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ABSTRACT

The introduction of technology resources into mathematics classrooms promises to create opportunities for enhancing students' learning through active engagement with mathematical ideas; however, little consideration has been given to the potential for technology to promote a more collaborative approach to learning. This paper draws on data from a three year longitudinal study of senior secondary school classrooms to examine pedagogical issues in using technology in mathematics teaching-where "technology" includes not only computers and graphics calculators but also projection devices that allow screen output to be viewed by the whole class. The researchers theorize and illustrate four roles for technology in relation to such teaching and learning interactions-master, servant, partner, and extension of self. The research shows how technology can facilitate collaborative inquiry, during both small group interactions and whole class discussions where students use the computer or calculator and screen projection to share and test their mathematical understanding. (Contains 23 references and 2 figures.) (Author/ASK)

Theoretical Perspective

Mathematics curriculum and policy documents now place increased emphasis on the processes of problem solving, reasoning, and communication, and endorse student discussion of mathematical ideas as a means of developing and reflecting on their understanding (NCTM, 2000; Australian Education Council, 1991). These moves for curriculum reform are supported by current research in mathematics education that draws on sociocultural theories of learning (Vygotsky, 1978; Wertsch, 1985; Wertsch & Rupert, 1993). From this theoretical perspective, mathematics teaching and learning are viewed as social and communicative activities that require the formation of a classroom community of learners where the epistemological values and communicative conventions of the wider mathematical community are progressively appropriated and enacted (Brown, Stein & Forman, 1995; Goos, Galbraith & Renshaw, 1999; Forman, 1996; Schoenfeld, 1989). In such classrooms, discussion and collaboration are valued in building a climate of intellectual challenge. Rather than relying on the teacher as an unquestioned authority, students are expected to propose and defend mathematical ideas and conjectures, and to respond thoughtfully to the mathematical arguments of their peers.

The increasing availability and power of electronic technologies such as computers and graphics calculators offers new opportunities for students to communicate and analyse their mathematical thinking, since the objects generated on the screen can act as a common referent for discussion (NCTM, 2000). Most importantly, technology can foster conjecturing, justification, and generalisation by enabling fast, accurate computation, collection and analysis of data, and exploration of multiple representational forms. Consistent with our sociocultural perspective, we regard technology as one of several types of cultural tools – sign systems or material artefacts – that not only amplify, but also re-organise, cognitive processes through their integration into the social and discursive practices of a knowledge community (Resnick, Pontecorvo & Säljö, 1997). The amplification effect may be observed when technology simply supplements the range of tools already available in the mathematics classroom, for example, by speeding tedious calculations or verifying results obtained by hand. By contrast, cognitive re-organisation occurs when learners' interaction with technology as a new semiotic system qualitatively transforms their thinking; for example, use of spreadsheets and graphing software can alter the traditional privileging of algebraic over graphical or numerical reasoning. Accordingly, learning becomes a process of appropriating cultural tools that transform the relationships of individuals to tasks as well as to other members of their community.

The Classroom Study

Data collection over three years from 1998-2000 involved five senior secondary mathematics classrooms from one independent school (two classrooms) and two government schools (three classrooms) in a large Australian city. Students participating in the study were in either Year 11 or Year 12, the final two years of secondary schooling, and were taking either Mathematics B alone (a calculus and statistics subject required for entrance to tertiary courses in science, business, and engineering) or Mathematics B and C (the latter being an advanced subject usually chosen by students wishing to specialise in mathematics at university).

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The introduction of technology resources into mathematics classrooms promises to create opportunities for enhancing students' learning through active engagement with mathematical ideas; however, little consideration has been given to the potential for technology to promote a more collaborative approach to learning. This paper draws on data from a three year longitudinal study of senior secondary school classrooms to examine pedagogical issues in using technology in mathematics teaching – where "technology" includes not only computers and graphics calculators but also projection devices that allow screen output to be viewed by the whole class. We theorise and illustrate four roles for technology in relation to such teaching and learning interactions – master, servant, partner, and extension of self. Our research shows how technology can facilitate collaborative inquiry, during both small group interactions and whole class discussions where students use the computer or calculator and screen projection to share and test their mathematical understanding.

