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The use of carefully-planned board-work to support the productive discussion of multiple student responses in a Japanese problem-solving lesson

--Manuscript Draft--

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Abstract:	In this paper, we analyse a Grade 8 (age 13-14) Japanese problem-solving lesson involving angles associated with parallel lines taught by a highly-regarded Japanese mathematics teacher. The teacher used carefully-planned board-work to support a whole-class discussion (neriage) in which he shifted the focus from individual examples to generalised properties. By comparing the teacher's detailed prior planning of the board-work (bansho) with that which he produced during the lesson, we distinguish between aspects of the lesson that he considered essential and those he considered contingent. Our analysis reveals how the careful planning of the board-work enabled the teacher to be free to explore with the students the multiple alternative solution methods that they had produced while at the same time having a clear overall purpose relating to how angle properties can be used to find additional solution methods.
Response to Reviewers:	Responses to Reviewers' Comments We would like to thank the editor and the reviewers for their very helpful comments, which have enabled us to improve the manuscript considerably. Below, we detail our responses to each comment. Editor's Comments Thank you for these positive comments. We have reworked the paper to fit the category "Mathematics Teacher Education around the World" in order to highlight issues of national significance that are also of wider interest and influence. [My main concern is that you need to revise your paper in the direction of making clearer the national significance on one side and the national context that can act as a frame for interpretations and make the paper more relevant to the international audience.] We have now done this by including additional background information in the introduction about the use of bansho within the national context (see pp. 2-3) and also clearly emphasising the international significance of the study in the conclusion on p. 20. [Make clearer the rationale of your paper so that to fit to the category of Mathematics Education around the world (see comments of Reviewer 3)] As mentioned above, we have now done this by expanding on the national and international significance of the study, both in the introduction and in the discussion and conclusion sections. [Make clearer the contribution of your study at the theory-practice level in relation to existing research literature (see comments of all reviewers but especially of reviewer 2)] We thank the editor for this comment. Please see our responses to R2 below on this point. [Make clearer links in the description of the lesson and its analysis with the board work (see comments of reviewer 1)] We have now restructured the analysis to strengthen these connections, including giving more explicit reference to the frame of variation theory (please see pp. 16-18).

[Provide details and justifications about the process of data analysis and make more apparent your analytical framework in the analysis. Justify why the variation theory and the use of examples are useful for what you want to study and provide more information about how you substantiated.]
We have now provided a more detailed justification of the use of variation theory for the analysis of the lesson, with particular reference to the use of variation theory in Japanese problem-solving lessons. We have made more specific connections to the lesson description and our analysis is now much more detailed (see pp. 16-18).

[Provide more contextual information about mathematics teaching in Japan in general and in board work in particular and place your particular case in this context and also use it for your interpretations]
We have now included additional information about mathematics teaching in Japan and the place of board work in this within the introduction on p. 2, and have returned to this in the discussion and conclusion on pp. 18-20.

[Rewrite the discussion and the conclusions section to fit better to the scope of the category "mathematics teacher education around the world". You can discuss your findings in relation to other studies in the area (e.g. how this process related to the work of Stein and her colleagues?) to show its contribution starting from the national context in Japan related to the focus of your paper and moving to the implications of the study to research about mathematics teaching and mathematics teacher education. What do the mathematics teacher educators learn from your study?]
We thank the editor for this very helpful comment. We have now expanded the discussion to make links with a wider literature base, including Stein, Engle, Smith, & Hughes (2008).

Reviewer #1's Comments:
Thank you very much indeed for this positive comment on our work.
(1) We thank the reviewer for drawing our attention to this point. If we understand the reviewer correctly, they are referring to distinguishing between when the teacher posed questions orally and when these were (additionally) written on the board. We have tried to be clearer throughout the lesson description about this point, and we have now discussed this issue on p. 19.
(2) We thank the reviewer for this helpful observation. We have now mentioned and discussed this point on p. 18.
(3) As mentioned above, we have now included more information on p. 2 about how the board is typically used in mathematics teaching in Japan, and we have now returned to this point in the discussion on pp. 18-19.
(4) and (5) Thank you for these comments - we have now corrected these.
(6) We have now included this in Figure 8 on p. 12.

Reviewer #2's Comments
(1) We have now outlined the theoretical and practical implications in the discussion and conclusion on pages 18-21. We see these principally as the ways in which strategic use of the board enables in-depth comparisons to be made between alternative solution methods, and we note how the teacher in this lesson was able to offer students a strategy for solution generation that was not tied to this specific content area and allowed students to creatively invent solutions that they otherwise might not have had access to.
(2 - literature review) We are aware that there is a very large area of literature relating to this, which we do not feel that we have space to do justice to. But we have included some recent references on p. 3 that we hope will be sufficient for the purposes of the present paper.
[Some comments]
(3 - long sentence on p.16) We have now moved these sentences into the conclusion.
(4 - citations) We have now cited Schoenfeld (1992) here, and been careful to include more citations where claims like this are made.
(5 – Japanese characters) An English translation is given in Figure 2, and we have now included this text also in the caption for Figure 5.
(6) We have now revised the manuscript carefully to clarify where we mean American and where we mean Western more generally (i.e. including Europe).

	Reviewer #3's Comments: (1 - category) We thank the reviewer for this comment and, as explained above, we have now reworked the manuscript to fit better within this category. (2 - emphasis) As we have mentioned above, we have now stressed the national significance of this paper by highlighting more clearly the national context in the introduction (see p. 2) and returned to this in the discussion on pp. 18-20. We have also now clarified on pp. 5-6 our reason for selecting a highly-regarded teacher for this lesson. (3 – general comment) As mentioned above, we have now reworked the paper to better fit this category. We have also now changed the title to: " The use of carefully-planned board-work to support the productive discussion of multiple student responses in a Japanese problem-solving lesson". (4 – sections) We thank the reviewer for these comments. We have now reworked the discussion and conclusion in the light of the other comments made to ensure that the distinctive contribution of the paper is clear. (5 - focus) We have now tried to make this the focus throughout the paper.

The use of carefully-planned board-work to support the productive discussion of multiple student responses in a Japanese problem-solving lesson

Abstract [150-250]

In this paper, we analyse a Grade 8 (age 13-14) Japanese problem-solving lesson involving angles associated with parallel lines, taught by a highly-regarded Japanese mathematics teacher. The teacher used carefully-planned board-work to support a plenary discussion (*neriage*) in which he shifted the focus from individual examples to generalised properties. By comparing the teacher's detailed prior planning of the board-work (*bansho*) with that which he produced during the lesson, we distinguish between aspects of the lesson that he considered essential and those he treated as contingent. Our analysis reveals how the careful planning of the board-work enabled the teacher to be free to explore with the students the multiple alternative solution methods that they had produced, while at the same time having a clear overall purpose relating to how angle properties can be used to find additional solution methods.

Keywords [4-6] bansho; blackboard; chalkboard; discussion; Japanese problem-solving lesson; neriage

Introduction

The *Japanese problem-solving lesson* has been of considerable interest in the West at least as far back as its description as "structured problem solving" in *The Teaching Gap* (Stigler and Hiebert 1999, p. 27). According to Takahashi (2006, p. 38), the style of the Japanese problem solving lesson is starkly different from how problem solving is commonly taught in mathematics lessons in the West, which "are usually focused on the process of solving a problem and not [necessarily] focused on developing mathematical concepts and skills. These problem-solving lessons often end when each student comes up with a solution to the problem". In contrast to this, the Japanese problem-solving lesson devotes substantial time to students devising *their own* ways of solving a problem, and this is seen as preparation for the crucial *neriage* phase of the lesson, in which the teacher leads an extended plenary discussion, during which different solution methods are shared and compared (Foster 2019; Takahashi, 2006). In Japan, the teacher's skill in facilitating this discussion is seen as critical (Takahashi, 2006, p. 42), and "Japanese teachers see *neriage* as the heart of teaching mathematics through problem solving: the solving of the problem by each student at the beginning of the lesson is preparation for *neriage*" (Takahashi 2011, p. 199, original emphasis).

