Abductive reasoning in design, tinkering and making: Studying problem solving activity in makerspaces

Michael Tan, Dragan Trninic, Zhi Ying Ng
National Institute of Education, Learning Sciences Lab, Singapore

Abstract

While some current research has focussed on instruction in makerspaces, less attention has been paid to the processes of learning. Abductive reasoning is argued to be central to design and a key ingredient across essentially all practice-based domains. We present the results of an ongoing study in which three adult- and five student-dyads participated in a time-limited creative problem solving task. Using an inductive content analysis method, we coded video segments of activity describing the problem solving strategies that they undertook, assisted by their speech to discern intention. Using a Consensual Assessment Technique, we rated their creative outcomes. Broadly, the better performing dyads approached the creative problem from a 'top down' approach, proposing solutions to respond to the prompt which were then built. On the other hand, the poorer performing groups tended to work 'bottom up', combining material resources to find a creative combination which could work. We argue that these approaches can be productively characterized as better and worse attempts at abductive reasoning (please note we mean "better and worse" from the expert's perspective), and compare these findings to Schoenfeld's seminal work on metacognition during novice and expert problem solving

Introduction

Makerspaces have become a recent phenomenon that has attracted considerable attention in many places around the world, most notably in parts of Europe and the United States. Based on theories of constructivism and constructionism, learning activities in makerspaces can vary from a computer supported collaborative learning format, through to design studio activities (see, e.g., Martinez & Stager, 2013; Honey & Kanter, 2013; Bevan, Gutwill, Petrich, & Wilkinson, 2015). In the former, recent changes in the availability and accessibility of tools that afford computer aided design, digital fabrication, rapid prototyping, and microprocessor integration have given early constructionist principles a much wider appeal and radically lowered barriers to entry (Dougherty, 2012). For instance, most reasonably funded schools should find little difficulty affording kits containing the Arduino microcontroller and associated electronics that could radically transform the functioning of students' design and technology projects. From passive objects, microcontrollers can imbue interactive intelligence to designed objects, and become part of customised data logging projects with highly advanced functionalities. Importantly, because the hardware and software are open sourced, access to and modification of the design of the devices are open to students; online social portals have gathered plans and designs, ready for others to extend, improvise, and modify.

While access to these devices can afford to its users a radically enhanced instructional affordance that conventional classrooms cannot, nonetheless real barriers exist to effective use of makerspaces as part of school instruction. For one, it can be hard for educators to fit activities in makerspaces into conventional curricula goals for school systems with strong accountability regimes in place. Secondly, while the costs may be low, many schools may find difficulty justifying the purchase of this equipment because of their relative newness and untested nature. Finally, and perhaps most importantly, many educators may find themselves apprehensive at the thought of integrating unfamiliar devices and perhaps even instructional approaches to their pedagogical routine. Indeed, it is probably safe to say that a large part of the educative gains that may be accrued from activities in makerspaces have more to do with a reimagined pedagogical approach, than the existence of devices and technologies.

Pedagogical approaches to instruction in makerspace can be based on a problem/challenge based learning approach, a scientific inquiry approach, or a design based approach. In our assessment, and in specific recognition of the context in which we carry out this investigation, we decided to adopt a design based approach. We believe design to be a method for innovation, which has a particular timeliness to the local context where governmental stakeholders are emphasising the economistic imperative of innovativeness. Beyond that, seeking to avoid an industrial, deskilled production line form of making, we also believe and argue for the importance of a craft-like appreciation for materials and tools, in the service of the development of students' design intentions. Wanting to move away from preparing students for a life of consumerism, it is important for them to firstly demystify sophisticated technologies essentially indistinguishable from magic (after an aphorism attributed to Isaac Asimov), and then to be empowered to produce technological devices of their making. A core reasoning approach central to design, and, as it occurs, scientific inquiry, is that of abductive reasoning.

Abductive reasoning

The mode of reasoning undergirding design, and by extension, innovation and other creative practices, is that of abduction (Kolko, 2010; Takeda, 1993; Tomiyama, Takeda, Yoshioka, & Shimomura, 2003). Here, abduction is distinguished from deduction and induction as follows: in deductive reasoning, we start with a rule (e.g. *all chalks are white*), we notice a case (*this is chalk*), and then we have our result (*this chalk must be white*). Conversely, for induction, we begin with a case (*this is chalk*), note the results of investigation of this case (*this chalk is white*), and can then infer a rule (*all chalks must be white*). Abduction is the unusual mode of inference, in that it starts with a result (*this is white*), followed by a rule (*all chalks are white*), and infer a property of the case (*this is chalk*). Notice that abductive reasoning is distinct from deduction in that while deduction provides for *necessarily* true inferences, abduction does not.