This paper reports on a three year longitudinal study that investigated the role of electronic technologies (graphics calculators and computers) in supporting students' exploration of mathematical ideas and in mediating their social interactions with teachers and peers. Numerous research studies have examined the effects of technology usage on students' mathematical achievements and attitudes, and their understanding of mathematical concepts (e.g. Adams, 1997; Lesmeister, 1996; Quesada & Maxwell, 1994; Weber, 1998). However, the quasi-experimental design of many of these studies is based on the assumption that the same instructional objectives and methods are valid for both pen and paper and technology enhanced tasks. Less is known about how the availability of technology, especially graphics calculators and their peripheral devices, has affected teaching approaches (Penglase & Arnold, 1996). Some studies have found changes in classroom dynamics leading to a less teacher centred and more exploratory environment (e.g. Simonsen & Dick, 1997). However, it appears that negotiation of such a pedagogical shift is mediated not only by teachers' mastery of the technology itself, but also by their personal philosophies of mathematics and mathematics education (Tharp, Fitzsimmons & Ayres, 1997; Thomas, Tyrrell & Bullock, 1996).

Unlike much previous research in this area, our study explicitly addresses technology as a tool that is integral to the mathematical practice of students and teachers in particular learning environments. We theorise four roles for technology in relation to teaching and learning interactions – "master", "servant", "partner", and "extension of self" – to show how technology re-organises interactions between human and technological agencies, and changes the ways that knowledge is produced, shared, and tested. In contrast with other similar studies (see Doerr & Zangor, 2000), our findings suggest that technology can facilitate collaborative inquiry through both small group conversations and whole class discussions where students use screen projection devices to present their work publicly for critical scrutiny.

While at the time of the study the syllabuses for both subjects did not yet mandate the use of graphics calculators and computers, teachers were strongly encouraged to make use of these technologies wherever appropriate. All classes had ready access to either desktop or laptop computers equipped with generic (e.g. spreadsheet) and mathematical (e.g. graphing) software. The independent school and one of the government schools provided students with graphics calculators for use both at school and at home. The other school owned several class sets of calculators that were made available to students only during mathematics lessons when their use was planned in advance.

At least one lesson every week was videotaped and observed, but more frequent classroom visits were scheduled if the teacher planned a technology intensive approach to the topic. Audiotaped interviews with individuals and groups of students were conducted at regular intervals to examine the extent to which technology contributed to students' understanding of mathematics, and their perceptions of how technology changed the teacher's role in the classroom. At the beginning and end of each year, students also completed a questionnaire on their attitudes towards technology and its role in learning mathematics (see Geiger, 1998). This paper draws on videotape, observational and interview data.

How Do Students and Teachers Use Technology?

Few studies have investigated how and why students use technology to learn mathematics in specific classroom contexts, and how the roles of students and teachers might change when technology is integrated into the mathematics curriculum. Amongst these, Doerr and Zangor (2000) in an observational case study of two pre-calculus classrooms identified five modes of graphics calculator use: computational tool, transformational tool, data collection and analysis tool, visualising tool, and checking tool. Taking a somewhat different approach, Guin and Trouche (1999) categorised their observations of students using graphic and symbolic calculators into profiles of behaviour, in order to understand how students transformed the material tool into an instrument of mathematical thought that re-organised their activity. The nature of this transformation varied according to whether the student displayed a random, mechanical, rational, resourceful, or theoretical behaviour profile in terms of their ability to interpret and coordinate calculator results. With respect to classroom interactions, Farrell (1996) observed a shift in both teachers' and students' roles towards that of consultant and fellow investigator, accompanied by a similar movement away from teacher exposition towards planned or informal group work.

Our own conceptualisation of technology usage in mathematics classrooms differs from previous research in that it encompasses interactions between teachers and students, amongst students themselves, and between human and technology, in order to investigate how different participation patterns offered opportunities for students to engage constructively and critically with mathematical ideas. Our analysis of technology focused classroom interactions is framed by four metaphors we have developed to describe the varying degrees of sophistication with which teachers and students work with technology. Note that these modes of working are not necessarily tied to the level of mathematics taught, or the sophistication of the technology available.

In addition, we have observed that teachers and students do not necessarily remain attached to a single mode of working with technology.