Japanese mathematics education places great importance on problem solving and a student-centred approach to learning. There is a strong emphasis on mathematical thinking and the development of mathematical concepts and skills. In contrast to mathematics teaching in many other parts of the world, generating interest in mathematics and giving opportunities for collaborative, creative mathematical activity are central (Takahashi, 2006). As Takahashi (2006) reported, each mathematics lesson typically centres on one carefully selected key problem that relies on and extends prior knowledge, and textbooks contain "a *series* of problems and activities rather than a *set* of problems and activities" (Takahasi, 2006, p. 42, emphasis added), with teachers facilitating discussion around a selection of student solutions.

An essential feature of conducting the *neriage* is very careful use of the blackboard, and this gives rise to the Japanese term *bansho*. Kuehnert, Eddy, Miller, Pratt, & Senawongsa (2018, p. 363) described *bansho* as "the intentional use of board space for facilitating student learning". *Bansho* is a highly developed skill, and planning for effective use of the board is an important part of teachers' professional development. *Bansho keikaku* (boardwork planning) is central to lesson planning and includes consideration of the lesson content, the resources being used, and likely student responses (Tan, Fukaya, & Nozaki, 2018).

Japanese classrooms nearly always contain at least one very large blackboard that stretches across the entire width of the classroom (see Figure 1), and this provides very particular opportunities for structuring the *neriage* phase of the Japanese problem-solving lesson by showcasing multiple solution methods side by side, for comparison and discussion. This emphasis on careful use of the board (e.g., see Seino and Foster 2020) contrasts starkly with how classroom boards are typically used in Western classrooms, where the board tends to occupy a much smaller fraction of the front wall, and where only a small amount of content is normally visible at any one time (Foster & Baldry, 2019). The teaching of problem solving, and its interaction with the teaching of content knowledge, is an area of considerable interest in the West, where teacher expertise is often considered to be limited (e.g., English & Sriraman, 2010; Felmer, Pehkonen, & Kilpatrick, 2016).

In this paper, we analyse a particularly expert instantiation of a classic Grade 8 (age 13-14) Japanese problem-solving lesson, which involves angles associated with parallel lines. Our purpose is to illuminate how one highly-regarded teacher's carefully-planned board-work enabled him to lead a rich discussion that took account of multiple student responses to the task. This discussion was both extremely responsive to the students' invented methods while at the same time having a clear didactical focus and purpose in supporting generalisation. In our experience, this combination is rarely achieved in mathematics classrooms in the West, and we seek to explore in detail features of the lesson and its planning which seemed to facilitate such an approach. Through our analysis of a mathematics lesson perceived, both locally and by a range of international visitors, as being of exceptionally high quality, we seek to answer the question: *How can the use of carefully-planned board-work in the discussion of multiple student responses to a problem-solving task support a shift in focus from individual examples to generalisations?*

Figure 1. A typical blackboard in a Japanese classroom

The use of the board to support problem-solving discussions

Episodes of problem solving in the mathematics classroom are valuable in so far as students learn something from them that can help them in future situations (Foster, 2019). Sometimes a mathematics teacher's focus can be merely on 'doing problem solving', or narrowly on 'solving the problem', as an end in itself, and this can displace the necessity of learning something broader from the situation (Foster 2019). The culture of the Japanese problem-solving lesson (Hino, 2007; Takahashi, 2008) avoids this danger by placing a strong emphasis on the *neriage* phase of a lesson, during which an extensive, detailed discussion takes place concerning the students' different solutions. Conceived of as "the heart of the lesson" (Takahashi 2008, p. 4), in the *neriage* phase students are guided by the teacher in exploring the similarities and differences among the approaches that they have taken. Teachers plan for the *neriage* in detail by anticipating the variety of methods that students are likely to bring to the discussion, which includes not only the most efficient and desirable methods but also ones that can usefully highlight misunderstandings or offer didactically insightful contrasts. According to Takahashi (2006, p. 43), "developing a plan for using the blackboard is [a] major component of lesson planning". Teachers' careful crafting of the order in which solutions will be made public, and how the board will be used to support productive mathematical discourse, is named *bansho* (Kuehnert, Eddy, Miller, Pratt, & Senawongsa, 2018).

Productive classroom discussions allow learners to think publicly, and to be guided to reflect on and evaluate their own and others' mathematical ideas. These discussions support the development of mathematical discourse practices (Stein et al., 2008) and give the opportunity to "share ideas and clarify understandings, develop convincing arguments regarding why and how things work, develop a language for expressing mathematical ideas, and learn to see things from other perspectives" (Smith et al., 2009, p. 549). Orchestrating whole-class discussions built on student-developed solutions that lead to powerful, efficient and accurate mathematical thinking is a highly pedagogically-demanding task (Stein et al., 2008). All too easily, during a whole-class discussion, the dialogue can descend into a string of unconnected presented solutions, where individuals are held accountable for *their* method and no more. It can be very hard for one student to follow the details of another student's approach, and links to deep conceptual ideas may remain below the surface, and the evaluation of the usefulness, efficiency and accuracy of various strategies unargued. Such merely 'show and tell' discussions cannot be relied on to move a class forward mathematically (Takahashi, 2008).

A few researchers have explored the role that board-work can play in supporting effective whole-class discussions (e.g., Foster & Baldry, 2019; Tan, 2018). Friedland, Knipping, Rojas and Tapia (2004) described working at the chalk board (or whiteboard) as "thinking aloud" (p. 17). Billman et al. (2018) highlighted the constructive nature of physically reproducing or representing mathematics in front of a group of learners, as opposed to revealing ready-made slides. The presentation and construction in 'real time' helps to slow the pace, so that learners can more easily follow the steps in producing the mathematics (including diagrams), can process the explanations being given, and can recognise the precise, clear and correct notation being used. In a study of university lectures, Greiffenhagen (2014) described writing mathematics as "indispensable for doing and thinking mathematics" (p. 502), quoting lecturers who stated that boards allow students to see ideas "materialising in front of you", making "mathematics visible as a process, not just as a product" (p. 521). Greiffenhagen summarised this as the board allowing the processes and structures of mathematical reasoning to be made visible.

Several studies (e.g., Stein et al., 2008; Kuehnert et al., 2018; Schoenfeld, 1998; Lampert, 2001; Smith et al., 2006) have identified key activities concerning the use of the board that may support productive discussions. These include:

1. Teachers *selecting* specific students' work to discuss, not because their solutions are necessarily the 'best', or because they have the right answer, but because the teacher

perceives that a solution can be harnessed in the discussion to support productively working towards the lesson's mathematical goal(s).

2. Teachers *sequencing* student responses in a purposeful way, perhaps ensuring that the most common or concrete solution strategies (e.g., perhaps using drawings or concrete materials) are considered first, followed by more innovative or abstract ones. This validates less sophisticated methods, ensuring the involvement of as many students as possible from the beginning, and develops progression between solutions, as students move from concrete to more abstract models.
3. Teachers and students *making mathematical connections* between student responses and key concepts, thus ensuring that the key mathematical ideas and their connections are the focus of the lesson. This may include a comparison of the different solution strategies, and considering their accuracy, efficiency and suitability for other related problems.

These approaches improve the "chances that [the teacher's] mathematics goals for discussion will be achieved" (Stein et al., 2008, p. 329), with mathematical ideas building on each other into powerful connected concepts.

How material is organised on the board is potentially an important feature for the students' learning. In Greiffenhagen's (2014) analysis of an undergraduate lecture, the organisation of the lecturer's board helped to highlight the interconnectedness of the mathematics presented, supported recognition of when an assumption was no longer needed (by erasing), clarified when something was an aside (in the form of "scratch work"), and embodied the written nature of mathematics, as in a textbook or journal article. In the context of a Japanese problem-solving lesson, Kuehnert et al. (2018) described how the board was partitioned into three sections, which were devoted to different aspects of the learning: activating prior knowledge, exploring the problem, and discussing and extending the problem. In both of these studies, the tools needed to solve a problem were represented: in the form of prior knowledge by Kuehnert et al. (2018), and by the inclusion of a lemma to be used within the constructed proof in the lecture analysed by Greiffenhagen (2014). In both cases, these tools were placed at carefully demarcated locations on the board, and drawn on and explicitly discussed at different moments during the lesson or lecture. They acted as prompts for the learning ahead and exemplified the ways in which mathematics was presented as an organised body of knowledge. The boards recorded a coherent story of the lesson or lecture, and sections could be revisited, reviewed or used as reference during discussions or explanations (see Baldry & Foster, 2019). Connections were highlighted, including between different mathematical representations, in the lesson analysed by Kuehnert et al. (2018), and the construction of 'side proofs' by the lecturer observed by Greiffenhagen (2014). In discussing the use of the board during the summing-up phase (*matome*) of a Japanese problem-solving lesson, Shimizu (2006) concluded that:

> By not erasing anything the students had done and placing their work on the chalkboard in an organised manner, it was much easier for them to compare the multiple solution methods proposed. Also, the chalkboard served as a written record of the entire lesson, giving both the students and the teacher a bird's-eye view of what had happened during the lesson. (p. 133)

The part played by the *bansho* in the *neriage* would seem to be critical to the success of that most crucial phase of the lesson. However, studies have not so far analysed in detail the ways in which experienced Japanese teachers do this, and our analysis below attempts to illuminate this aspect of pedagogical practice.

