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Collaborative Learning in Problem Solving: A Case Study in Metacognitive Learning

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Abstract
Problem solving and collaborative communication are among the key 21st century skills educators want students to develop. This paper presents results from a study of the collaborative work patterns of 133 participants from a university level course designed to develop transferable problem-solving skills. Most of the class time in this course was spent on actually solving puzzles, with minimal direct instruction; students were allowed to work either independently or in small groups of two or more, as they preferred, and to move back and forth between these two modalities as they wished. A distinctive student-driven pattern blending collaborative and independent endeavour was observed, consistently over four course offerings in four years. We discuss a number of factors which appear to be related to this variable pattern of independent and collaborative enterprise, including the thinking and learning styles of the individuals, the preference of the individuals, the types of problems being worked on, and the stage in a given problem at which students were working. We also consider implications of these factors for the teaching of problem solving, arguing that the development of collaborative problem solving abilities is an important metacognitive skill.

La résolution des problèmes et la communication collaborative sont parmi les compétences clés que les éducateurs du XXIe siècle veulent que leurs étudiants acquièrent. Cet article présente les résultats d'une étude menée sur les modèles de travail collaboratif de 133 participants d'un cours universitaire conçu pour développer des compétences en matière de résolution des problèmes. La plupart des activités de classe de ce cours ont été consacrées à résoudre réellement des casse-tête avec un minimum de directives; les étudiants avaient la permission de travailler soit indépendamment soit en petits groupes de deux ou plus, selon leur préférence, et de passer de l'une à l'autre de ces modalités, comme ils voulaient. On a observé un modèle distinct dirigé par les étudiants eux-mêmes qui était un mélange de travail collaboratif et de travail indépendant, et ce dans quatre cours séparés offerts en quatre ans. Nous discutons un certain nombre de facteurs qui semblent être liés à ce modèle variable d'entreprise indépendante et collaborative, y compris les styles de réflexion et d'apprentissage des individus, les préférences des individus, les types de problèmes sur lesquels les étudiants ont travaillé et l'étape, lors de la résolution d'un problème donné, où les étudiants travaillaient. Nous prenons également en considération les implications de ces facteurs pour l'enseignement de la résolution de problèmes et nous discutons le fait que le développement de compétences pour la résolution de problèmes en collaboration est une compétence métacognitive importante.

Keywords
collaborative learning, problem solving, metacognitive learning

The core 21st century skills set out by Kay (2010) consist of problem solving and critical thinking, creativity and innovation, and collaboration and communication. These skills are clearly interrelated in a variety of ways, and the development of problem-solving skills especially is often tackled through collaborative approaches. There are a variety of such pedagogical approaches, including group work and brainstorming, collaborative and co-operative work, and inquiry-based and problem-based learning (Brears, MacIntyre, & O'Sullivan, 2010; Campisi & Finn, 2011; Edens, 2000; Madhuri, Kantamreddi, & Prakash Goteti, 2012); these educational strategies are often driven by an emphasis on providing students with the skills and attributes to become "self-determined" and "highly autonomous" life-long learners (Blaschke, 2012, p. 56).

Collaborative work refers broadly to work that students do together, to explore a solution to a problem or to prepare a project, and may refer to a variety of strategies in which students interact with each other (Osman, Duffy, Chang, & Lee, 2011). Such work can be accomplished either inside or outside the classroom, and can be graded or not. At its most basic level, group work outside of class time can mean simply a piece-meal approach, where students divide up the tasks for a project, each do a section, and then combine the results into a finished project. This approach invokes little in the way of problem-solving, collaboration or communication skills, and many students seem to dislike this type of group work because of difficulties in scheduling and the unreliability of team members. Cooperative work can be defined as a form of collaborative learning, having the following characteristics: tasks assigned are clear and straightforward to do; students must depend on one another to complete the task; the instructor acts as a guide or mediator, but without giving constant assistance; and students are ultimately responsible for working together and accomplishing a collective goal (Slavin, 1990; Willis, 2007). The use of teams or groups in such settings can provide a safe atmosphere in which students can take risks, become engaged learners and act as teachers in that they help others learn. Bruffee (1984, 1993) speaks eloquently of the use of peer-tutors, in the context of knowledge as socially constructed through conversation rather than transmitted from teacher-expert to students. Another type of collaborative learning frequently used at the post-secondary level of education is problem-based learning (Savery, 2006), which also asks students to tackle large, usually open-ended problems, often in a specific content-area or discipline such as medicine or business. Nevertheless, implementing collaborative learning strategies in the classroom does not appear to necessarily ensure either student engagement or achievement of learning objectives (Summers & Volet, 2010).