Technology as Master

Teachers and students may be subservient to the technology if their knowledge and usage are limited to a narrow range of operations over which they have technical competence. In the case of students, subservience may become dependence if lack of mathematical understanding prevents them from evaluating the accuracy of the output generated by the calculator or computer.

Technology as Servant

Here technology is used as a fast, reliable replacement for mental or pen and paper calculations – that is, technology is not used in creative ways to change the nature of activities in which it is used. For example, a graphics calculator can be restricted to the purpose of producing answers to routine exercises; or an overhead projection panel can be limited to providing a medium for the teacher to demonstrate calculator operations to the class.

Nevertheless, we have noted interesting variations in the way teachers operate with technology in this mode. One emergent property of the graphics calculator involves its use in conjunction with other material resources in ways that further enhance the calculator's capacity for linking multiple representations of a concept. For example, one teacher used transparent grid paper, plastic cut out polygons, and the overhead projector to physically demonstrate the results of matrix transformations such as

$$\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \text{ and } \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}.$$

Students then investigated further with their own polygons and grid paper by recording the coordinates of the vertices before and after transformation, with the graphics calculator taking care of the matrix calculations so that conjectures on the geometric meaning of the transformations could be formulated and tested. While the technology is still used to support the teacher's preferred approach involving manipulable materials, it becomes an intelligent servant that complements the effective features of more conventional instruction.

Technology as Partner

Here a rapport has developed between the user and the technology, which is used creatively to increase the power students have over their learning. Students often appear to interact directly with the graphics calculator, treating it almost as a human partner that responds to their commands – for example, with error messages that demand investigation. The calculator acts as a surrogate partner as students verbalise their thinking in the process of locating and correcting such errors. Calculator or computer output also provides a stimulus for peer discussion as students cluster together to compare their screens, often holding up graphics calculators side by side or passing them back and forth to neighbours to emphasise a point or compare their working.

Creative partnerships between teachers and technology are also possible. For example, instead of functioning as a transmitter of teacher input, the overhead projection panel can become a medium for students to present and examine alternative mathematical conjectures. This emergent property of technology is illustrated by the practice of inviting students to compare and evaluate programs they have written to simplify routine calculations, such as finding the angle between two three-dimensional vectors. The public display of student work facilitated whole class discussion with the student-presenters themselves leading the dialogue and trying out different command lines in response to suggestions from peers in the audience.

A further emergent feature of the viewscreen as part of the mathematical practice of the classroom is its attraction for students who are initially reluctant to accept the social and cultural norms of a community of learners. Here we observed how one student consistently rejected the teacher's invitations to discuss his thinking with peers, participate in whole class discussions, and generally take some responsibility for advancing his mathematical understanding. This situation changed when the student was persuaded to use the viewscreen to show the class an animated program he had created that depicted the adventures of mathematical objects as human-like characters. The enthusiastic and admiring response to his "movie" (and several "sequels") was significant in drawing this student into the kind of mathematical discussion he had previously resisted, and he became a willing participant in subsequent technology-focused discussions.

Technology as Extension of Self

The most interesting mode of functioning, this involves users incorporating technological expertise as an integral part of their mathematical and/or pedagogical repertoire. From the teacher's perspective, writing courseware to support an integrated teaching program would be an example of operating at this level. Similarly, students may incorporate a variety of technological resources into the construction of a mathematical argument. An illustration of technology in this role is provided in the following section.

A Classroom Episode

This episode spans two consecutive lessons in a Year 11 Mathematics C classroom in the independent school referred to earlier. The teacher (the fourth author of this paper) was an expert and innovative user of technology with considerable experience in curriculum design. As the option existed within the Mathematics C syllabus for schools to design and teach a topic of their choice, the teacher had chosen to introduce students to iteration as one of the central ideas of chaos theory. This topic was presented as a teacher-prepared booklet containing a series of spreadsheet examples and tasks for students to work through at their own pace. One particularly challenging task involved using iterative methods to find approximate roots of equations such as $x^3 - 8x - 8 = 0$. The equation may be expressed in the form $x = F(x)$, and a first approximation to the solution is obtained by estimating the point of intersection of the curves $y = x$ and $y = F(x)$. This approximate solution is used as the initial value in a two column spreadsheet, where the first column provides input x-values for $F(x)$ in the second column, and the output of $F(x)$ becomes the input of subsequent iterations. Figure 1 shows the calculation when $F(x) = \frac{x^3}{8} - 1$. Cell B3 contains the formula =(1/8)*((A3)^3)-1 and cell A4 contains =B3, both these formulae then being copied down into the other cells in these columns.

