

Re:design for Learning

A study of the co-construction of a technological tool for mathematical learning

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Abstract

This dissertation examines the development and use of an educational technology with the aim of enriching our understanding of the relationships among technology, teachers, students and mathematical activity. Drawing inspiration from the premise articulated in the genetic analysis research of Vygotsky (1978, 1986) that to understand a learning situation we must study it *in situ* and, in addition, investigate its history, I propose that examining the development of an educational technology can help us to better understand how and why it comes to be used the ways it does in classrooms. Starting with the development of a technology, I follow it into mathematics classrooms and examine the ways teachers and students work with it. For this investigation, I draw on a growing body of research in the field of Science and Technology Studies that examines the development and use of technology and the relationships between humans and their tools (Akrich, 1992; Bijker, 1997; Latour, 2007; Suchman, 2006). This research offers approaches to understanding the complex non-linear nature of the interactions between a technology's development and the ways it is used. In addition, I draw on the sociocultural approach of Activity-Theory (Vygotsky, 1978; Leont'ev, 1978) to help me conceptualize learning as tool-mediated activity. I present the findings of this study in three journal articles that show that the development of educational technology is not necessarily a linear process, that teachers and students find innovative ways to shape the tools they use, and that their innovations may become formalized as part of new versions of a technology. The findings also illustrate that the introduction of new educational technology has wide-ranging mediational effects on the human and material relationships within classroom networks of activity and that the development and use of technologies designed for mathematical learning reflexively mediate and are mediated by mathematical activity.

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Chapter 1. Introduction

The genesis of this project lies in my interest in what Sørensen refers to as the ‘materiality of learning’ (2009). This interest in the objects involved in learning situations begins with my time working as an industrial designer. After graduating from design school, I started my professional practice creating objects as diverse as swimming goggles and telecommunications systems for doctors to interact with patients at a distance. While the objects I designed were diverse, my primary interest throughout was in the relationship between humans and their tools. Later, I had the opportunity to develop interactive museum exhibitions and these experiences sparked a desire to understand more about the role of tools in how we learn so that I could create better technologies to support learning. This interest developed into a passion for examining the relationship between the development and use of technology for learning that has driven my research throughout graduate school.

My interest in the materiality of learning is broad and cuts across learning settings and subject areas, but for this project I was drawn to the sheer volume and richness of digital technologies used in mathematics classrooms. In recent years, digital technologies such as computer algebra systems (CAS) and dynamic geometry software have developed into useful education-focused tools (Hoyle & Noss, 2003; Kidwell, Ackerberg-Hastings & Roberts, 2008). Current mathematics education research suggests that technologies have the potential to help learners make connections with and between mathematical concepts and enrich their mathematical thinking (Kaput, 1998; Kaput & Schorr, 2008; Noss, Healey & Hoyle, 1997). Research indicates that technologies such as graphing calculators, dynamic geometry software and CAS encourage learners to make mathematical conjectures, investigate those conjectures,

and engage in mathematical reasoning as they make meaning of mathematical concepts (Harvey, Waits & Demana, 1995; Heid & Edwards, 2001; Hollar & Norwood, 1999; Knuth & Hartmann, 2005; Laborde, Kynigos, Hollebrands & Strässer, 2006; Yerushalmy, 2006). Simultaneously, the most recent mathematics curricula in many jurisdictions now focus on the pedagogical importance of working with multiple ways of representing mathematical concepts, such as those offered by educational technologies and strongly encourage their use (National Council of Teachers of Mathematics, 2000; Ontario Ministry of Education, 2005; Qualifications and Curriculum Authority, 2007). This support and other factors, including the shrinking cost of computers, have led to the increasing presence of digital technologies in many classrooms.

Examining literature that discusses digital technologies and mathematical learning through the lens of my interest in technology development, I was surprised to find little discussion of development processes or the ways that these processes may influence learning. I found this despite calls from a number of mathematics education researchers that inquiries into technology in classrooms move beyond questions of whether or not technology should be used and ask more nuanced questions about the nature of technology and its use (Drijvers & Trouche, 2008; Hoyles & Noss, 2003, 2008). My experiences as a designer of technology for learning alluded to a complex relationship between development, users and learning, and suggested that examining the role a technology's development plays in mediating learning might yield important insights. In addition, my reading of sociocultural research on learning and particularly the genetic analysis work of Vygotsky (1978, 1986) suggested that it is not enough to examine a learning situation *in situ* and that we must also understand its history. In the case of educational technology, its history mediates the ways it comes to be used by learners and this history begins with its development. This indicates that without examining how and with what purpose an

educational technology is created, our understanding of why it is used the ways it is in classrooms may be limited.

For this project, my aim is to deepen understanding of learning with educational technology by examining the relationship between its development and use. Based on the idea that the origins and history of a technology are important to understanding its use and taking inspiration from the Vygotskian tradition of genetic analysis, I examine the ways a technology becomes part of learning situations in mathematics classrooms. Starting with the development of a technology, I follow it into the classroom and examine the ways teachers and students work with it. For this investigation, I draw on a growing body of research in the field of Science and Technology Studies that examines the development and use of technology and the relationships between humans and their tools (Akrich, 1992; Bijker, 1997; Latour, 2007; Suchman, 2007). This research offers approaches to understanding the complex non-linear nature of the interactions between a technology's development and the ways it is used. Drawing on theorizing of the sociotechnical relationships between development, technology and use, and sociocultural theorizing of cognition and learning, this project examines the development and use of digital technologies for mathematics education.

Research Questions

The aim of this project is to enrich our understanding of the ways technologies mediate activity in mathematics classrooms by performing a genetic analysis of the ways they are developed and used. To perform this examination, I followed a technology from its development

through the ways teachers situate it in classrooms and students work with it during mathematical activity. The following research questions served as a guide throughout the project.

Within the network of activity that comprises developing and using technological tools for mathematical learning, how are those tools co-constructed?

- In what ways is that co-construction mediated by mathematical activity?
- In what ways does that co-construction mediate mathematical activity?

In this context, the term ‘network of activity’ refers to all activity related to the development and use of the particular educational technology chosen for examination. This activity includes the work of technology developers, the instructional practices of teachers and the work of students to perform mathematical tasks. The term ‘co-construction’ refers to the ways developers, teachers and students all shape a technology as they work with it while it, in-turn, shapes their practices. This concept draws on the work of several Science and Technology Studies researchers who have investigated the relationship between a technology’s development and use (Akrich, 1992, 1995; Bijker, 1997, Lindsay, 2005; Woolgar, 1991). The term ‘mathematical activity’ refers to the practice of performing mathematical tasks. This includes such tasks as calculation, problem solving and exploring relationships between mathematical concepts. As with the term ‘network of activity’, in the context of this study, ‘activity’ is understood through sociocultural and sociotechnical lenses both of which consider all activity to be mediated by cultural tools including technologies (Shaffer & Clinton, 2006). These terms are further examined in the theory chapter of this document.

Manuscript Structure

I have chosen to report on my doctoral project in the form of a *dissertation as articles*. This entailed writing three articles for submission to peer-reviewed journals and developing a framing document that further reports and contextualizes the project. To that end, this document includes an introduction, a review of relevant literature, a discussion of the theoretical perspective that I draw on, a description of several important aspects of the empirical context of this study, and an account of the method I employed. After these chapters, the three journal articles are provided. Each of these articles reports on a different aspect of the findings of this project and has been submitted to a peer-reviewed journal. Following the articles, I offer a discussion and conclusion for the whole project.

Chapter 2. Review of Relevant Research

In this chapter, I discuss research in the field of mathematics education and in the field of Science and Technology Studies. As both these fields encompass an enormous variety of research, the goal of this chapter is not to summarize the available literature but is instead to draw on selected research to offer a background that helps to situate the study. Following the genetic analysis approach that I take in this study, this chapter offers a historical view of digital technology for mathematical learning that helps to situate the use of the particular technology that I have chosen to examine. Within this structure, I discuss a variety of important aspects relating to the use of digital technologies for mathematical learning. Then, I discuss research that more broadly examines the relationships among technology, its development and its use.

Digital Technologies for Mathematical Learning

Technology of one form or another has been part of mathematics classrooms for centuries. Digital technologies, however, have only been widely used in schools since the mid 1980s with even the earliest examples of use occurring only in the late 1960s and early 1970s (Kidwell, Ackerberg-Hastings & Roberts, 2008). This section will discuss significant advances in digital technologies as tools for learning in mathematics classrooms and speak to some of the important threads that tie different technologies together.

Environments for mathematical exploration.

One of the earliest types of digital technology developed specifically for mathematical learning is programming tools (Hoyles & Noss, 2003; Kidwell, Ackerberg-Hastings & Roberts, 2008). These technologies consist of computer programming languages that, as with all

programming languages, follow mathematical rules. When learners use them to create programs, they are working within a mathematical environment and exploring mathematical concepts. Despite having been first created more than 30 years ago these technologies, typified by the *LOGO* system (Feurzeig & Papert, 1967), have been a consistent focus of research and development ever since (Clements, Battista & Sarama, 2001; diSessa, 2001; Noss, 1986; Yelland, 1995).

The first major study of *LOGO* use in classrooms, and in fact an early study of classroom computer use in general, was the Brookline Project (Papert, Watt, di Sessa, & Weir, 1979). Conducted over an entire school year with all the grade six students in an elementary school as participants, the Brookline Project involved the use of four computers with *LOGO* and sister program *Turtle Graphics* installed. Each grade six student was given between 20 and 40 hours to work with the mathematical environment of *LOGO* and with the *Turtle* system that also simulated Newtonian physics. All students engaged with the technology and 16 students with a spectrum of ability levels were chosen for detailed study. The programming activities of these students were recorded using software and paper copies of their work were collected. In addition, researchers conducted observations and collected observational notes from the teachers involved in the project. Interviews were conducted regularly with the teachers and informal meetings with school administrators and parents also yielded data. Of particular interest in the findings of the Brookline project was that two particular programming styles were employed by the students when creating *LOGO* programs to solve mathematical problems. Some students worked in a top-down fashion, working toward a pre-planned goal, and others worked from the bottom up, changing their course after each programming step. Interestingly, both programming styles were observed to lead to similar results and often the style could not be determined from the final

product. This finding highlights a key goal of early digital technologies for mathematical learning like *LOGO* by suggesting that they provide learners with opportunities to work in a variety of ways rather than restricting them to a single path.

Following the Brookline Project, further developments to the *LOGO* system and the creation of other similar systems led to a wide variety of studies of programming tools and mathematical learning (Barker, Merryman, & Bracken, 1988; Hoyles & Noss, 1987; Miller, Kelly, & Kelly, 1988; Noss, 1986). Despite assertions by *LOGO* developers that experimental research designs are inappropriate for evaluating learning with programming tools (Papert, 1986), several studies attempted to define their pedagogical usefulness experimentally (Clements & Battista, 1990; Clements & Gullo, 1984; Emihovich & Miller, 1988; Pea & Kurland, 1984; Rieber, 1987). Clements and Battista, for example, examined the use of *LOGO* to support learners in developing understanding of geometric concepts such as angle and angle size. They assigned six pairs of fourth grade students to work on geometry activities using either *LOGO* or more traditional paper and pencil methods. The pairs using *LOGO* worked within the *Turtle Graphics* part of the system that allowed them to program the movement of a graphical turtle that left a trail as it moved. By programming the movements of the turtle the students were instructed to draw simple geometric constructions such as rectangles and triangles. The activity required the pairs to negotiate the concept of angles and how they are measured while defining a path for the turtle to follow. Using pre- and post- tests of the students' geometry skills and structured interviews, Clements and Battista (1990) found that over the course of several activities, children in pairs that had access to *LOGO* developed more mathematically accurate conceptualizations of angle than those who had only worked with paper and pencil.

Despite studies such as Clements and Battista's (1990) that found experimental evidence for the pedagogical benefits of *LOGO*, the experimental research of others such as Pea and Kurland (1987) found no particular benefits. In contrast, much more consensus can be found amongst findings from qualitative investigations of learners' experiences with programming tools. These studies tend to emphasise the richness of mathematical activity that takes place while learners are creating environments with tools such as *LOGO* (Hoyles, Healey & Sutherland, 1991; Kieran & Hillel, 1990; Kynigos, 1993; Noss, 1986). In particular, a number of researchers have highlighted the ways that programming tools encourage learners to develop explicit understandings of algebraic and geometric properties and promote the development of formal mathematical language (Hoyles, Healey & Sutherland, 1991; Kieran & Hillel, 1990). For example, Hoyles, Healey and Sutherland investigated the processes through which learners make mathematical generalisations in relation to activity with *LOGO*, spreadsheet software, and paper and pencil. They conducted video-recorded observation of four pairs of 12-13 year old students as they engaged in mathematical activities using each tool. By analysing the decisions of the student pairs during mathematical activities, Hoyles, Healey and Sutherland (1991) found that the formal mathematical programming language of *LOGO* was particularly useful for scaffolding students' generalizations. In addition, they found that students working with *LOGO* were more likely to use formal mathematical language in discussing conjectured generalisations than they were when working with paper and pencil. This finding suggests an important relationship between the formal mathematical language interface of technologies like *LOGO* and learners' abilities to express mathematical conjectures in formal ways.

When attempts have been made to measure the effectiveness of programming tools experimentally, findings have been mixed. The results of qualitative investigations of

technologies like *LOGO*, however, indicate that they offer learners unique opportunities to investigate and explore mathematical concepts. The approaches to learning embedded within these tools, which are most often associated with the enduring influence of Seymour Papert, speak to a mathematics pedagogy that focuses on providing learners opportunities for mathematical experiences in which they can formulate and investigate their own theories about mathematical concepts instead of repeatedly performing procedures with little thought to broader concepts (Yelland, 1995).

Opening up new ways to represent mathematical concepts.

With the early success of *LOGO*, mathematics education researchers began to examine other technologies and their possibilities for classrooms (Harvey, Waits & Demana, 1995; Heid, 1988; Hölzl, 1996; Kaput, 1994). Perhaps due to the relative ease and speed with which iterative changes can be made to digital tools, many of these researchers chose to investigate tools of their own creation or customization. Particularly representative examples of this kind of research are the investigations that have taken place as part of the *SimCalc* research program (Kaput, 1994; Kaput & Roschelle, 1997; Kaput & Schorr, 2008; Nemirovsky, 1994; Roschelle, Kaput, & Stroup, 2000; Tatar, Roschelle, Knudsen, Schechtman, Kaput, & Hopkins, 2008). This series of projects that involved the creation of *SimCalc MathWorlds*TM software is focused on engaging learners with ‘the mathematics of change’ (Kaput & Roschelle, 1997). Each investigation of the large *SimCalc* research program is related to the use of innovative software tools that encourage learners to explore fundamental concepts from calculus through graphical representations that reduce the need to negotiate formal symbolic notations. Through these alternative approaches to representing the mathematics of change and variation, the goal of *SimCalc* is to democratize the knowledge that forms calculus so that broader groups of learners may engage with them (Kaput,

1994; Kaput & Schorr, 2008). The projects under the *SimCalc* umbrella have been instrumental in showing that digital tools created for mathematics education can help learners to make rich connections across different representations of mathematical concepts (Kaput & Schorr, 2008; Roschelle *et al.*, 2000; Tatar, Roschelle, Knudsen, Schechtman, Kaput, & Hopkins, 2008). In a relatively large-scale experimental study, for example, *SimCalc* researchers randomly assigned 21 seventh grade mathematics classrooms to treatment or control groups. The teachers in the treatment group replaced their usual instructional unit on rate and proportionality with a unit designed by *SimCalc* researchers for use with their *MathWorlds*TM software. Professional development workshops, provided by the researchers, were offered to help the treatment group teachers implement the replacement unit that took the form of a large project that took about 15 classes to complete. During the course of the experiment, the researchers administered pre- and post-unit tests of the mathematical content knowledge of the teachers and questionnaires that addressed the teachers' backgrounds. In addition pre- and post- unit tests of student mathematical content knowledge were conducted, the teachers were asked to provide daily logs of their classroom activity and the researchers observed classrooms. The findings of this experiment show that students in the treatment group who could manipulate the graphical representations of mathematical concepts offered by *MathWorlds*TM progressed to more complex mathematics than the students in the control group and scored higher on tests of their basic understanding of the concepts of rate and proportionality (Tatar, Roschelle, Knudsen, Schechtman, Kaput, & Hopkins, 2008). In addition, the results suggest that with appropriate professional development support, a wide variety of teachers with different levels of mathematical content knowledge and comfort with technology can effectively make use of technologies that provide access to new ways of representing mathematical concepts. This finding has particular significance as an issue often

raised in relation to the introduction of digital technologies in mathematics classrooms, namely the increased burden it may place on teachers who lack comfort with using technology or the mathematical content they are expected to cover in their classes (Russell, Bebell, O'Dwyer, & O'Connor, 2003).