Problem solving generally involves a mix of both linear and creative styles of thinking (Polya, 1945). On the creative side, brainstorming is often seen as a desirable method for individuals to work together. As formulated by Osborn (1963) the idea of brainstorming is for a group of people to generate a large quantity of ideas or possible solutions, without judging or critiquing them at the time. Despite the popularity of this approach ever since, however, researchers such as Diehl and Stroebe (1987) have shown that brainstorming groups actually produce fewer ideas than individuals working alone.

Our study examines the role of ad hoc student collaborative endeavour in the development of individual problem-solving skills, at the post-secondary level. In this context, we use the term "collaborative learning" loosely to imply ad hoc, informal and interdependent student-to-student interactions in which the individuals work together as

necessary so that each may acquire individual (as opposed to collective) skill or knowledge. We suggest that students, in this context, move fluidly (and perhaps sub-consciously) between "independent" and "interdependent" endeavour as best meets their individual learning needs, and that knowing how and when to do so is an important metacognitive skill. Our participants were students taking a university-level course designed to foster development of problem-solving skills across a broad spectrum of areas. *Problems and Puzzles*, offered through the Liberal Education Program and taken by students either for interest or to fulfill a science liberal education requirement, was designed to develop general and transferable problem-solving and critical-thinking skills, beyond disciplinary borders, through the study of puzzles. Course topics included the history of problem solving and examples of classic and historical puzzles; various problem-solving techniques, including how to write and solve equations; logical reasoning methods; connection to "real-life" problems; and metacognition and cognitive psychology as key aspects of problem solving. The puzzles and problems used included logic puzzles, equational puzzles, and lateral thinking or creative puzzles (see the Appendix for examples). In general, the puzzles challenged students to read new information carefully, identify relevant information, organize their thinking, make deductions and describe their conclusions.

The course met for 39 classes over a thirteen-week semester. Lecturing was minimal, and at least two-thirds of every class period was spent in active work on puzzles. Students were encouraged to construct their own understanding of and solutions to problems, and to share them with fellow students and instructors. In this way, the teachers of the course served as facilitators and collaborators and not as experts, and a community of inquiry (Vaughan, 2010) was created in which the teachers and students all learned from each other (Wismath, 2013).

Metacognition is identified as an important problem-solving and critical thinking attribute (Flavell, 1979, 1987; Schoenfeld, 1992; Scruggs, 1985; van Gelder, 2005) and thus was a significant theme throughout the course. Usually loosely described as "thinking about thinking" (Flavell, 1979), metacognition includes knowledge about strategies for learning and problem solving, as well as knowledge of different thinking and learning styles and their strengths and weaknesses, both in general and with respect to one's own abilities (Lai, 2011; Papaleontiou-Louca, 2008; Sternberg, 1986). It further includes metacognitive regulation via the executive processes of deliberate planning and monitoring of one's thinking during problem solving activity. This overseeing of one's own thinking and activity is considered fundamental to good problem solving skills and to intelligence in general (Schoenfeld, 1992; Sternberg, 1986). Students in the course were introduced to the theory of metacognition, and were also encouraged to carry out metacognitive work, both during class time and in regular course assignments which required them to reflect on their progress and discuss their own thinking and learning.

During class time spent working on puzzles, students in the course were encouraged to work independently or collaboratively in small groups, or to shift back and forth between these modes, as and when they wished. The distinctive pattern of shifts between collaborative and independent enterprise which emerged, apparently influenced by a variety of factors to be discussed below, suggests that optimal collaborative work is highly contextual, and that student perception of such work is complex and nuanced. Our observations intimate that the skills of problem solving, collaboration, and metacognition

are very much intertwined. We argue therefore that learning how and when to work with others can be considered a metacognitive skill, the development of which merits careful study and facilitation.