	A	B
1	x^3-8x-8=0 rearranged as x=x^3/8-1	
2	x	F(x)
3	-1.5	-1.421875
4	-1.421875	-1.35933065
5	-1.35933065	-1.31396797
6	-1.31396797	-1.28357265
7	-1.28357265	-1.26434517
8	-1.26434517	-1.25264282
9	-1.25264282	-1.24569243
10	-1.24569243	-1.24162534
11	-1.24162534	-1.23926640
12	-1.23926640	-1.23790525

Figure 1. Spreadsheet method for solving equation by iteration.

Depending on the way in which the original equation is rearranged and the initial value chosen, the iteration may converge on a solution, or generate increasingly divergent outputs and hence no solution. Rearranging $x^3 - 8x - 8 = 0$ as $x = \frac{x^3}{8} - 1$ yields only one of the three roots (–1.236). To find the other roots of this cubic equation (–2 and 3.236), students must investigate other rearrangements and a range of initial values.

In an earlier study, Goos (1998) found that students attempting this task quickly discovered that they could create an alternative, graphical, representation of the problem with the graphing software installed on the school's computers. Plotting the graphs of $y = x$ and $y = F(x)$ enabled students to make a realistic first approximation to the roots of the equation (see Figure 2). In addition to spreadsheets and function graphing software, students participating in the present study chose to use their TI-83 graphing calculators to tackle this task.

Episodes involving one group of students have been reconstructed with the aid of lesson observation notes and videotape records, and the transcript from a group interview conducted soon after the lessons in question. Interview questions and student responses are integrated into the following account, and distinguished by *italics*. Critical points where the teacher intervened are highlighted in **boldface** type. (The first author observed the lessons and interviewed students.)

Lesson 1

Four students (Hayley, Nerida, Sally, David) clustered around a laptop computer, sharing the responsibilities of pencil-and-paper and keyboard work. (Other similar groups were working on the same task in the classroom.) Initially the students used graphing software only, although this was intended to be primarily a spreadsheet task:

Hayley: Should we be using the spreadsheet?

Nerida: I don't think so ... the spreadsheet's just a way of checking.