Unlike *SimCalc MathWorlds*TM, many of the digital technologies widely used in mathematics classrooms were not developed by educational researchers for their own studies. Instead, these technologies were often initially created for professional mathematicians and then adapted and commercialized for schools. A particularly popular example of this is dynamic geometry software such as *The Geometer's Sketchpad*TM (Jackiw, 1988-2010) and *Cabri-Géomètre*TM (Baulac, Bellermain & Laborde, 1988-2010) neither of which, somewhat surprisingly given their now wide adoption by schools, was initially developed specifically for educational use (Goldenberg, Scher & Feurzeig, 2008). *Cabri-Géomètre*TM, for instance, was initially developed as way for non-programmer mathematicians to exploit the power of computers to explore graph theory, but was then modified into a system for visualizing geometry first introduced in university courses and then later to schools (Laborde & Laborde, 2008). This category of interactive software allows users to build geometric constructions and then manipulate them by dragging and modifying elements while watching the way connected elements respond (Goldenberg, Scher & Feurzeig, 2008). Both *The Geometer's Sketchpad*TM and *Cabri-Géomètre*TM began life in the context of development programs that were not focused on pedagogy but their potential in educational settings was quickly noticed and developers adapted and commercialised their creations (Goldenberg, Scher & Feurzeig, 2008). Since their introduction, both *The Geometer's Sketchpad*TM and *Cabri-Géomètre*TM have been widely

adopted by schools and through successive iterations they have developed into highly specialised technologies geared specifically toward supporting mathematical learning.

A key feature of dynamic geometry software is that it allows learners to represent and manipulate geometric constructions by dragging graphical elements with a computer mouse. It was this power to represent concepts in dynamic new ways that drove much of the excitement about the technology as it emerged in the late 1980s (Laborde & Laborde, 2008). Educational researchers quickly became interested in the potential of dynamic geometry software and its gradual introduction into schools was supported by the spread of the idea that access to multiple ways of representing mathematical concepts is a significant benefit to learners (Sträßer, 2002). As is often the case with new technologies, early research on dynamic geometry software in schools spoke of its potential in overwhelmingly positive terms (Hollebrands, Laborde & Sträßer, 2008). For example, Hölzl investigated the effects that the dragging modality of dynamic geometry software has on learners' understanding of geometric concepts by observing 14-year-old students working on a task involving equilateral triangles. Using *Cabri-Géomètre*TM, the students were asked to construct a triangle and then manipulate it while conjecturing about the characteristics needed to make it equilateral. Hölzl's (1996) findings reveal a technology that supports new ways of thinking about geometric properties by offering learners the ability to engage with constructions through dragging and manipulating elements in real-time. He found that the software helps to foreground the relationships between elements of geometric constructions and shifts the focus of activity from constructing figures as one would with paper and pencil to investigating them by varying their properties.

Later, researchers began to unpack the details of dynamic geometry software use in classrooms along with both its pedagogical benefits and limitations (Chazan, 1993; Christou,

Mousoulides, Pittalis, & Pitta-Pantazi, 2004; Gawlick, 2002; Guven, Cekmez, & Karatas, 2010; Hadas, Hershkowitz, & Schwarz, 2000; Healy & Hoyles, 2001; Jones, 2000; Laborde, 2001; Mariotti, 2000). Of particular significance, research that has examined teachers' integration of dynamic geometry software into mathematical tasks shows that they often ask students to exploit the visualizations that dynamic geometry software provides to conjecture properties of geometric relations but rarely do they suggest the technology be used to help construct formal mathematical proof for those conjectures (Christou, Mousoulides, Pittalis, & Pitta-Pantazi, 2004; Chazan, 1993; Guven, Cekmez, & Karatas, 2010; Hadas, Hershkowitz, & Schwarz, 2000; Jones, 2000; Laborde, 2001; Mariotti, 2000). Based on this finding, researchers have expressed concern that students using dynamic geometry software to explore geometric properties might only use empirical experience to support their assertions and never move to producing a formal proof (Chazan, 1993; Hadas, Hershkowitz, & Schwarz, 2000; Laborde, 2001). For instance, based on observation of a series of secondary school teaching scenarios that involved geometry tasks with *Cabri-Géomètre*TM and were developed by a researcher in collaboration with teacher participants, Laborde notes that, "It was as if the process of elaborating a proof should deal with theoretical objects unrelated to their representations" (2001, p. 306). This suggests that there is a disconnect between an inductive approach to developing evidence for a mathematical conjecture supported by dynamic geometry software and a deductive one of formal mathematical proof. Offering a different perspective, however, several other researchers suggest that while dynamic geometry software does disrupt the classical notion of what constitutes proof in mathematics, there is a relationship between the kind of inductive exploration that the software promotes and the deductive reasoning needed to construct a formal proof (Christou, Mousoulides, Pittalis, & Pitta-Pantazi, 2004; Edwards, 1997; Guven, Cekmez, & Karatas, 2010; Jones, 2000). The

findings of these studies suggest that while there is a potential for technologies like dynamic geometry software to obscure some mathematical concepts or procedures, that risk can be managed if they are carefully situated in classroom activity.

Computer algebra systems (CAS) followed a similar path to dynamic geometry software into educational settings. Initially developed by mathematicians for their own use, a range of software tools that could manipulate formal mathematical symbolic notation began to be used in universities in the 1980s (Heid & Edwards, 2001; Kidwell, Ackerberg-Hastings & Roberts, 2008). Tools such as *muMath/Derive*TM (Rich & Stoutemyer, 1979) and *MAPLE*TM (Geddes & Gonnet, 1980) moved from university mainframe computers to student computer labs to graphing calculators used in high schools as computing power increased and machine sizes and costs decreased (Kidwell, Ackerberg-Hastings & Roberts, 2008). Similarly, research on the pedagogical use of CAS has also followed a path from universities to schools. Early studies showed that university students who used CAS to perform computational tasks had improved their conceptual knowledge of calculus over those who had exclusively used paper and pencil approaches (Beckmann, 1988; Heid, 1988; Palmiter, 1991). Palmiter, for example, reported significantly higher final exam scores for undergraduate students who were part of an experimental group who had access to CAS throughout a calculus course over a control group who did not. Offering similarly encouraging findings, Heid observed undergraduate students' use of CAS to manipulate symbols and create graphs during problem-solving sessions in a 12-week calculus for business class. When interviewed at the end of the semester, Heid found that students in the experimental group demonstrated a better understanding of such calculus concepts as derivatives than those who had used solely paper and pencil techniques. This work alluded to the potential for CAS in schools and a broad range of theorizing and research in a

variety of educational contexts followed (Artigue, 2002; Chappel & Kilpatrick, 2003; Drijvers, 2000; Drijvers & Kieran, 2006; Forester & Mueller, 2001; Harvey, Waits & Demana, 1995; Judson, 1990; Kieran & Yerushalmy, 2006; Lagrange, 1999; Tall, 1996; Tall, Smith & Piez, 2008). Many of these investigations, especially those with experimental designs that compare treatment and control groups, show higher performance on measures of conceptual knowledge across different age levels for those learners who have had access to CAS (Chappell & Kilpatrick, 2003; Judson, 1990). Similar to dynamic geometry software, however, other researchers have challenged the notion that handing-off procedural mathematical tasks to CAS frees learners to conceptualise the broader concepts of mathematics and question its pedagogical advantages (Drijvers, 2000; Pimm, 1995; Stacey, 1997). They suggest that some ways of using technology may actually make conceptualizing mathematical concepts more difficult by creating black-boxes into which problems go and solutions come out without any indication of the procedures that have been performed or concepts needed to understand them.

Reflecting such concerns as black-boxing, much of the recent research involving CAS examines differences and relationships between conceptual and procedural mathematical knowledges (Artigue, 2002; Chappell & Kilpatrick, 2003; Drijvers & Kieran, 2006; Kieran & Saldana, 2005; Lagrange, 1999). For example, Artigue articulates a framework for understanding mathematical learning with CAS that replaces the notions of concept and procedure with those of theory and technique while emphasising the importance of a third element, task. Speaking to the notion of technique in the context of her framework, Artigue notes that, “A technique is a manner of solving a task and, as soon as one goes beyond the body of routine tasks for a given institution, each technique is a complex assembly of reasoning and routine work” (p. 248). Drawing on Artigue’s framework, Drijvers and Kieran suggest that when a learner undertakes a

mathematical task with CAS there exists a reflexive relationship between that task and the technique they use as mathematical theorizing emerges (Drijvers & Kieran, 2006; see also Kieran & Saldana, 2005). In a study of CAS use in six tenth-grade mathematics classrooms, Drijvers and Kieran investigated these reflexive relationships. Each class was observed and video-taped for 12-15 sessions and the students were interviewed at various points. Using video-tapes of the observations and interviews in conjunction with material artefacts such as activity sheets and records from the CAS, Drijvers and Kieran compared instances in which students used paper and pencil or computerized approaches to factoring expressions in the general form $x^n - 1$. From this analysis, they developed descriptions of the techniques and theories that emerged in the students' work and supported the concept of reflexive interactions among tasks, techniques and theories. Their findings suggest that students benefit from the interaction of the different tasks and techniques of factorization with paper and pencils and factorization with CAS and suggest that the technology can be useful in providing learners a means for quickly verifying their mathematical conjectures. As researchers such as Drijvers and Kieran demonstrate, there is legitimate concern that technologies may act as calculational black-boxes or disrupt concepts such as the classical notion of mathematical proof, but a growing body of research involving the use of technologies such as dynamic geometry software and CAS indicates that learners benefit from a rich array of tools that encourage them to engage with a variety of ways of approaching mathematics (Christou, Mousoulides, Pittalis, & Pitta-Pantazi, 2004; Drijvers & Kieran, 2006; Edwards, 1997; Guven, Cekmez, & Karatas, 2010; Jones, 2000; Laborde, 2001; Monaghan, 2004; Pierce, Stacey & Wander, 2010).

Handheld devices.

Handheld computing devices are a relatively recent technological development that brings together several existing mathematics education technologies including dynamic geometry software and computer algebra systems (CAS) on a single platform. The emergence of pocket-sized, inexpensive and increasingly powerful devices has prompted a surge in both the development of digital technologies for mathematics education and research that involves them (Ares, Stroup & Schademan, 2009; Drijvers & Kieran, 2006; Drijvers & Trouche, 2008; Hegedus & Penuel, 2008; Hollar & Norwood, 1999; Kaput & Roschelle, 1997; Kaput & Schorr, 2008; Lagrange, 1999; Tatar, Lin & Dickey, 2005). A variety of handheld devices such as personal data assistants have been explored as platforms for mathematics education software (Kaput & Roschelle, 1997), but the bulk of both research and development has focused on pocket calculators. Calculators have become increasingly sophisticated since their introduction and in the past decade significant advances in computer processors and digital displays has dramatically closed the gap between what might be considered a calculator and what might be considered a computer (Kaput & Schorr, 2008). The latest generation of calculators have enabled a range of applications including spreadsheets, graphing, dynamic geometry software, and CAS to form a single interconnected mathematical environment on a device accessible because of a relatively modest cost of between \$100 and \$200. Researchers who develop software as part of their investigations such as those involved in the *SimCalc* program along with commercial developers such as the creators of *Cabri-Géomètre*TM have adapted their creations to run on calculators and other handheld devices. As these developments have been introduced, they have blurred the boundaries between what were commonly considered to be separate pieces of mathematical software and expanded the possibilities for digital technology use in classrooms.

This has stimulated new theorizing about the relationship between mathematical learning and technology and opened up new pedagogical possibilities (Noss, 2003).

One area of theorizing that has been particularly active in relation to studies of handheld devices in mathematics classrooms is conceptualizations of the relationship between learners and technology (Drijvers & Trouche, 2008; Hegedus & Moreno-Armella, 2010; Shaffer & Clinton, 2006; Trouche & Drijvers, 2010). In an example of this work, a growing body of mathematics education research draws on the anthropological notion of ‘instrumentalization’ (Drijvers & Trouche, 2008; Hegedus & Moreno-Armella, 2010; Lagrange, 1999; Trouche & Drijvers, 2010; Verillon & Rabardel, 1995). This concept describes the process by which a technology changes from a tool to an instrument as it is used. In the context of mathematical learning, the theory suggests that tools become mathematical instruments as learners’ use them to perform mathematical tasks and develop schema associated with that use (Drijvers & Trouche, 2008). Research drawing on the instrumental approach focuses on the ways that teachers organize the technologies available to them in the classroom for pedagogical purposes and describes the ways teachers guide their students to make technology meaningful in the context of their mathematical activity (Drijvers, Doorman, Boon, Reed, & Gravemeijer, 2010; Trouche, 2004). For example, working with videotapes of lessons in 29 eighth-grade classrooms where software projected onto a large screen and handheld devices were used, Drijvers, Doorman, Boon, Reed, and Gravemeijer (2010) identified a variety of ways the different technologies in the classrooms were configured. Each configuration or orchestration describes a different way that the teachers included the projected software and handheld devices for performing and sharing mathematical activity in their classrooms. The findings suggest teachers’ choices about which configurations to

use relate strongly to their teaching techniques without digital technologies and to their views on mathematics teaching in general.

Similar to the instrumental approach to understanding the relationship between technology and learner, based in part on research with handheld devices, Shaffer and Clinton (2005, 2006) have proposed their own theorization. Their ‘toolforthoughts’ approach also recognizes the reciprocal relationship between learner and technology, but does not limit the role of the technology to that of a mere object waiting to be made an instrument by learners. They argue that while theorizing that understands technology solely as a servant to human activity may have served researchers well when investigating analogue objects such as linking-cubes in a mathematics classroom, complex computational technologies such as handheld devices have a much more active role in their interactions with humans. They note that while focusing solely on humans as actors in learning situations, “may not be a problem in a theoretic culture of static inscriptional systems. In a virtual culture based on offloading of symbolic processing, however, using human action to analyse activity obscures the active role tools play” (2006, p. 289). Based on this view, they suggest that researchers examining learning with computational technology may be better served by conceptualizing technologies as active partners in mathematical learning (Shaffer and Clinton 2006). Like research drawing on an instrumental conception of the relationship between learners and technology, Shaffer and Clinton’s approach opens up new ways of understanding the role technology has in mathematical learning. These recent theoretical approaches speak to the need for research that supports the development of a richer understanding of the kinds of complex computational technology typified by the latest generation of handheld devices.

Understanding the Relationships Among Technology, Its Development and Its Use

This project addresses the use of technology for mathematical learning as many of the studies mentioned so far in this chapter have done, but seeks to build understanding of the role of complex digital technologies in mathematical learning by expanding the scope of investigation to include a technology's development. This broadened scope necessitates that the study not only be situated within the body of research literature related to technology use in mathematics classrooms, but also in relation to literature that discusses the relationships among technology, its development and its use.

