Engaging K–12 Teachers in Mathematical Puzzles and Problems

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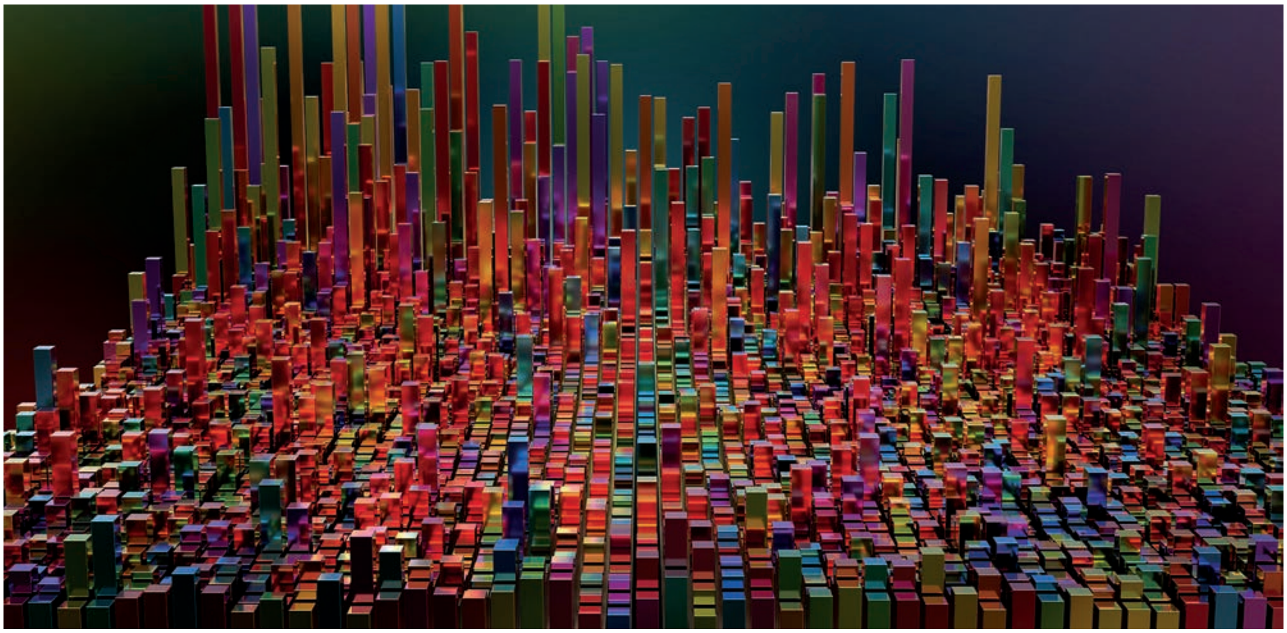

Engaging students in solving mathematical problems and puzzles is an excellent way to get them thinking mathematically and communicating their ideas (Karp and Wasserman 2015). Often, the challenge for teachers is finding not only problems and puzzles but also the time to experiment with them before giving them to students.

This article describes the experiences of a group of K–12 mathematics teachers who participated in a professional development series on puzzles and problems. The PD series introduced the teachers to mathematical problems and theories related to problem solving in the mathematics classroom, as well as giving them follow-up opportunities to visit each other's classrooms.

The intent of this PD series was twofold:

- To provide teachers with experience in engaging with mathematical puzzles and problems themselves in a safe environment in order to increase their confidence in implementing those puzzles and problems in their classrooms
- To provide opportunities for teachers to observe each other as they engaged in mathematical activities with their students and then reflect on the outcomes with each other

Puzzles and Problems Sessions

The PD series was aimed at increasing the teachers' confidence in themselves as problem solvers and their confidence in engaging their students as problem solvers.

Elements of the PD sessions were based on Marynowski's (2013, 2014, 2015) previous work with secondary mathematics teachers. The essential components of the sessions were

- content provided by an expert in the field,
- an expectation that the teachers would integrate the ideas into their practice,
- a commitment to observing each other's practice, and
- time provided for teachers to engage in the sessions and peer observations (Alberta Teachers' Associa-

tion 2014; Darling-Hammond and Richardson 2009; Desimone and Pak 2017).