In most learning carried out in school, a typical approach to reasoning would involve teachers as epistemic authority presenting cases, truth claims to be accepted on the authority of the teacher or her trusted sources, from which students are supposed to obtain the inductive inference of abstract knowledge claims. For instance, in the natural sciences, during lectures (and more rarely, in demonstrations), teachers point out interesting phenomena, from which general scientific principles are introduced. Conversely, in exercises, students are supposed to deductively apply these principles in contexts which increase in apparent dissimilarity from the contexts of its acquisition. The fact that we are able to send off space probes to the outer reaches of the solar system and beyond, and gain useful knowledge from such ventures is amazing evidence for the stability of the natural universe and our ability to understand it through these reasoning processes. It may be tempting to believe then, that because scientific and technological knowledge appears to grow via inductive accretion of 'facts' and deductive application of principles into new contexts, that these reasoning strategies are most important to communicate to students. This, however, is likely to be wrong, as it confuses the logic of reporting with the logic of discovery.

Essentially, recent studies into the practice of scientists reveal an approach which may better characterize the scientific method, *as practiced*, as being more designerly in nature than the classical inductive "scientific method" that we usually introduce to students. For instance, Robert Milikan proposed evidence for the quantization of the electronic charge, after measuring the values of the charges of oil drops suspended in an experimental container. In contrast to Felix Ehrenhaft, who pursued a more classical approach, Milikan was ultimately found to have discarded data points that did not fit in with his initial hypothesis (Niaz, 2003). While on the one hand appearing very closely to resemble scientific misconduct, Milikan was eventually cleared of any wrongdoing, and his findings are widely reported in scientific textbooks without attention to any hint of the controversy. Finally, we should all be familiar at least with the methods of Albert Einstein, who famously performed thought experiments based purely on conjectures taken to their logical end. While what is less often recognized is that Einstein's thought experiments emerged from the material reality of his everyday experience (e.g., trains and timeclocks, see Galison, 2003; Nathan, 2012), the point here is that Einstein did not have near-light speed phenomena to inductively generate relationships with. Collectively, a different image of the practice of science emerges: as an imaginative and creative activity, rooted in *but not chained by* one's lived experience. The logic of discovery has been widely mischaracterized. Instead of being inductive, scientific knowledge, *as practiced*, grows via an abductive inference process, whereby scientists abduce what could be the case, and then proceed to investigate the implications of these suppositions. Educationally, with recent attention to authentic scientific inquiry, science educators would do better to structure experiences that offer more opportunities to explore this form of reasoning. A possible justification for making and makerspaces as an activity for science instruction may lie, not in the way it shows 'real life application' of scientific concepts, but in the opportunities it confers for students to practice abductive reasoning.

It is in this nature of the problem solving approach that the design and innovation shares with innovation in scientific knowledge. Abductive reasoning takes place in all practice-based disciplines, most obviously in Detection, Diagnosis, and Divination (Shank, 1991, 2008) . For a very clear instance, when one presents oneself to a physician with an apparent illness, the physician takes in the symptoms (result), considers the known medical knowledge regarding symptoms and illnesses (rule), and then issues a diagnosis (case) of the condition that ails one. What is pertinent is that the amount of experience that the practitioner possesses helps determine the accuracy of the diagnosis; certainly that is one reason why tend to trust more senior physicians to medical students. As with abductive reasoning in general, a general epistemic risk exists—one can never be completely certain if the diagnosis is accurate. Finally, the only way in which one becomes more adept at abductive reasoning, is in the practice of abductive reasoning; textbook knowledge and abstract preparation will not necessarily help the pre-service teacher (say) in deciding instructional strategy when suddenly thrust into a class and school context that does not present itself in ways resembling the rules that one can be intellectually prepared for.

Indeed, we return to the observation that much of practitioners' significant knowledge is tacit, anti-intellectual knowledge-how, and a longing for algorithmic if-then rules can only provide a crutch when the inevitable case of non-conformity to known rules emerge. Practitioners need to know which risks can be taken, and which ought not to, in dynamic contexts which do not necessarily resemble textbook cases (see, e.g. Clandinin, 2013; Popkewitz, Wu, & Martins, 2015). This is not to say that formal knowledge is not necessary—we of course demand that our doctors and educators know what they are talking about when they do their jobs. Nonetheless, the argument here is in support of practical knowledge, acquired through practice, not merely as a means to improve student outcomes in design and more practical/manual/menial professions, but also to better ensure higher quality outcomes for people involved in, for instance, academic research or perhaps even computer application development, traditionally perceived as purely abstract work. The curriculum argument here is for a better appreciation of abduction as a reasoning practice that is far more common than realised, but is seldom formally recognised as such.