In the field of mathematics education, a number of researchers have described their own processes as they have developed technologies intended for use in their own studies (diSessa, 2001; Kaput & Schorr, 2008; Tatar, Lin & Dickey, 2005). These accounts of the development of technology for research purposes offer a sense of the decisions made by teams developing tools intended to support mathematical learning. Literature related to dynamic geometry software, in particular, gives some insight into the way that technologies for mathematical learning are developed. Creators of both *The Geometer's Sketchpad*TM and *Cabri-Géomètre*TM along with their mathematics education colleagues have written about the development of dynamic geometry software (Goldenberg, Scher & Feurzeig, 2008; Laborde & Laborde, 2008; Roschelle & Jackiw, 1999). Goldenberg, Scher and Feurzeig (2008), for example, describe the historical development of both software applications and discuss some of the intentions and ideas behind them. Having interviewed creators of both technologies, they suggest that instead of making design decisions based on a particular pedagogy, "each designer was motivated by his own set of principles – mathematical, aesthetic, and human factors among others" (Goldenberg, Scher and Feurzeig, 2008, p. 62). They also suggest that despite the rigorous rules of geometry and

mathematics in general, “very little about the programs was inevitable from the start. The underlying mathematics of geometry and algebra certainly guided their development, but did not dictate how features would operate, nor even which features to include” (p. 79). As the two programs evolved and became accepted in the mathematics education community, their development began to attend to pedagogy and the mathematics education needs of teachers and students. While describing the development of their application, *Cabri-Géomètre*TM, Laborde and Laborde note:

One of the important features of Cabri is its strong interrelation with mathematics throughout its development. It originated from the needs of a community of researchers in mathematics. Although Cabri was not immediately accepted by the teaching and research communities, it became accepted over time and the development process was able to take advantage of innovative uses of Cabri by teachers and researchers in mathematics education. (2008, p. 49)

Laborde and Laborde point to the important relationships among the development of an educational technology, the technology itself, and members of the mathematics education community such as researchers, teachers and students. Such accounts of the development of technologies for mathematical learning provide some insight into the specific motivations and processes of developers. These insights are useful in orienting this examination of the development and use of technology for mathematical learning but do not address the broader issue of conceptualizing the complex relationships between technology, its development and use.

A much richer source of investigations into the relationships among technology, its development and its use can be found in the field of Science and Technology Studies. In this

field, a growing body of research specifically examines the ways technologies are developed and the relationship between their development and use (Akrich, 1992; Bijker, 1997; Latour, 1996a; Lindsay, 2005; Oudshoorn & Pinch, 2005; Suchman, 2007; Woolgar, 1991; Yaneva, 2009). Current Science and Technology Studies research seeks to unravel the complexities of development-use relationships without resorting to the technologically deterministic conceptions that characterised earlier understandings. Earlier approaches tended to view the practice of developing technologies in terms of systematic problem solving steps (Cross, 2007; Dorst & Dijkhuis, 1995; Simon, 1992). These steps were most often understood as including activities such as defining user needs and predicting the behaviour of users identified as representing archetypal groups. In such activities, users were generally considered to be part of monolithic groups with relatively rational and predictable actions. Development processes grounded by such conceptions of user actions often yield technologies that have been designed with highly restrictive notions of how users will interact with them. Specifically in relation to the development of educational technologies, such understandings of development processes often conceptualize the relationships between developer, technology and learner in primarily behaviourist terms, assuming that learning can be predicted and prescribed through the design of a technology (Häkkinen, 2002; Jonassen, 1991).

Disrupting prescriptive ways of understanding the relationship between design decisions and user behaviour, researchers working in the field of Science and Technology Studies have proposed alternative approaches (Akrich, 1995; Bijker, 1997; Suchman, 2006). These approaches understand the relationship between the development and use of technology to be reflexive, suggesting that a technology is constantly and dynamically shaped by both developers and users as it in turn shapes them. Suchman (2007), for example, equates prescriptive approaches to

understanding the relationship between design and use to the notion of plans within cognitive science, noting that:

The model posits that action is a form of problem solving, where the actor's problem is to find a path from some initial state to a desired goal state, given certain conditions along the way. Actions are described, at whatever level of detail, by their preconditions and their consequences. (p. 52)

From a long-term ethnographic study of the development and use of a photocopier help-system, Suchman found that instead of acting as a prescription for particular behaviour, the technology acted as a resource for the situated actions of users. Based on this, she suggests that “the contingency of action on a complex world of objects, artefacts, and other actors, located in space and time, is no longer treated as an extraneous problem with which the individual actor must contend but rather is seen as the essential resource that makes knowledge possible and gives action its sense” (p. 177). Thus, Suchman proposes that the role of developers is not to predict the behaviour of users but it is instead to support users in finding their own ways of working with a technology.

In concert with the rejection of the notion that behaviour can be prescribed through technology, several researchers in the field of Science and Technology Studies propose that users play an on-going role in creating technologies (Bijker, 1997; Lindsay, 2005; Oudshoorn & Pinch, 2005; Pinch & Bijker, 1984; Woolgar, 1991). They suggest that users actively reconfigure the technologies they use as they use them in a process of co-construction. As Bijker describes in relation to his sociological study of the historical development and use of bicycles, “...an artifact does not suddenly appear as the result of a singular heroic intervention; instead, it is gradually

constructed in the social interactions between and within relevant social groups” (1997, p. 270). From this perspective, users continue development as they and the technologies they use reflexively co-construct each other. In an example of a study adopting this perspective, Lindsay (2005) examined the history of an early personal computer called the *TRS-80* that was sold between 1977 and 1984. Through documentary research and interviews with users, she found that despite the relatively short time that the *TRS-80* was available commercially, during the 25 years following its withdrawal from the market a large group of users continued to work with it, adapting it and reconfiguring it for their own purposes by creating their own software and enhancements to the system. Since the manufacturer no longer existed, these users worked together often taking on roles such as developer or technical support agent themselves. Lindsay’s (2005) findings suggest that development of particularly digital technology does not end with its manufacture and can extend well beyond the involvement of its creators, reconfiguring in ways that they could never have imagined.

Further unpacking the relationships between development, technology and users, researchers working from the sociotechnical perspective of Actor-Network theory (ANT) suggest that when humans and technologies interact, the capacity to act is not limited to the humans, but is instead a product of interactions between actors both human and non-human (Akrich, 1995; Callon, 1986; Latour, 1996b, 2007; Law, 1992; Yaneva, 2009). A key example of research that draws on ANT to examine the relationship between technology development and the actions of users is the work of Akrich (1992, 1995). Drawing on ANT, Akrich studied the development of technologies including a national electric utility and an interactive television system. Based on these studies, she proposes that rather than describe designs as prescriptions for user actions, they be conceptualized as scripts out of which the actions of users emerge (Akrich, 1992, 1995). From

her perspective, scripts are similar to Suchman's (2007) notion of resources and represent the imagined user actions that a developer envisages for a technology. In the scripting process, developers construct and appropriate representations of envisaged user actions and inscribe them in a technology, "the designer expresses the scenario of the device in question – the script out of which the future history of the object will develop" (Akrich, 1992, p. 276). Users then translate the developer's script as they use a technology. Building on the ANT notion that both humans and non-humans are actors in social networks, Akrich's approach allows the conception that designs influence the formation of networks without dictating them or the practices of the actors within them (Akrich, 1992, Yaneva, 2009).

Conclusion

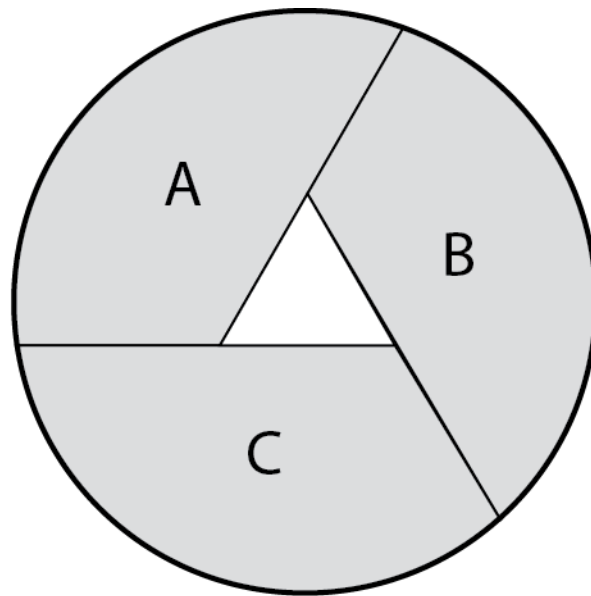
By reframing the relationship between developers and users, researchers in the field of Science and Technology Studies such as Akrich (1992), Bijker (1997) and Suchman (2007) suggest approaches to understanding the development of technology that share common ways of moving beyond technological determinism without ignoring the role that technology plays in its relationship with humans. These approaches challenge the notion that user behaviour is prescribed through design and suggest that technologies are co-constructions of both their developers and users. Similar to recent theorizing of the relationship between learners and technology in the field of mathematics education (Drijvers & Trouche, 2008; Shaffer and Clinton 2006), conceptualizations of the relationship between development and use from the field of Science and Technology Studies show the complexities of interactions between technologies and humans. This research highlights the importance of investigating the development of a technology for understanding the ways that it is used. As the work of researchers investigating

the ways users reconfigure technologies indicates, the development of a technology is not just its history but is also its present (Akrich, 1992; Bijker, 1997; Lindsay, 2005; Woolgar, 1991).

Chapter 3. Theoretical Perspective

Seeking to enrich our understanding of the ways digital technologies mediate mathematical learning by broadening the scope of investigation to include the development of technologies, this project draws on both the fields of Science and Technology Studies and mathematics education. From the wide range of theoretical perspectives employed in these fields, I have chosen to work with three interrelated theories to construct a lens that helps me to understand the development and use of technology for mathematical learning. These theories are each useful for addressing different aspects of this study but are interrelated and are all broadly located within the realm of socially and culturally attuned perspectives on human activity. In particular, I draw on the sociotechnical perspectives elaborated in the work of researchers in the field of Science and Technology Studies examining the development and use of technology (Akrich, 1992; Bijker, 1997; Kagan & Bowker, 2001; Pinch & Bijker, 1984; Suchman, 2007) and on the work of researchers engaging with Actor-Network theory (ANT) to understand the relationships among humans and non-humans (Callon, 1986; Latour, 1996, 2007; Law & Mol, 2001). In addition, I draw on the sociocultural perspective on cognition of Activity-Theory (Leont'ev, 1978; Vygotsky, 1978, 1986). From these three perspectives that share a common focus on the socially and culturally situated nature of human activity, I have identified three interrelated theoretical assumptions that together construct the theoretical lens I use in this project. Drawing on work in the field of Science and Technology Studies, I assume that technologies are co-constructions of both developers and users. Drawing on ANT, I conceptualize humans and technology as both acting in networks of social activity; and drawing on Activity-Theory I understand learning in terms of tool-mediated activity. The relationships of these key theoretical assumptions are visualized in Figure 1 using the metaphor of a camera lens.

Simplifying their function for the purposes of this discussion, the blades of a lens iris open and close to control the amount of light that passes through to the camera. This manipulates the brightness and depth of field of a photograph and shapes the parts of the image that will be visible and in focus. Similarly, the key assumptions of a theoretical lens shape the view a researcher has of the phenomena they are examining and influence the aspects they attend to.



- A: Technologies are co-constructions of both developers and users
- B: Humans and technology both act in network of social activity
- C: Learning is tool mediated activity

Figure 1: Representation of key theoretical assumptions

While the blades of the iris of most camera lenses move in and out together always staying centred, the blades of my theoretical lens do not. Instead, the three key theoretical assumptions of this study represented in Figure 1 move in a separate yet interrelated fashion to frame my approach. As I examined different aspects of the development and use of a technology for mathematical learning, I drew on the three theoretical assumptions in different proportions to

help me focus on different aspects. The three articles that report the findings of this study are each framed through the theoretical lens visualized in Figure 1, but in each case the shape of the frame is different. Detailed aspects of each of these frames are discussed in the articles that are included as chapters in this document but to provide an overview of the ways that I use them and how they relate to each other, I examine the three key theoretical assumptions in the following sections.

Technologies Are Co-constructions of Both Developers and Users

In recent decades, research in the field of Science and Technology Studies that has examined the development of technology and the process of innovation has proposed a number of theoretical stances that suggest common ways of conceptualizing the relationship between humans and technology (Akrich, 1992; Bijker, 1997; Kaghan & Bowker, 2001; Pinch & Bijker, 1984; Suchman, 2007). These approaches recognize that human cognition is situated and take a pragmatic and culturally attuned approach to understanding technology development (Kaghan & Bowker, 2001). As touched upon in the previous chapter, a key feature of this common approach is the avoidance of privileging either humans or technology by recognizing the inherently reciprocal nature of their relationship. Writing about this relationship, Bijker, for example, notes that, “the technical is socially constructed, and the social is technically constructed. All stable ensembles are bound together as much by the technical as by the social” (1997, p. 273). This reciprocal conception allows the role of technology to be conceptualized while avoiding the essentialist positions of either technological or social determinism.

Of particular importance to this study, researchers in the field of Science and Technology Studies working to find ways of understanding the reciprocal relationship between humans and technology have also elaborated on the relationship between the development of a technology and its use (Akrich, 1992, 1995; Bijker, 1997, Latour, 1996a; Lindsay, 2005; Pinch & Bijker, 1984). These researchers expand on the notion that humans and technology have a reflexive relationship by suggesting that the development of technology can be understood to be mutually co-constructive. They propose that humans constantly and dynamically shape the technologies they use as they, in-turn, are shaped by these technologies (Bijker, 1997; Kaghan & Bowker, 2001; Oudshoorn & Pinch, 2005; Pinch & Bijker, 1984). Bijker, for instance, articulates that “the development of technical designs cannot be explained solely by referring to the intrinsic properties of artifacts” (1997, p. 270). Illustrating this notion, he describes the development of bicycles in the 1800s as many new and varied designs were emerging. He examines the ways different social groups interpreted different designs and how this process led eventually to the relatively stable artefact that we now know. For example, the early ‘Ordinary’ bicycle, which is often referred to as the ‘penny-farthing’ due to its very large front wheel and comparatively small back wheel, was a popular design in the 1870s. Bijker notes that at the height of its popularity the ‘Ordinary’ was widely considered by many cyclists to be unwieldy and dangerous whilst being considered to be an excellent design only suitable for the skilled rider by others. In the hands of different cyclists, the ‘Ordinary’ bicycle became a different artefact with different values attributed to it despite the fact that it had the same intrinsic properties. Both the bicycle and cyclists were co-constructed as they interacted. As Bijker describes:

Society is not determined by technology, nor is technology determined by society.

Both emerge as two sides of the sociotechnical coin during the construction processes of artifacts, facts, and relevant social groups. (p. 274)

This idea, which is key to the way I understand the development of technology in this study, recognizes that we never simply *use* technology but instead we negotiate it, shaping it for our own needs as it shapes us. It understands that technologies are not solely the products of their developers and that they are dynamically constructed as they are used. Speaking to this idea, Pinch and Bijker propose that “the different interpretations by social groups of the content of artefacts lead via different chains of problems and solutions to different further developments” (1984, p. 423). As they describe, the development of artefacts such as technologies is an on-going process in which users play a part. Users translate technologies for their own purposes, and together, users and technologies reciprocally construct each other’s activity (Bijker, 1997). This conception is key to the way I examine the development and use of technology for mathematical learning in this study.