Method

As part of an on-going research project, we have collected a variety of quantitative and qualitative data during each of the four times this course has been offered between 2010 and 2014. Research ethics approval was obtained from our institution for this on-going study, and efforts were made to ensure appropriate confidentiality and anonymity of participants. Students were informed of the on-going research, were given the choice to participate, were able to opt out at any time, and were assured that the instructor of the course would not know who was participating. Data from each course offering was collected, coded, and analyzed by a research assistant after the course had ended and all grades were submitted. From a total enrolment of 175 students, we have complete data from 133 (n) study participants. The same primary instructor has taught the course each time, with the same teaching team, and similar student demographics each time. Participants came from four different faculties (Arts and Science, Management, Education, and Fine Arts), and represented a variety of disciplinary majors encompassing sciences, social sciences, humanities, arts and management.

The quantitative data we collected consists of the following:

- basic demographic information including age, gender, year of study, major and reason(s) for enrolling in the course;
- the Barsch Learning Style Inventory (Barsch, 1991), in 2010 and 2012, and the VARK Learning Style Inventory (Fleming, 1995; Fleming & Mills, 1987) in 2013 and 2014 administered at the start of the course;
- the Gregorc Thinking Style Inventory (Gregorc, 1979), administered at the start of course; and
- an attitudes and attributes survey (5-point Likert scale) developed by the researchers, administered at both the start and end of the course.

Ad-hoc (informal) in-class participant-observations were conducted by the course instructor, another faculty colleague and a teaching assistant (Mayan, 2009). Reflective discussions arising from these observations provided a lens through which the qualitative data was viewed. Our primary qualitative data consists of a series of guided reflection assignments that were done as part of the course (and graded for completion only). These assignments formed part of the metacognitive emphasis of the course, encouraging students to reflect on their problem solving and their progress, but were also designed to provide data on other aspects we wished to study, such as collaborative work, metacognitive activity and transfer of skills. Since these assignments were already organized to elicit student response to such topics, no specific thematic analysis was done; student responses were thus analyzed to provide summary data.

To ensure that participants could speak freely about their experiences, we also had research assistants not connected in any way with the course or the research conduct two smaller post-course focus-group discussions, in 2012 and 2013, using questions similar to those in the reflection assignments.

In this paper we are reporting on transitions between independent versus interdependent or collaborative work behaviour of students in the course, as observed from self-reported quantitative data as well as in-class observations and participants' oral and written comments. We describe our observation of an apparently fundamental pattern in the manner in which students worked together in the course, and indicate some of the factors we believe affected this pattern. We also describe how the participants themselves viewed the collaborative process, documenting their reported increasing metacognitive awareness of collaboration as a key problem-solving skill.

Results

We have observed a very distinctive pattern of independent and collaborative work during class time. We discuss here the pattern observed, and a number of factors that we believe impacted the choice of how and when to work with others: individual preference, thinking and learning styles, type of puzzle being worked on and changing student perception of the metacognitive goals of the course.

Independent and Collaborative Work Cycles

As noted above, a majority of the time spent in class was devoted to working on puzzles and problems. On rare occasion a two- or multiple-person game or strategy search was assigned which required students to work in pairs or triads, but otherwise students were allowed to work alone or with others, or to shift between these modes, as they wished. Students were told this at the beginning, and seating was usually somewhat flexible to allow small groups to form as desired.

The dominant pattern we observed during class work time was one of cycles between independent and more interdependent or collaborative endeavour. Students generally appeared to begin work on a new problem individually, taking time to read and absorb the puzzle and often to attempt the application of an initial strategy to solve the puzzle. If this did not lead to success, many students appeared to then switch to a mode of attack in which they consulted with others around them, comparing different understandings and approaches. Once this led to new ideas for how to address a problem there seemed generally to be a return to individual independent work, to check out details and push forward to a solution. For some more difficult problems there might be another round of consultation before a successful solution was finally discovered. Ultimately, once students solved a problem, they would often again turn to their peers to "debrief" by comparing solutions and methods.

This cyclic pattern has been observed by the instructors and teaching assistants over four course offerings. The students likewise described this pattern in their reflections, with the following student comment typical of a large number of similar comments:

> I like to spend the start of a problem solo, and then I will shift to collaborative work most likely. It is nice to see how other people would like to solve the problem, and it is helpful to see all of the steps they go through. Once these steps and strategies are established, I then often shift back to solo work. I will then reflect on the question and decide what strategy I am going to use and try it by myself a few times. At the end, I may double check with a partner and compare how we got each other's answers.

We theorize that this cyclic pattern may be related to the four-step process of problem solving, introduced by Polya in his well-known book *How to Solve It* (1945, 1973). Often identified as the seminal work in mathematical problem solving, this book described a general process for solving problems of all types, a process which has been used as the basis of most problem-solving literature since then. Polya's four steps are:

1) Understand the problem, through careful and deep reading;
2) Devise a plan to solve the problem;
3) Carry out the plan;
4) Look back, to reflect on the solution and the process of solving.