The Study

This study was conducted in the social context of Singapore, within a high performance school system where there is a high degree of adherence to a centrally mandated curriculum via high stakes accountability and tracking measures at Grades 6, 10, and 12. Under such a tightly controlled schooling system, makerspaces, touting transdisciplinary learning presents a compartmentalisation challenge to most teachers and administrators—they did not know which subject ought to handle it. Of the schools we managed to get access to, none had dedicated makerspace facilities, on account that few administrators saw the value of such a space. However, we were able to gain access to an art teacher who had, through her own initiative, transformed her art classroom to become a makerspace, given the curriculum constraints and a lack of extensive budget for large ticket items such as digital fabrication machines. When we visited, this was indeed the case, her instruction was marked by a high degree of student choice and autonomy over the projects that they could attempt, the design prompt for the students was made deliberately vague enough to accept a wide range of responses, and the students had a large choice of materials and methods with which to achieve their intended goals. Specifically, students were tasked to design and build an artefact which depicted an experience of being a

Michael Tan
michael.tan@nie.edu.sg

Singaporean, and they were assigned, in addition to any kind of recycled material they wanted to bring to class, magnetically connectible electronics components (littleBits) (a trademark), and a collection of craft materials featuring interesting shapes, textures, and colours. This was a grade eight class in a selective, high academic achievement all-boys school, without a formal program in design and technology.

In order to get a better understanding of the learning processes that were taking place in this classroom, we decided to organise student pairs to work in time limited design problem solving challenges, and to video record their work and talk as they worked through their solutions. We report here on a study conducted with six pairs of students assigned to an idealised rapid design problem solving task. The design prompt was "Within an hour, design and make a device that could signal your teacher's attention during class group work session". The students were offered a small plastic toolbox, filled with 14 pieces of littleBits, two A3 sized pieces of foam core cardboard, 10 wooden skewers, a box cutter, a steel rule, a cutting mat, a hot melt glue gun, and some paper and pencil to sketch their draft ideas on. littleBits is a system of magnetically connectable electronics components which allows students to quickly snap together electrical and electronic circuits with little consideration as to the polarity and other electrical constraints. They come in color coded modules, with the different colors representing its function as either: power supply, power/signal wire, signal input, and device output. The magnets and physical module interface ensure power, signal, and ground connections were correctly connected. Signal inputs came in the form of human adjustable modules (buttons, potentiometers), to other sensors which could receive input from physical events, such as touch, sound, and light signals. Output modules included motors, lights, and speakers. Some typical modules are shown below:

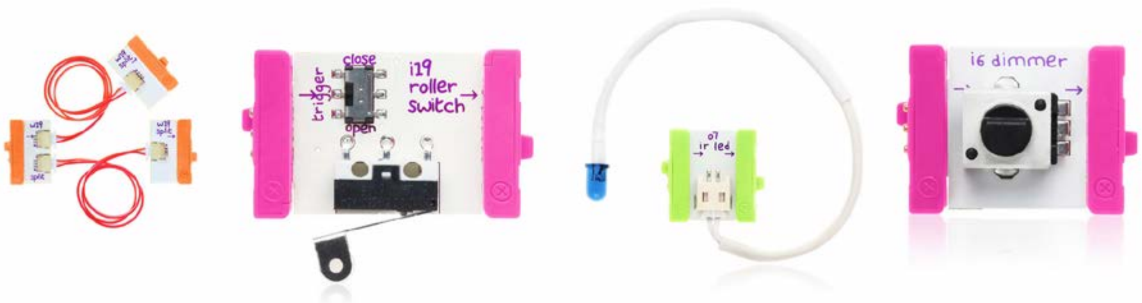

Figure 1. Example littleBits modules. Each 'bit' is approximately 3 cm wide, and coloured connectors are 2 cm high

As can be imagined, the combinatorial possibilities for connecting different modules offer a fairly wide solution space from which candidate designs may derive from. When the flexibility of cutting and joining the other materials is added, the solution search space offered to students was wide indeed. As a means to constrain the design outcomes between our participants (so as to aid comparison and analysis), we chose a subset of all available modules, using modules that students had familiarity with; we offered student pairs modules as shown in Table 1.

While we initially considered a stimulated recall activity as a means to get single participants to recount their intentions as they proceeded in the design task, we eventually decided to get students in pairs so that their talk events in handling the mutual coordination of design intention could be made explicit. The task was briefly explained to the students and 2 volunteers were recruited per class at each available session. Student talk and action was recorded by a pair of cameras, one in front, and another behind and above the shoulders, so that there were no blind spots. Students were suggested to spend the first half hour planning their design solution, and the next half hour implementing it. Because we were actually interested in the role tinkering played in their design problem solving approach, we did not actively restrict their planning phase activity, and in fact suggested that they could 'play around' with the materials as they liked.