Humans and Technology Both Act in Networks of Social Activity

To help me conceptualize the relationship between humans and technology, I draw on Actor-Network theory (ANT). ANT understands the social world in terms of material-semiotic networks of both humans and non-humans mediating each other’s activity (Latour, 2007). Within these sociotechnical networks, ANT suggests that relationships between humans and non-humans be considered analytically similar to relationships among humans (Callon, 1986). The theory conceptualizes relationships among actors, both human and non-human, in reciprocal

terms suggesting that when interacting the capacity to act cannot be located in either party but instead emerges from their interaction (Latour, 2007). From this perspective, investigations drawing on ANT tend to focus on the ways sociotechnical networks emerge as humans and non-humans interact and their practices stabilize. These networks are understood to be composed of semiotic relations between network-objects themselves enacted by nested networks of humans and non-humans (Law, 2002; Law & Mol, 2001). As network-objects, for instance, educational technologies are elements of classroom sociotechnical networks that are enacted through nested networks that include such network-objects as their developers, the teachers and students who use them, electronics, and software. Network-objects such as educational technology become what Latour (1990) refers to as ‘immutable’ as the networks that form them become stable. These network-objects stabilize in the context of patterns of relations but the networks that connect them remain fluid. In this fluid space, the relations between network-objects constantly adapt as new elements emerge or existing elements reconfigure. Throughout this fluidity, however, there is a degree of continuity that allows networks to remain intact. Otherwise, “If everything is taken apart at the same time the result is rupture, the loss of shape-continuity, the loss of identity. The result is more likely to be the creation of an alternative object” (Law, 2002, p. 99). In cases of rupture, network-objects often become new entities such as a phonebook being repurposed as a doorstop. As these new entities emerge so do new sociotechnical networks around them.

From an ANT perspective, the role complex digital technologies may play in networks of activity is important but equally as important is the perhaps less dramatic role of simpler artefacts such as chairs or keys (Latour, 1991, 1996, 2007) As Latour notes, “no matter how apparently simple a mediator may look, it may become *complex*; it may lead in multiple

directions which will modify all the contradictory accounts attributed to its role” (2007, p. 39).

Latour suggests that as we create and use objects, no matter how simple they appear, we instantiate our thoughts and intentions in them. These thoughts and intentions are then translated as they mediate the activity of other actors both human and non-human and the objects they are instantiated in become actors in their own right (Latour, 2007). To illustrate this phenomenon, in his essay *Technology is society made durable*, Latour (1991) offers the case of hotel keys. Guests at some hotels are asked to leave their room key at the front desk when leaving the hotel and to reclaim it upon returning. This rule created by hotel management is often inscribed on a sign at the front desk asking guests to return their keys. Suppose however, hotel guests tend not to comply with the request, keep their keys and sometimes lose them? Some hotels respond by translating the inscription on the sign to the room keys themselves by attaching large key chains. In this case, the hotel delegates the enforcement of the rule that keys be left at the front desk to the room key itself by giving it the property of being impractical and cumbersome to carry. By doing so the key itself interacts with hotel guests in such a way that guests are happy to leave it at the front desk instead of carrying it around. This example illustrates the ways that an intention can be inscribed and translated through seemingly simple objects that then both mediate and are mediated by human activity. Speaking to this case, Latour notes:

The programme, ‘leave your key at the front desk’, which is now scrupulously executed by the majority of the customers, is simply not the one we started with.

Its displacement has transformed it. Customers no longer leave their room keys: instead, they get rid of an unwieldy object that deforms their pockets. (p. 43)

As this example illustrates, from an ANT perspective both developers (in this case hotel management) and users (in this case hotel guests) inscribe their thoughts and intentions in objects

that are then translated as the objects interact with other humans and non-humans. This conception is key to the way the relationship between humans and technology is understood in this study.

Learning is Tool-Mediated Activity

Since this study is not only concerned with the relationships between the development and use of technology, and between humans and technology but is also concerned with learning, a theoretical approach to understanding learning with technology is needed. Despite providing a frame for conceptualizing the interactions of humans and technology, ANT lacks ways of understanding the internal properties of actors such as cognition (Engeström, 2001; Miettinen, 1999). Addressing this, it is common amongst researchers who draw on ANT to study learning and educational settings to work with aspects of other theoretical approaches as well (Fenwick & Edwards, 2010). By carefully working with aspects of other theories, educational researchers investigating such diverse areas as the geography of different literacies in schools (Edwards, Ivanič, & Mannion, 2009), the construction of knowledge in science classrooms (Fountain, 1999), adult education policies (Emad & Roth, 2009), and educational technology (Samarawickrema & Stacey, 2007; Shaffer and Clinton, 2006) have all engaged with the ideas of ANT to help inform their work. A particularly salient example of researchers drawing on ANT in combination with other theory is Shaffer and Clinton's (2005, 2006) notion of 'toolforthoughts' that was mentioned in the previous chapter. This conceptualization of the relationship between technology and learning combines elements of ANT with the sociocultural approach to understanding human development and cognition of Activity-Theory. In this study, I draw more

heavily on ANT than Shaffer and Clinton (2006), but I also turn to aspects of Activity-Theory to help me understand cognition.

Originating with the ideas of Vygotsky (1978, 1986) and Leont'ev (1978), Activity-Theory is particularly concerned with the socially and culturally situated nature of cognition. As a sociocultural approach to understanding cognition, it, “takes as its point of departure the *mediated* nature of human knowledge and action” (Säljö, 1999, p. 151). Like ANT, Activity-Theory is focused on the semiotic means through which knowledge and action are mediated and both theories share a common attention to moving beyond essentialist divides between nature and society. As Miettinen describes:

The nature, culture, and production of ANT and the concept of work and object-oriented activity of the activity theory are methodologically parallel, basic solutions to the problem of transcending dualistic oppositions between nature and society, between the subject and the object. (1999, p. 175)

Activity-Theory attends to cognition in much more detail than ANT and offers me ways of conceptualizing learning with educational technology. In particular, Activity-Theory contends that all human activity including learning takes place within systems that are mediated by cultural tools (Säljö, Eklund & Mäkitalo, 2006; Wertsch, 1991). These include both material artefacts such as pencils and screwdrivers and intellectual tools such as language and algorithms for multiplying numbers. Tools, both material and intellectual, are understood to mediate all human activity and are recognized as the resources through which we make meaning (Wertsch, 1998).

The conception that tools are the crucial resources with which we make meaning is an important part of the way mathematical learning is understood in this study. It is also key to an ecological approach to conceptualizing the relationship between humans and their environments that is not only found in Activity-Theory but is also central to a broader sociocultural family of theories that includes such approaches to understanding the mind as situated and distributed cognition (Greeno, 1991; Hutchins, 1996; Rogoff & Lave, 1984). This common approach asserts that cognition is not confined to the brain of individuals but instead reaches far beyond to involve the body and the environment (Bateson, 2000; Säljö, 1999). As Roth and Lee describe, referring specifically to Activity-Theory, “Its inherently dialectical unit of analysis allows for an embodied mind, itself an aspect of the material world, stretching across social and material environments” (2007, p. 189). From this perspective, learning is an activity that takes place not only in the head of learners but also in the material world. As Säljö articulates:

Human learning has always been a matter of mastering tools of different kinds, intellectual (such as, for instance, becoming competent in how to do a division or a multiplication by using algorithms) as well as physical (learning how to build a house or cultivate land). (1999, p. 147).

This suggests that understanding the mediation of the material tools used in learning situations is vital to understanding the learning itself.

One Frame, Different Shapes

Returning to the metaphor of the iris of a camera lens represented in Figure 1, the blades each represent the three major theoretical assumptions framing this study. I draw on each

theoretical assumption to understand the development and use of technology for mathematical learning and each moves in a separate yet interrelated way as I focus on specific aspects. In the three articles that report the findings of this study, I use the three assumptions in different proportions to focus the theoretical perspective on different aspects of the study (see Figure 2).

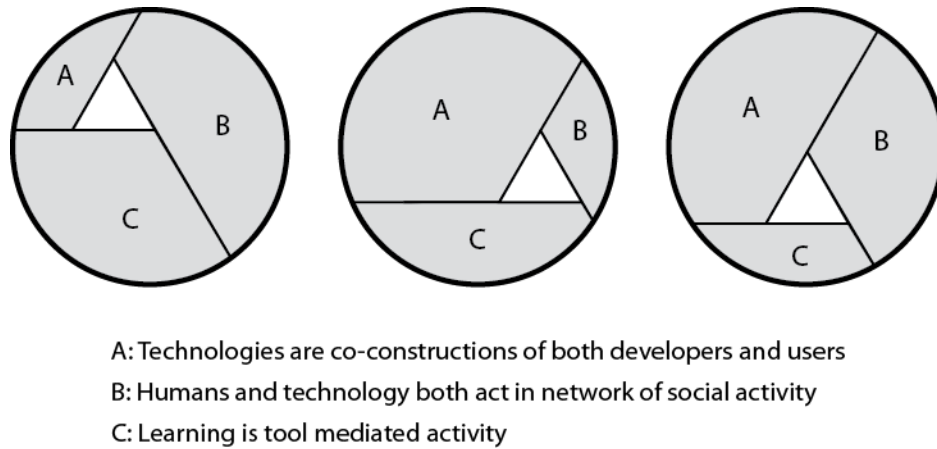


Figure 2: Different theoretical foci

One article focuses on the way a technology for mathematical learning is co-constructed by developers, teachers and students. In this article, I describe the reflexive process through which a technology was initially configured by its developers, then reconfigured by its users and how that reconfiguration feeds-back into new versions. While this article is framed by all three key assumptions, as illustrated in Figure 2, it particularly draws on the concept elaborated in the work of researchers in the field of Science and Technology Studies (Bijker, 1997; Kaghan & Bowker, 2001; Lindsay, 2005; Pinch & Bijker, 1984) that technology development does not finish once a product is shipped, but rather continues as users and technology co-construct each other.

Another article focuses on the relationships among teachers, students and materials such as textbooks, blackboards and paper and pencils. In this article, I examine the network of humans

and materials in classrooms and the ways it adapts to the introduction of a technology. Through this analysis, I address ways that technology mediates the mathematical activity in classrooms. Again, this article draws on all three theoretical assumptions but the idea articulated by researchers working with ANT (Latour, 1991, 2007; Law & Mol, 2001) - that when humans use technology both are actors and activity emerges from their interaction in complex networks - is especially important.

The final article illuminates the ways that mathematical activity mediates and is mediated by the co-construction of a technology. In this article, I trace the ways developers envisage users engaging with a technology, the ways it is situated in classroom instructional practices, and the ways it is involved in mathematical activity with students. All three key assumptions framed this examination but I particularly drew on the notion developed by researchers working with Activity-Theory (Leont'ev, 1978; Vygotsky, 1978, 1986; Wertsch, 1991) that cultural tools mediate all human activity including learning and the view expressed in ANT that both humans and technology are actors in sociotechnical networks.

Chapter 4. Empirical Context

My aim for this study is to enrich understanding of the roles of educational technology in mathematical learning by performing a genetic analysis of an educational technology's development and use. For this investigation, I chose to examine the development of a particular technology and its use within a particular educational setting. In this chapter, several key contextual issues related to the technology and the educational setting of this study that help to situate the research are addressed.

Technological Context

The specific technology I chose to examine in this study is *Texas Instruments TI-Nspire™* graphing calculator technology¹. I selected TI-Nspire for three primary reasons. First, the technology is relatively new and has a number of advanced features such as the ability for users to create and share files that I felt had the potential to support a variety of interesting new forms of mathematical activity. Second, despite having many new features, TI-Nspire is developed from a long line of *Texas Instruments* graphing calculators that have been widely used in schools. This legacy gives TI-Nspire an entry point into the educational technology market that many innovative new technologies do not have and it has found relatively wide acceptance in schools in the past three years, particularly in Europe, North America and Australia. This made finding teachers who were using TI-Nspire as part of their instructional practices and were willing to participate in the study possible. Third, *Texas Instruments* continues to actively

¹ TI-Nspire™ is a registered trademark of Texas Instruments Inc. To avoid repetition the trademark symbol is omitted for the remainder of this document.

develop TI-Nspire and produce new versions of the technology. This made it possible for me to interview developers who were still working on the technology and to talk with them about their process and intentions while they were still involved in creating it. Together, these factors allowed me to interview members of the development team while they were still working on the project and to interview and observe teachers and students using the technology.

As a graphing calculator, TI-Nspire has evolved from a long history of calculator use in schools. This history begins with the development of electronic handheld calculators in the mid-1960s and continues with significant developments like multiple line displays, the ability to graph functions and the ability to manipulate algebraic symbols emerging in the late-1980s and early 1990s (Kidwell, Ackerberg-Hastings and Roberts, 2008). Calculator technology has seen many advancements since its invention, but particularly in the past decade innovations in computer processors and digital displays have enabled technologies like TI-Nspire to close the gap between what might be considered a calculator and what might be considered a computer (Kaput & Schorr, 2008). Like earlier graphing calculator models, TI-Nspire is a relatively inexpensive handheld device (see Figure 3). It hosts a range of software applications including dynamic geometry software based on *Cabri-Géomètre*TM, spreadsheet and graphing tools, and a computer algebra system (CAS) that allows users to work with algebraic symbols along with numbers. Unlike earlier graphing calculators, however, all these applications are interconnected allowing, for instance, variables to be shared between graphs and geometric constructions. In addition, with TI-Nspire users can create, save and share digital documents that make use of all the different functions of the device.



Figure 3: TI-Nspire handheld calculator

The handheld calculator shown in Figure 3 is actually part of a family of tools that consists of two different handheld calculators, computer software, display adapters for use with projectors, and accessories that provide features such as wireless networking and connections to scientific probes for data collection. For this study, I observed the use of one of the handheld calculator versions and the accompanying computer software. Though very similar, the two handheld calculator versions have different features. The one that I examined hosts all the software applications mentioned earlier such as dynamic geometry, graphing, spreadsheets, and CAS. The other version has all the same functionality but lacks CAS capabilities. This non-computer-algebra version serves a particular role in the United States as it is allowed during American College Testing (ACT) university entrance exams, which have banned the use of CAS.

In addition to the two versions of the handheld calculator, the TI-Nspire family also includes computer software (see Figure 4).

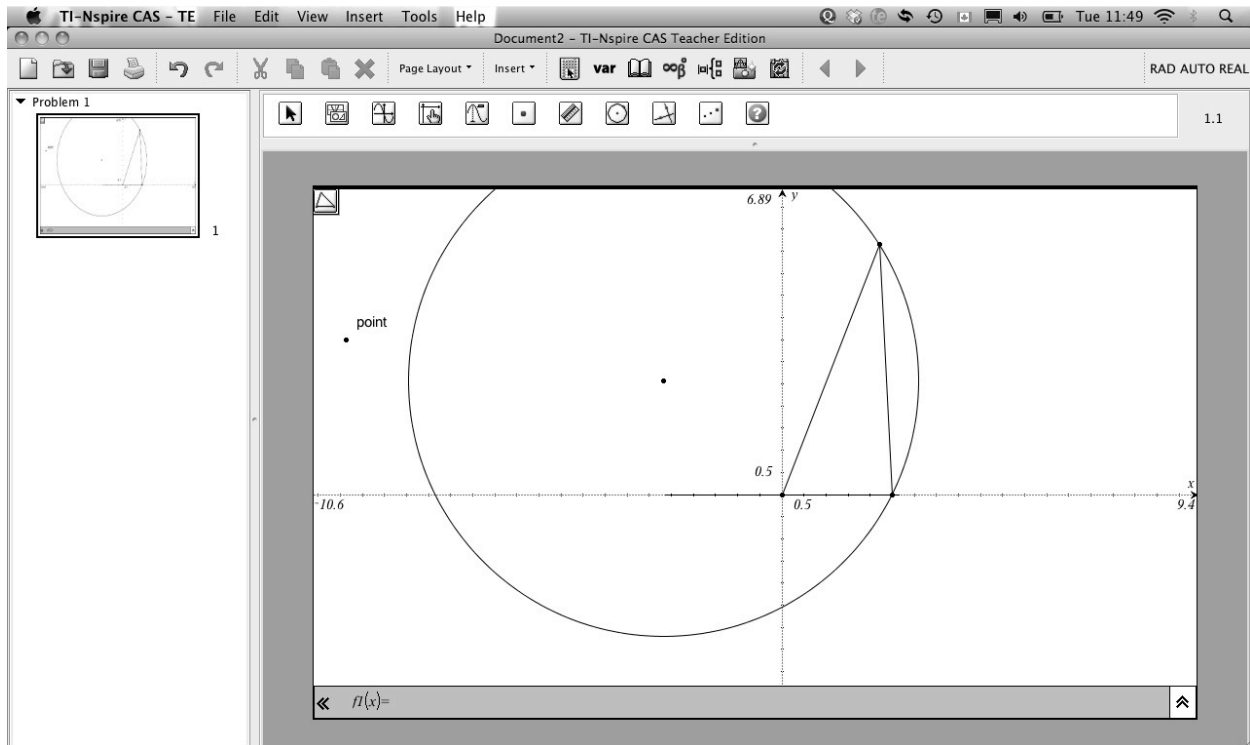


Figure 4: TI-Nspire computer software

This software emulates the same features as the handheld calculators while affording users the ability to make use of the large screen and full keyboard of a computer. Since the functions of the software are identical to the handheld calculator, a common practice is for teachers to project the software on to a screen at the front of their classrooms so that they can share ways of using TI-Nspire with their class.

