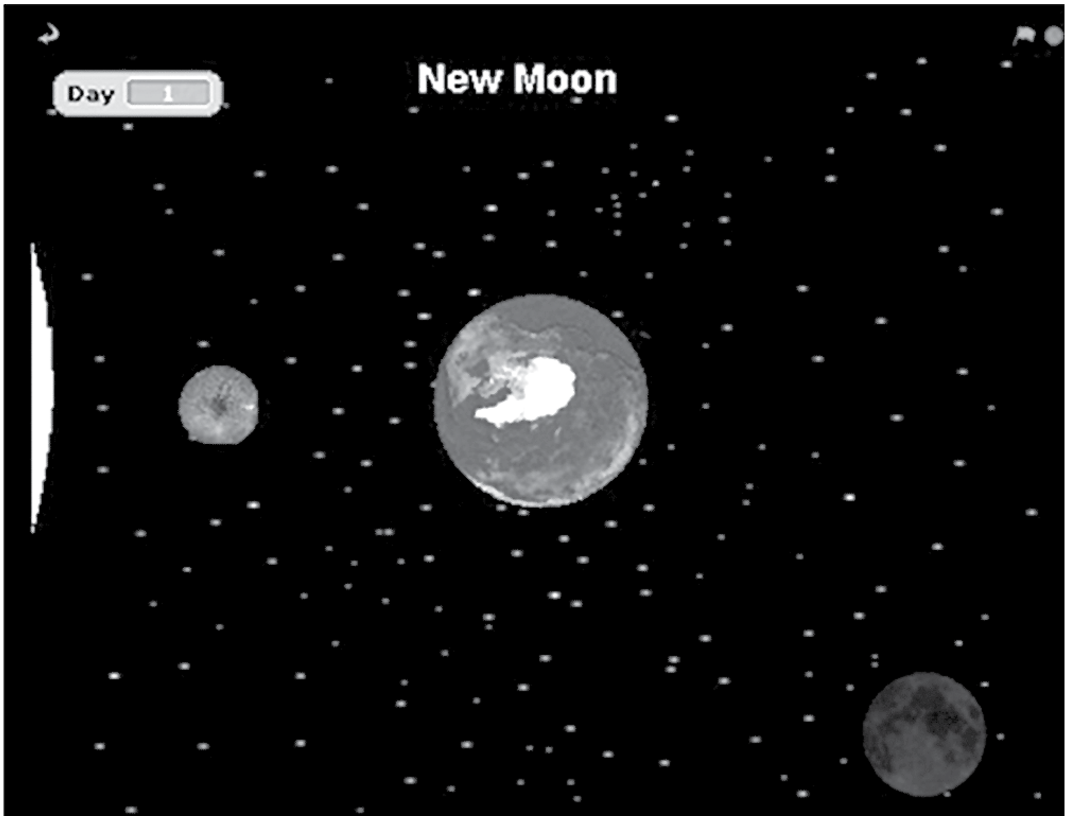

Figure 2. *Screen shot of construction kit with graphics given to students*

The students were given seven hours of class time to work with partners to create a program that met as many of the seven requirements as possible. Students were given a construction kit that contained the relevant graphics for their program (Figure 2).

Within the time period allowed for the design task, all of the Grade 6 students experienced at least some success at meeting the challenge. All of the groups successfully programmed at least three of the tasks required for their model, and several groups (6 out of 14) completed all seven of the required tasks.

The group projects were analyzed and reviewed for evidence that the students demonstrated the computational thinking concepts as proposed by Brennan and Resnick (2012). We found that, even without explicit instruction in the computational thinking concepts, all of the students' projects had evidence that students engaged with the concepts of sequence, simple events, broadcast events, conditionals and operators. Further, we also found that more than 80 per cent of the students had used loops and parallelism. The only concept that was used by only a small number of students was the data concept.

The observational data that was collected supported the finding that students had engaged in several of the computational thinking practices proposed by Brennan and Resnick (2012). Multiple examples were found of students using the incremental and iterative process and the testing and debugging process as they developed their models. As for the abstracting and modularizing process, the task's initial design gave the student the model for how to break up larger concepts into small modularized components and was evident as students worked on developing the pieces of code that would make the program execute the tasks.

A good example of the computational thinking processes being used involved the students solving the problem of showing night and day on the Earth as the Earth rotated. The initial solution used by many groups involved shading in half of the Earth, much as they had done on their paper-and-pencil diagrams. However, running the simulation created a night that rotated with the Earth, putting the shaded in half on the side nearest the sun. This solution resulted in an interesting discussion with students about how to simulate night and day.

Researcher: Tell me about the night and day on Earth [referring to their program].
Student K1: It is a shadow. Dark at night. Light in day.
Researcher: So, how does it relate to the sun?
Student K1: What do you mean?
Researcher: Well, how does where the sun is in space make it night or day on Earth?
Student K1: Well, the light from the sun hits the Earth here.
They run their program.
Student K2: Oh ... wait a minute. The shadow needs to be on the side away from the sun.

Students quickly realized that creating a shadow would require a new sprite. In their model, the sun and the shadow did not move, but the Earth revolved underneath. Testing and debugging, an iterative and incremental process, and abstracting and modularizing are all necessary analytical skills needed for the students to figure out a solution that allowed them model night and day, even though we did not explicitly inform the students that that was required.

In addition to the computational thinking experiences identified in this project, we found that many ideas that students had about the content they had learned during the Sky Science unit were solidified as the students worked through the programming tasks. One teacher–student discussion that highlights the value of this type of project in solidifying understanding was about the direction of the Earth's revolution. Scratch uses arrows of direction to show rotation, rather than words.

Student A1: Which way does the Earth rotate?
Teacher: Oh, come on, you know the answer to this. It's in your notes.
Student A1: No, I know it is counter-clockwise.
Teacher: Right.
Student A1: But which one is that in Scratch? (The student is pointing to the motion programming blocks.)

Although the student was able to state the correct vocabulary to describe the motion, the practical example of needing to make the model work revealed a crucial piece of information that we assume a student can answer when they state that something revolves counter-clockwise.

In an online survey conducted after the project was over, 74 per cent of the students agreed or strongly agreed that "creating a program about the Moon and the Earth helped me understand how lunar phases work."

Many studies involving the use of the Scratch programming language, specifically in core curriculum subjects, have found that students experience positive feelings about using Scratch to show an understanding of curricular concepts and were excited and eager to use Scratch (Baytak and Land 2011; Burke 2012; Calder 2010; Wolz et al 2011). We found that the majority of students enjoyed using Scratch, 82 per cent agreeing that Scratch was easy to use and 82 per cent agreeing that computer programming was fun.

Grade 8—Developing Medical Sensors (Science and CTF)

(10 hours of class time)

Students' use of abstraction and modularizing was one of the key learning focuses in a science/CTF project about medical sensors. As part of the first author's work with the Design the Shift project through the Calgary Board of Education Summer Institute in 2014, he designed a cross-curricular project to go with his classes' yearlong essential question in Grade 8 math/science: "How do we know when something 'makes sense?'" Framed within this inquiry question, and integrated with the Cells and Body Systems unit in Science 8, students were given the following challenge:

> You will create a noninvasive sensor, either from scratch or by repurposing an already existing sensor (say, a microphone), that will send information to a computer program (on computer or cellphone/tablet) or a mechanical device of your creation. When the computer program or device receives the information from your sensor it will display the information in a meaningful way to the people who are using the sensor. The following constraints exist in this project:
>
> - Your sensor may not make direct contact with a body fluid. You may not collect fluid or tissue samples for your sensor.
> - Your sensor proposal must be approved by the teacher before it is constructed, to ensure that your proposed sensor poses no risk of injury.
> - The representation of the data that is shown on the computer or mechanical device is changed as the information arrives in real time.
> - You need to decide if your program reports only in real time or if it also records the data.

- You need to develop a page explaining how the user's information is used by the program, including any actions that you are taking to make information private or public and the rationale for your choice.

The key understandings in computational thinking that are required for students to make this project a success are abstracting and modularizing the problem. Students have to think about the information they want to collect and then develop several prototypes of the sensor as they try to get their software/computer to receive the information. Once the information is received, the student has to develop a way to present the information and/or preserve the information over time so that finally they can present the data that they have collected. This type of project planning was new to many of the students who were used to coming up with a single solution or looking at the problem holistically.

During this task, Grade 8 students created several interesting successful projects, including

- a sensor made out of tinfoil and connected to Makey Makey to time the patellar reflex (ie, the reflex that occurs when one is hit just below the knee and the leg moves) and to collect information about the average reaction time in Grade 8 boys and girls,
- a sensor using a microphone and a paper towel tube that heard a heart beating and ran an animation of the heart beating in real time, and
- a breath rate calculator, using a microphone and a paper bag, that timed how many breaths in and out a Grade 8 student took in one minute.

Unsuccessful projects often showed ingenious potential and great ideas, even if the project proved to be beyond the teacher's and students' technical ability to create the project. Unsuccessful projects often resulted in a greater understanding of the system as a whole, as groups were asked to think about what changes in design or what different technologies we would need to have access to in order to make the projects successful. Examples of great ideas include

- a camera one could use on urine in a toilet bowl to determine how hydrated a person was,
- shining a light from a cellphone LED through a person's finger to detect one's pulse and
- building a blood pressure cuff and having it report to a computer the person's blood pressure.

Although only 75 per cent of the groups were successful in meeting the goals for the entire challenge, all students gained an appreciation for both the complexity of the human body a realization of how the data that was collected needed to be interpreted as part of a medical practitioner's work, and a deeper understanding of how their miniature computational system was similar to the other systems that the class had been studying throughout the year in science. Finally, the student reflections showed a developing understanding of how a computer cannot make sense of the data it receives without a human programming it to make sense of the data it receives.

A key element of the medical sensors project was challenging students to discuss not just the coding and how the computer would "make sense" of the data it was receiving from the sensors, but also to provide an opportunity for students to think about the ethics questions surrounding the information they collected. Questions such as, Who owns the information? Does the researcher own it? Does the school own it because the data was on the school computer? and Do you own the information collected from your body? required students to engage in thoughtful inquiry about broader ethical issues. With the use of wearable fitness technology, the class engaged in many rich discussions about exactly how the data these types of devices collect is used and by whom. Each of the ethical discussions engaged students in rich discourse and ongoing reflection about the ramifications of their data collection. Noncoding examples of computational thinking occurred as students had to think about their projects in the context of the wider system of the real world, governments and ethics. The students' ideas were quickly extrapolated to wearable technologies and cellphones that collected information about the people using them, and this became the foundation of logical arguments using if/then statements about how we should think about protecting this data.

Grade 8—Pythagorean Triple Calculator (Mathematics)

(1 hour of class time)

Wing (2006) describes one of the skills in computational thinking as "reformulating a seemingly difficult problem into one we know how to solve, perhaps by reduction, embedding, transformation, or simulation" (p 33). In this mathematics example, the challenging problem of identifying Pythagorean triples is solved by the students creating simple software by relying on operators and variables to reduce the problem into something that is easiest to test. Unlike the other two projects described in this paper, the Pythagorean Triple Calculator task is an example of a relatively quick application of computational thinking to the curriculum.

A Pythagorean triple is a set of three integers that are the sides of a right angle triangle. For example, the smallest Pythagorean triple is 3, 4 and 5. After finding a few triples in class and using just our calculators and the Pythagorean theorem, the teacher and students decided they needed a larger data set to seek patterns. The group wanted to know if there was a way to predict triples in advance or if there was a formula that would calculate triples.