Table 1
List of littleBits™ modules provided for teams

Power	**Input**	**Output**	**Wire**
Power (x2)	Slide dimmer	DC motor (x2)	Fork wires (x2)
9V battery (x2)	Light sensor	Servo motor	
	Button	Buzzer	
	Pressure sensor	Long LED	
	Pulse generator		

Through a 14 week course (of one hour long sessions weekly), students were provided a design prompt to plan and make an interactive art object which represented a cultural expression, introduced to littleBits and Makey Makey as technological tools with which to create their objects. Throughout the course, the teacher, Alice (all names pseudonyms), prioritized general, just-in-time information as to the operation of the electronic components over specific instructions for construction. Alice made frequent exhortations in class of the importance of innovativeness, and provided a classroom context in which creative dispositions could be nurtured. In response to local schooling norms where students had little agency in their classroom activities, she deliberately instituted a rule concerning use of materials and tools, that "if you ask me whether you can use something, the answer will be no." Instructions like these seemed to set up paradoxical frames, which have been known to contribute to creative mindsets (Miron-Spektor, Gino, & Argote, 2011; Amabile & Pillemer, 2012). Video data were analyzed using Transana 3.0. Through joint viewing sessions within the research team, pertinent episodes were identified where phenomena of interest were indexed and placed into broad categories of activity which we could identify as part of their reasoning processes. Through a competitive cross validation process, we inductively generated theoretically distinct categories which could maximally discriminate across activity segments of video.

As comparison, we wanted to investigate how expert pairs would approach this same problem. We approached 3 adult pairs of designers and engineers, who served as community coaches at a local makerspace. They were tasked with the identical challenge and data collection protocols.

Analysis

We made use of the perspective of embodied cognition to make sense of their actions and gestures. With embodied cognition, philosophers and researchers posit the hypothesis of cognitive externalisation, that is, that the world is its own best representation (Clark, 2008; Noe, 2009); and that certain actions need to be considered as epistemic if, as a consequence of the action, we obtain more reliable information about reality (Kirsh & Maglio, 1994). Hence, as Clark and Chalmers (1998) argue that a notebook should be considered part of the cognitive apparatus of one's memory, so we look for particular artefacts and body-based actions that contribute to creative problem solving. Specifically, considering the insight and divergent idea generation phase of design, we proposed that certain actions and ways of ordering the immediate environment around oneself can serve a cognitive function to provide insight into problems, just as trajector-based cultural practices (Hutchins, 2014) reduce the cognitive load for embedding meaning by seeing the world in a particular way. We therefore set out to characterise actions taken by students as they 'tinkered' their way to solving a design prompt. In this regard, we began to code, most broadly, participants' speech and action. Of all the codes categories we generated, the ones pertinent to this presentation are shown below:

For speech:

Ideating: Participants talk about diverse possibilities of solution to the design problem. This talk falls into two subcategories:

- Bottom up: Participants talk about the affordances of individual components and materials that may provide possible means to solve the problem; however, there may not be any supposition to integrate these affordances into a system. e.g. "Look at this buzzer, I think we can use this to make a loud noise."
- Top down: Participants talk about higher level functions, about explicit means to solve the problem. e.g. "I think we should have a means to make a loud noise to attract attention so that it can be noticed even when the teacher is not looking in the students' direction."

For actions:

Tinkering: In tinkering, participants are exploring, there is no clearly defined large scale problem that the actions are directed towards solving. Tinkering is further divided into the following subcategories:

- Bottom up: Participants appear fairly undirected in almost random attempts to connect components and materials together to create a structure that is larger than a single component. Similar to ideating, participants appear to be exploring the physical affordances of materials and tools without an attempt to fit the objects into an overarching plan. There appears to be a **global impasse**, participants do not appear to have a plan of how to proceed.
- Top down: Participants appear fairly directed in material explorations. Usually, a problem has been identified, but because there is a **local impasse**, participants are at a loss of how to proceed. Top down tinkering is a localised exploration to discern solutions to a part of the problem.

We made use of a consensual assessment technique to make ratings of the creative outcomes of the students' work sessions. At the time of writing, this work is still in progress, and thus ratings have only been assessed by the research team. In order to get a quantitative sense of the distribution of coded segments, we counted the amount of time student pairs spent performing the coded speech and actions, as a percentage of the total time spent on task.

Results

We noticed a trend towards an increase in student creative outcomes with an increase in the ratio of segments coded top down (TD) against bottom up (BU). On the other hand, an excessively high ratio of TD : BU also resulted in poor creative outcomes. For the five student pairs that we collected data from, their results are tabulated as follows:

Table 2
Creative outcomes against (top down : bottom up) ratio. A larger value meant we observed pairs spending more time in top down speech and action categories.

Outcome:	best				worst
TD : BU ratio	12	3.6	2.3	31 (no error)	2.1

Michael Tan
michael.tan@nie.edu.sg

Table 3
Creative outcomes for expert adult groups.