Method

The teacher and class

In order to explore the potential of carefully-planned board-work, we chose to study a Japanese problem-solving lesson taught by an extremely experienced Japanese mathematics teacher. The teacher, a co-author of this paper, is very highly regarded in Japan, and is one of the authors of the textbook series used in the school (which is one of the most popular books approved and used in Japan). Based on conversations with Japanese teachers and academics who co-observed the lesson with us, as well as our experience observing lessons in Japan, we believe that the style of lesson presented would be regarded as typical of the intended style of a Japanese problem-solving lesson. However, the teacher in question is far from typical, and was selected in order to showcase an outstanding example of the enactment of such a lesson. The purpose of this choice was to try to learn as much as possible about how the board might be used in such a lesson, when taught by an expert teacher.

Although the Japanese problem-solving lesson is particularly common at elementary level, here we describe a Grade 8 junior high-school lesson. The lesson was chosen as it was a typical problem-solving lesson that the teacher was willing to open to 12 international observers, including the other authors of this paper. The teacher was teaching his own class, and reported that this was a normal style of lesson for these students. We had access to simultaneous audio translation into English, and the lesson was video recorded by a handheld ipad, which was focused on the front of the room, but was roving around the room during seatwork. The research team also had full access to all of the lesson-planning documents, including the teacher's board plan, all of which were translated into English for analysis. Typically, board plans are made for key lessons, such as the introduction of a new unit, when investigating the structure of a lesson or open lessons.

All of these documents are freely available to view at https://figshare.com/XXX.

The analytical lens: variation theory

In recent years, international comparison studies have drawn attention to the role of variation in understanding curriculum design and the analysis of classroom practice (e.g., Al-Murani, Kilhamn, Morgan, & Watson, 2019; Huang & Li, 2017; Sun, 2011). Whilst earlier research often focussed on understanding Chinese mathematics classrooms, analysis from a perspective of variation theory has now been undertaken in a wide range of settings (Huang & Li, 2017), including Japanese problem-solving lessons (Hino, 2017). Variation theory is now recognised "as a lens by which to interrogate both instruction and learning" (Clarke, 2017, p. 299), and one that can be applied to different cultural contexts. Moreover, Mason (2017) argued that student explanations, a key element of Japanese problem-solving lessons, are an essential part of pedagogy informed by variation theory; consequently, variation theory was adopted as the analytical framework for this study.

With origins in different traditions, variation theory can be interpreted from different perspectives, but the underlying principle is that learning is discernment, which requires learners to experience variation against a background of invariance (Lo, 2012). Often, the invariant aspect is a mathematical relationship or concept that is the intended object of learning, and is made more visible through systematic variation in defining and non-defining features (Marton & Pang, 2006). For example, to understand the 'three-ness' of triangles, the number of sides (defining) and the orientation/side length (non-defining) are both varied. Adler and Ronda (2015) argued that variation theory can be used to analyse "what is mathematically available to learn" (p. 1), though, importantly, Watson (2017) highlighted that this includes "what is made available to be learnt through the pedagogy that accompanies the designed task" (p. 89). As such, the intended and enacted objects of learning are both open to analysis through this approach.

As examples play an important role in the mathematics classroom, a number of studies have explored how the sequencing of tasks within exercises can be analysed (e.g. Watson & Mason, 2006), whilst others have analysed 'One Problem Multiple Solutions' and 'One Problem Multiple Changes', which are task structures commonly found in Chinese textbooks (Sun, 2013). However, learners experience variation in different ways; while a task may offer some of the structure, what the teacher draws attention to through their pedagogical actions will also influence what is made more or less visible to the learner (Watson, 2017). Here, the context of the Japanese problem-solving lesson means that 'One Problem Multiple Solutions' provides the overall structure, with mathematical features that the teacher draws attention to during the *neriage* being the key focus of our analysis. In this context, the starting point is the varied solution methods generated by the students. The teacher's goal in the *neriage* phase of the lesson is to structure students' reflections on that variation, illuminating the similarities and differences across the different solution methods produced (Hino, 2017). This allows different aspects of the intended object of learning to be brought into focus in a structured sequence, drawing out the key learning points from the lesson.

The analytical method

Our data sources were a video recording of the entire lesson; the relevant pages from the textbook; the teacher's detailed lesson planning documents, including his detailed board plan; and field notes from the observers (the other authors of this paper). We began by constructing a verbatim transcript of the lesson in Japanese, with a timeline, and this was then translated into English. All of the analysis was conducted on this translated transcript; however, the entire analysis was overseen by the Japanese co-author, who was also the teacher of the lesson, and another Japanese collaborator also undertook detailed readings of draft analyses, to ensure that any misunderstandings due to translation were corrected.

To understand how the classroom board developed during the lesson, we time-stamped on an image of the board each change, and also annotated the transcript with images of the board at different stages of the lesson. This process was assisted by the common practice in Japan of not erasing content that has been written, so it was straightforward to document the times when each addition to the board was made. We also noted the teacher's and students' gestures when they were speaking standing at the board. (The entire annotated transcript, anonymised, is available at https://figshare.com/XXX.)

The next stage in our analysis involved identifying the mathematical focus of the classroom activity at each phase of the lesson. To do this, we created a time-line, identifying which diagrams were involved in the discussions at each point, and then we identified the strategies in the problem-solving process which were the focus of activity. We compared this lesson description to the planning documents in order to consider the enacted object of learning in relation to the intended (see Pillay & Adler, 2015). In this problem-solving lesson, the lesson objectives were related to mathematical ways of working. Consequently, this comparison provided a framework for identifying key features in the problem-solving process. Noting which features were being attended to allowed the marking of variant and invariant aspects and how these changed over time. We then selected extracts from phases of the lesson (see below) that seemed to exemplify how mathematical foci were identified, and which we felt afforded particular insight into how shifts in attention were orchestrated by the teacher, and how variant/invariant relationships were used.

All of our analysis and interpretations were checked with the teacher, as a co-author.

The lesson

The mathematical problem

The lesson that we now analyse is based on the problem shown in Figure 2, which relates to the Japanese hiragana character “ku” (く), which looks somewhat similar to the geometrical diagram shown in the problem. This task appears in the textbook (Fujii & Matano, 2016, p. 103), and has been widely discussed among researchers, since the same problem (with different values for the angles) was included in the Trends in International Mathematics and Science Study (TIMSS) video *JP1 Finding The Value of an Angle* (see http://www.timssvideo.com/jp1-finding-the-value-of-an-angle#tabs-1). The TIMSS study, in addition to presenting the task, indicated several possible alternative solution methods (shown in Figure 3), and the textbook task that formed the basis for the observed lesson described in this paper included the first two of these. The observed lesson departed from the textbook after the initial sharing of alternative strategies, and, in this lesson, the focus remained on the initial problem, whereas the textbook (and TIMSS lesson) changes the conditions of the problem by allowing point *P* to move.

The rationale for the style of the Japanese problem-solving lesson is the maxim attributed to George Pólya, that “It is better to solve one problem five different ways, than to solve five problems one way”, and the intention in the teacher’s lesson plan (see Figure 4) was to give students adequate time to generate multiple possible solutions, and then to share some of these and discuss them with the whole class.

Problem When *l* // *m*, find four methods to solve for the size of $\angle x$.