The teacher challenged the students to use Scratch and their existing knowledge of the Pythagorean theorem to create a program that would allow them to find all of the triples where c ≤ 100. Although the students did not have a programming technique that would allow them to instruct the computer to find all of the sets of triples, they did have a basic understanding of how to use variables and formulas. Existing knowledge of variables and formulas allowed students to use a trial-and-error method to test whether the numbers they had were a true triple. The most common solution to this challenge involved a visual inspection of the numbers by the students (Figure 3).

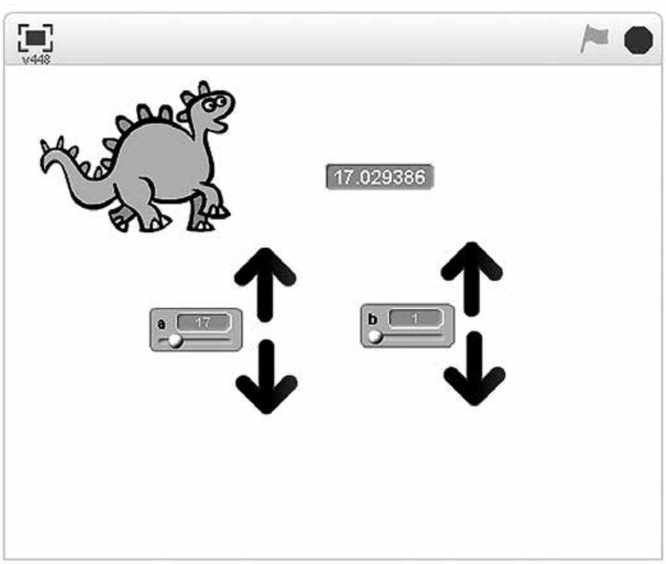

Figure 3. *A Grade 8 student's Pythagorean triple checking program*

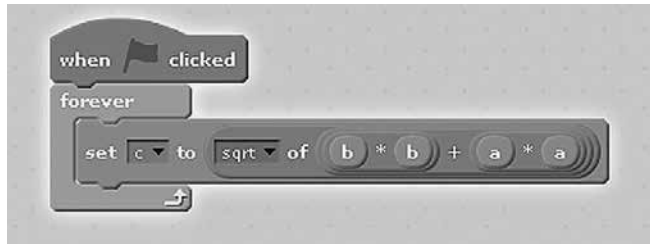

Figure 4. *Student-developed code for the Pythagorean theorem in Scratch*

Once students had figured out a way to control or input variables for a and b, they used the Pythagorean theorem to calculate c. An example of the code used for this task is shown in Figure 4. As part of the task, students were required to determine how they would know if their formula was working. For example, students needed to figure out whether Scratch followed the order of operations. When the teacher asked students who were using their program how they knew they were getting accurate results, the students started to realize that they needed to test their program against known results, which is a key part of computational thinking, rather than just assuming that their formula was correct. Once the students determined through testing that their code was indeed working as expected and they were confident that the results they were generating were accurate, they proceeded to hunt for triples.

Most of the students' programs, either by using a timer or using the arrow keys, showed each combination in which a and b were integers that could be checked. If the calculation resulted in a non-integer for c (as shown in the number beside the dinosaur, Figure 3) the students knew that it was not a triple. The students' knowledge about non-integers later became useful when students needed to test their hypothesis for patterns. Students could take their set of numbers generated from their hypothetical pattern and quickly test to see whether it was correct.

Conclusion

The current call for educators to provide coding and computational thinking experiences for all of our students is one the authors argue that Alberta educators need to answer, and soon. Along with ministries of education in other Canadian provinces, Alberta Education needs to consider adding coding and computational thinking to the program of studies. Research and practice on coding and computational thinking in schools has documented the learning benefits when young people are engaged in meaningful work that is challenging and worthwhile and when they are supported by engaged teachers who provide regular feedback on their learning (Jacobsen, Lock and Friesen 2013). Based on current research and three classroom projects in Alberta that have combined programming with science and mathematics, the authors have illustrated the learning benefits of coding; these include computational thinking and programming tasks as rich discipline-based inquiry, problem-based learning and inquiry-based learning experiences, and also as design tasks that enable students to explore mathematics and science concepts and to build on their understanding of the world around them. Our research has demonstrated that when carefully thought out and well-designed tasks are given to Alberta students as part of how they demonstrate their understanding of curriculum concepts, students can gain experiences in computational thinking, even if they are not explicitly taught step-by-step methods for creating a program, and solidify their understanding of the curricular concepts as well. Through the classroom examples provided, one can conclude that, even if the students have very limited coding experience and create solutions that lack elegance, student engagement in design tasks allows students to gain quality computational thinking experiences and develop a deeper understanding of how the information learned in class can be applied using technology. Teachers' designs of design tasks and creating opportunities for students to use coding to learn and demonstrate their understanding of concepts from the math and science curriculum, rather than searching for opportunities for students to learn to code, will allow students to develop a deep and rich understanding of computational thinking as a tool to understand the world around them.

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Reframing Coding as “Mathematization” in the K–12 Classroom: Views from Teacher Professional Learning

Pratim Sengupta, Barb Brown, Kenzie Rushton and Marie-Claire Shanahan

Abstract

There is now a growing body of literature that argues for the use of computational programming and modelling in K–12 science classrooms. However, one of the common pedagogical challenges of using computational modelling in the classroom is the overhead of learning programming, which interrupts curricular flow because it requires specialized technical knowledge. In this article, our goal will be to illustrate a pathway for integrating computational modelling and programming in the science classroom for teachers with little or no background in programming. Drawing upon our findings from an ongoing series of design-based professional learning sessions with 56 teachers in K–12 public and charter schools in Alberta organized by the Galileo Educational Network, we will argue that (a) when teachers, with little or no background in programming, view programming as a way to “mathematize” the world, they can visualize and implement seamless integration of programming and modelling with their science curricula; and (b) the use of multiple and complementary forms of programming and modelling (eg, physical, virtual and embodied) can facilitate such integration.

Introduction

A growing body of literature argues for the use of computational modelling and programming (coding) in K–12 science classrooms (Sengupta et al 2015; Wilensky, Brady and Horn 2014). However, one of the common pedagogical challenges is the overhead of learning to code, which interrupts curricular flow because it requires specialized technical knowledge and practices (Guzdial 1994; Sherin, diSessa and Hammer 1993). Previous research has shown that framing coding in the science classroom as *mathematizing*—ie, using computer programming and computational modelling as a way to represent continuous phenomena, such as motion, using a series of discrete mathematical representations—can be an effective way to integrate coding in the K–12 science classroom (Sengupta et al 2015; Dickes et al 2016). In this paper, we present a descriptive analysis of how inservice teachers were introduced to this notion of *coding as mathematizing* through a series of design-based professional learning sessions and how some of them proposed to implement coding as mathematizing in their classrooms.

Theoretical Background

Design-Based Learning and Design-Based Professional Learning in Educational Computing

Design plays an integral role in this work, not only as a concept for teachers to understand but as the essential way in which they come to understand. In the context of learning computational modelling and coding as part of K–12 science or math classroom practice, design-based learning is not only a pedagogical approach for teaching computational thinking (Wing 2006), but computational modelling and coding are also themselves design-based practices (Sengupta et al 2013). From the perspective of supporting teachers through professional learning, it is therefore crucial to engage teachers in the work of design in the professional learning sessions where they experience computational thinking. Science educators have shown that science teachers must experience and design learning activities that emphasize design-based learning as part of their preparatory courses in order to integrate rich tasks (eg, modelling) with their classroom practice (Windshitl and Thompson 2006). Researchers have also argued for the need for ongoing research-based professional learning and support in order to help teachers design intellectually engaging tasks and provide students with rich learning experiences (Donna 2012; Timperley 2011). Therefore, we believe that professional learning sessions in educational computing must adopt a design-based professional learning approach in which teachers engage in an iterative process of design, enactment, evaluation and redesign in collaboration with researchers and disciplinary mentors (Fishman et al 2013; Friesen and Jacobsen 2015).

Design interweaves action and reflection (Schön 1983). For teacher professional learning, *action* must encompass two levels: learning within the sessions and learning within teaching practice. This also means that learning during the sessions must be interwoven with teachers' actions in their classrooms. Toward this end, we adopted Friesen and Jacobsen's approach emphasizing that in these sessions, teachers must learn to "bring forward evidence of the students' learning, to analyze and determine how that student work reflects the deep understandings identified in the design, and to determine next learning steps for students and next teaching steps for themselves" (Friesen and Jacobsen 2015). In order to accomplish this, professional learning sessions must be ongoing and interconnected rather than episodic in nature, and provide opportunities for teachers to reflect on and share their attempts at adapting some of the activities designed during the professional learning sessions in their classrooms. In the context of our work, this meant that teachers' experiences in the classroom in between two professional learning sessions and their feedback during the sessions shaped the learning activities in subsequent sessions.

Coding as Mathematizing

Previous research on educational computing suggests that a particular genre of computing—agent-based computation—can serve as an effective computational medium for adoption by classroom teachers with little or no background in programming. The term *agent*, in the context of agent-based programming languages and modelling platforms (ABMs), indicates individual computational objects or actors that obey simple rules assigned or controlled by the user. These rules are usually designed to be body syntonic, meaning that the user can imagine them by imaging how their own bodies might obey the rules (Papert 1980). Examples of ABMs designed specifically for young learners include Logo (Papert 1980), Boxer (diSessa et al 1991), Scratch (Resnick et al 2009), Alice (Kelleher and Pausch 2005) and so on. However, earlier studies demonstrated that teachers find it difficult to integrate such general-purpose programming and modelling languages with their science and math curricula (Sherin, diSessa and Hammer 1993; Guzdial 1994).

To address this issue, researchers have been developing domain-specific ABMs, such as CTSiM (Sengupta et al 2013) and ViMAP (Sengupta et al 2015), with the goal of making it easier and more intuitive for teachers to integrate them with their day-to-day science and math teaching. The coding commands in ViMAP include both general coding abstractions (eg, loops, conditionals), and domain-specific commands that are explicitly designed for modelling and simulating domain-specific phenomena and topics such as population dynamics or measuring and modelling motion. Year-long studies of researcher–teacher partnerships in elementary and middle school classrooms show that teachers with no prior background in coding are able to effectively integrate ViMAP with K–12 science classroom activities by reframing coding as a way of progressively refining "units of measurement" (Dickes et al 2016; Farris, Dickes and Sengupta 2016; Sengupta et al 2015). Sengupta et al (2015) termed this *coding as mathematizing*—a pedagogical approach of reframing discrete forms of computer programming as a way to mathematically represent physical and biological phenomena that involve change over time. In these activities, the computational code serves to define a unit of measurement (eg, a *step*), which is then repeated as the program is run to produce the desired phenomenon (eg, trajectory of a continuous motion). These studies also demonstrated that teachers would design additional physical and embodied modelling activities *outside* the computer in order to connect the experience of coding more deeply to the key scientific disciplinary ideas and representational practices (eg, multiplicative reasoning and graphing). In this study, we present a brief report of how teachers can experience such activities—where coding is reframed as mathematizing and modelling—as part of a series of design-based professional learning sessions.