The content of the sessions was drawn from the Liberal Education 2200: Problems and Puzzles course offered at the University of Lethbridge.[1] The format of the sessions incorporated elements of the school division's peer mentorship program. About half of the usual course content was covered, in six three-hour sessions, and the content was modified to integrate instructional strategies and peer mentorship. The participants had the opportunity to obtain credit for Education 4850: Problem Solving in the K–12 Mathematics Classroom, a new undergraduate course that integrated mathematical content and professional development.

For the peer mentorship portion, the school division provided release time and substitute teachers so that the participants could both engage in the half-day sessions and have time to observe each other's practice.

Each session integrated literature on and support for the teachers in peer mentorship, offered opportunities for the teachers to share what they had tried in their classrooms between sessions and what they had seen and experienced during their peer observations, and engaged the teachers as active problem solvers. The teachers were invited to observe at least one other teacher's class between sessions. The series of sessions took place from September to December 2017.

As already noted, the teachers could participate as part of a course for university credit or participate in the PD series only. Twenty teachers engaged in the PD series only, and six teachers opted to take the course. Those who took the course were able to apply for a mathematics bursary provided by Alberta Education.

Since the participants taught at various levels from kindergarten to Grade 12, the focus of the PD series was not on specific learning outcomes that could be addressed through the problems but, rather, on general problem-solving strategies, competence and confidence. Thus, the teachers were asked to adapt their learning about the puzzles and problems and integrate that learning into their individual contexts.

Research Questions and Processes

Several themes have previously been identified in work with university students in regular offerings of the Problems and Puzzles course, including patience, persistence and other mental attributes in problem solving; solo versus collaborative work; and confidence building (Wismath and Orr 2015; Wismath, Orr and Zhong 2014).

One goal of the research project described here was to examine those themes in this new context, with an abridged version of the course and in work with practising K–12 teachers. Another goal was to explore the impact of engaging in a four-month PD series on problem solving in the teachers' own mathematics classrooms, as well as the impact of their visits to each other's classrooms.

The participants completed a 15-question pre- and post-survey (Appendix A) on how they envisioned themselves as problem solvers to see whether engaging as problem solvers influenced their perceptions of themselves (Wismath, Orr and Zhong 2014). Additionally, the post-survey invited participants to share their experiences and what they had noticed about themselves and their students.

The quantitative results and qualitative comments from the survey are not the focus of this article; however, they are used to illustrate that a change in the participants' perceptions occurred through engaging in problem solving as active learners. The quantitative data illustrates the change in the participants' ratings of their attitudes toward problem solving, and the qualitative data provides illustrative comments from the participants. The qualitative data was analyzed for specific themes and illustrative examples following a thematic analysis approach (Braun and Clarke 2006).

What follows are comments from the lead facilitator of the sessions, the survey results and detailed reflections from four participants.

Lead Facilitator's Experiences

As a professor of mathematics who has taught a variety of undergraduate mathematics courses over many years, I (Shelly Wismath) have long been aware of the tension between content and process and have been frustrated at how little we talk about the process of thinking about and creating mathematics when we focus on content. This concern has become stronger in recent years, as I have turned to teaching general math and quantitative skills to students majoring in subjects other than math and science.

Such concerns were at the forefront when I had the wonderful opportunity to develop a course on problem solving called Problems and Puzzles, which I have taught regularly since 2012. In an attempt to keep the focus on content to a minimum and to make the course accessible to students of all majors, I have used puzzles as the vehicle for problem solving, including math word puzzles, counting problems, logic puzzles, and historical examples of puzzles and riddles.

The math level required for the course is generally not more than beginning high school level. Although we spend one week on using pairs of linear equations, the methods needed are taught in class, as is the often more challenging process of translating sentences into equations (for example, "Mary is five years older now than twice John's age four years ago"). Minimal class time is spent on lecturing to identify themes or strategies; rather, most of the time is allotted for students to work on new puzzles and discuss a variety of approaches and solutions afterward.

A number of key themes have emerged from my teaching of this course, as well as from an associated research project carried out over several course offerings (Wismath and Orr 2015; Wismath, Orr and MacKay 2015; Wismath, Orr and Zhong 2014; Wismath and Zhong 2014).

First, a primary goal of the course is to allow students to develop metalevel and metacognitive skills. Rather than focusing on specific content, students gradually focus on abstracting ideas from a complex context, observing and testing for patterns, using careful reasoning, and communicating their thinking process to others. They learn strategies such as working backward; identifying subgoals; using charts, tables and diagrams to represent and organize information; and making small-scale models. In weekly reflection assignments, they are encouraged to assess their own skills and growth and to think about how problem solving is used in their particular areas of study. This metacognitive reflection produces increased awareness of transferable metalevel skills, as students realize that they can use these strategies in other academic work, such as writing essays, analyzing textual arguments, setting subgoals and studying for tests (Wismath, Orr and Zhong 2014).