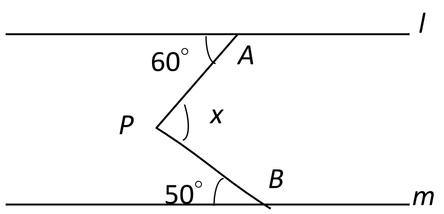


Figure 2. Problem involving angles associated with parallel lines

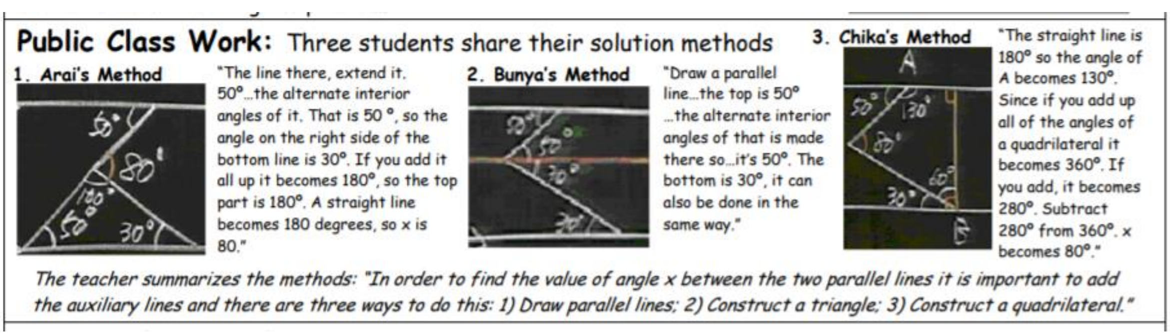


Figure 3. Possible alternative solution methods given in the TIMSS 1999 study (Reproduced from http://www.timssvideo.com/jp1-finding-the-value-of-an-angle#tabs-3)

Lesson Content: Solving for corner angles shaped like the Japanese Hiragana Character 「く」 (types of angles within parallel lines) using various methods.

(1) Objective

・ Students can solve for the corner angles in the shape Japanese Hiragana Character 「く」 (types of angles within parallel lines) using various methods.

・ Students will cultivate the attitude, ability & skill for ways to observe diagrams by using previously learned properties of diagrams.

(2) Lesson Plan

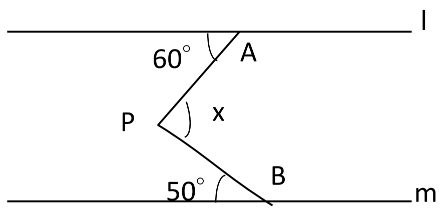
Time	Lesson Content	Anticipated Response	○Teaching Point ●Assessment
	1. Present the Problem	1. Students understand the problem.	○Problem presentation procedure ①Draw parallel straight lines ② Take A and B on l and m ③ Take point P. ④ Connect point P and points A and B ⑤ Give the corner size. ⑥ Distribute worksheet
	<u>Problem</u> When l // m, find four methods to solve for the size of ∠x  		
	2 Independent study	2 Work on their own solutions.	○ In the explanation of the solution, confirm that the reason is given by using "So That" and "From". ○ Have students write several methods during self-solving.
	3 Double-check your hypothesis (idea) First focus on those solutions which were difficult to understand. *"Why did you draw this line?"*	3 Share various ideas. *"I thought that if I could make a triangle, I could use the sum of the interior angles."* *"I wanted to use the properties of parallel lines"*	○ Check and share the grounds for drawing the auxiliary line.
	4 Allow students to contemplate (think) about the nature of the diagrams used in each solution *"What are the properties used as proof?"*	4 Refer back to the properties of the diagram used in each solution.	○ Give solutions from the viewpoint of the nature of the underlying figure.
	5 Allow students think about methods that use the properties of other diagrams not used in this problem "Can you find it using (the nature of diagrams not highlighted in this problem)?"	5 Find new methods to solve the problem by referring to the properties of the diagram.	○ Look at the figure with the eyes of the nature of the figure.
	6 Summary Review the various solutions to check the clarity of each explanation.	6 Reflect on the solution.	○ Confirm that you can see the figure with the eye of the nature of the figure, and draw auxiliary lines so that you can use the nature you want to use.

Figure 4. The teacher's lesson plan – short version (translated). See www.figshare.com/XXX for the full version.

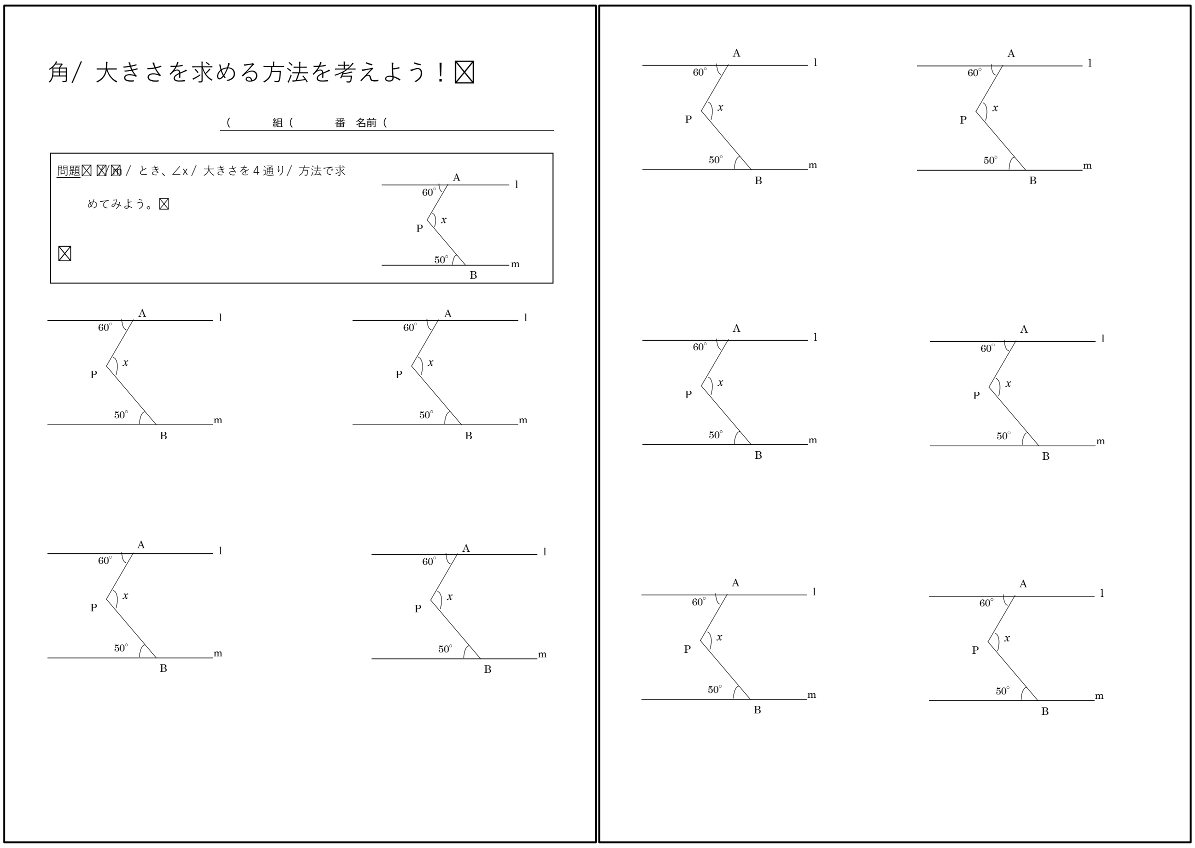
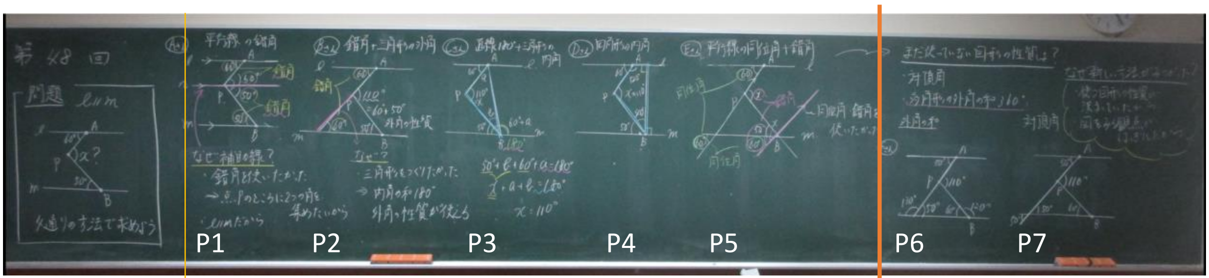


Figure 5. Student worksheet containing space for 10 solutions to the problem.