Research Questions

The research questions in this study were as follows:

1. How do teachers with no prior background in programming experience coding as mathematizing by engaging in modelling activities during design-based professional learning?
2. What views of "technology" emerge through teachers' interactions with coding as mathematizing during design-based professional learning?
3. How do teachers envision incorporating coding as mathematizing in their classrooms?

Setting and Method

In our study, teachers from six school authorities (n=32) participated in four half-day sessions, held once monthly, at the University of Calgary. These workshops were designed collaboratively by professional learning leaders at the Galileo Educational Network and STEM education researchers in the Werklund School of Education, University of Calgary. The learning activities were designed with the following objectives: (a) to introduce the participants to coding, computational modelling and engineering design by engaging them in design-based learning activities; and (b) to support teachers in adapting these activities as well as envisioning and designing similar learning activities for their classrooms, as guided by the teaching effectiveness framework (Friesen 2009).

During each session, participants worked in groups of three or four, based on their grade levels. We used the ViMAP computational modelling platform (Sengupta et al 2015), which was designed specifically for modelling kinematics and ecology in K–12 classrooms, and a commercially available, low-cost robotics kit (Ozobot Bits). Teachers also designed learning activities that did not involve computer programming, but involved other forms of modelling such as embodied modelling and mathematical modelling using LEGO-based engineering design. In between successive sessions, some participants documented activities they designed and carried out in their classrooms, based on their experiences in the professional learning sessions, in the form of blog posts shared in a group blog. Participants also joined a closed Facebook group, which allowed them to share significant moments both during the sessions and from their classrooms. In some cases, the blog and Facebook group posts about their classroom activities helped us understand how the participants enacted ideas from the professional learning in their classrooms.

In addition, the following data sources were used to inform the findings: (a) documents generated during the professional learning activities, (b) learning activities that the participants designed during the professional learning sessions, (c) responses to pre- and postsession open-ended questionnaires before and after every session, and (d) the researchers' observations and field notes made during the professional learning sessions.

We conducted a thematic analysis (Miles and Huberman 1994) across the data sources, coding participants' work (writing, videos, photographs and computer programs) in order to answer the two research questions stated earlier. Our analysis focused on (a) the types of challenges and benefits identified by the participants during each activity in their open-ended responses, (b) their explanations and use of relevant disciplinary concepts (eg, coding abstractions, mathematical, physics and biological concepts) during these activities, and (c) their explanations of how different forms of representations and technologies were helping, shaping or hindering their conceptual work.

Findings

Coding as Mathematization and Modelling: Teachers' Perspectives

The initial two sessions focused on introducing the students to coding using ViMAP (session one) and Ozobot Bits (session two). Their experience with ViMAP introduced them to the notion of *mathematizing*—ie, how computational modelling could be used as a way to represent continuous phenomena, such as motion, using a series of discrete mathematical representations. That is, the computational code would serve to define a unit of measurement, which would then be repeated as the program was run to produce the desired motion. We noticed that although majority of the participants were able to develop ViMAP models of motion, several participants (20 per cent) found it challenging to create and design models of motion. This was evident in their written reflections at the end of the activity, as well as their verbal reports to the facilitators. During session two, participants used mobile devices to film their group activities and capture particular "aha!" moments while engaging with mathematical modelling using Ozobot Bits, design thinking and iterative modelling through coding.

When we asked participants to design a learning activity using Ozobot Bits and/or ViMAP for their classroom, we noticed that all the groups designed activities in which the robot had to be programmed in order to produce a model of motion, similar to their ViMAP activity in session one. These activities proceeded in the following sequence, proposed by Sengupta and Farris (2012): The student first learns to use coding commands in the context of creating a shape that they are already familiar with, and then proceeds to use the shape as a representation of a physical phenomenon (motion). For example, a square can represent a period of motion in which an object is moving at a constant speed. Here, the length of each side of the square represents the distance travelled by the moving object at regular intervals of time. Several teachers commented that a key value of this activity is that students can learn about geometry, coding and kinematics in an integrated manner. Interdisciplinary learning integrates ways of thinking and disciplinary knowledge from two or more disciplines (Strober 2010). As teachers shared their experiences in the learning session in the form of a class discussion, a clear consensus emerged: computing can be integrated into the science and math curricula as *modelling*—in a manner that complements rather than detracts from curricular goals.

Some teachers also noticed that using the shape as a representation of motion leads one to think about which parts of the model are good analogies. For example, as the ViMAP turtle or the Ozobot is tracing the square, it is changing its direction of movement as it completes creating each side and begins to draw the next side. Teachers noted that this could create a productive context for discussion on incompleteness of models (ie, models are always incomplete representations of reality), and at the same time make students think about what makes their model a good model. Indeed, science educators now agree that such forms of discourse about modelling are critical to the design of authentic science education (Lehrer 2009; Windschitl et al 2012). The value of computing in the classroom, therefore, extends beyond the computer—it can lead to productive scientific discourse about models and modelling.

At the end of session three, we asked teachers to explain how they might be able to adopt some of the design- and mathematization-based activities that they experienced in the professional learning sessions for their classrooms. We analyzed their responses in terms of the forms of mathematization and found connections to mathematical processes and strands as outlined in current mathematics program of studies (Alberta Education 2016). All of the teachers indicated that they will design graphing and modelling activities (data analysis strand) that involve modelling continuous processes by using discrete units of change. More than one-third of the teachers (36 per cent) explicitly mentioned that they would design activities that would emphasize graphing change over time using discrete measurements (measurement strand), similar to the graphing activities they had conducted during the professional learning sessions. Similarly, teachers (31 per cent) explained that they would use "programming-like thinking" without using computers in the form of using pseudo-code or other formats of rule-making activities (patterns and relation strand). The goal of the students in these activities would be to invent and discover rules that could explain patterns of behaviour of an observed phenomenon (eg, a video or a real-life event), or a simulated phenomenon using embodied modelling (mathematical processes—eg, communication, connections, problem solving, reasoning, visualization). In addition, 10 per cent of the teachers indicated that they would use step-by-step modelling, ie, use embodied modelling activities (similar to a butterfly foraging model they had enacted during the sessions), and/or LEGO to create discrete mathematical representations of continuous processes and phenomena (eg, motion, population growth and so forth) without specifying any particular mode of modelling, while another 10 per cent of the participants indicated that they would design activities that would help their students pay attention to patterns of repetition for modelling change over time (patterns and relations/ measurement strands). One participant (3 per cent) specifically indicated that she would design mathematical problems that involve scaling in order to integrate computational modelling into her curriculum.

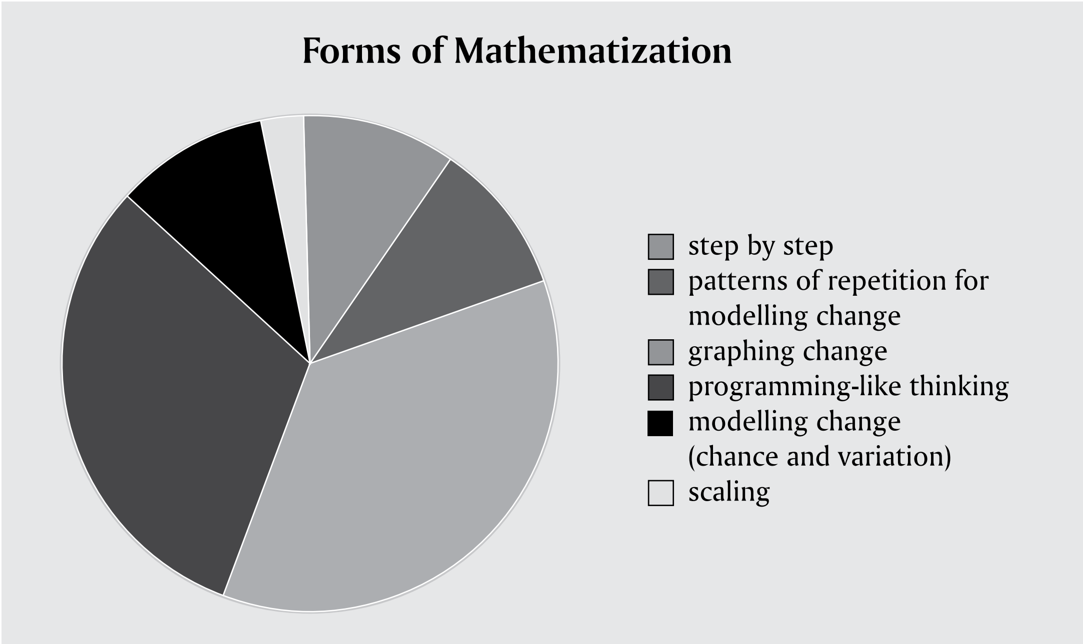


Figure 1. *Forms of mathematization in teacher's modelling work in professional learning sessions*

Expanding Views of Technology Beyond the Computer

At the end of each professional learning session, participants were asked to explain the most important understanding they had reached that day regarding designing an integrated STEM learning activity. Comments from participants reveal their images of what counts as productive technology for STEM integration, and the role technologies can play in STEM integration, from session one to session four. For example, in session one, one participant commented that "technology seems to be the most important element" in STEM learning, and majority of the teachers indicated that coding and computational modelling was what they considered to be technology. By session three, participant comments demonstrated a change in assumptions about the technological characteristics of STEM learning designs. One participant noted that "STEM is not just about technology" and can also be "low tech." This change was shaped by and evident in, for example, their use of embodied modelling of foraging behaviour and interdependence in ecosystems, and the subsequent use of LEGO graphs to represent change in energy (Figure 3, page 34).

By the end of session three, the majority of the participants' postactivity reflections illustrated that they began to envision technology as both computational and noncomputational artifacts, where those artifacts can contribute to deepening conceptual understanding of key disciplinary ideas, fostering creativity in representational practices, or both. We believe that this was shaped to a great extent by their modelling activities during the sessions. For example, in session two, we noticed that several groups integrated robotics, coding and the use of found objects in their modelling. For example, one group invented a "pencil" strapped to an Ozobot Bit to make it trace the shape, while the program governing the robot's behaviour would specify variables such as speed and acceleration. Another group invented a mathematical grid for an Ozobot Bit to help with coding, to make it easier for students to interpret the robot's movements in terms of discrete mathematical units. Furthermore, we also noticed that the teachers who were apprehensive of programming in session one were more comfortable with physical modelling and made substantial contributions in their groups toward inventing new representational infrastructures using physical objects (eg, graphing with paper grids, engineering pencil holders for Ozobots and so on). Similarly, in session three, the teachers conducted the embodied modelling activity in which they acted as butterflies, foraged for nectar, tracked their energy and mapped their foraging pathways. Afterward, they also created mathematical models of the change in their energy through graphing and modelling with LEGO. The same theme continued in session four, as evident in teachers' work during the sessions and their written explanations of opportunities that they might be able to design for incorporating mathematization in their classrooms. Teachers' responses demonstrated that they were considering how their activity designs might involve using both unfamiliar technologies in STEM, such as coding, robotics and physical computing, and familiar technologies such as cell phone cameras, which can be used to record events using the slow-motion functionality, for mathematical analysis of motion and periodic events. This again was shaped by their modelling experiences during session four, in which teachers conducted two kinds of modelling activities that both emphasized the use of physical objects for mathematical modelling.