Outcome:	best	———	worst
TD : BU ratio	18.3	2.4	1.9

The best performing student group proposed and created a prototype of a system that had a display panel that could be placed on a wall, with lights arranged according to seating pattern in the classroom (Fig. 2). Students were supposed to activate the system by pressing a button on their desks, which activated an LED indicator on the panel, and another on their desks. Teachers would then be able to refer to either of the panel or the desk LEDs to come to the aid of the student requiring assistance. While the materials provided did not allow for a full scale implementation of their ideas, we nonetheless awarded this project the highest rating as it precisely was not constrained by a lack of materials. This project made good use of the foam core board, cutting and shaping the board deliberately into a fairly complicated shape that exhibited competence with material processing, and well developed ideas.

Conversely, the poorest performing student group prepared a simple device where a single switch simultaneously activated a buzzer, a pair of LEDs, and a servo motor that was connected to a flag (Fig. 3). This device was to be placed next to students. The quality of the artefact was fairly low, with little use of the foam core board except as a base for which the flag pole was attached via a liberal lump of hot glue.

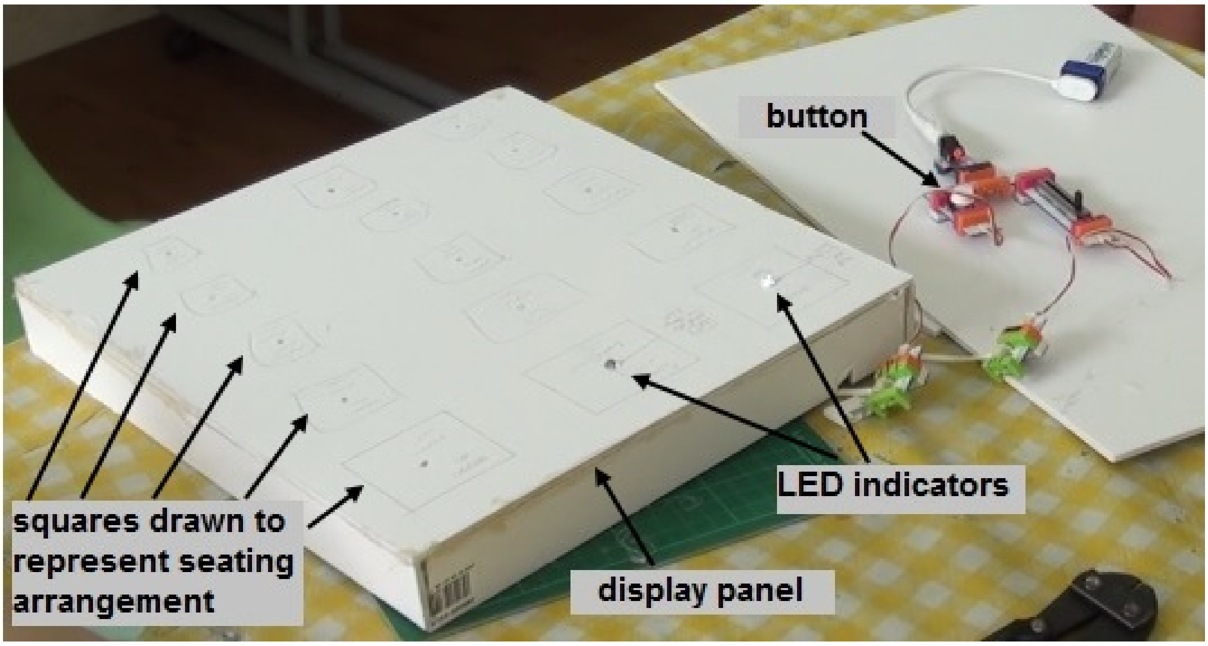

Figure 2. Best outcome, student group. We judged this design to be the best outcome as it was a system that was closest to being a practicable system for use in actual classrooms.