The text reads: "When *l* // *m*, find four methods to solve for the size of ∠*x*."



Section 1 Section 2 Section 3

Figure 6. The teacher's board plan prior to the lesson (with question reference codes)

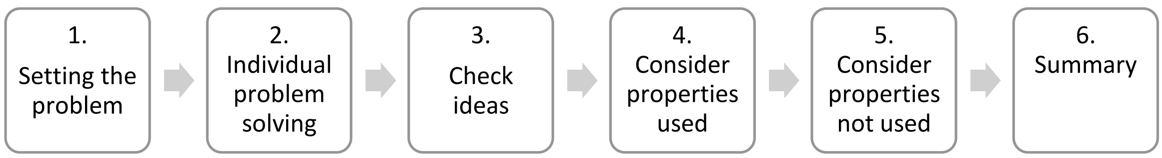


Figure 7. The six phases of the lesson.

The observed lesson

The observed lesson aligned closely with the teacher's lesson plan (see Figure 4). For convenience, we analysed the lesson in the six phases outlined in the plan (figure 7) and used these as descriptive reference points.

In his planning, the teacher identified two *essential* key examples (P1 and P2 in Figure 10), which he was confident that the students would produce, and these were also the two solution methods identified in the textbook. (In our analysis, we number the *p*lanned examples as P1, P2, etc. and the examples that the students *c*onstructed in the lesson as C1, C2, etc.) The examples P1 and P2 were so important to the lesson that the teacher determined in his planning that he would discuss them even if they did not arise from student contributions in the classroom.

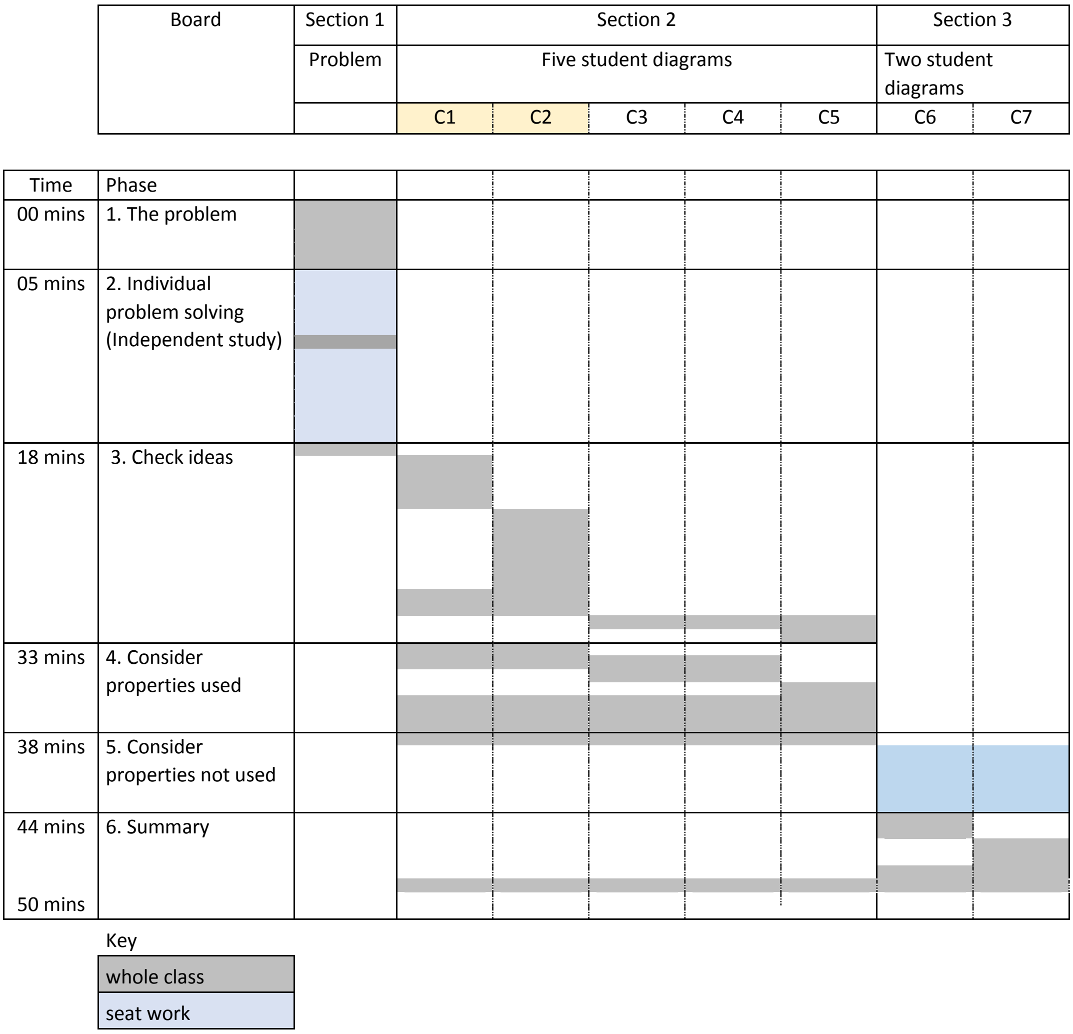


Figure 8. Timeline of the lesson

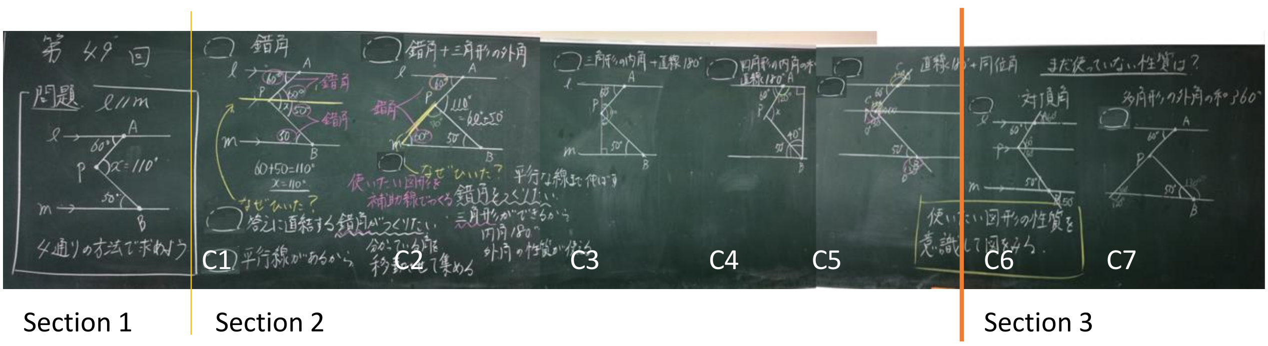


Figure 9. The board at the end of the lesson (with question reference codes)