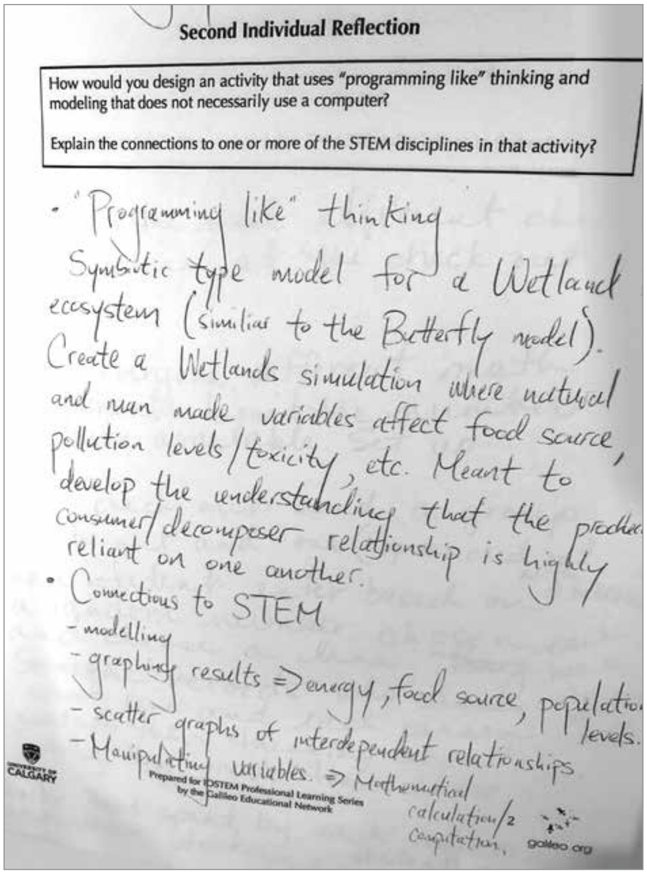
As discussed previously, at the end of session three, we asked teachers to explain, in writing, how they envisioned incorporating and/or appropriating the ideas, technologies and activities for design and mathematization in their classrooms without necessarily using the computer. We found that only 10 per cent of the teachers explicitly stated that they would use computational programming and/or simulations, while 77 per cent of the responses indicated that they will not use computational software or hardware. Here we discuss two illustrative examples of activities that highlight how teachers planned to integrate key elements of computational thinking and modelling with their science and math classroom activities.

We believe that this expansion of conceptualization of technology beyond the computer is also significant for pragmatic reasons. At the end of session four, we asked the participants to explain potential barriers to the adoption of the new technologies that they were introduced to in the professional learning sessions. In their written responses, all participants demonstrated intentions and a desire to take action and begin developing technology-rich learning designs; responses generally started with "I hope to …" or "I would like to …" or "I think I will try …" or "My goal is to …." In the cases where action was not possible, participants pointed to accessibility issues that prevented developing technology-rich learning designs. More than half of the participants also expressed concerns about limited permissions to install these programs on school computers. Accessibility to new technologies and software (eg, ViMAP and Ozobot Bit) through school jurisdictions and the long wait times and bureaucratic obstacles for installing new software continue to be a barrier for the teachers. All the teachers mentioned these issues, either in their written responses or during focus group conversations during the sessions. Despite this barrier, participants clearly shared a desire to introduce "programming to model an idea or data" with students in their classrooms, ranging from K–12. This new appreciation for noncomputer integration of programming was made possible because their views of what counted as productive forms and use of technology for STEM integration expanded over time.

Mathematization Without Computers for the Classroom: Two Illustrative Examples

We now present two illustrative examples of how teachers imagined activities that emphasized mathematization without using computers. The first example (Figure 2) illustrates how a Grade 3 teacher (Tara, pseudonym) proposed to integrate "programming-like thinking" within her regular science teaching practices by designing an activity similar to the embodied butterfly foraging modelling activity of session three. While explaining her response verbally, she elaborated that she would design a set of rules for different agents in an ecosystem to model symbiotic relationships and environmental pollution in an ecosystem. Students in her class would enact these rules through embodied modelling, and while enacting these rules, they would also collect data during each step. An important learning objective, according to Tara, is to help students model continuous processes—environmental change and population dynamics—that unfold over time in terms of discrete steps. In order to model how different variables are related to one another, the teacher proposed that students would design units of measurement and then graph how the variables change over time (eg, using bar and line graphs) and are related to one another (eg, using scatter plots). For the teacher, thinking with and about variables and modelling mathematically how the variables were related to one another are examples of computational thinking.

The second example uses programming-like thinking in order to model linear equations by a Grade 9 teacher (Molly, pseudonym), as shown in Figure 3. Molly



Second Individual Reflection

How would you design an activity that uses "programming like" thinking and modeling that does not necessarily use a computer?

Explain the connections to one or more of the STEM disciplines in that activity?

- "Programming like" thinking

Synthetic type model for a Wetland ecosystem (similiar to the Butterfly model). Create a Wetlands simulation where natural and man made variables affect food source, pollution levels/toxicity, etc. Meant to develop the understanding that the producer/consumer/decomposer relationship is highly reliant on one another.

• Connections to STEM
- modelling
- graphing results => energy, food source, population levels.
- scatter graphs of interdependent relationships
- Manipulating variables => Mathematical calculation/computation.

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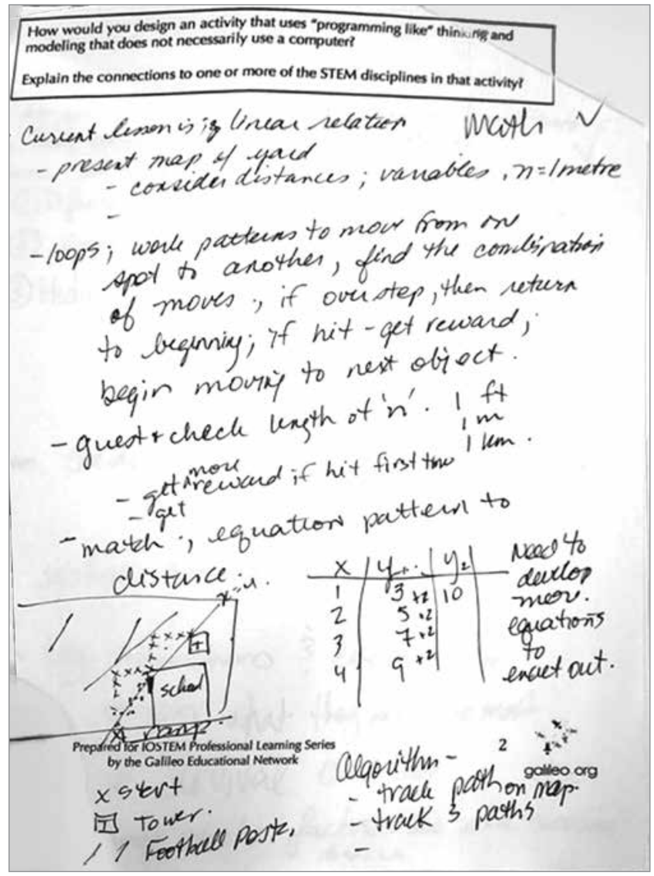
Figure 2. Mathematizing science through embodied modelling and graphing



How would you design an activity that uses "programming like" thinking and modeling that does not necessarily use a computer?

Explain the connections to one or more of the STEM disciplines in that activity?

Current lesson is on linear relation   Math ✓
- present map of yard
  - consider distances; variables, n=1metre
- loops; work patterns to move from one spot to another, find the combination of moves, if over step, then return to beginning; if hit - get reward; begin moving to next object.
- guess + check length of 'n'. 1 ft, 1 m, 1 km.
- get more reward if hit first time
- get math, equation pattern to distance.

x	y_1	y_2
1	3 +2	10
2	5 +2	
3	7 +2	
4	9 +2	

Need to develop more equations to enact out.

school

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x start
⊡ Tower
/ / Football Posts.

Algorithm -
- track path on map.
- track 3 paths
-

Figure 3. Modelling mathematical relationships using programming-like-thinking

proposed an activity in which her students would use pseudo-code to create programming-like rules using loops, conditionals and variables in order to model linear mathematical relationships. For example, consider the equation $y = m.x$, which is an equation that can also be modelled as a straight line passing through the origin of the graph. Molly wanted her students to reverse engineer the graph by representing the straight line using combinations of horizontal and vertical movements in small steps (similar to differential calculus). She envisioned an activity in which students would learn to "see" a diagonal straight line, and therefore a linear equation, as a combination of small *x*- and *y*-movements. This was evident in both her written work and her diagrammatic representations.

Conclusion

The essence of technology is nothing technological, as Heidegger famously remarked (Heidegger 1954). Rather, technology is better understood not as a set of tools but as a contextually embedded practice (Franklin 1999). The field of educational computing has traditionally focused more on the invention of computational platforms and languages, rather than supporting the codesign and appropriation of computational thinking and practices in classrooms. The latter, we believe, is crucial for deepening and broadening our understanding of how computing can become a mainstay in the K–12 STEM classroom. Our recent longitudinal studies based on researcher–teacher partnerships in elementary and middle school classrooms show that, using a common pedagogical approach, teachers reframed programming as a way of progressively refining "units of measurement" (Farris, Dickes and Sengupta 2016; Dickes, Farris and Sengupta 2016). Our current paper further extends this work by highlighting how teacher professional learning can be designed to support curricular integration of computational thinking and programming in K–12 science and math classrooms.

In particular, this paper also shows that during professional learning sessions, teachers do indeed find it intuitive and productive to frame coding as an opportunity to deepen science learning by potentially engaging their students in the iterative design of units of measurement. Data modelling, embodied simulations and reverse engineering graphs of change over time became prominent in the teachers' designs as three forms of activities that can facilitate seamless integration of generative computing with their curricular needs and foster interdisciplinary experiences. Furthermore, as they were designing these activities through a design-based professional learning approach, many teachers identified the beneficial role that designing learning in the company of peers can play in fostering "science talk."

Engaging teachers in authentic disciplinary work is a key characteristic and goal of design-based professional learning (Friesen and Jacobsen 2015). Therefore, design-based professional learning at the intersection of educational computing and science education must also present teachers with opportunities to engage in disciplinarily authentic opportunities of design-based work along both scientific and technological dimensions. The descriptive analyses we have presented in this paper suggest that reframing coding and computational thinking as *mathematizing* and modelling can serve as a productive strategy for introducing teachers to such authentic practices. Using such a reframing, teachers can begin to envision a place for these practices in their classrooms in ways that are authentic to the discipline and that also result in worthwhile designs for student learning.

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Raging Skies: Development of a Digital Game-Based Science Assessment Using Evidence-Centred Game Design

Man-Wai Chu and Angie Chiang

Abstract

Digital game-based assessments have been gaining popularity; however, there is often an imbalance between entertainment and educational game elements, yielding barriers for both students and teachers. This paper examines the development processes of an interactive game-based assessment, Raging Skies, in which learning tasks are purposefully embedded and integrated into the game's design and framework so that specific knowledge and skill-based outcomes may be measured. This case study discusses some of the challenges and criticisms facing digital game-based assessments as outlined in the literature.