Like many technologies, TI-Nspire continues to be revised as developers refine and enhance it. Since it became publicly available in July 2007 there have been several major revisions to both the handheld calculators and the computer software. Each revision has introduced new features and refined existing ones. During data collection for this study, the teachers and students that participated used version 1.6 of both the handheld calculator and computer software. At the time, this was the most up-to-date version of the technology available.

Educational Context

Another important aspect of the empirical context of this study is the educational context of the teachers and students who participated. The setting for the in-school elements of this study was a large suburban secondary school in Ontario. The province of Ontario has a mathematics curriculum that is particularly supportive of the use of digital technologies such as dynamic geometry software and computer algebra systems (CAS), and this characteristic of the provincial curriculum is important to situating the in-school phase of this study. In addition, the school in which this study was conducted has a program that supports each student having their own personal TI-Nspire to use. This program is also important for understanding the educational context in which the fieldwork for this study was conducted.

Support for technology use in the Ontario mathematics curriculum.

The province of Ontario has a centralized curriculum that sets out the content to be covered in courses. Throughout the latest 2005 edition of the Ontario ninth and tenth grade mathematics curriculum document, special attention is given to the use of tools and in particular information-communication technology in the classroom. At a number of key points, the Ontario curriculum document describes a wide range of technologies including dynamic geometry software, computer algebra, spreadsheets and graphing software as both useful computational tools and as important means of representing mathematical work (OME, 2005). For instance, the curriculum document indicates:

Information and communication technology (ICT) provides a range of tools that can significantly extend and enrich teachers' instructional strategies and support students' learning in mathematics. Teachers can use ICT tools and resources both for whole-class instruction and to design programs that meet diverse student

needs. Technology can help to reduce the time spent on routine mathematical tasks and to allow students to devote more of their efforts to thinking and concept development. Useful ICT tools include simulations, multimedia resources, databases, sites that give access to large amounts of statistical data, and computer-assisted learning modules. Applications such as databases, spreadsheets, dynamic geometry software, dynamic statistical software, graphing software, computer algebra systems (CAS), word-processing software, and presentation software can be used to support various methods of inquiry in mathematics. (OME, 2005, p. 27)

Throughout the document, the use of a variety of technologies is suggested and they are positioned as important resources for mathematical learning. This positioning also goes beyond broad statements of support and extends to specific requirements for content to be addressed during courses. In a section describing the mathematical processes that students are expected to engage in throughout their ninth grade course, for example, two of the seven major processes listed specifically require the use of digital technologies. Under the heading *Selecting Tools and Computational Strategies* the curriculum requires that students, “select and use a variety of concrete, visual, and electronic learning tools and appropriate computational strategies to investigate mathematical ideas and to solve problems” (OME, 2005, p. 29). Similarly, under the heading *Representing*, students are required to, “create a variety of representations of mathematical ideas (e.g., numeric, geometric, algebraic, graphical, pictorial representations; onscreen dynamic representations), connect and compare them, and select and apply the appropriate representations to solve problems” (OME, 2005, p. 29). These requirements and regular mention of digital technologies throughout the sections of the curriculum document that

refer to specific mathematical topics to be addressed during courses, help to shape an institutional context that advocates the use of technologies such as TI-Nspire. This promotes a culture of supporting teachers who choose to work with technology and this culture is an important part of the educational context in which this study was conducted.

Student ownership.

Another important aspect of the particular educational context of this study is that the students in the classrooms I observed either owned or had been lent a TI-Nspire on a long-term basis. Many schools chose to buy class-sets of technologies that are used exclusively during class-time, but at the school where I conducted this study students are encouraged to buy their own. Through a program where the school purchases TI-Nspire handhelds in bulk, the technology is sold to students at a lower price than it is available in stores. This program also allows the school to make a small profit on each TI-Nspire that is used to fund the purchase of extra calculators to lend to students whose parents cannot or chose not to buy one. Under this scheme, the majority of students who participated in this study owned their own TI-Nspire and others had chosen to borrow one for the entire term. This afforded the students much more access to the technology than they would have had if their teachers had chosen to use class-sets that could only be borrowed during class-time. The students had access to TI-Nspire at any time of their choosing including during other classes such as science and while doing homework. Along with an institutional culture that supports teachers' use of technology, this wide access to TI-Nspire is an important aspect of the context of this study.

Chapter 5. Method

In this section, I discuss the research methods I used for this study of the development and use of TI-Nspire. I begin by addressing my data collection activities with technology developers, teachers and students and then describe the ways that I analysed the collected data. In each section, I describe the procedures used and give rationales for their selection.

Data Collection

Data collection for this study involved two major phases. One phase involved TI-Nspire development team members and the other involved secondary school mathematics teachers and their students. I will discuss these data collection phases in the following sections.

Interviews with TI-Nspire development team members.

One of the key ideas guiding this study is the notion that technologies in classrooms come from somewhere and have been designed with purpose. To understand the processes and intentions of TI-Nspire developers, I followed the lead of a number of researchers in the field of Science and Technology Studies who have also chosen to interview developers directly when investigating technologies (Akrich, 1995; Latour, 1996a). Much can be learned from the design of technologies themselves and from supporting documents, but interviews with developers are a particularly rich source of insight into the processes, decisions and intentions that lead to them (Latour, 1996). Drawing on this premise, I interviewed a total of six development team members. This group included four professional developers who work at *Texas Instruments* and two mathematics education researchers who consulted on the project. These participants were chosen

to reflect the wide diversity of individuals involved in the TI-Nspire development process (see Table 1).

Table 1

Developer and Consultant Participants

| Participant | Profile |
|--------------------------------------|--|
| Developer One | Senior manager and long-time graphing calculator developer. |
| Developer Two | Product manager with previous experience working as a mathematician. |
| Developer Three | Product manager and experienced teacher turned developer. |
| Developer Four | System architect who is relatively new to engineering graphing calculators. |
| Mathematics Education Consultant One | Mathematics education researcher and teacher educator who is involved in <i>Texas Instruments</i> supported teacher educator professional development. |
| Mathematics Education Consultant Two | Mathematics education researcher and teacher educator with a long-time interest in dynamic geometry who has been involved in the development of graphing calculators for many years. |

I interviewed each development team member following an interview guide (see Appendix A) that focused on the TI-Nspire development process and the extensive professional development activities for teachers that *Texas Instruments* supports. I audio-recorded these semi-structured interviews and they took place in-person at the offices of the participants. While I would have preferred to video-record the interviews, the participants requested that only audio be recorded due to the sensitive nature of the commercial secrets in their offices. It had been my intention to bring a TI-Nspire to the interviews and to use video to record instances in which participants manipulated it as they referred to specific features. Instead, I made written note of such instances and during analysis the notes along with audio cues from participants tapping on the TI-Nspire or touching keys, for example, proved to be a useful source of information.

Classroom observation and interviews with teachers.

The other phase of data collection involved teachers and students who make regular use of TI-Nspire. As mentioned in the previous chapter, the two teachers in this study worked at a large suburban Ontario secondary school and the students from a ninth grade mathematics course taught by each teacher participated. While both teachers are confident technology users, they each have different backgrounds and different ways of including technology in their practices that reflect some of the diversity of approaches that exist. To gain an understanding of the educational culture in which TI-Nspire was being used, I interviewed the two teacher participants and spent a week observing and video-recording in their classes. I recorded video throughout the activities with teachers and students to provide a richer record of the interviews and observed sessions than audio recording could offer (Kress, 2003). Particularly important for this study was the ability of video to record participants' interactions with TI-Nspire and other materials.

The first activity I conducted with the teacher participants was an initial interview that focused on their use of TI-Nspire and their experiences with technology in the classroom (see Appendix B for the interview guide I followed). These interviews provided me an opportunity to learn about the participants' backgrounds, their goals and their feelings about teaching mathematics and the role of technology in their practices. The interviews were video-recorded and a TI-Nspire was always present so that both the teachers and I could refer to it. Each interview lasted for between one and a half and two and a half hours. From these initial conversations, I developed an understanding of each teacher's distinct background and experience teaching with technology. One teacher is a former school board mathematics consultant with a long history of classroom technology use. This teacher is also involved in the *Texas Instruments* supported T^3 professional development conferences and community that

supports teachers in sharing their practices with technologies like TI-Nspire. The other teacher trained as a mathematics teacher but spent several years teaching computers and programming. At the time of the study, he had only relatively recently returned to teaching mathematics.

Following the initial interviews, I observed a series of five consecutive sessions in each teacher's class. These sessions were recorded with multiple microphones and a single video camera that was focused on the teacher's practices with TI-Nspire. The diagram in Figure 5 illustrates the basic configuration of one classroom during observation. The other classroom layout was not identical, but the general position of major elements such as student desk groupings, the teacher's desk, the video projector and blackboard, and my position with the video camera was the same. As Figure 5 indicates, during the observed sessions I stood in the back corner of the classrooms with a tripod-mounted video camera. This position provided me a broad viewpoint on the classroom from which I could follow the teacher.

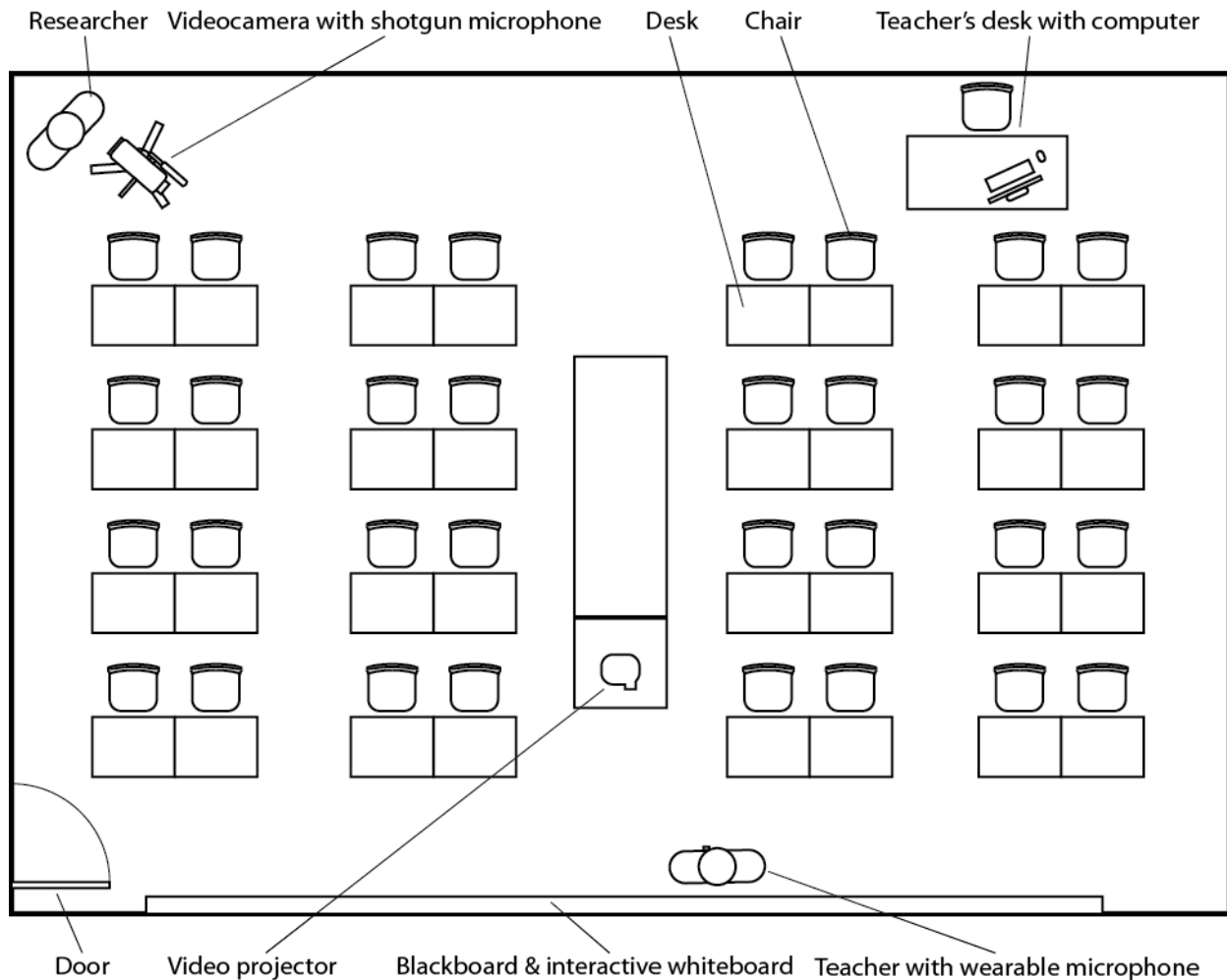


Figure 5: Classroom layout

At first, I used only a single shotgun microphone mounted onto the video camera to capture sounds from the classroom. This microphone provided far superior sound quality to the built-in microphone of the camera and gave a good balance of directional recording in the direction the camera was pointing and omni-directional recording of the classroom as a whole. Upon review of the first recorded session, however, I decided to augment the shotgun microphone by asking the teachers to wear an additional microphone. This additional microphone made recordings of the teachers much more reliable particularly when they were interacting with an individual or small group of students. In these situations, teachers often bend

down to work with students and they tend to speak more quietly than when addressing the class as a whole. Where the camera-mounted microphone often failed to adequately pick-up these conversations, the wearable microphone provided a clear recording.

Similar to the way I used both camera-mounted and wearable microphones to capture the sounds of the classrooms in general while maintaining attention on the teacher, I also used ‘in-camera editing’ to focus on the actions of the teachers while maintaining an impression of the broader classroom context. As I used only one camera during the classroom sessions, this involved selecting where to focus recording as the classes unfolded. In general, I followed the teachers with the camera since my intention for the classroom observations was to concentrate on the ways they included TI-Nspire in their instructional practices and situated the technology for their students. This focus on the teachers guided the majority of the ‘in-camera editing’ decisions made about where to focus recording but I also made efforts to maintain a wide view as much as possible using panning and zooming sparingly. As Derry, Pea, Barron, Engle, Erickson, Goldman, *et al.* suggest, while a certain amount of pan and zoom may be needed to get a detailed view of activities of interest, “too much selection at recording time may rule out later lines of analysis” (2010, p. 48). Drawing on this principle while concentrating my in-camera selection decisions on the teacher, I constantly considered the balance between recording detailed views of teacher activities such as writing on the board or interacting with an individual student and maintaining an impression of the activity in the classroom as a whole.