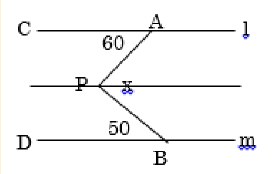
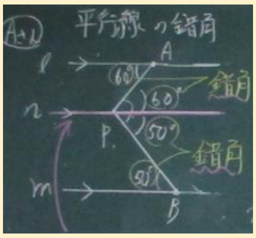
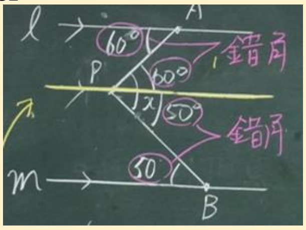
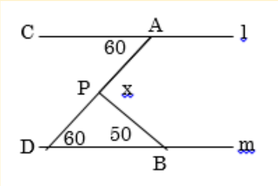
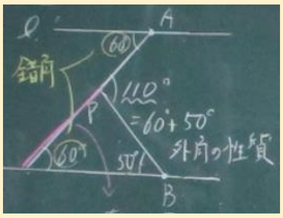
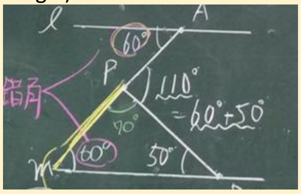
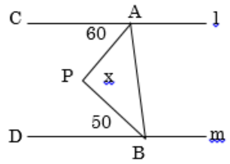
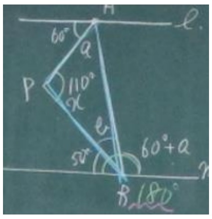
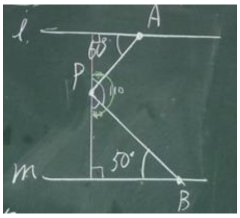
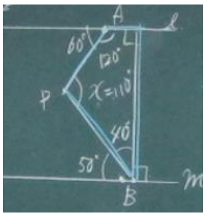
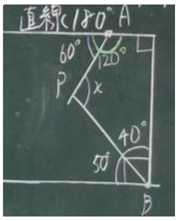
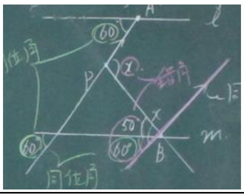
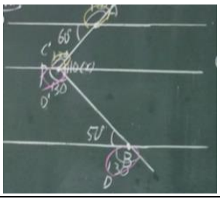
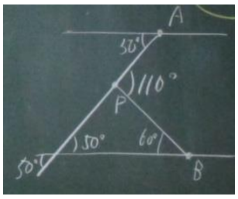
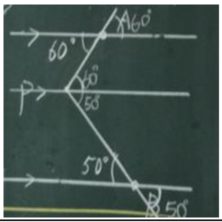
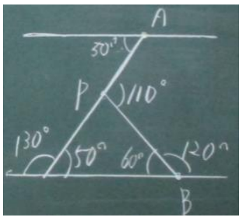
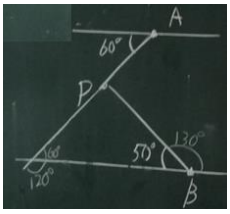
Geometric property	Lesson Plan	Board Planning	Angles Lesson
		Section 2	
Parallel line + alternate interior angles	A. 	P1 	C1 
Alternate interior angles + exterior angle of triangle	B. 	P2 	C2 (and interior angles of a triangle) 
Straight line + interior angle of triangles	C 	P3 	C3 
Sum of four interior angles + straight line		P4 	C4 
Corresponding angles + different properties/ diagrams		P5 Coresponding + alternate interior angles 	C5 Corresponding + straight line 180 
		Section 3	
Vertical angles		P7 	C6 
Sum of exterior angles		P6 	C7 

Figure 10. A comparison of diagrams in planning documents and the board in the lesson.

We now summarise the six phases of the lesson.

At the start of the lesson (**phase 1**, 5 minutes), the teacher introduced the problem (Figure 2), writing it on the board and stating that the goal was to find at least four different ways to solve the problem. This initiated the variation in solution strategies.

In **phase 2** (13 minutes), the students worked largely independently to generate solutions on their worksheets, which were laid out with 10 copies of the drawing, and space beside each one to write their different solutions and annotate their reasoning (Figure 5). While they were doing this, the teacher drew five copies of the diagram on the board and then walked around the classroom, observing the students' work and making notes for himself on a seating plan.

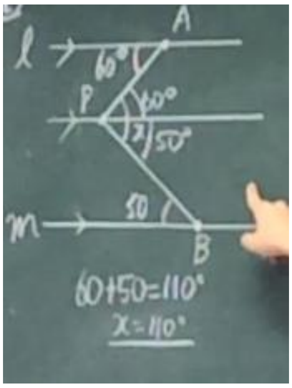
After five minutes, there was a brief plenary discussion, where the answer of 110° was shared. The teacher strategically chose five students and instructed them to draw their completed diagrams on the board, with each diagram labelled with the particular student's initials. While they were doing this, the other students continued working on finding more solutions. The teacher's detailed lesson plan stated:

> Ask students to write 5 different ways on the board. Be sure to pick up A&B [P1&P2]. Select students who wrote explanations how he/she drew auxiliary lines or used new symbols.

Although the students had written explanations of their solutions on their own worksheets, the solutions C1-C5 written on the board consisted only of the completed diagrams, without explanatory annotations. The teacher ensured that the first two diagrams that the students drew (C1 and C2) matched the two solution methods marked as essential in his board plan (P1 and P2). Two of the other three solutions were different from the other solutions that the teacher had written on his board plan (see Figures 6 and 9). C3 used the same identified properties, but with a different diagram, and C5 had a different diagram and combination of properties. Students also generated several other different solutions that were not shared with the whole class, but this phase resulted in five diagrams that formed part of alternative solution strategies being moved to the shared space of the class board.

In **phase 3** (15 minutes), the teacher invited students who had *not* drawn the diagrams to explain C1 and C2.

T	… From this diagram, who can interpret how S1 thought? [some students raised hands] OK let's ask S6. How did you think?
S6	I drew parallel line with *l* and
T	Parallel line, wait, can you explain by pointing to the figure?
S6	[S6 comes to the board and gestures] I drew parallel line with *l* and *m*, find *P* by using alternate interior angle of this.



Extract 1

The teacher then drew attention to the drawing of the auxiliary line, which was highlighted as the key lesson content for this phase of the lesson.

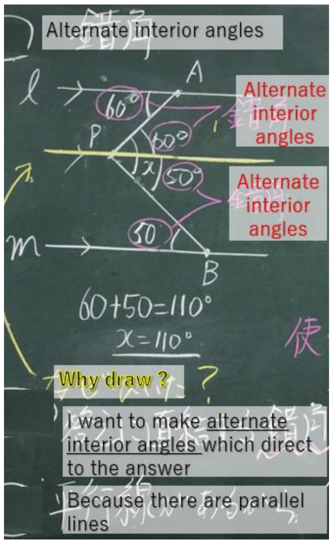
T I draw line here [repeating a student's explanation while overdrawing the auxiliary parallel line in yellow], and here are alternate interior angles and this is alternate interior angles, too [circling angles and naming in red]. And add them, it becomes 110°

⋮

For the first [pointing at the yellow line], you draw a line here. Everyone drew this. Why did you think to draw this line? [writing in yellow "why this line" with an arrow to the auxiliary line; some students raise hands] OK S7.

S7 Because I can make alternate interior angles by drawing this line so that to get answer directly.

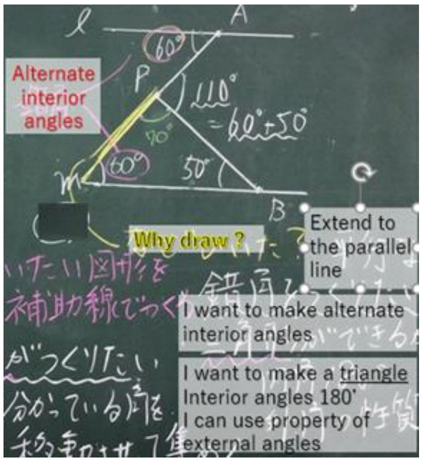
T I can make alternate interior angles to get answer directly. Wait S7, I can make alternate interior angles to get answer directly [the teacher writes the student's initials and this explanation on the board underneath the diagram]



Extract 2

The teacher elicited two further explanations about why this line – "because there are parallel lines" and "put angles which are known together" – which he added to the board before the focus moved to C2.

In a similar manner, student explanations were sought for C2, and, as the diagrams were initially drawn without accompanying explanations, different strategies were possible. Alternate angles, identified in red by the teacher, were the common starting point, but the first student used the property that the sum of the interior angles of a triangle is 180°, and added 70° to the diagram, and a second student used the property that the exterior angle of a triangle is equal to the sum of the two opposite interior angles. After this, as the teacher highlighted the auxiliary line in yellow, he sought further responses to "why this line"; he wrote attributed student explanations under the diagram.



Pointing to C1 and C2, the teacher continued, drawing attention to the invariance in the use of auxiliary lines while the position of the lines varied:

T Now, I asked about auxiliary lines by using two common ways you used. Then, alternate interior angles can be used for this way [pointing at C1], and making a triangle and alternate interior angles can be used for this way, so extend the line. After all, what is your way of thinking when you think about using an auxiliary line?

⋮

S13 Draw auxiliary line in order to use a property of geometric figures, which I want to use.

Extract 3

The teacher then stated that there was not time to discuss C3, C4 and C5 in detail, although in fact there were 18 minutes of the lesson remaining. Instead, he asked “When you observe these three, does anyone have questions how did he/she think?” One student asked about C5, and the teacher sought a volunteer who explained that corresponding angles were used. The teacher repeated “he explained these are corresponding angles”, while pointing at the two pairs of angles, so as to emphasise the approach. During this phase, there was the example of the same geometric property being used in different ways (alternate interior angles) and different geometric properties being used to solve the one problem.