Introduction

Over the past decade, there has been a growing concern regarding the shortage of science, technology, engineering and mathematics (STEM) skilled workers to fill the many job vacancies in North America (US Department of Education 2015). A recent report has indicated that in Canada, the supply-and-demand ratio for STEM workers has improved, but concerns are now being raised regarding the quality and level of their skills (Council of Canadian Academies [CCA] 2015; National Science Foundation [NSF] 2015). To address this concern, the CCA and NSF have indicated a need to develop STEM-proficient students through high-quality programs from preprimary education through to secondary school. Their hope is that initial investments in building fundamental STEM skills at a young age will develop higher-quality STEM students for the workforce. However, the types of educational programming needed to develop a high-quality STEM-literate population warrant investigation. Before designing new educational programs to improve the quality of the STEM skills students acquire, it is important to investigate gaps in the current methods of teaching and assessing science knowledge and skills.

Developing a strong foundation of science content knowledge is important for success in the field, but equally important is an understanding of scientific inquiry, which explains the process of how scientists came to form these theories (National Research Council [NRC] 2006, 2014). While there are many tools to assess students' conceptual understanding of content knowledge, there are very few tools to assess the process of science inquiry, particularly in a standardized way. Hence, there is a need for assessment tools that can capture evidence of science inquiry skills, which requires an investigation of the process students use to complete a task. In order to capture this evidence, we need new assessment formats that break the mould of traditional paper-and-pencil tests.

Assessments are currently facing a turning point at which the impact of technological advances, coupled with a wave of innovation in learning sciences, has opened the doors for new possibilities. These advances and innovations have created an environment that is ripe for investigation, because formats and capabilities of assessment have been revolutionized as a result (Shute et al 2016). These improvements allow for the development of high-quality, authentic digital tasks, resulting in the measurement of both content knowledge and process skills (Shute and Ventura 2013). Assessments that take the format of digital tasks (eg, technology-rich environments [TRE], search and simulation [Sim] scenarios) are being developed and used by large testing agencies such as the National Assessment of Educational Progress (Bennett et al 2007). Many of these digital task assessments use simulations to guide students through a learning environment such as a nature conservatory, like Taiga Park (Barab, Gresalfi and Ingram-Goble 2010), or a science laboratory, like TRESim (Bennett et al 2007). These digitally simulated assessments allow students to interact with a dynamic environment that is responsive to their actions and performances. The computer logs that capture students' actions throughout the simulation are analyzed for evidence of content knowledge and process skills (Shute and Ventura 2013). Although these assessments allow for interactive components, they still mimic and use traditional assessment formats such as multiple-choice items (Bennett et al 2007). Although the interactive learning environment often increases students' engagement, the embedded tasks often emulate that of traditional assessments, which may continue to elicit test anxiety-related performance (Chu 2017).

In order to combat the reliance on traditional test formats, such as multiple-choice items, as a measure of performance, some researchers have started to capitalize on digital activities for assessments insofar as they are embedded in actual digital gameplay (Mislevy et al 2014). Digital game-based assessments (eg, Physics Playground) have started to gain popularity in recent years (Shute and Ventura 2013). Some of these assessments use existing commercial games (eg, Portal 2 and Lumosity), which are primarily designed to provide entertainment, to measure skill-based outcomes such as problem solving, spatial skill and persistence (Shute, Ventura and Ke 2015). Critics of these game-based assessments have indicated that the problem with retrofitting commercial games for use in education settings is that the observable evidence needed to support the resulting inferences made on a specific skill may not be built into the game (Mislevy et al 2014). For example, commercial games may be used by researchers to measure persistence, but if the game was not originally designed to assess this skill then the results may not be valid. Therefore, making conclusions regarding students' skill levels based on the data collected from these games may lead to weak and inaccurate inferences.

Conversely, there are educational games that focus more exclusively on teaching and assessing specific educational knowledge and skills than their commercial counterparts (Shute and Ventura 2013). However, these games have been criticized for essentially being a high-tech worksheet instead of using the evidence collected during the interactive portions of the task in a more purposeful way (Mislevy et al 2014). Additionally, these games do not develop good game mechanics (eg, in-game rewards, such as points or trophies, for high performance), which leads to lower student engagement levels when interacting with these assessments (Shute and Ventura 2013). Hence, there appears to be a need to develop digital game-based tools that more equally balance entertainment and education so that new assessments may be developed that capitalize on the benefits of each (Mislevy et al 2014). Specifically, these assessments should incorporate the development of data capture methods that more purposefully demonstrate the acquisition of specific content knowledge and process skill outcomes from a program of study.

This paper describes the development of a digital game-based assessment that used a framework called *evidence-centred game design* (ECgD), which was designed to balance the entertainment and education elements during the development stages. This dynamic, digital game-based assessment is called Raging Skies (a more thorough description follows), and aims to measure both science content knowledge and process skills. Raging Skies directly and purposefully embeds various outcome-informed tasks into gameplay. This assessment tool was specifically designed to measure a set of content knowledge and process skill outcomes related to an elementary school science program of study. This investigation of the developmental stages of the game seeks to resolve the imbalance that much of the literature on game-based assessments identifies and to offer solutions to the competing priorities of entertainment and education games.

Our discussion is structured into three sections: describing the ECgD framework in more detail, a description of the developmental process of Raging Skies and a survey of the challenges faced during the development of the game.

Evidence-Centred Game Design (ECgD)

The analysis of the production framework is guided by ECgD, in which digital games function as both assessments and learning tools to measure content knowledge and skill-based competencies (Mislevy et al 2014). One aim of ECgD is to synthesize two design development frameworks—game and assessment—into one unified process, as shown in Figure 1.

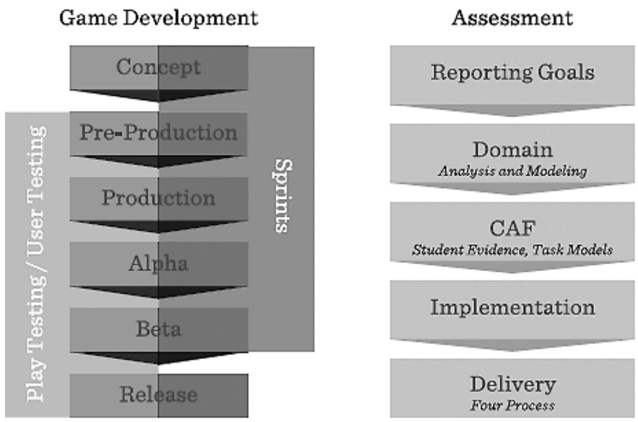


Figure 1. *Design frameworks for games and assessments that are integrated using ECgD. Adapted from Mislevy et al 2014, 135. Reprinted with permission.*

On the right side of Figure 1 is the evidence-centred design (ECD) framework that is often used to develop assessments based on evidentiary reasoning so that judgments of students' level of knowledge and skills may be made (for more details please see Mislevy, Almond and Lukas 2003). The ECD framework guides educators to articulate the observable evidence needed to support the inferences they wish to make regarding students' achievement of specific knowledge and skills (Behrens et al 2010). The left side of Figure 1 shows the design process typically used to guide the development of recreational digital games, emphasizing repetitive implementation, testing and enhancing of the product during what is called the "sprint" period. The majority of the development process is done after alpha- and beta-user testing phases when feedback is provided to the development team outlining usability, requirements and constraints (Mislevy et al 2014).

By unifying both of these frameworks, ECgD attempts to reflect a meaningful integration of both game and assessment, as shown in Figure 2. It illustrates the importance of developing an assessment product that has a meaningful context for students to learn and educators to measure specific content knowledge and skill-based competencies. Once this meaning or macro-level defining stage is complete, micro-level designs follow to address the types of actions students need to perform during an activity. These actions indicate whether or not students have provided sufficient evidence of mastering a construct. Considering the constellation of perspectives outlined in Figure 2—meaning, construct, knowledge, actions, evidence and activities—it is important to develop a product that adequately represents each domain (ie, games, learning and assessment) and evokes evidence of players' capabilities (Mislevy et al 2014).

The integration of games and assessment results in an ECgD framework that follows four phases (Mislevy et al 2014, 136):

1. Definition of competencies from a non-game realm
2. A strategy for integrating externally defined competency with gameplay competency
3. A system for creating formative feedback that is integral with the game experience
4. A method for iteration of the game design for fun, engagement and deep learning, simultaneous with iteration of the assessment model for meaning and accuracy

It is important to note that ECgD is not a retrospective process, instead designing the game's mechanics to suit the assessment and learning needs of interest during the initial planning stages. It is, therefore, important to consider the goals of games, assessment and learning early during the development process.

ECgD builds upon the principles of technology-rich and simulated learning environments that situate assessment tasks within a digital game environment. ECgD often seamlessly embeds assessments into the learning environment so that students are not pulled away from an engaging flow of tasks with an explicit test (see Shute and Ventura 2013). This seamless integration allows the digital game environment to be

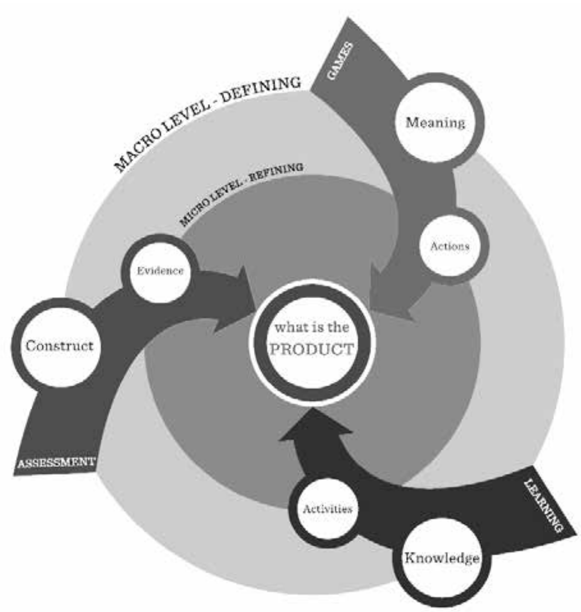


Figure 2. *Model of unifying frameworks from the disciplines of games, assessment, and learning. Adapted from Mislevy et al 2014, 136. Reprinted with permission.*

highly immersive and engaging, thus helping to reduce test or evaluation anxiety (Shute and Ventura 2013). Part of this engagement is due to the real-time interactions between the user and the digital game, which is often viewed as feedback. This real-time feedback is made possible by using computers as a method for administering ECgD assessments. Although many, if not most, of the ECgD assessments are administered using computers (Rowe, Asbell-Clarke and Baker 2015; Rupp et al 2010), the framework itself does not mandate the use of digital technology.

Raging Skies

Using the ECgD framework, a team of researchers and digital-game developers created a computer game-based assessment entitled Raging Skies. This role-playing game transports students into the world of storm chasers, asking them to use various resources (eg, weather balloon and thermometer) located on their vehicle to collect information regarding the weather phenomena (ie, wind speed and temperature). The game uses real-time footage of storms across North America as players are asked to collect data, identify the type of storm and report on it. The footage is overlaid with animated elements to mimic a first-person experience. Figure 3 shows a diagram of the vehicle dashboard that players will use throughout the game to activate each of the tools. This game-based assessment was developed to capitalize on its format so that both content knowledge and process skills may be measured. The development of the game was guided by the four steps of the ECgD model, which are presented in the following sections.

Definition of Competencies

Competencies are the knowledge and/or skills that the game-based assessment intends to measure. The competencies that were assessed in Raging Skies are outlined by the specific learner outcomes listed in Alberta's Grade 5 science program of studies under the Weather Watch unit (Alberta Education 1996; Leighton and Gierl 2007). Two types of learner outcomes in the program were of particular interest—content knowledge and science inquiry skills. These two types of outcome were specifically selected because they support one another during the learning process. For example, prerequisite content knowledge is needed so that it can be applied during the process of science inquiry. On the other hand, science inquiry is defined as the process of acquiring new knowledge. Hence, these two types of learner outcome form a mutualistic relationship in which both knowledge and skills benefit when addressed together. The specific learner outcomes that were used to guide the development of Raging Skies are as follows:

Knowledge Outcomes

5.8.2 Describe patterns of air movement, in indoor and outdoor environments, that result when one area is warm and another area is cool.