This fundamental method of approaching problems was introduced to the students at the very beginning of the *Problems and Puzzles* course, and students were consistently encouraged to apply its precepts to the assigned puzzle-solving tasks. Initially most students concentrated on the second and third steps only, but showed an increasing metacognitive awareness of the first and last step as the course progressed. We argue that the first and third steps of Polya's method tend to be tackled by students individually first, with the second and third stages lending themselves more to discussion with others. The following comments from student reflections, about when and how they worked alone or with others, support this view.

> During class, I initially like to work alone. I need to be alone with my thoughts to fully wrap my head around the problem. Once I understand what the problem is asking, I can try to solve it using my initial instincts. If I repeatedly try and fail to solve a problem, then I like to collaborate. I like hearing how others are approaching the question. It can give me an idea of where I am going wrong and can help me think of the question in a different way. As well, I can ask the other group members how they interpret a particular phrase in a question. I find this very useful.

> I have found that when starting a problem I generally like to be able to think about it and understand it by myself. This allows me to set up some sort of organization or process to give me a basis for how I will go about solving the problem. I usually work on the puzzle or problem by myself first anyways and then in the end I will collaborate with others to compare our final ideas.

> Generally, I like to switch between working with others and figuring out the problem by myself. First off, I like to try and understand what I am looking for on

my own. Or at least try to understand what I do not know and what I need to find. It is good at this stage to try to get to the solution. After this, I like to work with other people and discuss. It is likely that they may have tried a different way of solving, or looked at the problem through a different lens or point of view.

Individual Preference

While the cycles between individual and collaborative work were obvious to both instructor observers and student participants, we posit that a number of factors also impacted how and when students chose to work alone or with others. The first of these factors was the individual student's own preference for how to work. Many of the students reported beginning the course with definite individual preferences for independent or collaborative work, and interestingly these preferences did not seem to change significantly over the duration of the course. On the attitudes and attributes survey completed at the start (pre-test) and end (post-test) of the course, several items asked students to indicate their attitude towards general solo or joint work. There was no significant change (at an alpha level of 0.05) on SPSS paired *t*-tests, comparing pre- to post-test responses, on the following four survey items:

1) "I like to work alone."
2) "I like to work with others."
3) "I like to 'brainstorm" ideas."
4) "I like to 'talk through' ideas with other people."

Table 1 below shows the results for the first two of these survey items, over the four semester offerings (n = 133). Both questions yielded an average between 3.5 and 4 (where 3 indicates "neutral" and 4 indicates "agree"), with very minor changes from pre- to post-test scores; the variation was positive in some semesters and negative in others, but overall there was no change for the "I like to work alone question" and a very slight though not significant downward shift of -0.06 on "I like to work with others."

Table 1
Pre- to Post-Test Scores on "Alone"/"With-Others" Item

Item	n	Pre-Av.	Post-Av.	Diff.	Pre-SD	Post-SD	P-value
Work Alone	133	3.73	3.73	0.00	0.849	0.962	0.415
Work with Others	133	3.71	3.65	-0.06	0.935	0.962	0.415

Note that these two items on the survey did not ask students to compare their preferences, only to indicate agreement or disagreement with the statements. Our participants were asked on reflection assignments to discuss their attitudes towards

working alone, working with others, or utilizing a combination of these modalities, and in this case were asked if they had a preference. Although the proportions differed slightly each semester, our data overall indicates that approximately 45% of students reported a preference for working alone, about 35% reported a preference for working with others, and about 20% reported a preference for a combination of these modes of endeavour. However, most of those who indicated a strong preference for working alone also acknowledged the benefits of working with others, at different points in the problem-solving process as described above. The following student comment is typical:

> It seems most of the time that I will work by myself and exhaust all options and ideas, and if everything has failed at that point I find it helpful to bounce ideas off my peers and listen to any insight that they have.

Students who reported a preference for working alone most of the time cited the following reasons for occasionally working with others: to obtain help in understanding a problem at the start; to seek help when stuck; to check their work with others; to compare solutions at the end; and to see alternate solutions after solving a problem. These reasons support our view of the stages of independent versus collaborative enterprise at different stages of problem solving.