Mathematics textbooks that include problem solving usually start with the four-step method of George Pólya (1973):

1. Understanding the problem
2. Devising a plan
3. Carrying out the plan
4. Looking back

In class, students can choose to work alone or in informal small groups and can shift back and forth as they wish. Our research team has found distinct cycles in collaborative versus solo work that correlate with Pólya's four steps (Wismath and Orr 2015). Students usually start working on the puzzles alone, to get a full understanding of the information and the goals of the problem. If they are able to, they work alone until they reach a successful conclusion. However, if they get stuck, they then turn to collaborative work, comparing notes and brainstorming new approaches, as in Pólya's second step. They then go back to working alone for the third step (carrying out the plan). They cycle through this consult-and-carry-out phase as many times as needed. Finally, the metacognitive "looking back" step is a collaborative one, as students increasingly benefit from sharing their approaches and hearing the many ways other students thought about the same problem.

Researchers on learning in a variety of disciplines have tried to identify plateaus and thresholds in learning—stages in which student growth seems to level off for a while and stages in which sudden growth leading to a new plateau can occur as students grasp some "threshold concept" that allows for a breakthrough in understanding (Cousin 2006). Our research team found three such thresholds in student growth over the course (Wismath, Orr and Mackay 2015).

The first threshold involves getting started. Instead of waiting for guidance, students gradually became more willing to plunge in and try one of their strategies. We think that the tendency to wait for guidance stems from a pedagogical approach that inadvertently teaches students that the worst thing they can do is make a mistake, or "fail." In fact, in problem solving, making mistakes is where the learning occurs, as it gives students a chance to figure out what went wrong and why and how to fix it. Solutions usually don't come immediately; rather, they are achieved through an iterative process of trying and fixing.

The second threshold is related to patience and persistence. As students cross this threshold, they no longer give up as soon as they get stuck on a problem but, rather, persist in trying various methods.

Finally, many students move over a third threshold, involving increased attention to Pólya's first step, as they realize that acquiring a deeper understanding of a problem upfront and spending time making a careful mental model mean less of a guess-and-check approach and less work overall.

These thresholds also offer a rich metacognitive learning experience, as students become more aware of how to be successful problem solvers.

A final component of growth that we studied was confidence. We measured students' confidence as problem solvers through a pre- and post-course survey, using items on a five-point Likert scale, and observed a statistically significant increase in their confidence over the duration of the course. A gender breakdown of this data revealed, however, that despite decades of effort to improve both the confidence and the success of girls and women in math and science,

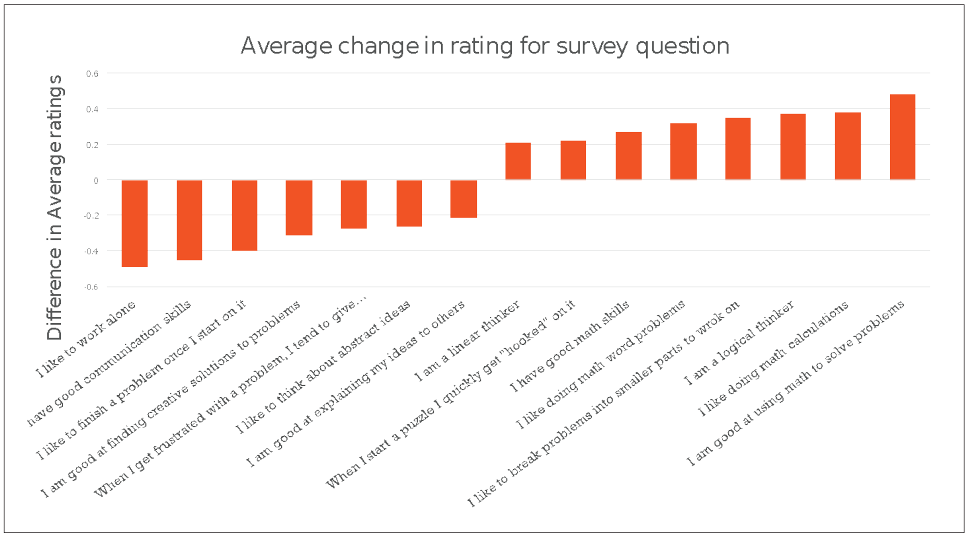

FIGURE 1. *Average change in participant ratings from the pre-survey to the post-survey.*

there was still a strong gender difference in confidence (Wismath and Zhong 2014). At the start of the course, the female students had a much lower average confidence score than the male students (3.14 versus 3.94). By the end of the course, the female students' average confidence score had increased more than that of the male students (3.86 versus 4.44). Again, this shows both a metacognitive skill gain and the importance of addressing gender in teaching mathematics and problem solving.