5.8.3 Describe and demonstrate methods for measuring wind speed and for finding wind direction.

5.8.5 Describe and measure different forms of precipitation, in particular, rain, hail, sleet, snow.

5.8.8 Identify some common types of clouds, and relate them to weather patterns.

***Figure 3.** Screen capture of the vehicle dashboard from the proof-of-concept prototype from the digital-game-based assessment Raging Skies. Students may click on the icons, highlighted by the boxes, on the dashboard to activate the different tools used to collect data regarding the weather outside of the vehicle. Copyright 2016 by MindFuel. Reprinted with permission.*

5.8.10 Recognize that weather systems are generated because different surfaces on the face of Earth retain and release heat at different rates. (Alberta Education 1996, 27)

Skill-Based Outcomes

5.1.2 Identify one or more possible answers to questions by stating a prediction or a hypothesis.

5.2.3 Record observations and measurements accurately, using a chart format where appropriate. Computer resources may be used for record keeping and for display and interpretation of data.

5.2.4 Reflect and interpret: state an inference, based on results. The inference will identify a cause and effect relationship that is supported by observations. (Alberta Education 1996, 24)

Instead of selecting all 28 Weather Watch learner outcomes, only these 8 were specifically targeted for Raging Skies. Focusing on a few selected outcomes allows for more evidence for each outcome to be collected, thereby improving the reliabilities of the claims made from the assessment (American Educational Research Association [AERA], American Psychological Association [APA] and National Council on Measurement in Education [NCME] 2014).

Just as the two types of learner outcomes are interconnected, the eight specific outcomes that represent the two types are also connected. To represent the connection between the eight specific learner outcomes, a competency model was developed. Competency models are often developed using extensive literature reviews of the constructs being measured, such as those undertaken by the curriculum specialists when developing the learner outcomes (Shute 2011; Shute and Ventura 2013).

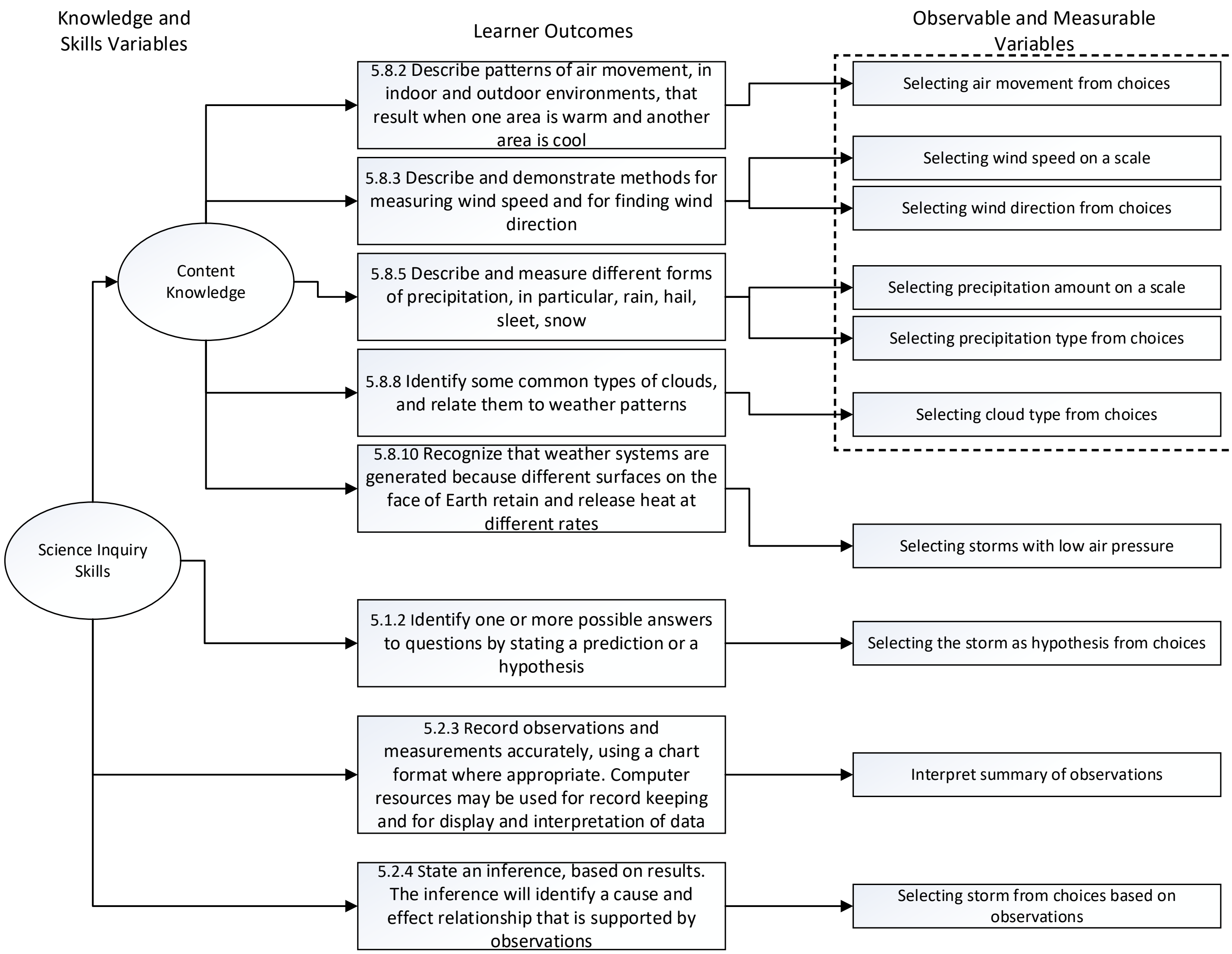
Figure 4 (page 42) shows the competency model used to guide the development of Raging Skies, which illustrates how the learner outcomes are connected to each other. The competency model also identifies the observable and measurable variables that are used as evidence to support the corresponding learner outcomes. Using the model as a whole, the evidence collected from the observable and measurable variables is then used to support claims of proficiency of the learner outcomes and corresponding knowledge and skills variable. For example, during the assessment, students are asked to collect information on six observable and measurable variables that represent different aspects of the storm; they are highlighted using a dash-lined box in Figure 4. Students' performance on these six variables is used to indicate their proficiency on the corresponding four learner outcomes. In order for the assessment to provide the necessary opportunities to collect evidence of students' performances for each learner outcome, the team of researchers and digital-game developers worked collaboratively to integrate the competencies with the gameplay. This process is discussed in the next section.

Integrating Competencies with Gameplay

The production team started to write a story that would be realistic for students while ensuring that the game mechanics could properly capture evidence for each learner outcome. The introduction of the game was designed to be highly captivating and realistic to students so that they would become immersed into the game-based assessment's story line. This immersion into the assessment's game-based environment is referred to by many gaming communities as *flow* (Shute et al 2009). Research in game design has suggested that optimal flow is achieved when the intrinsically motivating environment has elements of challenge, control and fantasy to keep the players engaged in the game such that they lose their self-consciousness and sense of time (Gee 2007; Rieber 1996). Raging Skies is designed to maximize students' flow so that they do not view the game as an assessment, which often elicits anxieties related to testing (Shute and Ventura 2013).

One way that Raging Skies keep players engaged is the use of a reward system, such as in-game money to add a competitive element and increase replayability. Players are provided with an account to track the amount of in-game money accumulated and used; this gives students the ability to purchase upgrades to and customizations of their equipment (eg, change the colour of their dashboard) as well as gas for driving to future storms. Players are able to access their account frequently to determine how much more they need to reach their next level of upgrade or customization. To get players motivated to start the game, Raging Skies uses a guided tutorial during the first administered task so that enough in-game money can be earned to keep the player engaged.

Figure 4. *Competency model of learner outcomes from Alberta's Grade 5 program of study's Weather Watch unit, designed specifically for the game-based assessment Raging Skies. The dotted line outlines six observable and measurable variables that represent different aspects of the storm.*



In order to further increase student engagement, a competitive element of racing against computer-generated storm chasers was added. The first student to identify the storm (when playing against the computer) earns extra in-game money, which allows them to purchase gas and upgrade/customize their equipment. The amount of in-game money rewarded to students is proportional to their performance during the storm task. As such, the amount of in-game money received by the student is a form of formative feedback regarding their performance during the storm task.

Formative Feedback During Game

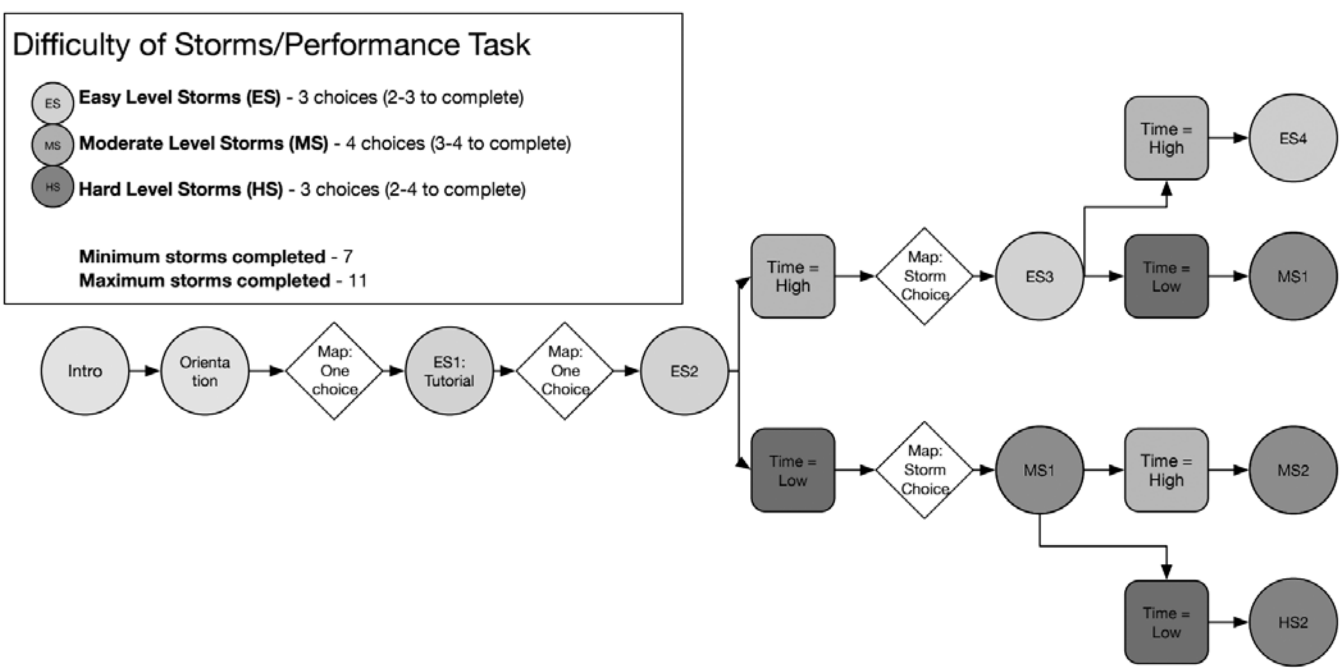
After students identify the storm type, they are given formative feedback regarding their performance in measuring the six different elements of the storm and identifying the storm type. An example of a student feedback report is provided in Figure 5. The feedback report indicates students' level of performance using in-game money as their reward system. The better the student performs during the storm task, the more in-game money they will receive.