Michael Tan
michael.tan@nie.edu.sg

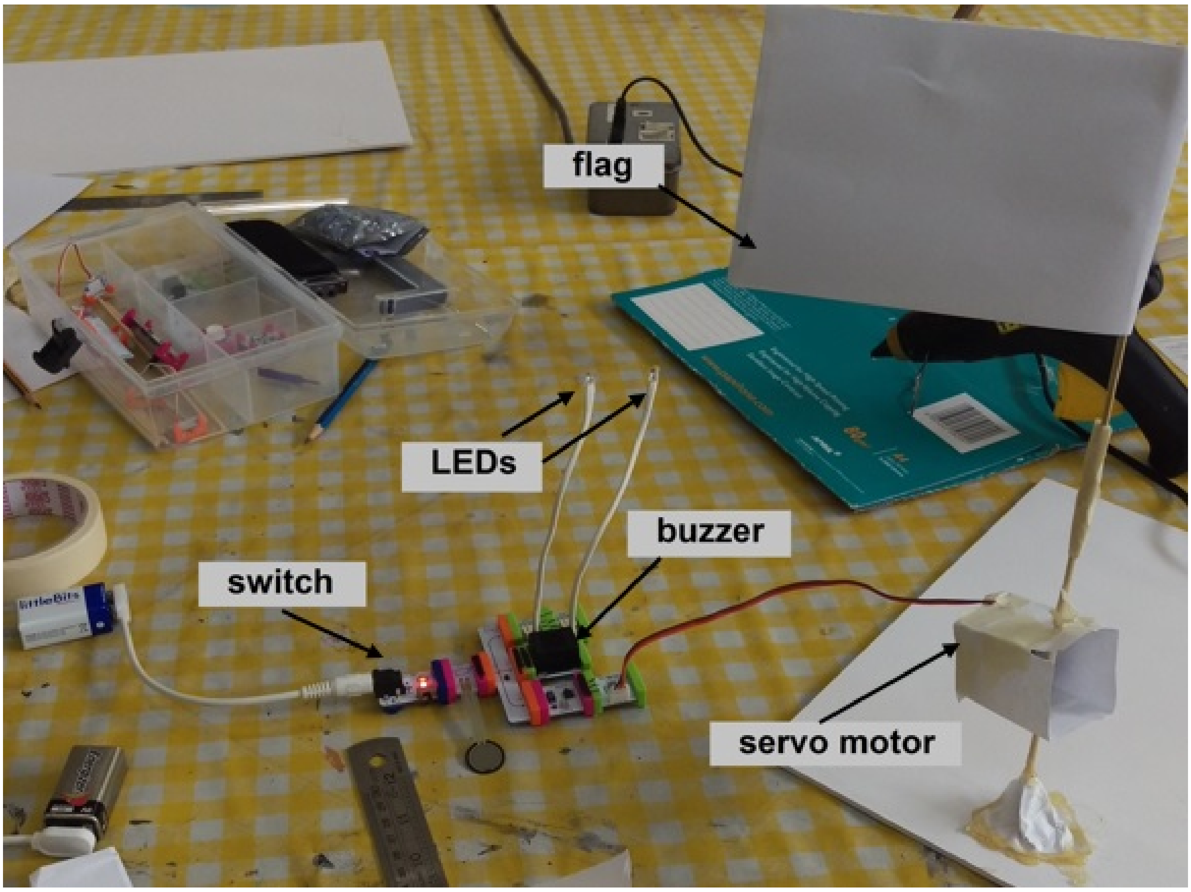

Figure 3. Poorest performing outcome, student group. A single switch activates all three devices (light, sound, motor) simultaneously.

As for the adult pairs, the best performing group designed a system consisting of a paper sign decorated with a 'HELP' message, a pair of LEDs that was activated by darkness, and a buzzer that was supposed to be directed by a bullhorn type enclosure so as to channel the sound only towards the teacher and not disturb the students' neighbours (Fig. 4). The quality of the construction was high, as expected with their extensive experience in working with materials, and designing solutions to problems.

The poorest performing adult pair prepared a rotating sign turned by a servo motor, with an LED attached to the sign and another on the desk (Fig. 5). An optional buzzer gave the users of their design an escalating system of alarms to attract their teacher's' attention. Although poorest among the adult pairs, this group nonetheless did significantly better than any of the student pairs in terms of their material handling skills. In analysis of their talk and actions, it was interesting to note some of the characteristics of the best and worst performing pairs. In the following sections, we develop more detailed descriptions of the problem solving trajectories.

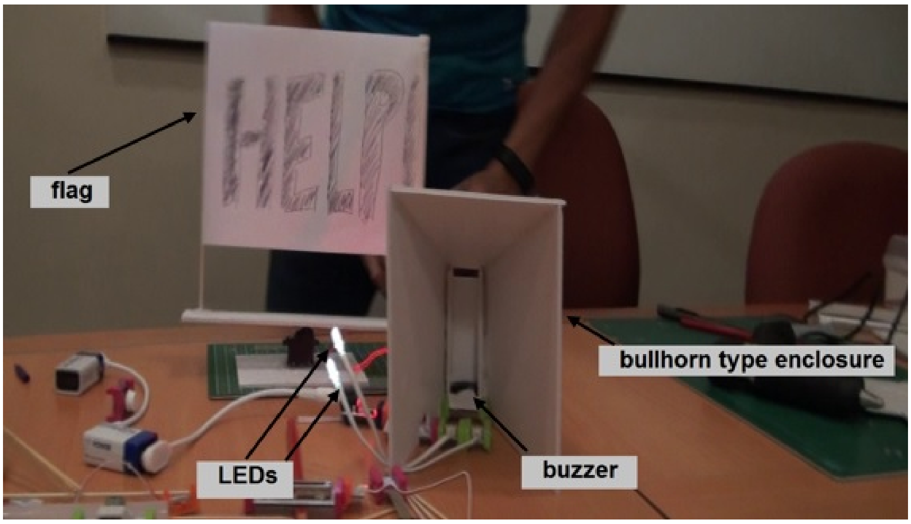

Figure 4. Best outcome, adult group.