In **phase 4** (5 minutes), the teacher stated that he wanted the students to devise more new ways:

T Since it will not be very positive for you if you think with the same way, I want you to derive new way of thinking. To derive new ways, I want you to look back.

Extract 4

He then reviewed the geometric properties used in each of C1 to C5 with some student contributions. This drew attention to the variation in geometric properties that could be used to solve the same problem, the planned lesson content for this phase. For example:

T What is the property of geometric figures used here? [Indicating C4]

S14 Sum of the four interior angles

⋮

T OK then, let’s look back, let's look back property of geometric figures used, this one used alternate interior angles [C1], this one used alternate interior angles and sum of exterior angles of triangle [C2], this one used sum of interior angles of triangle and straight line [C3], this one used sum of interior 4 angles [C4], this one used straight line and corresponding line [C5].

Extract 5

Following this, in **phase 5** (6 minutes), the teacher asked:

T When you observe these, you used many properties of geometric figures which you learned in grade 8. Is there anything you haven't used yet?

Extract 6

This key question led to student suggestions of vertically-opposite angles being equal and the sum of the exterior angles of polygons being 360°. The teacher then gave the students a further five-minute period of independent study in which to find more ways of solving the problem, using some of the properties that they had just mentioned. Directing the students to properties not yet used, the planned lesson content for this phase, provided them with a strategy for reflecting on the variation in geometric properties. As in phase 2, the teacher circulated, and finally chose two students to write their solutions on the board. The first solution used vertically-opposite angles [C6] and the second solution used the sum of the exterior angles of a polygon [C7].

In **phase 6** (6 minutes), the teacher led a discussion in which the two students who had offered C6 and C7 explained their approaches and talked about their different ways of thinking before and after identifying “ways not yet used”. The teacher summarised the importance of viewing diagrams from the perspective of geometric properties, writing “observe figures by being aware of property of geometric figures” underneath C6 and C7. This reflected the second lesson objective: “Students will cultivate the attitude, ability & skill for ways to observe diagrams by using previously learned properties of diagrams” (figure 4). The discussion moved on to which method the students preferred, where ‘ease’ was the criterion offered by the students and accepted by the teacher.

In overall terms, the students’ thoughts and ideas were very prominent throughout the plenary discussion. Although the teacher spoke more words in total than the students, he often repeated the student contributions word for word, while summarising on the board, with the students’ initials included to indicate the origin of the ideas. In this way, the students’ words formed a large part of the discussion.

Analysis

The problem posed for this lesson had multiple possible solution strategies, with common approaches documented in the associated curriculum materials (Fujii & Matano, 2016). The lesson had two stated objectives: solving the problem using various methods; and developing ways to observe diagrams using previously-learned properties (see Figure 4). While the evidence was that students met the first objective, the comparative analysis of the lesson plan and lesson indicated that both the intended and the enacted object of learning were encapsulated in the second objective; as detailed below, the lesson structure allowed different ‘ways of seeing’ diagrams to be brought into focus.

Established classroom norms for seatwork were for students to work on their own, occasionally talking quietly to their adjacent peers, and for the teacher to circulate, monitoring students’ work, without interacting one-to-one. In the first independent study episode, this gave the teacher time to prepare the board and select which students he would ask to complete five diagrams on the board. The students generated a range of solutions, some of which matched those anticipated in the planning documents, and the teacher was able to select students to complete the first two diagrams (C1 and C2) to match the approaches that he had decided beforehand were essential. There were some differences between the planned solutions and those used in the remaining diagrams (C3, C4 & C5), but the relevant geometric properties were the same (Figure 10). These five solutions were returned to and used in different ways throughout the lesson.

Initially, C1 and C2 were discussed in detail. Both solutions involved drawing an auxiliary line that facilitated the use of alternate interior angles; the use of both features was invariant across these first two examples, but with their positions varying. This provided the opportunity for students to separate the roles that these features can play from their particular placement. The teacher drew attention to the auxiliary line (‘why the line?’) in the initial discussions of C1 and C2 (see Extracts 1 and 2). The close proximity of C1 and C2 on the board, and the associated discussion, could have allowed the students to notice the use of an auxiliary line as an invariant feature, with varying location. However, the teacher then juxtaposed these two examples, pointing to both, and asked a question about drawing auxiliary lines, which drew a more generalised response from a student (see Extract 3); this pedagogical action appeared to shift attention from the individual examples to a more general feature (Watson, 2017), namely the role of the auxiliary line. While students experience variation in different ways (Mason, 2017), this explicit comparison in a sequence of exchanges provided an opportunity for the role of the auxiliary line to be made more visible, and for students to discern this strategy as one that could be applied in multiple ways.

Different additional geometric properties were used in the discussion around C2. This limited variation for the same problem began to open up the possibility of discerning the role that geometric properties could play, separate from their individual features. This was opened up further in the subsequent discussions of all five diagrams. With examples C3, C4 and C5, while the teacher provided an opportunity for students to ask about solutions that they did not understand, these were not discussed in detail. Instead, the teacher reviewed all five diagrams (C1-C5), highlighting which geometric properties had been used (see Extract 5). With the same problem, the role of the geometric properties remained invariant, while the specific properties used varied, potentially making the general application of the strategy more visible to students. This shift, from considering the individual application of properties to exposing their strategic use, was taken one stage further when students were asked to identify 'properties not yet used' (Extract 4). This was possible, as different solutions drew on different combinations of geometric properties. The apparently simple act of having sufficient diagrams accessible for review was a necessary feature, but the examples also had to be carefully selected in order to provide access to an appropriate breadth of properties (see Takahashi, 2006). As with the auxiliary line discussions, the teacher appeared to use the variance and invariance in the examples to draw attention to more general features.

After a couple of unused properties were suggested, a second episode of independent study followed, in which students were asked to generate further solutions. The process of using so-far-unused properties provided the students with a general strategy for finding new solutions, which could be characterised as providing a vehicle to structure students' reflections on the inherent variation. Identifying a property as the starting point gave students access to an alternative perspective on the relationship between a specific case and the general. As before, the teacher monitored their work and selected two students to write their solutions on the board. In the final phase of the lesson, through questioning of students and direct explanation, the teacher showed how an awareness of geometric properties can be used to interpret diagrams. The crafting of the selection and ordering of solutions provided a structure for the exploration of similarities and differences in the subsequent discussions (Takahashi, 2006). In particular, the sequencing allowed different aspects of the diagrams to be brought into focus. Finally, the teacher shifted attention to the *evaluation* of the different approaches by asking which approach the students preferred and why.

The board was central to the *neriage*, and the kind of discussion which took place would have been inconceivable without carefully-considered use of a large board. As planned, the teacher summarised student explanations in the available space under each diagram. In addition to communicating value for these student contributions, this also controlled the pace of the discussions, giving students time to process the ideas (Billman, 2018), and transformed transient verbal contributions into a more permanent record that could be looked at carefully and revisited throughout the lesson (see Extract 2). The student initials written beside each solution positioned students as answerable for what they had produced, and there was an expectation that they could be questioned about it. Labelling solutions with students' names meant that the method could be referred to by invoking that student's name.

The use of the board facilitated shifts in attention throughout the lesson and to different features at different times (Figure 8). The three-part structure of the board, described by Kuehnert et al. (2018) – activating prior knowledge, exploring the problem, and discussing and extending the problem – was clearly visible from the layout on the board, although these three phases occurred in a different order. The problem drew on prior knowledge, in so far as students had studied geometric properties of parallel lines in the preceding lessons. First, within the lesson, C1-C5 allowed the problem to be explored, with the role of the auxiliary line and geometric properties discussed. Second, the teacher activated prior knowledge of geometric properties. Third, the problem was extended by shifting attention to 'properties not used'. Throughout the lesson, items not only had specific places on the board, but also were organised with visible similarities, so as to support students' noticing of similarities and differences. For example, the 'title' written above each diagram was the geometric property used, and yellow chalk was used consistently to mark out the auxiliary line, along with the associated 'why this line?' question. Through gesture, and some overwriting, features were revisited during the lesson, and were used as stimuli for the subsequent stages of the lesson, in ways similar to those described by Greiffenhagen (2014).