Figure 5*. Screenshot of the formative feedback report that students receive after a storm task. Students are rewarded with in-game money so that they may purchase upgrades, customize their equipment (eg, change the color of their dashboard) and purchase gas to reach the next location.*

After students are shown their formative feedback report, they are able to click on the portions for which they did not receive the full amount of in-game money (eg, variables in which the student received only $50) to review their answers and reselect their choice. Students are given one opportunity to reselect their choice for each variable for which they did not receive the full amount of in-game money. However, a correct selection during the second attempt does not result in additional in-game money being given; instead, this opportunity is designed to provide students with formative feedback so that they may improve their performance on later storms.

The design of Raging Skies is based on both game design (eg, presenting easy tasks first and then increasing the difficulty) and assessment principles (eg, computer adaptive testing) (Weiss 1982). These principles indicate the importance of administering different storm tasks to students based on their performance on previous storm tasks. Figure 6 presents a diagram of the adaptive process based on students' performance on previous storm tasks. The first storm task administered to students after their tutorial storm is rated to be at moderate difficulty level. If students perform well on this storm task, they are provided with in-game money

Figure 6*. Adaptive process based on students' performance*



so that they may purchase gas to travel to their next location. Alternatively, a weak performance on this first storm task would result in a smaller amount of in-game money for gas. Less in-game money for gas will result in the student only being able to reach closer storms, which are rated to be a lower difficulty level.

Students are incentivized to reach storm tasks with a higher difficulty rating because they will be able to receive more in-game money during those tasks. For example, students may receive a maximum of $1,250 during a moderate-difficulty storm task, but they may receive up to $1,875 during a high-difficulty storm task. This adaptive process continues throughout the assessment so that each student will have a customized experience that matches their performance. Throughout the assessment, students are presented with multiple storm tasks (ie, 7 to 11 storm tasks) so that enough evidence may be collected to ensure that reliable claims may be made regarding their performance of each learner outcome.

The previous sections discussed the first three phases of the ECgD framework in terms of game development (ie, concept and preproduction) and assessment (ie, reporting goals, domain and conceptual assessment framework [CAF]). Raging Skies is currently in the production stage, in which the developers have taken the designs from the previously discussed three phases to write the computer codes needed for this assessment. The next section of this paper will discuss the next steps for this project, which will involve the fourth, and final, step of the ECgD framework.

Iterations of Game Design and Assessment Model

ECgD stresses the importance of the iterative process involved when developing a game-based assessment. Although there are four steps to consider when developing such an assessment, it is imperative that the development is informed by both game-design and assessment principles. Raging Skies is currently being validated through a process in which information about whether or not this game-based assessment is in fact measuring the intended learner outcomes is being collected (Kane 2013). Validation is critical to good assessment development and is important for ensuring that irrelevant concepts are not interfering with the measurement of the intended purposes and goals (AERA, APA and NCME 2014). The validation results allow for enhancements to be made to the assessment by both the digital game developers and educational assessment researchers.

Throughout the development of this game-based assessment, the ECgD framework guided this project. Previous researchers who developed game-based assessments using this framework identified some of the challenges they encountered (Mislevy et al 2014). The Raging Skies game developers and educational researchers were able to avoid some of these challenges. However, the team still encountered additional challenges during the development process. A discussion of some of the challenges faced during this development process is discussed in the next section.

Challenges During the Development of Raging Skies

Although the ECgD framework does a good job of integrating the entertainment and educational elements of game-based assessment, some challenges presented themselves during the development process. The challenges that the development team faced occurred during Phase 1 of the ECgD framework—defining the constructs. Specifically, the development team had difficulties in identifying proper methods to collect the evidence needed to support the observable and measurable variables and in representing the open-ended nature of science inquiry skills.

The development of Raging Skies used the lessons learned from existing game-based assessment development literature to prevent recurrence of previously encountered issues. For example, studies that investigated the difficulties associated with developing game-based assessments indicated that the multidimensionality of the constructs (eg, creativity) were problematic when trying to define the construct and when identifying observable and measurable evidence (Kim and Shute 2015). The development of Raging Skies avoided this issue of needing to define multidimensional constructs by using learner outcomes from the program of study. The program of study defined the constructs of interest (ie, content knowledge and science inquiry skills) for the Weather Watch unit by identifying the outcomes that are associated with each construct (Alberta Education 1996). Although the outcomes identified by the program of study may not fully encompass all aspects of the construct for the unit, the curriculum team who wrote the program identified the main elements that are important for Grade 5 students to know. Developing a game-based assessment that is guided by specific learner outcomes allows teachers who use the Alberta Grade 5 science program of study to use Raging Skies as a classroom resource.

Although the development team was able to avoid the challenges associated with defining constructs by using learner outcomes, one difficulty that the team encountered was the issue of using a creative format to collect evidence of student performance. The team identified observable and measurable variables for each learner outcome, as shown in Figure 4, so that appropriate evidence could be collected. However, when operationalizing the observable and measurable variables, the team faced the challenge of designing a collection format that would mimic how real-life storm chasers measure and document their findings. One of the main challenges was to develop a collection method that did not emulate multiple-choice items because the development team did not want this game-based assessment to be viewed as a fancy digital worksheet. However, for many of the observable and measurable variables, a multiple-choice item format was implemented to collect the necessary information. For example, when students are asked to identify the wind direction using the weather balloon launched from their vehicle, they are provided with only three choices: straight, clockwise and counter-clockwise. The three choices made the recording of the measurement seem like a multiple-choice item.

Of course, this item format was avoided when possible. For example, when students were asked to record the wind speed, they were given a full scale, such as the one shown in Figure 7, to record their findings. This format of recording wind speed emulates the real world in terms of providing students with a scale so that they can focus on the accuracy of their measurement. However, it could be argued that this scale still emulates the multiple-choice item format because it provides students with 20 possible choices to select. The research team was unable to develop a better method of recording students' measurements during the storm task; this is an area that will, hopefully, be enhanced with future iterations of this assessment.

Another challenge faced by the development team was ensuring that the storm tasks allowed for the open-ended solutions needed to assess science inquiry skills. Science inquiry focuses on how a scientist would acquire knowledge and skills, a process that is relatively open ended. However, the learner outcomes selected from the program of studies represented only a small subset of this construct. Additionally, the selected subset of outcomes were typically quite closed ended. For example, learner outcome 5.1.2 indicates that students should "identify one or more possible answers to questions by stating a prediction or a hypothesis" (Alberta Education 1996, 24). The learner outcome indicates the need to focus on the open-ended nature of answering a problem because there could be multiple correct answers. However, in the context of Raging Skies, the objective of the game was for students to identify the storm type; hence, only one correct answer is present. This created a closed-ended problem for each of the storm tasks administered, and also prevented the open-ended nature of science inquiry to be assessed.

Figure 7. *Wind speed scale*

During the validation process, these two challenges will be shared with students and educators in hopes that possible solutions will be presented to the development team so that future iterations of Raging Skies will be enhanced. Future research needs also to focus on using more real-life formats to document the measurements taken during a storm task and providing more open-ended storm tasks that allow for multiple processes and solutions to be accepted. Possible solutions to these challenges will greatly enhance science assessments that aim to be authentic and measure science inquiry skills.

Classroom Relevance

A preliminary version of Raging Skies is currently available on the MindFuel's Wonderville.org website (https://wonderville.org/asset/stormchasers) for use by students and educators. Although Raging Skies is still being validated, the game-based assessment provides students and educators with an opportunity to approach the Weather Watch learner outcomes with a realistic simulation. This new approach of addressing the learner outcomes may provide additional insight in terms of guiding students' learning and informing teachers' practices. Once this assessment has been validated, it will also provide students with feedback regarding their performance on skill-based outcomes.

Digital game-based assessments, although starting to become more popular, are still in their infancy (Shute and Ventura 2013). In order to address some of the criticisms of entertainment and education game-based assessments, it is important that new games use proper game design and rigorous assessment properties (Mislevy et al 2014). The development process of Raging Skies led the development team to spend a substantial amount of time researching the learning objectives and mapping them to the different levels of student performance. This ensured that the assessment developed would be aligned with learner outcomes and adaptive to reflect student performance. By introducing game-based science assessments that are well aligned with learner outcomes from a program of study, this educational tool may be used in the classroom to provide evidence that students are learning specific content knowledge and process skills. Formative feedback provided to students and educators will target specific areas of weaknesses so that instruction may be adapted. With more of these educational tools being developed to enhance students' content knowledge and process skills, the vision of a high-quality STEM-literate population is possible.

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Guiding Students Toward Open Inquiry in a Novel Outdoor Setting

Lisa Corbett, Sue Arlidge, Savannah Poirier and Edward Johnson

Abstract

Open inquiry has been shown to result in high student engagement and satisfaction in the classroom. However, students and teachers are often wary of open-inquiry projects due to fears of frustration, loss of control and undesirable results. High school programs at the Biogeoscience Institute (BGI) in the Alberta Rockies have been guiding students toward open inquiry for over a decade. Their process involves a scaffolded approach that moves students from a state of confusion and dependency on teachers to complete ownership and confidence over their project. The key to the success of this program is the development of strong questioning skills. Students learn very quickly which questions will be testable in the field. Upon development of a strong question, students are then able to successfully and independently design and conduct their study. Students leave these programs with a strong understanding of the nature of science and the confidence that they have the ability to participate in the scientific process beyond the prescribed laboratories in class.

Keywords: open inquiry, testable question, scaffolding, environmental education, scientific process

Introduction

A group of high school students snowshoes to the top of a hill overlooking a panoramic view of the Rocky Mountains. Upon reaching the top, they are asked to come up with a question about the winter ecosystem and design a study that will answer their question (Figure 1). Although this is their first day on the field trip, students are able to come up with questions such as How does the orientation of the slope affect the distribution of moss? Why do animals stay active in the winter? What effect does the elevation of an area have on the vegetation under the snow? These questions, while not perfectly testable and requiring fine-tuning, represent an initial phase in the move toward creating independent novice scientists capable of open inquiry.

Programs at the University of Calgary Biogeoscience Institute (BGI), a field research station nestled in the heart of the Canadian Rockies, provide a unique opportunity for students to immerse themselves in a scientific institution. Surrounded by active research scientists, scientific equipment and nature's endless array of questions to explore, students are exposed to the true nature of science. Students are given the chance to explore science as a creative endeavour (National Science Teachers Association [NSTA] 1997) and realize that anyone with the ability to ask questions and the drive to answer them can contribute to scientific knowledge. At BGI, programs are aimed at guiding students from an initial point of fear and uncertainty regarding open-inquiry investigations to having the confidence to approach an unknown environment and conduct successful scientific investigations driven by their own questions.