Survey Results

Before and after the series of PD sessions for K–12 teachers, the participants responded to a questionnaire about their perceptions of themselves as problem solvers (see Appendix A). Figure 1 illustrates the average change in rating for each survey question, from the largest decrease to the largest increase.

The two most striking changes were that, after the sessions, the participants liked working alone much less and saw themselves as being good at using math to solve problems. They were also less likely to give up on a problem when they were frustrated, an improvement in persistence. In addition to providing teachers with experiences to improve their problem-solving skills, these sessions promoted resilience in persisting with difficult problems and built confidence.

In an open-ended question, the participants were asked what makes a good problem solver. Of the 17 comments, 8 focused on persistence, openness and flexibility. The following is a sampling of the responses:

- "Resilience, the drive to continue in the face of failure; Persistence; Tenacity."
- "Open-minded and the willingness to consider all possible solutions and weigh out which has the most benefits."
- "Flexibility—ability to look at different angles/viewpoints."
- "Being open to try."
- "Zoom out to see the forest. Get lay of the land. Then incrementally zoom in. . . . When you get frustrated, walk away to engage in 'diffuse mode' thinking or switch to a different aspect or perspective."

Five other comments focused on specific approaches to problem solving, such as the "ability to break the problem down to pieces that are manageable" and "us[ing] a variety of strategies to attempt the problem at hand [and] tak[ing] time to look at the whole problem and work through it piece by piece." None of the responses included proficiency in mathematics or in calculations as an important characteristic of a good problem solver. The participant comments echoed the idea that metacognitive and critical thinking are what are important in mathematics, beyond competence with numbers or arithmetic (Karp and Wasserman 2015).

The participants were also asked what had changed in their teaching practice after engaging in the sessions. Five participants mentioned incorporating more time for problem solving in their classes: "I am taking more time to introduce problem solving opportunities for the students. We take one math period a week to simply work on math problems such as frogs on a log or play spatial games." Four of the comments were more general, describing the overall feeling of the class: "I have introduced techniques, methods, ideas into my class. It has brought some fun back into the sometimes dry environment." Three participants commented on the peer mentorship process itself: "[I] gained courage to go outside of my walls to borrow ideas and thoughts from others—at all grade levels. Important to remember we as teachers are not an island." All 15 comments indicated that there had been some sort of change to the participants' practice.

Participant Experiences

The following reflections highlight the experiences and learnings of four participants in the PD series. Their stories illustrate how engaging in problem solving as learners translated into their teaching practice.

Verna's Experience

It was an honour to be part of this project. I have actively been involved in the school division's peer mentorship program for five years, and every year I evolve so much as a teacher and a lifelong learner. I became involved in peer mentorship because there were not a lot of PD opportunities I could participate in outside of the classroom. Having three children at home limited when I could be away and how much I could afford to spend engaging in PD opportunities. This year was an exceptional year, because in addition to being part of a wonderful program, I was able to take a university math course at the same time and earn credits toward my total years of education.

It was challenging for me, because as a social studies major, math scared me. I have never felt confident in my ability to think or teach mathematically, and I knew this class would make me do just that. It was an eye-opening experience for me, and I learned strategies that could help students who felt just like I did about math. The series of sessions was very condensed, which made it a little difficult to engage in classroom visits with colleagues. It meant a great deal of time outside of my own classroom, which was challenging, but it was well worth it.

I gained a lot of confidence throughout this collaborative project, and that confidence is now evident in my students, as well. From participating in this project, I have learned that math is more than calculations and worksheets, and math in my classroom is now fun!

Michelle's Experience

I joined the project because I was looking for new ways to make math fun and new ways to encourage problem solving in young students. I teach kindergarten, where we naturally do a lot of real-life problem solving every day, but I wanted an opportunity to introduce some critical thinking. I was also interested in seeing what teachers do in older grades and whether I could tweak anything to make it more age-appropriate. Sometimes we don't give young students the benefit of the doubt, and we assume that they can't do things, even though they may be up for the challenge.