After each class, the teachers were invited to participate in retrospective debriefing interviews that helped me to unpack the events of the session. These interviews were video-recorded and when possible took place in the participant’s classroom so that they had the same resources at hand as they had during class-time. This allowed me to observe and record instances

when the teachers referred to materials such as worksheets, textbooks and TI-Nspire. During these interviews, I also collected the material artefacts that had been used in the class including worksheets and digital TI-Nspire files created by the teacher and distributed to their students. If a debriefing interview could not be held in the classroom due to the arrival of another class, for example, they were then conducted either in the school staffroom or the mathematics department office.

Mathematical activity sessions and interviews with students.

In addition to focusing on the teacher participants, to get a more detailed view of student activity with TI-Nspire I invited students to participate in the study beyond the classroom observation. All students in the classes were asked to volunteer for a mathematical activity session that involved working on a mathematical activity related to their class work. Drawing inspiration from a number of mathematics education researchers who have examined student technology use (Clements & Battista, 1990; Hoyles, Healey, & Sutherland, 1991), I asked the students to participate in pairs so that I could observe their collaborative work and listen to their discourse as they negotiated the activity. As compensation and to encourage participation in the activity that involved giving up a lunch hour, I offered students \$15 *iTunes* gift cards that could be redeemed for media online. In one of the classes a pair of students volunteered while in the other only a single student volunteered but proposed that he had a friend who wanted to participate and had taken the same course in the previous semester.

The mathematical activity I asked the students to complete during the sessions was created in collaboration with a mathematics education researcher who is also an experienced school mathematics teacher. We designed the tasks to be similar to activities the students were familiar with from their classes and deliberately avoided requiring the use of TI-Nspire. Instead,

I provided the student pairs with linking-cubes to manipulate, paper and pencils, and TI-Nspire thus allowing me to observe *when* they chose to use the technology in addition to *how* they used it. During the development of the activity, I pilot tested it with a single ninth grade mathematics student who was not part of the study. I used insight from this experience to refine the activity, particularly the accompanying written instructions.

The activity itself involved working with a series of three patterns that were provided to the students as diagrams and as linking-cube models (see Figure 6). With the first three steps in each pattern provided, the students were asked to answer a series of questions that related to the patterns and their linearity. This focus on linear and non-linear patterns was chosen due to the relatively large amount of the Ontario ninth grade mathematics curriculum that is dedicated to working with linear and non-linear functions (OME, 2005).

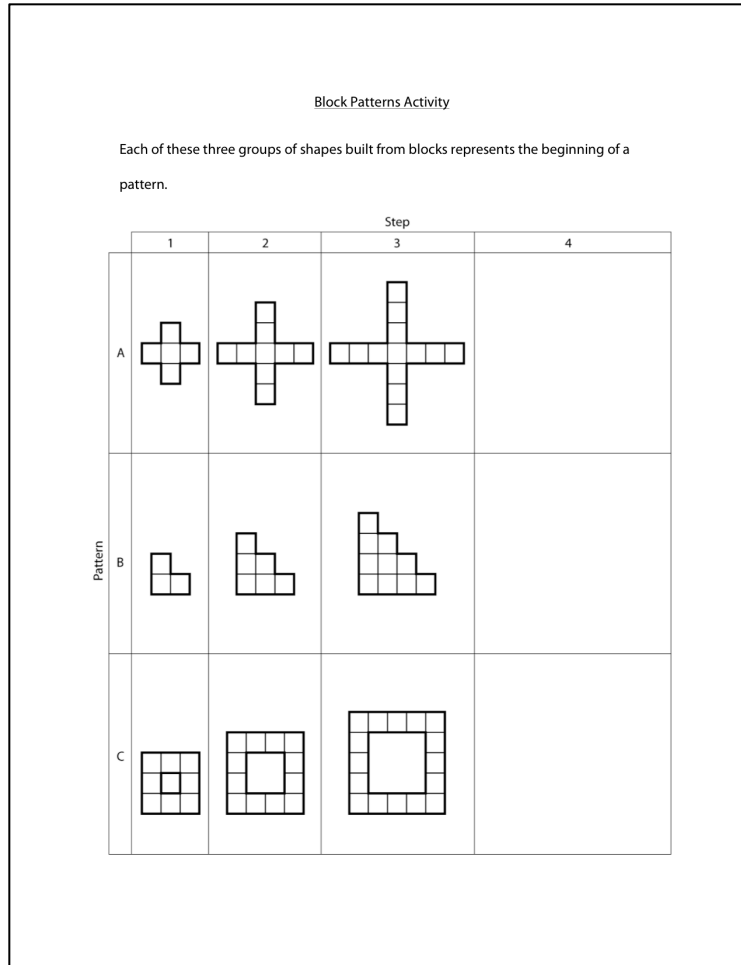


Figure 6: Mathematical activity session patterns

For each of the three patterns illustrated in Figure 6, a shape grew over a series of three steps and the student pairs were asked to create the fourth step and determine whether or not the change in number of cubes between steps formed a linear sequence. Patterns A and C grew in a linear sequence while pattern B grew in a non-linear sequence. Having shown the linearity of the patterns, the students were then asked to determine how many cubes it would take to build the fiftieth step in pattern A and asked to compare patterns A and C for similarities and differences (see Table 2).

Table 2

Mathematical Activity Session Tasks

| Question | Task |
|----------|---|
| One | Using the extra blocks, build the 4 th step in each of the three patterns... |
| Two | Looking at the relationships between step number and number of blocks, which of the three patterns have relationships that are linear? Show how you know... |
| Three | How many blocks would be needed to make the 50 th step in pattern A? Show how you know... |
| Four | Show how patterns A and C are similar and different... |

To record the students' activity while completing the tasks, I used two video cameras and two microphones. As Figure 7 illustrates, one camera with a shotgun microphone attached was placed facing the pair, a second camera without a microphone was positioned to record their working from behind and a tabletop microphone was placed on the desk. This arrangement allowed me to record the students' collaborative work and conversations from the front while also having a more detailed view of their paper and pencil, linking-cube and TI-Nspire activity from above and behind their heads. In addition, screenshots from the students' shared TI-Nspire were digitally captured using software on a computer placed off to the side that provided a clear view of their on-screen activity. This software was composed of the TI-Nspire *Link*TM program supplied by *Texas Instruments* that can capture single images from the screen of TI-Nspire and a custom program I wrote that automatically triggered TI-Nspire *Link*TM to take pictures twice a second and then compiled the resulting images into a video.

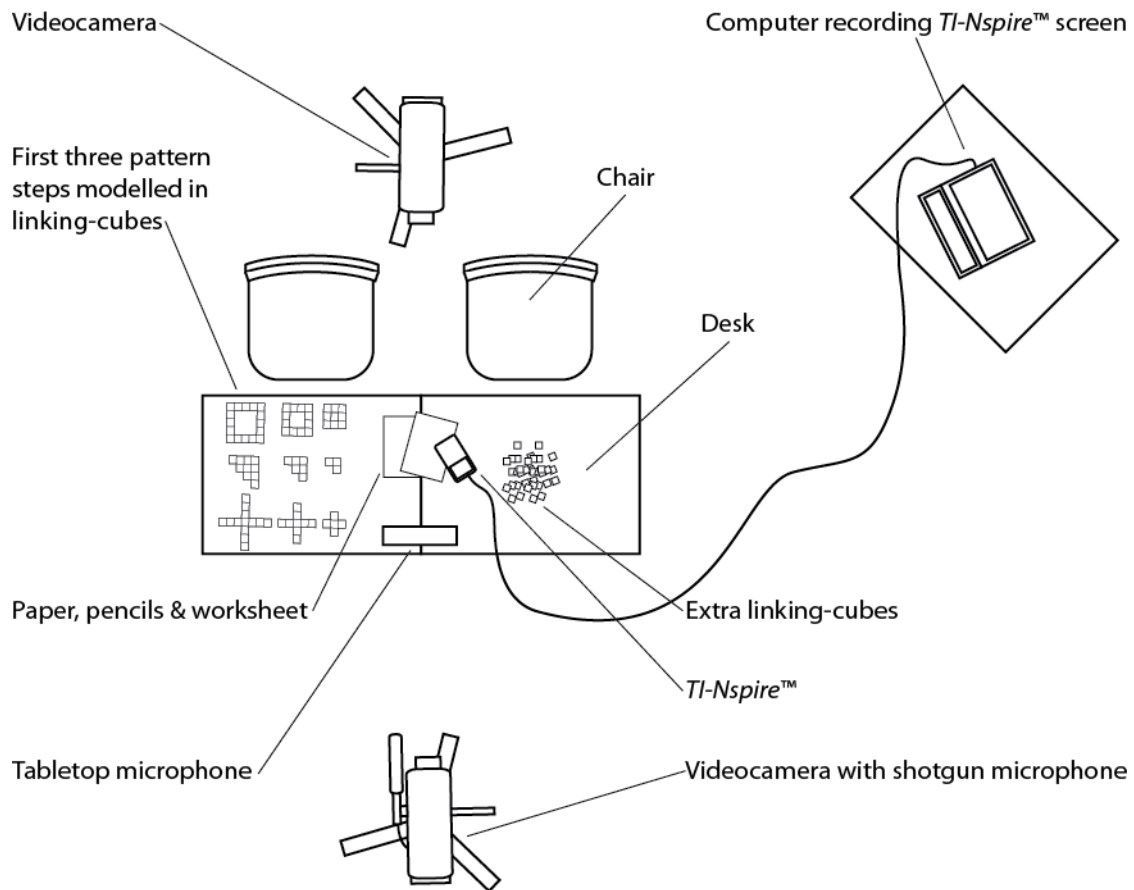


Figure 7: Mathematical activity session layout

Following the mathematical activity sessions, I combined the front and back camera recordings with the digital captures of the TI-Nspire screen and the two microphone recordings into a single video that enabled me to view them all at once. This process involved synchronising the separate audio and video recordings and digitally tiling the videos so that they would fit on a single screen (see Figure 8).

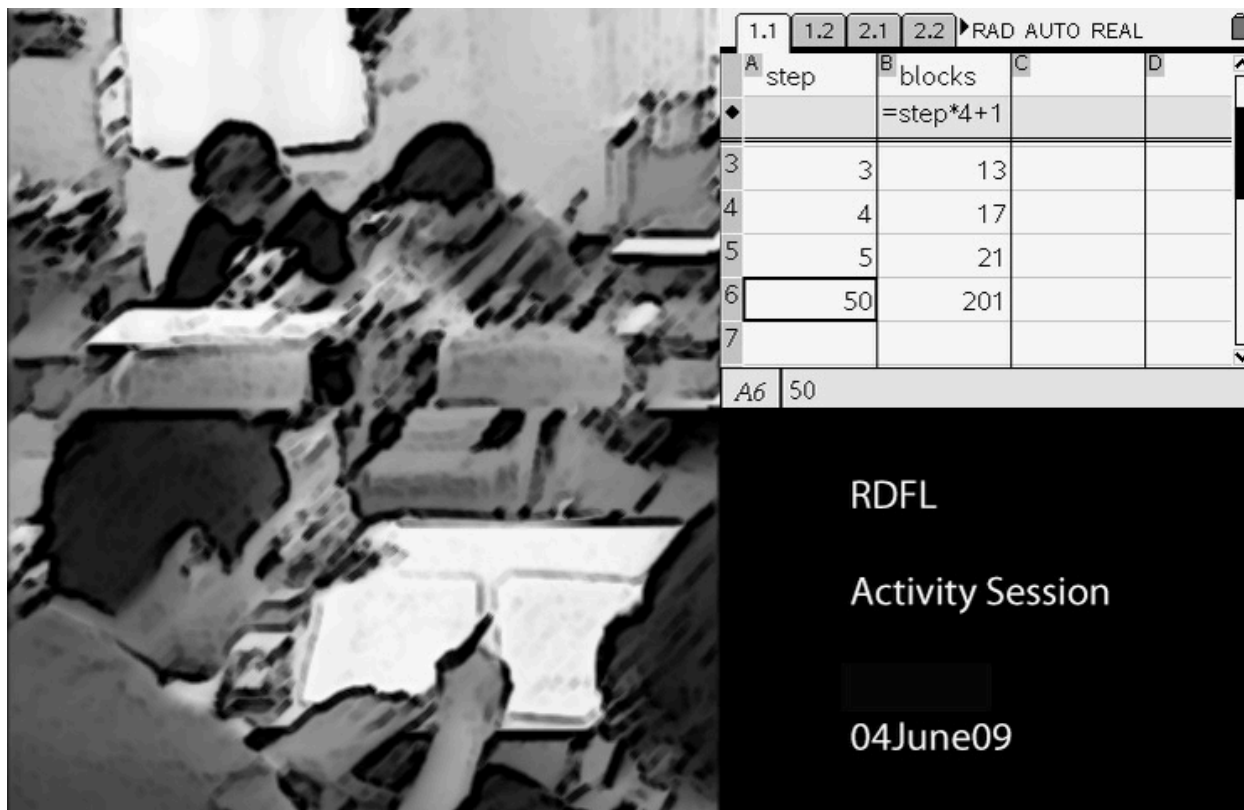


Figure 8: Activity session combined video

The resulting combined video allowed me to view both camera positions and the TI-Nspire screen at once and in relation to each other. While the process did result in smaller images of each individual video element, I was able to turn to the original non-combined videos in cases where higher resolution was helpful.

Following the completion of the activity, each student pair participated in a retrospective debriefing interview that provided insight into both their practices while completing the task and more generally with TI-Nspire (see Appendix A for the interview guide that I followed). I conducted these interviews directly after the mathematical activity in the same location but using only the forward facing video camera.

Data Analysis

Following each interview or observation session, I processed the recordings by converting the digital audio and video into formats suitable for transcription and analysis software. I then listened to or watched the recording to verify its quality and so that I could make a content log while the experience was still fresh in my mind. At this point, I made the decision not to transcribe the classroom observation sessions due to the volume of recordings but to rely instead on the video recordings and the content logs made directly after the classes. This decision meant that analysis would proceed with a combination of recordings and transcriptions so I turned to *Transana*, a qualitative analysis software package that allows efficient organisation and analysis of multiple media sources (Woods & Fassnacht, 2009).

Beyond providing me an environment for working efficiently with both recordings and transcriptions, *Transana* also allowed me to synchronize recording and transcript pairs so that sections identified in the different media would automatically correspond and allowed me to transcribe sections of the classroom observation videos as needed (see Figure 9). As Mavrou, Douglas and Lewis (2007) suggest having used *Transana* in the analysis of video data collected in schools in Cyprus:

Transana is unusual in its flexibility and novelty, especially regarding video data analysis, among recent computer-based qualitative analysis tools. For example, its use makes it very easy to return to the original source from which a clip has been taken. This allows the researcher to see the context for the clip and so to investigate questions about what happened before or after the selected clip (by definition, a sequence that was interesting to the researcher). (p. 175)

The advantage of this flexibility is the ability to select a passage in either a transcript or a recording with the same section in the other media automatically linked without losing the position of the selection within the interview or observational session.