Encouraging Open Inquiry

There has been a pedagogical shift from content-driven instruction to instruction rooted in inquiry. Lessons rooted in inquiry, such as the one described above, promote student engagement (Willms, Friesen and Milton 2009) and the development of critical scientific skills, such as asking questions, forming a hypothesis and designing an investigation (Bybee 2000; Crawford, Krajcik and Marx 1999; Cuccio-Schirripa and Steiner 2000; Hofstein et al 2005; Prince 2004; Yarden, Brill and Falk 2001). A major goal in Alberta science education is to create scientifically literate students (Alberta Learning 2014). In order to promote scientific literacy in students, educators must treat students as

Figure 1. *A student developing a question in a winter ecosystem*

scientists (Pearce 1999) who believe that they can conduct authentic science. There is a misconception that science is a stagnant, fixed accumulation of truths, rather than a dynamic entity to which students can contribute (White 2003; Windschitl et al 2007). Lessons at the BGI are rooted in inquiry and are scaffolded to gradually guide students toward independent development of investigable questions, or open inquiry.

A successful open-inquiry investigation requires a shift in the traditional roles of students and teachers such that students gain ownership of their own knowledge construction. During the course of an investigation, the teacher's role changes from initially providing the content, methods and background instruction required to navigate a topic (the more traditional role of a teacher) to that of coinvestigator as the inquiry unfolds. Often, students are the best judge of which questions they need to explore to make sense of their project, as they quickly become the content experts in their specialized topic of study. Instead of the teacher telling the students what they need to learn, the students search for their own understanding, and this is what motivates them to learn (Grennon, Brooks and Brooks 1993). Teacher feedback after inquiry projects at BGI often notes the surprised reactions from students when the teacher tells the students that they have no idea how to solve their problem, as it is an original piece of research. Students often comment that embarking on their own original line of inquiry is very exciting and empowering. Evidence shows that student performance increases in the STEM fields with more student-centred active learning (Brewer and Smith 2011; Freeman et al 2014; Haak et al 2011).

Open inquiry has been found to promote improved satisfaction in lessons (Sadeh and Zion 2012), problem solving and critical thinking skills (Cuccio-Schirripa and Steiner 2000; Prince 2004) and to improve students' ability to ask good questions (Crawford, Krajcik and Marx 1999; Yarden, Brill and Falk 2001), but it is not without its critics. Tan and Caleon's (2016) concerns regarding inquiry lessons identified that some felt an open inquiry is too abstract and results in frustration for teachers and students, and that teachers are often hesitant to give up control over their curricular checklist and often worry that student-driven inquiries may result in misconceptions.

With over a decade of experience with inquiry programs, BGI educators have observed these fears in both students and teachers. They have also observed in their program the development of broad untestable questions, a myopic focus on a question that does not lead to an interesting study, a lack of independence from the teacher and difficulty ensuring that the investigation design matches the question. Based on these observations and several studies on inquiry (Kirschner, Sweller and Clark 2006; Tan and Caleon 2016; van der Valk and de Jong 2009), educators at BGI have developed carefully scaffolded inquiry lessons, which have successfully guided students toward independent, well-designed, interesting open-inquiry investigations. Intentionally scaffolded lessons (Wood, Bruber and Ross 1976) keep students' learning within their appropriate zone of proximal development (Vygotsky 1978) and ensure ownership of their investigation (Keys 1998). Scaffolding at BGI occurs through a purposeful set of lessons that serve to curb frustration and promote positive experiences while not removing student ownership of the project. These lessons also highlight important aspects of the nature of science for students. This is the common thread throughout the program.

Scientific Questioning Is a Creative and Dynamic Endeavour

Crafting an investigable question is a key element to a successful scientific inquiry investigation (Chin and Osborne 2008; Millar and Osborne 1998). However, the development of an investigable question is not an obvious skill (Walsch and Sattes 2005). Much of the instruction in BGI's program focuses on the development of the investigable question. Students are encouraged to develop a question that interests them, because this will garner a high degree of ownership over the project (Chin and Osborne 1998). However, allowing students free reign can result in questions that are nonspecific, lacking measureable or observable variables. Examples include How do mice survive the winter? How does snow affect food sources? How does temperature affect birds? In order to guide students toward crafting an investigable question, three key stages occur throughout the program: investigation, practice and ownership.

Investigation

The first stage of the program is a critical lesson in question development. Instruction focuses on how to recognize and formulate investigable questions (Chin and Kayalvizhi 2002). This lesson gives the educator knowledge of the level of understanding of the students. Students categorize random questions into investigable and noninvestigable questions. They will identify what determines whether a question is investigable or is too general. They will be cautioned about words *why* and *how* in a question that may lead to one that is too broad to be testable (Chin and Kayalvizhi 2002). Students then develop their own questions using random biological artifacts provided by the instructor (such as a rotting log or a set of antlers). This is set up in a nonthreatening fashion, so they are minimally invested in the question (ie, they don't have to try to answer it) and can therefore analyze its contents—for example, How do rocks affect invertebrate distribution? They then develop the methods that could answer the question. At first, students struggle to narrow down the measurable variables, and may recognize that the word *how* means that they need to think of what aspects of rocks may affect invertebrate distribution. To help students focus on variables, the instructors regularly use these prompt questions: What can you observe, count or measure? What unit(s) would provide the results you anticipate? Once they identify variables and units of measurement, students can make their question more specific. For example, Are mayflies more abundant under limestone boulders, cobble or gravel? They can now test this question because they have identified a specific invertebrate family and a specific rock type, and are now looking for different sizes of rocks.

Creating Good Questions Requires Practice

The second stage of the program is when students have an opportunity to practise in a supportive and encouraging environment. This occurs in the lesson described at the beginning of this article, in which students are taken to field sites at novel environments (eg, land adjacent to a factory, sites at different altitudes and so on) and asked to formulate a question. At this point, they have become familiar with their field sites through group guided-acclimatization activities and have some directed background knowledge on what it means to develop a question and what must be measured to test the *how* question. Students follow Chin and Kayalvizhi's (2002) four criteria for the development of a strong scientific question: Can the question be tested? Is it interesting and challenging? Is it practical in terms of difficulty and time? and Is the answer known? Students need to incorporate these criteria into their question development, but because they still have opportunities to refine and retest their question, the risk is still low.

During one program, a student group asked Why do animals stay active in the winter? By using their question, we can see how the practice sessions help students understand how to refine their question. This student group began with the first criterion from Chin and Kayalvizhi (2002): Can the question be tested? They identified numerous variables relating to animal activity that can be tested: animal tracks, evidence of animals on trees and shrubs, observing animal activity and trapping live animals. However, the students quickly realized that although they could measure animal activity, none of these variables helped answer *why* animals were active in the winter. They were able, on their own, to identify the problem with the question and the need for question refinement. They collected what data they could and then, upon return to the classroom, were able to spend time redeveloping the question.

Student Ownership

Student ownership of the investigation occurs during the third stage of the program. This happens when students have time to reflect in the classroom. They look at their field data to ensure that they have identified the appropriate variables to answer their question. They also examine the scientific literature to ensure that they have met the final criterion for a strong scientific question, which is whether the answer is known (Chin and Kayalvizhi 2002). Students then finalize their question and research design, and begin to collect their data. They are at the final stage of ownership over the study and have complete autonomy over where they take the investigation.

The student group that was exploring animal activity returned to the classroom with an assortment of data collected. They then examined primary scientific literature that the program leaders provided. These articles had been preselected by instructors based on common themes in winter ecology and often had summary pages attached to the front to help the students understand some difficult concepts. The students learned about the insulation properties of snow and the use of movement in animals to increase metabolism. Reflecting upon their time practising in the field and then reviewing the literature, the students were able to refine their questions to the more specific: Are animals more active in areas where the insulation properties of the snow are lower? They were then able to design a study and collect the appropriate variables, with very little guidance from teachers or program instructors. Therefore, the students maintained complete ownership over their study.

Scaffolding open-inquiry investigations with guided instruction that backs off quickly has yielded successful open-inquiry projects and confident young scientists. A recent case study with a group of advanced placement chemistry students highlights a series of field trips and lab time sequenced over 16 months. Student and teacher interviews after the project highlight the most significant factors contributing to student success.

- The field research created links between their classroom chemistry and real-world applications of chemistry, such as measuring air emissions, soil testing, organic compound isolations and so forth. On the initial field day, students toured factory sites, dams, railway crossings, highways and natural habitats. The day was designed to stimulate curiosity and expose students to the questions an environmental chemist addresses, as well as teaching field research tools and methods.
- Time and practice in creating multiple testable questions in novel and interesting environment is a crucial step in refining research questions. According to the students and teachers in the case study, the most important catalyst for research ideas were the open-ended questions instructors offered at each field stop, such as How is the pH of flooded sites different from the uphill sites? How might soil chemistry change as you move away from train tracks? How might air quality be different on the east side vs the west side of factory? How could we count or measure that?
- Multiple field visits over time are required to gather data and work through an independent question.

Students Leave with Confidence

Once students go through the process of developing and testing a question, they begin to realize that they are capable of conducting authentic science and that they possess the tools to ask questions and design research studies. Student testimonials after the program often identify how they felt overwhelmed at the beginning but leave feeling comfortable with the scientific process.

> Student 1: The beginning of the field trip was a bit overwhelming because I was not overly sure of what to do; however, as we began collecting data from different sites all the pieces came together and made much more sense!
>
> Student 2: Learning new techniques and finding ways to come up with a question and make an experimental design is quite difficult in an open-ended situation … It helped us think outside the box and make our brains work harder to find new ways to interpret data and collect it to formulate questions and applications … These very ideas then could lead to a whole new scenario of taking the experimental design to the next step and creating an actual design [that] could be useful.

Assessment specialists from the Calgary Board of Education interviewed students from the chemistry case study after their projects were complete. Here are the student replies to What was the most important thing you learned?

- This was more than a project. I developed my own learning style. My goals were self-set. I could choose how much I needed to know. It felt like we had done *real* science.
- Working on a goal I set myself made me want to prove it to myself and I worked harder than usual. It was really exciting.
- We were rewarded for risk taking, but it felt vulnerable. There were so many unknowns—we had to

try many things. In the end it wasn't just one question; we answered multiple questions.

- I'm glad we weren't graded because it wasn't all about knowing the answer to the problem—it was more about how we developed a learning strategy, how we overcame obstacles and problem solved.
- Lack of prior knowledge is scary but it developed us as learners. It was enlightening.
- Q: What did you need from the teacher? A: Faith that the teacher is as invested as you are.
- I liked the open-endedness, the fluidity. I learned confidence. I like driving my own learning.

The same team of curriculum assessors asked the teacher to highlight her learning. These are her comments:

- Initially, students needed more formal instruction, such as specific lab skills and feedback/check-ins such as lab write-ups. They needed structure to build off limited experience. Over time, my feedback turned more informal, like a mentor, so we would problem solve issues together. It took time for the students to realize I honestly didn't have the answers and we were going to try to find them together.
- Students didn't need a grade on the final scientific posters. They knew that they had done their best work.
- The experts from the university, internal school staff and staff at the Biogeoscience Institute were critical for the success.
- Student feedback to the teacher stated that a pivotal moment was when a snow researcher showed his mathematical data to the students and assured them that uncertainty is part of being a scientist.

As evident by the comments, this was a positive experience for both the teacher and the students.

Conclusion

While open-inquiry teaching does require a different style of instruction, the rewards are perhaps surprising. Experienced teachers will discover the places that students' minds can go, and the unanticipated results can be extremely exciting, which will provide both students and teachers with renewed curiosity and the next set of questions to be tested. Long after students have forgotten the content, they will remember the process. They will know how to develop a question, an excellent stepping-stone toward being a scientifically literate student.

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