Many activities in the course required reading or advanced knowledge that kindergarten students haven't acquired yet, so it was unrealistic to take everything from the course back to the classroom. But the idea of thinking about the next step and trying to use reason can be used at any age, so I focused on that.

I introduced logic puzzles to my students. While they did enjoy the puzzles, we had to do them as a whole group, because my students cannot read. Wanting to stay in the area of logic, I moved to a couple of board games that require thinking about the next steps before making a move. I introduced Connect Four and Rush Hour to my students, and both have become popular choices during free play time. To win at Connect Four, a player must create a line (vertical, horizontal or diagonal) of four disks of the same colour before their opponent does. This is a difficult idea for some students, especially since they also have to closely monitor their opponent's lines. In Rush Hour, the player must figure out how to get an ice cream truck out of a traffic jam. The player is given a card that shows exactly how to place the vehicles on a grid and then must move the vehicles forward and backward until they have created an empty path for the ice cream truck to travel on. The game has various levels of difficulty, so everyone in my class can be successful. The only downfall is that it is a single-player game, so we don't have the bonus of learning how to take turns or what it means to win or lose.

These are just two examples of problem-solving games that can be used in the kindergarten classroom. If my budget allowed for it, I would stock my classroom with as many of these games as possible, as I clearly see the benefits every time my students play them. I will continue to use logic puzzles, as well, but I strongly recommend board games, because children can play them without adult guidance and are always happy to teach the games to their peers.

Lynn's Experience

In my teaching, I focus on developing understanding in math, not memorizing questions. My aim is to create problem solvers and critical thinkers who can use skills in a variety of situations, and this program seemed like a great opportunity to develop strategies for fostering this level of learning. This program invited me to see my classroom and my teaching through a unique lens of discovery and pursuit. Allowing the problem-solving process to occur can be frightening for a teacher. We do not want any wasted time or the stress of being "behind."

Through participating in the program, I started to view lessons and ideas through a lens of problem solving and processes, and I used puzzles to promote and reinforce the qualities that make a proficient critical thinker and a resilient problem solver. The answer to a problem became less and less important, as dead ends were rewarded and productive time did not always move in a straightforward, linear way.

Looking at my class through this lens has enabled me to let go of the constraint of time, and it has helped me promote the problem-solving process in my classroom. Rewarding resilience more than a correct outcome has helped my students feel more confident in math. This opportunity has rejuvenated my spirit in the classroom and has motivated me to continue challenging my students through trying different styles of learning and use of time at school. I, too, have found the puzzles engaging, and they have motivated me in my own learning and intellectual wellness. My students value effort and resilience more than they did before; they still get a great deal of satisfaction from finding the correct answer, but they no longer shy away from the sometimes-frustrating process of getting there.

Alana's Experience

Problem solving is an engaging and all-encompassing activity to do with children. I wanted to take part in this project because I had done research on teaching problem solving in an elementary classroom and wanted to further extend my knowledge and to see these practices used in everyday classrooms. How lucky I feel to have been part of this program and experience! From assisting in teaching this workshop series, I learned a great deal about how to help students learn how to struggle. Finding that perfect zone of proximal development—where the problems are challenging enough to stretch students' understanding and thinking to make new connections but are not so difficult that students get frustrated and give up—is essential. It was interesting to assist practising teachers through this process and offer hints or guiding questions. I found that the more I predicted where the participants would struggle, the better I was able to prepare questions that could guide them without giving the answer away or stopping their thinking.

This work has extended into my final teaching internship in Grade 2. I have been able to modify many of the problems to work for younger students. Currently, my students love the game Polar Bears Around the Drinking Hole (a version of Petals Around the Rose).[2] They ask to play during snack time and whenever we have a few free minutes. We have talked about making a prediction or a hypothesis and then testing it. About one-quarter of my students know the rules and can clearly explain them; we call them our drinking hole masters. My students have also played Frogs on a Log, after reading the book *Frog on a Log?* by Kes Gray (2015)—a great literacy tie-in. Students broke into pairs to work on the puzzle, and it was exciting to observe them as they worked together to move the frogs the quickest way possible. They have also started to work on simple logic puzzles, mostly about shapes and colours. These have required some direct instruction initially to help move students into independent work. The one concern I have with these puzzles is that they are often very text heavy, so students who struggle to read also struggle to understand the clues. During our measurement unit, we used toothpicks as a manipulative to measure; this was a perfect segue to toothpick puzzles (also known as matchstick puzzles). The students started with a shape formed by the toothpicks, and they had to change it to a different shape, using a limited number of moves. They spent time thinking about the definition of various shapes and enjoyed the kinesthetic learning.