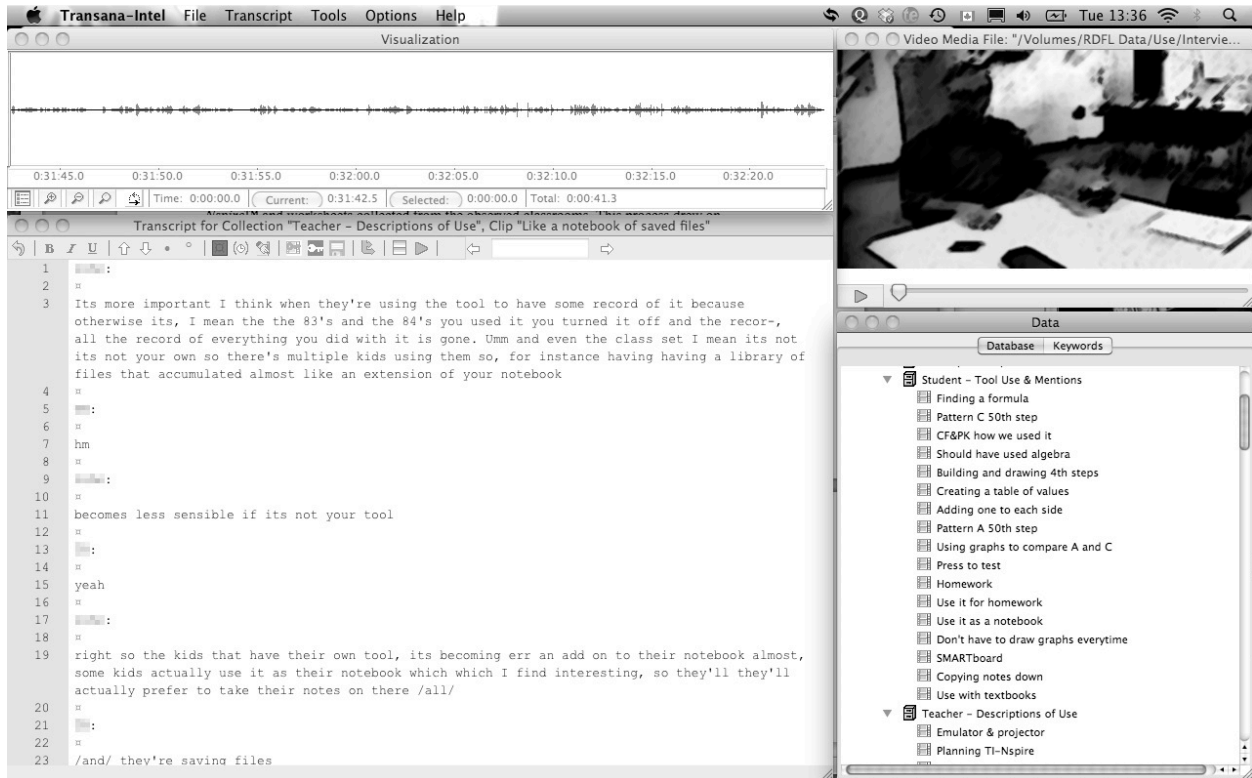


Figure 9: Analysis of a synchronized transcript and video in *Transana*

This freedom to move between recording and transcript while maintaining synchronisation afforded flexibility to the analytic process during which multiple passes of each interview and video-recording were made by repeatedly listening to or watching the recordings and reading the transcriptions. While I analysed the interviews and observational videos, I also examined artefacts such as digital documents created by the teachers to load on TI-Nspire and worksheets collected from the observed classrooms. This process drew on Interaction Analysis, a method for analysing multimodal data with a particular focus on video that foregrounds analysis of the

interactions between humans, their environment and the artefacts in it (Jordan & Henderson, 1995).

As an approach to the analysis of multimodal data, Interaction Analysis shares many of the same or similar theoretical assumptions that are drawn on in this study. In particular, the approach assumes “that knowledge and action are fundamentally social in origin, organization, and use, and are situated in particular social and material ecologies” (Jordan & Henderson, 1995, p. 41). This basic assumption is shared by both Actor-Network theory (ANT) and Activity-Theory and forms a key element of the theoretical perspective of this study. From this underlying assumption, Interaction Analysis suggests a number of ways of analysing video recordings. These methods include creating content logs that outline the activity on a recording as soon as possible having recorded an observational session and conducting collaborative viewings with other researchers (Jordan & Henderson, 1995). Drawing on these suggestions, I assembled content logs following each interview or observed session and at least one pass of the recordings was made in collaboration with another researcher. While this process did not have the scope of the multi-researcher discussions preferred by Interaction Analysis proponents, it did afford an alternative perspective on the data and allowed generative discussions to take place regarding analytic decisions.

While data collection had two distinct phases due to the different participant groups and the findings of this study are reported in three articles, for analysis I decided to treat all the interviews, artefacts and observational recordings as a single corpus. This decision reflects the aim of the study and in particular the theoretical notion that the development and use of technology is an on-going co-constructive process. With the choice made to analyse all the data at once, I sorted it by identifying elements of particular interest across the interviews, artefacts

and observational recordings. Using *Transana* to make selections, I proceeded by first identifying instances where participants spoke about TI-Nspire or related technologies and in the case of teacher and student participants used TI-Nspire. Simultaneously, I developed profiles for each of the participants by identifying instances in which they spoke about their backgrounds and the experiences that have led them to become involved with TI-Nspire. This initial sorting process allowed me to focus on those elements of the data that involved the technology. Following this, I then used *Transana* to add descriptive keywords to each data clip. These keywords identified activities in an instance such as a developer describing the ways he imagined a feature of TI-Nspire being used or a teacher demonstrating a way of working to a class (see Table 3).

Table 3

Descriptive Keywords

| Keyword Group | Keywords |
|----------------------|--|
| Participant | Developer, Consultant, Teacher, Student |
| Material | TI-Nspire, Interactive whiteboard, Blackboard, Projector, Overhead, Textbook, Worksheet, Algebra tiles, Computer |
| Mentions | Keystroke instruction, Description of use, Development approach, Minor mention (e.g. 'Don't forget your TI-Nspire), Goal for TI-Nspire, Issue with TI-Nspire |
| Use | Demonstration, Individual work, Group work, Off-topic, Take-up |
| Context | Ontario & technology, School admin, School board, Student ownership, Standardized testing, Graphing calculator history, Participant background |

Following this recursive process of adding keywords and repeatedly working with the data clips, I was able to search across all the interviews, artefacts and observational recordings to find similar instances.

Having performed an initial sorting, I examined the data for patterns of relations between humans and TI-Nspire by drawing on the work of ANT researchers concerned with the spatiality of sociotechnical networks (Law, 2002; Law & Mol, 2001; Sørensen, 2007b). These researchers describe the ways sociotechnical networks are enacted through the practices of human and non-human agents in terms of ‘fluid spatiality’. They suggest that the shape of sociotechnical networks is constantly adapting and is never fixed but, importantly, “while the connections which make a shape invariant in fluid space change shape, they do so *gradually* and incrementally” (Law & Mol, 2001, p. 6). As Law describes, “no particular structure of relations is privileged. This means that in a fluid, objects hold themselves constant in a process in which new relations come into being because they are reconfigurations of existing elements, or because they include new elements” (2002, p. 99). Examining the fluid networks enacted by the development and use of TI-Nspire, I concentrated on ‘edge cases’ of interactions between participants and the technology such as innovations, breakdowns and frustrations in an effort to identify stabilized practices (Latour, 2007). To analyse these stabilized practices, I drew on the work of Akrich (1995) to describe ways that developers inscribe the technologies they create with representations of envisaged user activity. In this work she identified such methods as market surveys, consumer testing, user feedback, personal experience and expert consultants as ways that developers create and appropriate representations that they then inscribe in their creations. Since Akrich only examined the initial development process and did not address the ways users interpret and reconfigure technologies, I also drew on the work of Latour (1996a, 2007), Pinch & Bijker (1984), Suchman (2007), and Woolgar (1991) to investigate the activity of teachers and students who translated developer inscriptions as they adapted and reconfigured the technology to meet their own needs. This process focused in detail on the activities of both

human and non-human actors in the classrooms and paid particular attention “to mundane heaps of material and immaterial stuff and how they become stuck (and unstuck)” (Fenwick & Edwards, 2010, p. 168).

Chapter 6. Findings

My research questions are addressed through three articles that have been submitted to peer-reviewed journals. These articles report the findings of this project and employ different aspects of the theory and method of the overall study. One article examines the ways that TI-Nspire is co-constructed by developers, teachers and students. In this article, I describe the reflexive process through which the technology was initially configured by its developers, then reconfigured by its users and how that reconfiguration feeds back into new versions. A second article focuses on the relationships among teachers, students and materials such as textbooks, blackboards and paper and pencils. In this article, I examine the network of humans and materials in classrooms and the ways it adapts to the introduction of TI-Nspire. Through this analysis, I address ways that TI-Nspire mediates the mathematical activity in the classrooms. The final article describes the ways that mathematical activity mediates and is mediated by the co-construction of TI-Nspire. In this article, I trace the ways developers' envisaged users engaging with TI-Nspire, the ways the technology was situated in classroom instructional practices, and the ways it was involved in mathematical activity with students.

Each of the three articles addresses the interrelated research questions that orient this project. At their core, the questions ask how educational technology, its development and its use mediate mathematical learning:

Within the activity system of developing and using technological tools for mathematical learning, how are those tools co-constructed?

In what ways is that co-construction mediated by mathematical activity?

In what ways does that co-construction mediate mathematical activity?

While these questions are not directly the topics of the three articles, they are addressed to some extent in each and together the articles seek to offer answers.

Of the three articles, the article titled *Joining the Class: Examining the Reflexive (Re)configuration of Educational Technologies as They Are Created and Become Part of Mathematics Classrooms* most directly addresses the question of how technologies for mathematical learning are co-constructed. In this article, I examine the development of TI-Nspire and discuss the reflexive process as technologies are created and become part of mathematics classrooms. To perform this examination, I draw on the interviews with developers, teachers and students along with the classroom observation and mathematical activity sessions to gain a broad perspective on the on-going development of the technology. Working with these data, I focus on the ways TI-Nspire was configured by its developers, reconfigured by teachers and students, and how those reconfigurations feedback into the configuration of new versions of the technology. The findings of this article that has been submitted to the *International Journal of Computers for Mathematical Learning* describe the configuration and reconfiguration processes that shape educational technologies as those technologies shape the activities of the developers, consultants, teachers, and students who create them. They show that this process can lead to a feedback cycle that allows the configuration of new versions of educational technologies to have an on-going interaction with teacher and student reconfigurations.

In the article titled *A Geography of Connections: Networks of Humans and Materials in Mathematics Classrooms Using Handheld Technology*, I examine the ways that TI-Nspire relates to other actors, both human and material, in mathematics classrooms. This article, which has been submitted to the journal *Forum: Qualitative Social Research*, addresses the ways sociotechnical networks of humans and materials form in relation to the technology in

classrooms. Working with the interviews with teachers and students, I identified a set of relationships among human and non-human actors that the participants described as having changed when TI-Nspire was introduced in their classrooms. The actors included teachers, students, textbooks, worksheets, paper and pencil, blackboards, interactive whiteboards, and TI-Nspire. Using these identified actors to orient my analysis, I drew on the Actor-Network theory (ANT) concept that the social is comprised of networks of both humans and non-humans to map the formation of sociotechnical networks in the two classrooms. The findings illuminate the complex set of mediators in classrooms where handheld technologies are used and show the interconnectedness of humans and materials such as the teacher, the textbook, worksheets, the computer lab, the board, paper and pencil, handheld technology and students. Similar to the first article, the findings reported in this article address the question of how technologies for mathematical learning are co-constructed but also speak to how that process is mediated by mathematical activity in classrooms.

Having developed an understanding of the co-constructive process through which TI-Nspire emerges and the ways it interacts with humans and materials in classrooms, in the article titled *Tracing Mathematical Activity with Handheld Digital Technology: From Development to Classroom Use*, I specifically address the ways the co-construction of the technology mediates and is mediated by mathematical activity. Working with the interviews, classroom and mathematical activity session observational recordings, and collected artefacts, I examine the mathematical activity that the developers envisaged happening with TI-Nspire, the ways that the teachers included it within their instructional practices, and the ways that the students worked with it to perform mathematical tasks. This examination particularly draws on the concept that all cognition including learning is tool-mediated action (Leont'ev, 1978; Vygotsky, 1978, 1986)

and on the understanding that the vision of user action that developers inscribe in a technology does not dictate actual use but rather serves as a resource out of which future activity emerges (Akrich, 1995; Latour, 1996a; Suchman, 2006). Drawing on these notions, the article illuminates ways that mathematical activity is mediated as technology developers, teachers and students interact with TI-Nspire. The findings of this article that has been submitted to the *Mathematics Education Research Journal* trace the relationship between mathematical activity and the technology from development to use and show that developers had a changing vision of the mathematical activity that they intended TI-Nspire to support. They illuminate the ways that developers inscribed a vision in the features of the technology that was initially focused on encouraging open and exploratory mathematical activity but later, in response to feedback from educators and market forces shifted to support a more calculation-oriented role. Despite this shift in envisaged mathematical activity that developers inscribed into TI-Nspire, the findings reveal that teachers and students engaged with the features of the technology regardless of intended style of activity in a variety of ways. The teachers situated the technology as way of reducing the burden of performing calculations and creating representations, and as way of checking calculations, verifying conjectures and supporting assertions. The students approached the mathematical tasks I asked them to complete by sometimes working with TI-Nspire as their primary mathematical environment and other times as purely a calculation tool. In both cases, however, similar to the way their teachers had situated the technology, they repeatedly worked with it to verify conjectures and as evidence for assertions.

In the next three chapters, the articles are presented as they have been submitted to journals. Each article has its own context, theory and method sections that focus on elements of the wider study to examine their particular topics. The findings of each examination are then

discussed and conclusions are offered. Following the three articles, the final chapter of this document will draw on the three articles to discuss the overall conclusions and implications of this project.

Chapter 7. Joining the Class: Examining the Reflexive (Re)configuration of Educational Technologies as They Are Created and Become Part of Mathematics Classrooms

Submitted to the *International Journal of Computers for Mathematical Learning*

Abstract

Seeking to contribute to a more nuanced understanding of the role of educational technology in schools, this paper illuminates the reflexive process of configuration and reconfiguration as technologies are created and become part of mathematics classrooms. As a technological case *Texas Instruments' TI-Nspire* is examined. To investigate the development and use of TI-Nspire, research from the field of Science and Technology Studies is drawn on that provides insights into the relationships between development, technology, and users. The findings show that professional technology developers, mathematics education researchers, classroom teachers, and students are all involved in shaping the ways educational technologies become part of mathematics classrooms through a co-constructive process of (re)configuration.

Introduction

The presence of digital technologies in classrooms is no longer an uncommon sight. Beyond general-use technologies installed in schools, such as laptops and video projectors and a multitude of mobile devices brought in by students and teachers, educational technologies developed specifically for schools form part of the landscape of many classrooms. Particularly within the realm of mathematics education, numerous software and hardware solutions have been created with the specific intention of supporting learning. A large amount of research has

been conducted that suggests these technologies can help learners make connections with and between mathematical concepts and enrich their mathematical thinking (Artigue, 2002; Clements, Battista & Sarama, 2001; Drijvers, 2000; Heid, 2001; Hoyles & Noss, 2003; Kieran & Yerushalmy, 2006). To a lesser extent some research has addressed the development of technologies for mathematical learning though this work has been largely limited to researchers investigating their own creations as part of design-based studies (diSessa, 2001; Kaput & Schorr, 2008; Tatar, Lin & Dickey, 2005). Little attention, however, has been paid to the processes through which many of the most widely used commercially produced technologies are developed. In this paper, I will examine the roles and processes of professional technology developers, educational research consultants, classroom teachers, and students involved in the development of *Texas Instruments'* TI-Nspire graphing calculator. Taking TI-Nspire as a case, this paper uncovers the reflexive process of (re)configuration as technologies are created and become part of mathematics classrooms.