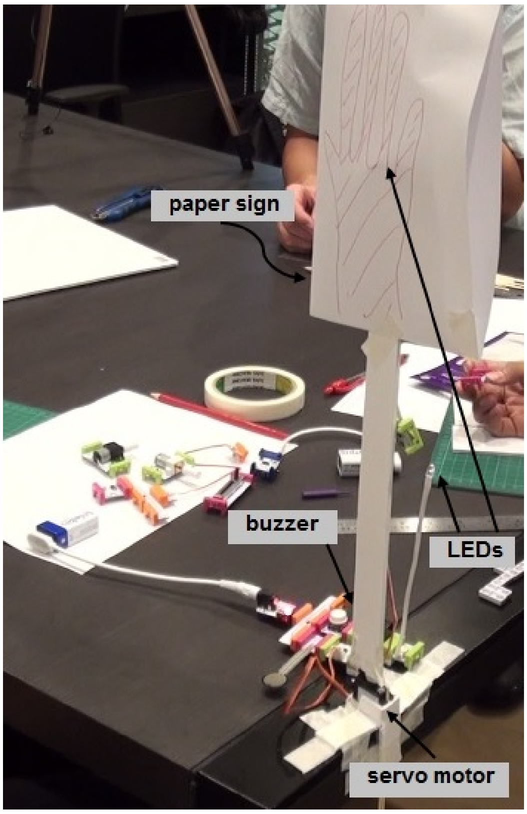

Figure 5. Lowest performing outcome, adult group.

Lower performing groups

Generally, for students and adults, their approach to problem solving seemed to be marked by a tendency to be overwhelmed by the combinatorial possibilities offered by the electrical componentry. This is not to say that they did not have segments of top down ideation or tinkering, but rather, that their approach was more strongly marked by a bottom up experimental approach. They would primarily tinker with the parts, without communicating with each other about their intentions, and then pause at intermediate 'resting' position on their problem solving routine, where one of them may be satisfied that the configuration resembled something useful. Then they would talk about how they could use their creations to serve a particular function, at which point some disagreement may ensue. These disagreements were resolved as time progressed, as they both had a clearer joint 'picture' of how each of their suggestions could be integrated into a holistic design.

Michael Tan
michael.tan@nie.edu.sg

It would appear that disagreements between the pairs played a significant role in hampering progress in problem solving. In some ways, this should be fairly obvious; as a lack of communication and a clear sense of direction may lead to two individuals solving different problems. For instance, the third placed student pair had a consistent pattern of one student offering an idea (Student B below), while the other (Student A) kept critically dismissing the idea:

Student A: what can we do?
Student B: [picks up servo motor and begins to insert a bamboo skewer into holes in its arm] or…?
[Student B continues to insert more skewers into the motor to demonstrate his idea, while A watches]
Student A: So you want this to be hanging around at each persons' table?
Student B: Not each persons'
Student A: then?
Student B: this wouldn't work
Student A: No, it's not going to work [student A reaches out and pulls the skewers from the device, and then puts the skewers away from student B]

The poorest performing adult team also had a similar lack of communicative fluency; at the beginning of the task, Adult A would make bids for Adult B's feedback, which were not often responded to as Adult B was more interested in exploring the components by himself.

While this rather negative communication approach may seem like an obvious hindrance to the creative process, it seemed that the problem solving approach chosen by the teams contributed more significantly to their performance. The medium performing group had a very serious communicative difficulty, which was revealed mid challenge as they having misunderstood the instructions as being a competitive contest rather than a cooperative venture. Even when corrected, they did not appear to communicate very well, as Adult C maintained a designer role, assigning discrete engineering challenges to Adult D, roles that they were used to playing in their professional careers. Nonetheless, they did spend relatively more time than Adults A and B in thinking about how their design could address the design problem. In contrast, the worst performing student pair spent a total of 53 seconds after the challenge was issued discussing possibilities for a design, or brainstorming possible definitions of the problem, before heading off to tinker with the components. It was *after* they managed to create a circuit or physical part that they then had the discussion of how they thought the circuit or part could be used for some purpose relevant to the problem.

High performing groups

The highest performing group was the third adult pair, Adults E and F. As to be expected, their interaction was marked by a high degree of useful communication. They spent a long time in humour-filled banter, generating ideas which were borderline outrageous (for instance, a most escalated level of alerting the teacher using a bow to shoot pointed skewers), followed by rapid prototyping sessions where an agreed upon idea was tested, or both decided to test two ideas concurrently. Interestingly, Adults E and F did not make use of extensive sketches to represent their ideas, preferring instead to make use of the materials and mimed actions to express their ideas. As this pair had extensive material handling experience, they were able to make objects to a high degree of finish.