As mentioned before, and in common with other descriptions of Japanese lessons, none of the board work was erased at any point during the lesson, thereby providing a coherent written record that facilitated comparison of multiple solutions (Shimizu, 2006). Here, the teacher drew attention to different mathematical features of the problem, making connections between the examples to highlight more general features.

Discussion

The problem used in this lesson is well known, has been used in Japanese classrooms for at least 20 years, and this and similar problems have been frequently discussed in the literature (e.g., Smudge, 1998). The classroom teacher was himself familiar with the problem, and knew it in depth, having taught it previously on many occasions. In addition to the lesson plan, the teacher had a photograph of a sketch on the board of how he anticipated his board to look at the end of the lesson, based on his experiences teaching this lesson previously. Consequently, the teacher was confident about his anticipation of the responses that students might give. He knew which methods were most likely to arise, but he was not completely bound by these. He had considered the problem in detail and decided on the geometrical properties that he wished to draw out. This meant that he had decided beforehand on solutions that he would definitely discuss (P1 and P2), because he felt that they were important to the lesson, and he could be confident that, by asking students to find four ways to solve the problem, these solutions would appear. The teacher's attitude to approaches C3–C5 was more flexible, however. He recognised the properties that were most likely to present themselves, and believed that methods such as using the exterior angle sum of a polygon were unlikely to appear during the first episode of seat-work, and were more likely to arise in phase 5 of the lesson (Figure 7).

The task used was designed to have multiple possible solution methods, and this is a common feature of the Japanese problem-solving approach (Becker et al., 1990). The students were clearly familiar with this type of lesson and understood their teacher's expectations. They worked independently during seat work and were prepared to offer their explanations and questions during whole-class discussion. As mentioned earlier, the format of this kind of lesson is very typical in Japan, and very familiar to the students. The novelty for the Japanese observers of this lesson was in seeing such an expertly-executed enactment of the lesson, and contemplating the teacher's skilful balancing of expected and unexpected solutions, and the teacher's particular emphasis on the strategy of brainstorming relevant geometrical properties and using these to stimulate the generation of additional solution methods.

No new mathematics content knowledge was explicitly introduced during this lesson – the students had met the geometric properties in previous lessons. Instead, the focus in this lesson was firmly on comparing alternative approaches and matching these up with the geometrical properties used. There was also the important idea of exploiting *unused* properties as a tool for generating new solutions and approaches. The teacher wished students to see the power of drawing auxiliary lines that allowed particular geometric properties to be brought into play (Figure 5). Here, the shift was from lines, to properties, then to *not-yet-used* properties, which were then discussed in the last phase of the lesson, in order to evaluate which approach might be preferable to use in the future. This allowed for the shift from specific individual examples to the desired generalisations.

The *neriage* phase of the lesson was carefully orchestrated by the teacher and decidedly moved very far beyond 'show and tell' (Stein, Engle, Smith, & Hughes, 2008). Based on his prior experience, and his knowledge of the class, the teacher had a very clear idea beforehand which solutions were most likely to occur. The two solutions used in the board-work, C3 and C5, were not identical to those in the photograph of the board-work from the mock-up lesson, or to those in the lesson plan; however, the geometric properties that the teacher had deemed essential were the same. After the first two solutions had been discussed, and relatively early in the lesson, the teacher stated that because he was "short of time" he would not be going through the remaining solutions in detail. We asked him in discussion after the lesson about his reason for saying this, and he stated that this was deliberate and strategic. He had decided that the details of these solutions were less important to him than giving further time for the students to generate their own solutions. However, he still checked if students had any questions regarding the solutions, with one student indeed questioning C5.

The teacher frequently moved back and forth between the diagrams on the board throughout the lesson, drawing out the connections. The purposeful set-up of the board to display each method side by side allowed the teacher to continually revisit the diagrams during the discussions. Each of the initial diagrams C1-C5 was referred to during at least three of the phases of the lesson (Figure 8). Continually moving among the diagrams, the teacher made strategic use of colour to draw attention to the key features of the diagrams. When referring to the auxiliary lines added by the students, the teacher highlighted these lines in yellow every time. Angles and their properties were consistently drawn in red, the use of different colours making it clear which parts of the board-work were later additions and which were part of the original drawing. There was also consistency in the teacher's use of language, with him repeatedly asking, 'Why this line?' when highlighting the auxiliary line in yellow, and he wrote this question on the board. Most of the discussion questions during the plenary were posed orally by the teacher, but this particularly central question was important enough for the teacher to write onto the board and keep referring to it.

Students were challenged to find new ways to solve the problem, with the teacher recognising that just being asked to try to find more would be tough. So, as a tactic for finding new solution methods, the teacher drew up a summary of all of the angle properties used in the solutions produced so far. In this way, the main summary (*matome*) of the lesson went beyond 'Show and tell' (Stein, Engle, Smith, & Hughes, 2008) by drawing explicit attention to focusing on geometrical properties that could be used to generate alternative strategies. Another key question the teacher asked was: "Is there anything not used yet?" (Extract 6). Students were already apparently confident in their understanding of the relevant geometrical properties; the purpose of this lesson was clearly to provide them with a strategy to find new ways to apply their knowledge for this particular problem. After the students stated some so-far-unused geometrical properties, more time was given to find additional solutions using these properties.

Conclusion

It is essential that episodes of problem-solving in mathematics lessons allow students to learn something *beyond* the details of that particular problem, that will benefit them in future problem-solving situations (Foster 2019). In this paper, we analysed a Grade 8 (age 13-14) Japanese problem-solving lesson involving angles associated with parallel lines that was taught by an extremely well-regarded Japanese mathematics teacher. We explored how the teacher used carefully-planned board-work to support a rich whole-class discussion (*neriage*), where the focus shifted from individual examples to generalised properties. By the end of this lesson, students were looking again at the problem in terms of aspects not yet considered, with a focus on the properties of geometrical figures. They were shown the strategy of listing known properties and actively seeking to use these to generate further solutions – a powerful approach sometimes referred to as "What do you know? What do you want?". With attention on the second objective, the teacher intended to develop not just a strategy for problem solving but mathematical ways of viewing, and thinking through the process of, problem solving.

This is strikingly different from our experience of typical problem-solving lessons within Western mathematics classrooms (our experience is mainly in the UK and the US), where problems are often broken down into smaller steps and a single solution is often accepted as adequate. A large number of problems would typically be tackled in an hour's lesson, rather than, as in this case, just one. This approach to problem solving can leave students believing that there is only one way to solve any problem, and can fail to give students powerful generic strategies to employ when an immediate approach to solving a problem does not present itself (Foster, 2019; Schoenfeld, 1998). Another difference we perceive between typical problem-solving lessons within Western mathematics classrooms (and also some lessons taught in Japan) and this lesson is the explicit way in which a strategy is offered to the students. Initially, the students were merely exhorted to find solutions. But, for the second phase of seat-work, they were equipped with a strategy based on listing known properties and seeking to build a solution from one or more of these. In this way, the students are being taught concrete strategies for succeeding with problem-solving tasks which are not content-specific. We believe that this is rare in problem-solving lessons within Western mathematics classrooms.

By the end of the observed lesson, the board contained a written record of an extremely rich discussion. By having all of the solutions visible at once, students had been able to follow the 'flow' of the lesson and repeatedly examine connections between approaches, as similarities and differences were brought to their attention (Shimuzu, 2006). At the end of the lesson, students were reminded that it is difficult to solve a problem when thinking aimlessly, and the importance of considering the possible geometrical properties was stressed. Often, in problem-solving lessons, the first method presented is the least sophisticated, but in this case the first method was among the most efficient, and was the one that most students said they would be most likely to use in the future. For us, this underscored the point that the purpose of the lesson had not been narrowly to solve this problem, but to enhance how to observe geometrical figures in a mathematical way. The strategy of starting with properties seemed to allow students to creatively invent solutions to the problem that they otherwise might not have had been able to access.

Finally, we note the relative stability of the Japanese curriculum: it is infrequently changed, and when it is changed this is by small increments. Any major revisions are carefully considered and researched before introduction within schools (Lewis and Takahashi 2013), and this supports a strong distributed knowledge among the teaching community. We strongly suspect that this enables a depth and sophistication to the teaching of problem solving in Japan that we have rarely seen elsewhere.

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