Students who indicated a personal preference for working alone provided a number of reasons for doing so. These included for many participants a strong sense of competition, a sense of independence and a desire to be the first to solve a problem, along with a great satisfaction and "the joy of discovery" if they could solve a puzzle by themselves. One student wrote about the "comfort and reassurance when I solve it on my own" and another spoke of "the feeling of accomplishment I get from it knowing it was all me." Others talked about being shy and therefore uncomfortable talking to others, or afraid to reveal ignorance, "feeling dumb if others find solutions and I don't." Other factors students described involved group dynamics: group work can get off-topic too easily, can move too quickly for individuals to keep up and can lead to frustration for quieter students if one person dominates. Some people described being easily distracted in groups, finding it hard to keep motivated or focused, and preferring to work at their own pace. This student sums up the feeling of many who prefer to work alone:

> I know that my main reasoning for working alone is because I am a control freak. I like to be in control of situations, and do things my way, so when I work with other people I have a hard time letting them take control of the situation, and the problem solving. I also like to work alone because I like the feeling of knowing that I have accomplished something on my own, and that I was capable of solving the puzzle alone. […] I do not like to work with people who think way different than me, for fear of looking dumb, or incompetent. I would prefer to stick to what I know, and to work with familiar people.

The following two student comments indicate attitudes about the benefits of working with others, particularly for problem solving:

> Ideally though, I would be able to work alone, but still able to confer with fellow students to gain some inspiration, or to see different strategies they are using, and then apply it to my own work. I like to use a system to solving problems, and group members tend to interfere with my process at the time. However I do like groups b/c of the ability to bounce ideas off each other, and to build on them. I guess what I am saying is, I like to process and dissect problems in a group, but the actual solving process I prefer to do myself. […] there is always the ability to reflect with another student, which for me is crucial in learning to solve, and understanding problems.

> Being able to talk out loud and have perspectives from everyone in the group really helps me figure out puzzles better. This is why I really like to work in groups for most things because I am able to get opinions from others and see what kind of strategies they may work with to try and figure out the problem. This helps me take my strategies and sometimes create a better strategy or even reinforce the fact that the strategy I originally had was actually a good thinking plan and that I should continue to use it. When I then take those strategies and work on my own trying to figure the puzzle out, I will typically only go back into group work if I get stuck on anything or believe that I have found the answer and get them to check it out.

These comments from participants suggest an emerging metacognitive awareness of the advantages and disadvantages of their own preference for working independently or with others, and the benefits of modifying one's preference at certain stages of the problem-solving process.

Thinking and Learning Styles

At the start of each semester offering, students were asked to complete thinking and learning style inventories, as described above. These instruments while forming components of our research data were primarily administered to students to provide them with some basic easily understandable information about themselves to "prime" instruction and discussion around the metacognition of problem-solving (Schoenfeld, 1992).

We anticipated that students' thinking and learning styles could potentially affect their preference for working alone or with others. Students who take in information in an auditory way often prefer to talk through their ideas, and might therefore prefer collaboration with others, while strongly Read-Write learners might prefer to work alone. With respect to the Thinking Styles inventory, there may be an expectation for example that AS thinkers prefer to work alone, in a quiet work environment without distractions, while AR thinkers prefer to work in a lively and stimulating environment and like to work with others.

Predominant attributes reported for the participants in our study were relatively evenly distributed across the V, A, R and K learning styles, as well as the AS, AR, and CS thinking style categories, with only a very few students identifying as predominately CR. To test whether these descriptors did correlate with reported "alone" versus "with-

others" preferences, we conducted a linear regression for each of the "I like to work alone" and "I like to work with others" survey items compared to scores on each of the four inventory groupings (V, A, R, K, CS, CR, AS, AR). However, none of these regression tests showed any statistically significant correlation (at alpha = 0.05 level).

Nevertheless, we did find some anecdotal evidence in student reflections that thinking and learning styles perhaps influenced their collaborative behaviour. For example, a Read-Write student indicated feeling that "working in a group tends to move faster than I can contribute; I need to write everything down." Another Read-Write learner wrote: "I need to write things down in order to understand them, so trying to talk through a problem with somebody else would be very difficult; I would probably just end up getting myself very confused."

Many AR students talked about how they worked well in small groups: "We like to feed off each others ideas and that eventually leads to one of us being able to solve the problem. That person then shows the rest of us how to solve and understand the solution." Another group of AR students who frequently worked together described their process as " [we] just kind of blurt things out until someone has a good idea!"