The two biggest challenges I faced were time and students' attitudes. We have only a certain number of hours in the day to address all of the curriculum content, and many of these problems do not have a direct connection to the curriculum. However, I find that the problems help students develop the skills of mathematical thinkers. They learn how to break down a problem and better understand what is being asked, how to articulate their ideas and how to have meaningful mathematics conversations, and they also start to see the mathematical connections to everyday life. When we first started to work on problems, many students became frustrated and upset, so we had to take a step back and talk about persistence. This ended up being our focus in health, and it has been amazing to see the students use strategies we have talked about in order to persevere through a problem.

Conclusion

As already described, this PD series involved six sessions, offered by the school district, as a vehicle to offer approximately half the content of an undergraduate course in problem-solving skill development. The associated research project looked at the previously identified themes of confidence, threshold (or transition) concepts, persistence and patience, and cooperative learning in this new context. The data collected, both quantitative and qualitative, shows that the teachers built both metacognitive appreciation for and skill and confidence in problem solving. As measured by a post-survey, two of the three largest increases in average data scores occurred on the indices measuring persistence and confidence.

The participants' qualitative reflections also demonstrate their increased confidence in their own abilities, both in solving problems themselves and in guiding their students' development as problem solvers. Verna's reflection highlights this growth: "I gained a lot of confidence throughout this collaborative project, and that confidence is now evident in my students, as well."

Michelle and Alana commented on how the university-level math content had to be modified for lower grade levels, but they identified metacognitive skills that they were able to use and build with their students, such as "thinking about the next step and trying to use reason." Alana also identified how she had helped her students pass the metacognitive threshold of persistence, along with other skills appropriate at the Grade 2 level: "They learn how to break down a problem and better understand what is being asked, how to articulate their ideas and how to have meaningful mathematics conversations." This idea of mathematical conversation also appeared widely as a benefit of both the sessions and the in-class peer mentorship. The teachers appreciated the value of working together and continued to do so outside of the formal sessions. Again, our quantitative data bears out this significant increase in positive teacher attitudes toward mathematical conversation.

Finally, the participants showed awareness of the significant thresholds in the development of problem-solving skills. All participants developed a tool kit of strategies to try themselves when working on new problems and to pass on to their students, and Lynn and Alana both noted the increase in students' effort and resilience, which mark the threshold of patience and persistence.

Overall, we argue that our survey data, as well as feedback from the participants, shows that this project was successful in meeting its goals. The puzzle-based approach to problem solving, sessions that allowed participants to practise this approach among a supportive group, and the opportunity to extend the learning to their own classrooms with peer support gave the participants a multifaceted way to develop their own skills in a fun and safe way, which they could then extend to their own students.

A useful follow-up to this project would be doing an assessment with the participants after one year, to measure the long-term impact on their teaching and on their students' progress as problem solvers.

Appendix A: Attitudes and Attributes Survey

The following survey was administered to participants both at the start of and after completion of the series of sessions.

Level of agreement with each statement: strongly disagree, disagree, neutral, agree, strongly agree

I like to work alone.

I have good communication skills.

I like to finish a problem once I start on it.

I am good at finding creative solutions to problems.

When I get frustrated with a problem, I tend to give up.

I like to think about abstract issues.

I am good at explaining my ideas to others.

I am a linear thinker.

When I start a puzzle I quickly get "hooked" on it.

I have good math skills.

I like doing word problems.

I like to break problems into smaller parts to work on.

I am a logical thinker.

I like doing math calculations.

I am good at using math to solve problems.

Notes

1. Liberal Education 2200: Problems and Puzzles, University of Lethbridge, list of topics covered, 2012, www.cs.uleth.ca/~wismaths/pandppage/topicslist.pdf (accessed October 18, 2021).

2. Petals Around the Rose game, Illuminations website, National Council of Teachers of Mathematics (NCTM), https://illuminations.nctm.org/lessons/petals/petals.htm (accessed May 6, 2019).

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