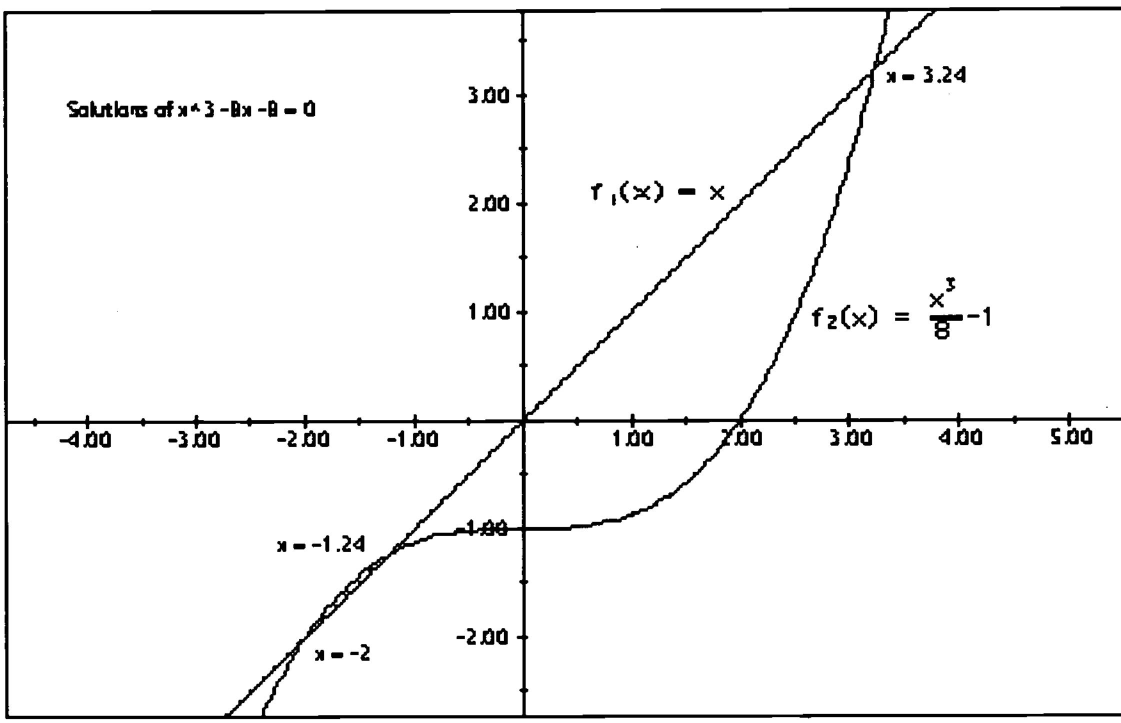

Figure 2. Graphical representation of iterative solution to $x^3 - 8x - 8 = 0$

The students rearranged $x^3 - 8x - 8 = 0$ as $x = \frac{x^3}{8} - 1$ and plotted it on the same axes as $y = x$. Three intersection points were clearly visible (see Figure 2), much to their dismay:

Sally: Oh no no! It's gone through it too many times!

They zoomed in on only one intersection point to find the x-coordinate, and obtained an approximate value of 3.24. Ignoring the other solutions, they used the TI-83's Equation Solver with this value entered as an initial guess. The group accepted this as "the" solution – there was no attempt to explore other two intersections. They then moved on to the next problem.

After a few minutes Nerida reminded the others that they zoomed in on only one intersection point for the cubic equation.

Nerida: We ignored the other two. Why did the Solver only pick up one?

The students seemed unaware of the limitations of the calculator's Equation Solver, which yields one solution that is closest to an initial guess within specified bounds. The lesson ended before this anomaly could be explored further.

Lesson 2

At the start of the lesson the observer mentioned to the teacher that this group of students had not used spreadsheets at all. The teacher repeated the task instructions to the whole class, emphasising the importance of the spreadsheet approach.

Interviewer: You accepted this (i.e. $x = 3.24$) as the only solution ... Did it occur to you to explore further?

Sally: We didn't realise! We only did when [the teacher] told us to.

The students started on the cubic problem again, this time using a spreadsheet. They entered a formula equivalent to their original rearrangement of the equation ($x = \frac{x^3}{8} - 1$) and "filled down" the columns until the values converged. However, their answer, –1.23 (see Figure 1), did not match the graphical result obtained earlier:

Sally: But we got 3.24!

Hayley reminded the group that there were three intersection points visible on the graph, and suggested they might find the other two solutions if they continued scrolling down their spreadsheet. When this was not successful they called the teacher over and requested clarification as to how the spreadsheet worked. He re-focused the group on the important elements of the task, and issued a challenge:

Teacher: Is it possible to use the spreadsheet to get all three solutions?

The students found that trying different initial values made no difference to their position: the spreadsheet values either converged on –1.23 or became increasingly large. David reproduced the graph previously plotted on the computer with the aid of the TI-83, thus enabling the graph and spreadsheet to be viewed simultaneously.

Interviewer: I noticed you used the TI-83 to draw graphs.

David: It's quicker than multi-tasking!

Nerida: Otherwise we'd have to swap around (i.e. between spreadsheet and graphing program) using the computer and it takes ages.

They continued trying different initial values, to no avail. After conferring once more, they called on the teacher again:

David: Are you going to tell us?

Teacher: No ... Take a walk around the class and see what the other people have done.

The four students dispersed to consult with other groups, and discovered two other ways of rearranging the equation: $x = \sqrt[3]{8x+8}$ and $x = \frac{8x+8}{x^2}$. These gave the "missing" spreadsheet solutions of 3.24 and –2 respectively.

Interviewer: Would you have thought have doing that (i.e. visiting other groups) on your own?

David & Sally: [in unison] No – We're too self-centred!

On reconvening the group, the students pieced together the information they had obtained, set up the relevant spreadsheets and confirmed they had found all three solutions. This resulted in some excitement as no other group had managed to do so.