When participants were asked about working with others of the same or different learning or thinking styles than their own, they identified both pros and cons. The two main conclusions seemed to be firstly, that working with a variety of styles helped give different viewpoints and possible solutions, but also was challenging if others in the group did not think the way you did; and secondly, that working with those of similar styles was very comfortable, but often resulted in everyone in the group getting stuck in the same way or direction. The following reflection illustrates this:

> I think the benefits of working with someone with your own style or opposite style is completely unique to the individual. I have experienced pros and cons in working with both. Working with another read/write person will often be a silent experience with short interjections if needed. The work gets done efficiently, however it is still mostly an individual work effort. On the other hand, working with a verbal person allows conversation to get going (that I wouldn't have initiated on my own), so even though I can't do the work on paper as fast as normal or the way I'd prefer to do it, it is a more collaborative experience that introduces ideas I may not have considered myself.

While thinking and learning styles did not prove to be statistically significant in the choice to work with others, the comments from participants again suggest an emerging awareness of when and why one would want to work with others.

Types of Puzzles

Another factor that influenced when students worked alone or with others was the type of problem being worked on. Our participants generally agreed that for simpler problems, it was easiest for them to work alone, but on more complicated problems they were more likely to turn to someone else to consult. Logic and word puzzles were often addressed independently, while open-ended puzzles appeared to require more consultation cycles as described above. This is consistent with our pattern of cycles for

consultation when stuck or to conclude a problem. Math-based puzzles (such as setting up and solving equations) seemed to us to be somewhat polarizing in this regard. Those who reported themselves as being adept at math tended to prefer to work on these types of problems alone, seeing them as routine and straightforward. Students who described themselves as weaker at math, or less confident, preferred to ask others for help right away on mathematical problems.

Metacognitive Awareness

We became increasingly aware, as we planned and delivered this course and gathered input from our student-participants, that the manner in which students worked together appeared to be a very complex mixture of a number of factors. As noted above, nearly half of our participants indicated a preference for working alone in many academic situations. They made clear distinctions between graded and non-graded work, and between in-class and outside-of-class group work. This student reflection captures the typical student response to group work:

> Having to rely on others to do things for me in a group while I do other aspects of the assignment is not enjoyable to me. … [I]n many sorts of assignments, the work sharing is often uneven. […] It can also be hard to focus everyone when gathered and working together. […] As a bit of a control freak, solo work has an appeal because of how you do not have to rely on anyone else's work ethic for your own grade. You can focus and get your project done on your own time and in your own way.

Working with others in our in-class setting did not involve the aspects that students identified as disliking, such as a group grade on a project in which each person completed a section so that each person's grade depended on everyone else's input. The in-class work on problems and puzzles was not directly graded. A portion of the overall course grade was designated for "participation" or "engagement"; this required students to be in class and putting in a full effort to solve problems, but not necessarily to solve them correctly or to participate in class vocally. This distinction focused student and instructor attention on a primary objective of the course: not simply to solve problems, but to develop metacognitive problem-solving skills. One student noted this as the difference between practical or pragmatic problem-solving as it might arise in a real-world setting – solve a problem quickly as it arises and move on without much further thought – and an academic attempt at deep understanding of the skills and mechanisms of problem solving. The same student noted the difference between activity geared towards doing well on a test and activity aimed at deep learning. That is, a distinction can be made between working together and learning together. As we discussed the pedagogical, psychological and metacognitive aspects of problem solving in class and on assignments, students demonstrated an increasing understanding of the learning goals of the course and of the importance of working with others to reach those goals. For example, one student who wrote of "strongly prefer[ing] solo work above group work because I am a perfectionist" went on describe a different attitude to working with others in this course:

> Although I like solo work for school marks, there are academic situations where I do enjoy collaboration. For instance, in Problems and Puzzles, I like working with other people to solve the problems. I think this is because there are so many strategies to use to solve problems; so seeing different ways that people go about them helps me to strengthen my own problem solving skills. I suppose I appreciate group work more when I feel that I am learning and am gaining something from it, as opposed to when I feel that I am the one putting the most work in. […] I enjoy group work when I feel that I can learn from it, but other than that, I prefer solo work.