Similarly, while the highest performing student group did not appear to spend a significant amount of their time in purely verbal brainstorming and considering the problem in detail before tinkering with materials, they were engaged in cycles of idea generation, testing, and refinement, all the while apparently 'thinking with their hands' (Kelley and Kelley, 2013): changing their ideas mid-speech as the artefact revealed affordances not initially presupposed, and conversely reconfiguring artefact as they changed their minds about things. For instance:

Student C: I don't think.. that the light is going to attract her attention, so, um..
Student D: wait, let me think [picks up buzzer] is this sound?
Student C: Is this sound? But sound will add to the noise, 'cos it's sound.
Student D: But yeah, here's a unique sound that she will not have heard it before. [connects buzzer to

active circuit, turning on the fairly loud buzzer]
Student C: very unique
Student D: [laughs]

The pair keeps the buzzer as part of the draft circuit that they work on, but ultimately abandon it when they came up with another plan about three minutes later, in the process of which they actually scrap the current draft and restart afresh. While sketches can serve as temporary placeholders for ideas, expanding the working memory and helping the generation of ideas, it appeared that the groups that did better used the materials as effective representations of itself, referring to the objects and pointing to where improvements can be made.

Interpreting Results

In making sense of our results, we found it useful to draw parallels between our observations and Alan Schoenfeld's seminal work on metacognition (1987, 1992). In his novice-expert studies of problem solving, Schoenfeld noticed that, when US students attempt to solve *non-routine* problems, the majority (~60%) take the approach of "read, make a decision quickly, and pursue that direction come hell or high water" (1992, p. 61). As Schoenfeld describes,

> The students read the problem, made a conjecture… and got bogged down in the calculation. They were still enmeshed in those calculations 20 minutes later… At that point, I… asked them how knowing [the calculation] would help them solve the original problem. They couldn't tell me. The students had spent twenty minutes on a wild goose chase. They had ample opportunity to stop during that time and ask themselves "Is this getting us anywhere? Should we try something else?" but they didn't. And as long as they didn't, they were guaranteed not to solve the problem. (pp. 192-193)

In contrast to novices, typified by the above example, the expert mathematicians Schoenfeld interviewed "generated enough potential wild geese chases to keep dozens of problem solvers busy" (p. 194). Yet the experts "ruthlessly" tested and rejected ideas they generated, thus never getting lost in the goose chase.

Schoenfeld (1992) used these and similar findings to argue content knowledge alone does not capture the difference in results observed from novices and experts. Rather, what mattered was how the problem solver used what they knew, that is, their metacognition--awareness and regulation of one's own cognition. Much of Schoenfeld's work on problem solving centers on the argument that metacognition can be taught and learned, not unlike typical mathematical content.

Similar to Schoenfeld's (1987) novices, the lower-performing dyads in our study tended to "get stuck" on what was immediately before them (heavily bottom-up), while higher-performing dyads generated multiple possibilities (more top-down). Notably, the one outlier dyad (see Table 2) generated multiple ideas but did little to interrogate them, building models part way, and immediately seeing potential for another purpose which they could be directed towards. We connect these observations ultimately to the creative risk taking involved in solving practical problems, the reasoning process underwritten by abductive reasoning.

In these limited trials, we confirm what must be an intuitive hypothesis: that it is better to use an abductive reasoning strategy of proposing a 'best guess' hypothesis, and then attempt to verify the hypothesis against material reality. It may also be worth noting that, in contrast to Schoenfeld's novices, our students always worked dyadically, meaning that the intra-personal metacognitive regulation could be done inter-personally. This cooperative component is typical of makerspace activity, and we shall return to this observation in the following section.

Discussion

This work is part of a larger study into the learning that occurs in makerspace activity in schools, and needs to be taken as an intermediate report of a work in progress. These results are certainly not conclusive, but suggestive of further avenues for research. While it may be the case that makerspaces can accommodate a wide range of activities, from instructional activity where students learn how to use various techniques and technologies, to multi-month problem solving projects, the activity that we had these participants undertake probably represents a typical middle-high challenge that may be used in a typical school context.

We see here a possible curriculum argument for the inclusion of makerspaces in more mainstream schools: if we want learners to become more innovative, to be able to creatively produce solutions to problems they have not encountered before, the makerspace context becomes a singularly useful one to practice the abductive reasoning process. As we noted at the end of the last section, what an individual must do intrapersonally, the dyad can achieve interpersonally. As Alan Schoefeld noted, metacognitive processes can be internalized (1992), and we offer that makerspaces provide a workspace where this internalization may occur. Indeed, the material nature of makerspace work means that various otherwise-invisible elements of thinking are made salient to the participants. Given Schoenfeld’s argument that metacognition in mathematical understanding can be nurtured, it only stands to reason that a similar skill can be developed for general abductive reasoning, which we ought to extend more generally to a wide range of creative activities.

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