Making a spur of the moment decision, the teacher asked the group to connect their laptop computer to the data projector and present their findings to the class. The students quickly decided who would operate the computer keyboard, data projector remote control (which permitted scrolling and zooming independently of the computer), and laser pen. Their explanations, although unprepared, were coherent and coordinated, and they were able to answer questions posed by other members of the class. Mathematical and communications technologies were thus used to share and support argumentation on behalf of the group of students.

Interviewer: *What made this task exciting compared with other things you'd been doing?*

Students: *[overlapping] It was new! Like a prac, very hands on. And we got involved because we were working with friends. We were doing it ourselves, not just listening to the teacher. And seeing something visual helped our understanding.*

Hayley: *You feel you've achieved something when you did it all by yourself!*

Implications for Learning and Teaching

The classroom episodes presented above illustrated how students' task performance was shaped by the tools available to them (graphing software, spreadsheet, graphics calculator) and by the sociocultural context of the classroom. In particular, the teacher's actions in orchestrating students' interaction with the task, the technology, and their peers proved to be crucial to their success in finding a solution to the cubic equation. The impact of four instances of teacher intervention could be summarised as:

1. directing the students to explore the problem with a spreadsheet, in addition to their first choice of a graphing program, so that potential *connections between numerical and graphical representations* of the task could be recognised;
2. issuing a challenge to find all three roots with spreadsheet methods, thus forcing students to confront the issue of *what counts as a "solution"*;
3. strategically withholding assistance and encouraging the students to consult with other groups, which simultaneously endorsed the values of *intellectual autonomy* (from the teacher) and *collaboration* (with peers);
4. inviting the group to present their findings to the rest of the class, to encourage *public and critical scrutiny of mathematical arguments*.

As has been noted elsewhere (e.g. Doerr & Zangor, 2000; Tharp, Fitzsimmons & Ayres, 1997; Thomas, Tyrrell & Bullock, 1996), teachers' beliefs about mathematics and mathematics education influence their pedagogical strategies in making use of technology. In an earlier study we examined the way in which this teacher established a classroom community of mathematical practice, the assumptions about teaching and learning mathematics implicit in our observations of teacher-student interactions, and the teacher's espoused pedagogical beliefs (Goos, Galbraith & Renshaw, 1999). The teacher's interventions listed above were consistent with his beliefs concerning students making sense of mathematics, teacher encouragement of conjecturing and justification, and the role of peer interaction in developing deep understanding.

Discussion

The relationship between technology usage and teaching/learning environments is not one of simple cause and effect. The four metaphors of master, servant, partner, and extension of self are intended to capture some of the different ways in which technology enters into the mathematical practices of secondary school classrooms. Whereas Doerr and Zangor (2000) in a similar study found that use of the graphics calculator as a private device led to the breakdown of small group interactions, our own observations show that graphics calculators as well as computers facilitated communication and sharing of knowledge in both private and public settings. Students interacted both with and around the technology; for example, the calculator became a stimulus for, and partner in, face to face discussions when students worked together in groups. Similarly, when students shared their work publicly via the overhead projection panel or data projector the technology was transformed from a presentation device to a discourse tool that mediated whole class discussion.

The NCTM's *Principles and Standards for School Mathematics* (NCTM, 2000) discusses the role of technology as one of six overarching principles describing features of high quality mathematics education. This Principle states that "technology is essential in teaching and learning mathematics"; it enhances mathematics learning, supports effective mathematics teaching, and influences what mathematics is taught (pp. 24-26). Our research contributes to this discussion by identifying emergent (unplanned, unanticipated) modes of technology use by teachers and students that characterise specific classroom learning environments.

These findings have theoretical and practical implications for mathematics teaching and learning. Theoretically, we have elaborated different ways in which technology may be appropriated as a cultural tool by teachers and students. From a practical perspective, our study demonstrates that graphics calculators, computers, and projection units are not passive or neutral objects, as they can re-shape interactions between teachers, students, and the technology itself. This highlights a number of challenges for teachers in integrating new technologies into their practice in addition to the obvious requirement to gain technical expertise. More attention needs to be directed to the inherent mathematical and pedagogical challenges in technology-enhanced classrooms if the goal of an investigative and collaborative learning environment is to be realised. Perhaps the most significant challenge for teachers lies in orchestrating collaborative inquiry so that control of the technology, and the mathematical argumentation it supports, is shared with students.

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