We hoped that our approach to in-class work, which encouraged students to work together as and when they wished, with a focus on developing their understanding and skills, created a classroom environment in which learning could flourish. Over the course of each semester, students began to see the instructors as facilitators and collaborators rather than experts, and a community of inquiry (Vaughan, 2010) was developed in which students were equal participants. An atmosphere of trust and comfort was developed, based on "high expectations in a low-stress environment" (Freeman & Walsh, 2013, p. 101). Students were encouraged to focus on learning, to take risks and feel uncomfortable, and to make mistakes and learn from them, in an environment where working on the class puzzles offered a "no-pressure" opportunity to take risks.

We conclude this section with a lengthy quote from a student reflection, which we suggest captures the metacognitive awareness students developed regarding working and learning with others, and their increased appreciation for the benefits of doing so:

> When it comes to working on puzzles in class, I almost always prefer group work to solo work. This is very unusual for me, because in other university classes, I prefer to work alone and find group work inconvenient. However, due to the context of this class and the complexity of assigned problems, this generally requires group collaboration. As we have progressed through the course, I find myself appreciating group effort more and more. […]I think I enjoy group work in this class more because it opens your mind to alternate ways of thinking and learning. In a sense, I think it gives people the chance to teach strategies and strengths to one another.
>
> Although I'm surprised by how much I value group work in this course, I am also very pleased that I have found an area of interest where I prefer group work. I think that this transition to enjoying collaboration may be reflected in my later career choices. While I generally prefer to work alone in other classes, I think this may because I am much more confident in my reading and writing skills when compared to my ability to problem-solve. Moreover, in most of my other courses, projects, papers, and assignments that I complete generally have a very structured format and strict criteria to be met. This layout caters to my style of concrete sequential thinking, and so I generally feel comfortably prepared. However, the problems we are presented with in this course do not necessarily allow for a systematic, formatted solution. Such problems take me out of my comfort zone

and may overwhelm or frustrate me. Having a partner or a group helps ground your thoughts and allows for an interconnected web of strategic thinking.

The teamwork that I have performed in this class has had a beneficial impact on how I interact and collaborate with other group work in different courses.

Discussion

Problem-solving courses at the post-secondary level are typically offered within the context of particular disciplines such as engineering, business or medicine, or to develop specific and distinct skills in subjects like mathematics or computer science. The problem-based learning approach (Savery, 2006; Wilkerson & Gijselaers, 1996), which grew out of education for medical students, also tends to focus on student learning in a content area through the use of open-ended problems in that area that students are required to research and address. These approaches generally use problem solving to teach content rather than using content to explicitly teach problem solving skills. The course and study reported on here are novel in that they consider the development of problem-solving skills as a learning outcome in a less content-focused environment, rather than using "problem-based learning" to achieve other content or context specific learning objectives.

The type of collaborative or interdependent learning that we suggest has evolved in this course shares some, but not all, of the characteristics of cooperative learning described by Willis (2007). The tasks used here are not always clear and straightforward, as some puzzles were deliberately open-ended and intentionally lent themselves to multiple approaches. Nor were the students responsible for the learning of others in any formal sense. However, an atmosphere was created in which students engaged in their own learning and were free to share with others, and in which the instructors acted as guides or facilitators but not experts. Increasingly over the duration of each semester, students became aware of the importance of figuring something out on their own and in cooperation with each other, and of both the benefits and drawbacks of working together. They also demonstrated clear individual preferences for when to work alone and when to work with others, closely tied to the general stages of problem solving. Student reflection assignment comments reveal a strong metacognitive awareness of the value but also the drawbacks of collaborative work, and a desire to learn together rather than simply to work together. Since the type of collaborative or interdependent learning described here does not fit exactly with any current models such as collaborative learning, co-operative learning, problem-based learning, or inquiry-based learning, we suggest that it may be best described by a new term such as "co-learning," to emphasize the process of learning rather than the outcome or produce of "co-labouring."

Our own development as instructors in this course has been influenced by what our students have told us about working with others. The primary instructor, a self-identified introvert, did not feel comfortable forcing students to work together, and so created a situation where students always had a choice of how to work; and the results of our student reflection research have confirmed for this instructor the extraordinary value of having students work together, when it is facilitated properly. The student assessment paradigm has also changed to reflect our evolving sense of how learning happens in this

course. What in the first two offerings of the course was labeled as a "Participation Grade" is now called an "Engagement Grade," and is accompanied by an explicit discussion of various ways engagement can be demonstrated beyond simply talking a lot in class. The original course offering also had two term tests, later reduced to one, and plans for the next offering involve having no tests at all. Students have made it clear that the kind of learning they accomplish and have come to value in the course is not suitable for demonstration through a short in-class test.

In her book *Quiet: The Power of Introverts in a World That Can't Stop Talking*, Susan Cain (2012) discusses the high value put on collaborative, co-operative and group work in education and business in recent decades, and claims that more introverted individuals do not fit this model and can be overwhelmed by it. We see evidence of this in our student responses, since many of them preferred to work alone in most academic settings. We also see connections of our work to Daniel Kahnemans's model of fast and slow thinking. Kahneman (2011) describes "fast" thinking as the quick, often intuitive, way people reach conclusions much of the time in life, getting an overview of a situation and making a quick reaction based on experience and feelings rather than on logical reasoning. His "slow" thinking on the other hand involves deeper and more logical thinking, with careful reasoning through complex ideas before a decision is made. We believe that fast thinking lends itself well to brainstorming and to an extroverted mode of sharing ideas, thoughts and feelings, while slow thinking tends to be more introverted and often requires solo work. This difference, we suggest, is clearly reflected in the cycles of independent and collaborative endeavour we have observed in our students in-class working on puzzles and problems. The first stage in Polya's (1945, 1973) process, the deep understanding of a problem, calls for slow thinking and careful reading, and our students tended to prefer to tackle this alone. The second stage of devising a plan can often, particularly in complicated problems, call for a variety of views to produce multiple ways to think about and attack a problem – an activity facilitated by collaboration and discussion. Then a quieter independent stage might be needed to work on the ideas generated in the group, to check out the details carefully and decide whether a particular strategy will be successful in solving a problem or puzzle. Finally, to enhance the development of problem-solving skills, an informal collaborative review of various strategies, what worked and what didn't for different people, adds to the metacognitive development of skills.

We argue, therefore, that optimal "co-learning" on problem solving is highly contextual. It depends on the person and his/her preference, on the problem, the purpose or goal being worked towards, and the cycles of the problem-solving process. Given opportunity to work with others when and how they chose, and metacognitive guidance on thinking and learning styles and on the goals of a problem-solving course, our students seemed to develop a natural rhythm of cycling between individual work and work with others. We have suggested that these cycles link closely to the four main problem-solving steps defined by Polya (1945, 1973).

This contextuality has implications in both the educational and business worlds. As Cain (2012) argues, wholesale "group work" is not necessarily right for all people, nor we argue is it right for all stages of a problem-solving process. Instead, there is a complex intertwining of factors influencing how and when people work together. Moreover, knowing how and even when to work together is a crucial metacognitive skill, which we

believe can be developed in our students. For teachers, this means that working with others in a way which truly enhances learning is a skill that should be carefully facilitated and encouraged. It necessitates a sustained attention to class dynamics, and the creation of a classroom environment in which students are able to move between modalities of working to suit themselves, the problem being worked on, and the stages of the process.

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APPENDIX

Puzzle Examples

Examples of typical puzzles used in this course:

1. **General**: Polya's Water Puzzle (Polya, 1945): You need to draw exactly six litres of water from the river, but the only two containers you have hold five litres and nine litres respectively. How do you measure out six litres of water?

2. **Problems solvable by equations**: Alice is five years older than Bob. But five years ago, Alice was twice Bob's age. Find their ages.

3. **Logic puzzles**: Four couples are formed from Kaylee, Sarah, Jenn and Anne, and David, Will, Sam and Ben. We know that Will is Jenn's brother. Jenn and Ben and dated for a while, but then Ben met his present wife. Kaylee is married to Sam. Anne has two brothers. Anne's husband is an only child. Use this information to identify the four couples.

4. **Number pattern puzzles**: If you multiply 7 x 7 x 7 …. x7, with one hundred occurrences of 7, what would the last (ones) digit of the answer be?

5. **Classic River-Crossing puzzles**: A farmer wants to take a fox, a goose and some corn across a river. He has a boat that will allow him to take only two of the three things at a time. He cannot leave the fox alone with the goose, or the fox would eat the goose. He cannot leave the goose alone with the corn, or the goose would eat the corn. How can he get all three things safely across the river?

6. **Creative-thinking puzzles**: You have 4 pieces of chain, each with 3 links. You want to join all the pieces together to form a necklace (one closed loop). It costs two cents to open a loop, and three cents to close a loop. If you only have fifteen cents, can you make the necklace?