Research on the Development of Technology for Mathematical Learning

Educational technology takes a prominent position in many mathematics classrooms, yet mathematics education research literature referring to the processes by which it is developed is largely constrained to the method sections of papers that report on technologies designed by researchers for research purposes (e.g. diSessa, 2001; Kaput & Schorr, 2008; Tatar, Lin & Dickey, 2005). This literature provides some insight into the decisions made by teams developing tools intended to support mathematical learning, but does not address the development of commercially produced and widely used technologies. Particularly representative examples of this kind of design-based research are the investigations that have

taken place as part of the *SimCalc* research program (e.g. Kaput, 1994; Kaput & Roschelle, 1997; Kaput & Schorr, 2008; Roschelle, Kaput, & Stroup, 2000; Tatar, Roschelle, Knudsen, Schechtman, Kaput, & Hopkins, 2008). This series of projects that involved the creation of *SimCalc MathWorlds*TM software is focused on engaging learners with ‘the mathematics of change’ (Kaput & Roschelle, 1997). While the *SimCalc* research program is comprised of several large projects, each investigation is related to the use of innovative software tools that encourage learners to explore fundamental concepts from calculus through graphical representations that reduce the need to negotiate formal symbolic notations. Through this alternative approach to representing the mathematics of change and variation, the goal of *SimCalc* is to democratize the knowledges that form calculus so that broader groups of learners may engage with them (Kaput, 1994; Kaput & Schorr, 2008). While literature relating to technologies designed by researchers for design-studies such as the *SimCalc* project often provide insight into the technologies themselves and their aims, it does not offer much discussion of the process through which they were realized.

Much of the discourse related to the development of technology in the mathematics education literature refers to technologies designed by researchers for their own research purposes. A notable exception exists, however, in relation to dynamic geometry environments and this literature offers some insight into the way that commercial technologies for mathematical learning are developed. This category of interactive software allows users to build geometric constructions and then manipulate them by dragging and modifying elements while watching the way connected elements respond (Goldenberg, Scher & Feurzeig, 2008). Two prominent software applications in the category are *The Geometer’s Sketchpad*TM (Jackiw, 1988-2010) and *Cabri-Géomètre*TM (Baulac, Bellemain & Laborde, 1988-2010). While both these

technologies began life in the context of research programs that were not focused on pedagogy, their potential in educational settings was quickly noticed and developers adapted and commercialised their creations (Goldenberg, Scher & Feurzeig, 2008). *Cabri-Géomètre*TM, for instance, was initially developed as a way for non-programmer mathematicians to exploit the power of computers to explore graph theory, but was then developed into a system for visualizing geometry that was first introduced in university courses and then later to schools (Laborde & Laborde, 2008). Since their introduction, both *The Geometer's Sketchpad*TM and *Cabri-Géomètre*TM have been widely adopted by schools and through successive iterations they have developed into highly specialised technologies geared specifically toward supporting mathematical learning.

Perhaps due to their origins as researchers, the creators of both *The Geometer's Sketchpad*TM and *Cabri-Géomètre*TM along with other mathematics education researchers have written about the development of both tools (Goldenberg, Scher & Feurzeig, 2008; Laborde & Laborde, 2008; Roschelle & Jackiw, 1999). Goldenberg, Scher and Feurzeig (2008) describe the historical development of both software applications and discuss some of the intentions and ideas behind them. Having interviewed creators of both tools they suggest that instead of making design decisions based on a particular pedagogy, “each designer was motivated by his own set of principles – mathematical, aesthetic, and human factors among others” (Goldenberg, Scher and Feurzeig, 2008, p. 62). They also suggest that despite the rigorous rules of geometry and mathematics in general, “very little about the programs was inevitable from the start. The underlying mathematics of geometry and algebra certainly guided their development, but did not dictate how features would operate, nor even which features to include” (Goldenberg, Scher and Feurzeig, 2008, p. 79). As the two programs evolved and became accepted in the mathematics

education community, their development began to attend to pedagogy and the mathematics education needs of teachers and students. While describing the development of their application, *Cabri-Géomètre™*, Laborde and Laborde note:

One of the important features of Cabri is its strong interrelation with mathematics throughout its development. It originated from the needs of a community of researchers in mathematics. Although Cabri was not immediately accepted by the teaching and research communities, it became accepted over time and the development process was able to take advantage of innovative uses of Cabri by teachers and researchers in mathematics education. (2008, p. 49)

They point to the important relationship between the development of an educational technology, the technology itself, and members of the mathematics education community such as researchers, teachers and students. This work and the work of others (Goldenberg, Scher & Feurzeig, 2008; Roschelle & Jackiw, 1999) to describe the development of commercially available technologies for mathematical learning provides some insight into the motivations of developers. It does relatively little, however, to describe the roles and processes involved as technologies are constructed and become part of the instructional context in mathematics classrooms.

A Theoretical Approach to Understanding Technology Development

While some researchers have offered insights into the development of commercially available technology for mathematical learning (Goldenberg, Scher & Feurzeig, 2008; Laborde & Laborde, 2008; Roschelle & Jackiw, 1999), their accounts do so without drawing on the wide range of literature related to the wider world of technology development. In the field of Science

and Technology Studies, a large body of research has evolved that conceptualizes the relationships between technology, developers, and users (cf. Akrich, 1992; Bijker, 1997; Cross, 2007; Dorst & Dijkhuis, 1995; Latour, 1996; Lindsay, 2005; Oudshoorn & Pinch, 2005; Simon, 1992; Suchman, 2007; Yaneva, 2009). While as Roschelle and Jackiw (1999) note the development of technologies for pedagogical purposes is distinct from the development of other types of technology, insights into development drawn from research into the broader technological world have much to offer research into educational technology.

Characterisations of technology development processes have often tended to describe development in terms of systematic problem-solving steps (Cross, 2007; Dorst & Dijkhuis, 1995; Simon, 1992). These steps most often include activities such as defining user needs and predicting the behaviour of users identified as representing stereotypical groups. In these activities, users are generally considered to be part of homogenous groups with relatively rational and predictable behaviour. Specifically in relation to the development of educational technologies, such understandings of development processes often conceptualize the relationships between developer, technology and learner in primarily behaviourist terms (Häkkinen, 2002; Jonassen, 1991). While such characterisations of educational technology development processes may accurately describe the creation of some tools, as Roschelle and Jackiw note referring to the development of educational software, “views of software design driven by means-ends analysis are giving way to a more iterative and transformative view” (1999, p. 783).

Reflecting a more iterative and transformative view, researchers in the field of Science and Technology Studies have offered an alternative approach to conceptualizing the relationships between development, technology and users (cf. Akrich, 1992; Bijker, 1997; Latour, 1996;

Lindsay, 2005; Oudshoorn & Pinch, 2005; Suchman, 2007; Yaneva, 2009). These researchers consider the relationship between the development and use of technology to be reflexive, suggesting that a technology is constantly and dynamically shaped by both developers and users as it in turn shapes them. Suchman (2007), for example, rejects the notion that human behaviour can be prescribed through technological development processes. Based on her long-term ethnographic study of the development and use of a photocopier help-system, she instead proposes that technologies be conceptualized as resources for the situated actions of users and not as prescriptions of particular behaviours. She notes that from this perspective, “the contingency of action on a complex world of objects, artefacts, and other actors, located in space and time, is no longer treated as an extraneous problem with which the individual actor must contend but rather is seen as the essential resource that makes knowledge possible and gives action its sense” (p. 177). Thus, the role of developers is not to predict the behaviour of users but it is instead to support users, in finding their own ways of working with a technology.

In concert with the rejection of the notion that behaviour can be prescribed through technology, researchers in the field of Science and Technology Studies propose that users reconfigure technology as they use it (cf. Bijker, 1997; Lindsay, 2005; Oudshoorn & Pinch, 2005; Pinch & Bijker, 1984). As Bijker (1997) describes in relation to his sociological study of the historical development and use of bicycles, “...an artifact does not suddenly appear as the result of a singular heroic intervention; instead, it is gradually constructed in the social interactions between and within relevant social groups” (p. 270). Users continue development as they reconfigure the technologies they use and their technologies configure them.

Further unpacking the relationships between development, technology and users, researchers working from the perspective of Actor-Network-Theory (ANT) offer a view that

considers agency in networks of human and non-human interaction to be located in the relations and not solely in the humans (cf. Akrich, 1995; Callon, 1986; Latour, 1996, 2007; Law, 1992; Yaneva, 2009). From an ANT point of view, “networks are composed not only of people, but also of machines, animals, texts, money, architectures – any material that you care to mention. So the argument is that the stuff of the social isn’t simply human. It is all these other materials too” (Law, 1992, p. 381). The approach foregrounds the vast range of mediators implicated in any social situation by acknowledging, “there might exist many metaphysical shades between full causality and sheer inexistence” (Latour, 2007, p. 72). By conceptualizing both humans and non-humans on a single plane of interaction, ANT provides a lens through which networks of social activity can be examined without limiting the richness of the actors and relationships in them.

A key example of the use of ANT to conceptualize the relationship between technology development and the actions of users is the work of Akrich (1992, 1995). Working from an ANT perspective, she studied the development of technologies including a national electric utility and an interactive television system. In these studies, rather than describe designs as prescriptions for user actions, Akrich refers to them as scripts out of which user actions emerge. From her perspective, scripts represent the imagined user actions that a developer envisages for a technology. In the scripting process, developers construct and appropriate representations of envisaged user actions and inscribe them in a technology “the designer expresses the scenario of the device in question – the script out of which the future history of the object will develop” (Akrich, 1992, p. 276). Users then interpret and translate the developer’s script as they use a technology.

By framing the relationship between developers, technology and users in dynamic non-linear terms, Akrich (1992, 1995), Bijker (1997), Latour (1996, 2007) and Suchman (2007) offer an approach to conceptualizing technologies that understands them to be co-constructions of both developers and users. This approach challenges deterministic assumptions about the ability of developers to predict and prescribe the actions of users and celebrates the innovative ways that users contribute to the technologies they use. In particular, the theoretical tools provided by the approach offer a lens through which to examine technology development without resorting to deterministic stances on the relationship between humans and tools. In order to study ways that educational technologies become part of the instructional context in mathematics classrooms, I draw on these theoretical tools from the field of Science and Technology Studies to conceptualize the relationships between developers, teachers, students and technology.

Method

As a case for examining the co-constructive process of configuration and reconfiguration as technologies are created and become part of mathematics classrooms, I have chosen *Texas Instruments'* TI-Nspire graphing calculator. With a long history of use in schools, the development of electronic handheld calculators began in the mid-1960s, with significant developments like multiple line displays, the ability to graph functions and the ability to manipulate algebraic symbols emerging in the late-1980s and early-1990s (Hamrick, 1996; Kidwell, Ackerberg-Hastings and Roberts, 2008). While calculators have become increasingly sophisticated since their invention, in the past decade advances in computer processors and digital displays for handheld devices combined with the broad use of data networking has dramatically closed the gap between what might be considered a calculator and what might be

considered a computer (Kaput & Schorr, 2008). Part of the latest generation of graphing calculators, *Texas Instruments*' TI-Nspire includes a range of software applications including a dynamic geometry environment based on *Cabri-Géomètre*TM, spreadsheet and graphing tools, and a calculator with a computer algebra system that allows users to work with algebraic symbols along with numbers. All of these applications are hosted as a single interconnected environment on a relatively inexpensive handheld device. In addition, TI-Nspire is a relatively recent technology that continues to be developed yet is currently in use in many schools. This made access to members of the development team while they were still working on the project and to teachers and students using the technology possible. For these reasons, I chose TI-Nspire as a technological case for this study of the development of educational technologies.

Drawing on my theoretical framework to conceptualize both the initial development of TI-Nspire and its continued development through use, data collection for this project included two major phases. One phase involved professional technology developers and mathematics education consultants and the other involved secondary school mathematics teachers, their classrooms and their students. For the practical reasons of location and timing, each of these phases was treated separately during collection but the resulting data was analysed as a single ensemble.

During the professional technology developer and mathematics education consultant phase of data collection, audio-recorded interviews were conducted with developers and consultants who were directly involved in the development of TI-Nspire. These developers and consultants have a wide range of professional experience and come to the development of educational technologies from a variety of backgrounds (see Table 1). Each developer and

consultant participated in a semi-structured interview that focused on the TI-Nspire development process and the extensive professional development activities that *Texas Instruments* supports.

Table 4

Developer and consultant participant profiles

| Participant | Profile |
|--------------------------------------|--|
| Developer One | Senior manager and long-time graphing calculator developer. |
| Developer Two | Product manager with previous experience working as a mathematician. |
| Developer Three | Product manager and experienced teacher turned developer. |
| Developer Four | System architect who is relatively new to engineering graphing calculators. |
| Mathematics Education Consultant One | Mathematics education researcher and teacher educator who is involved in <i>Texas Instruments</i> supported teacher educator professional development. |
| Mathematics Education Consultant Two | Mathematics education researcher and teacher educator with a long-time interest in dynamic geometry who has been involved in the development of graphing calculators for many years. |

During the classroom teacher and student phase of data collection, I interviewed two teachers who regularly include TI-Nspire as part of their instructional practices and spent a week observing and video-recording in one of their ninth grade classes. First, audio recorded interviews that focused on the teachers' use of TI-Nspire and their experiences with technology in the classroom were conducted. Each teacher has a distinct background and experience teaching with technology (see Table 5). Following the initial interviews, I observed a series of five sessions from the back of each teacher's class. These sessions were recorded with multiple microphones and a single video camera that was focused on the teacher's practices with TI-Nspire. After each class, the teachers were invited to participate in retrospective debriefing interviews that helped to unpack the events of the session.

In addition to focusing on the teacher participants, I also invited four students to participate in the study beyond the classroom observation. Two students from each class were asked to volunteer for a lunchtime mathematical activity session that involved working in pairs on a mathematical activity related to their class work that was video-recorded with multiple cameras (see Table 5). To record the students' activities best, one camera was placed facing the pair, a second was positioned to record their working from above and video of the screen of their TI-Nspire was digitally captured. These three video sources were then combined into a single screen that enabled them all to be viewed at once. To create the mathematical activity, I collaborated with an experienced school mathematics teacher and mathematics education researcher to create a similar activity to those the students were familiar with from their classes. During the development of the activity, it was pilot tested with a single ninth grade mathematics student. Following the completion of the activity, each student pair participated in a retrospective debriefing interview that provided insight into both their practices during the activity and more generally with TI-Nspire.

Table 5

Teacher and Lunchtime Activity Student Participant Profiles

| Participant | Profile |
|----------------------------------|--|
| Teacher One | Former school board mathematics consultant with a long history of classroom technology use and involvement in the <i>Texas Instruments</i> supported T^3 professional development conferences and community. |
| Lunchtime Activity Student One | Student in teacher one's grade nine mathematics class. Owns a TI-Nspire and uses it both inside and outside of school. At the time of the study, he had used TI-Nspire for one semester. |
| Lunchtime Activity Student Two | Friend of student one who took the same mathematics class in the previous semester. Owns a TI-Nspire and uses it both inside and outside of school. At the time of the study, he had finished one semester of using TI-Nspire. |
| Teacher Two | Trained as a mathematics teacher but spent several years teaching computers and programming and has only relatively recently begun teaching mathematics. |
| Lunchtime Activity Student Three | Student in teacher two's grade nine mathematics class. Owns a TI-Nspire and uses it both inside and outside of school. At the time of the study, he was at the end of his first semester of using TI-Nspire. |
| Lunchtime Activity Student Four | Student in teacher two's grade nine mathematics class. Owns a TI-Nspire and uses it both inside and outside of school. At the time of the study, he was at the end of his first semester of using TI-Nspire. |

Once interviews and observations had been completed, I transcribed and added the interview recordings and the observational videos to the qualitative analysis software package *Transana* that allows efficient organisation and analysis of multiple media sources (Woods & Fassnacht, 2009). Within *Transana*, each recording and transcript pair was synchronized so that sections identified in one medium would automatically correspond with the same sections in the other. This freedom to move between recording and transcript while maintaining synchronisation afforded flexibility to the analytic process during which multiple passes of each interview and video-recording were made by repeatedly listening to or watching the recordings and reading the transcriptions. While I analysed the interviews and observational videos, I also examined artefacts such as digital documents created by the teachers to load on TI-Nspire and worksheets

collected from the observed classrooms. This process drew on Interaction Analysis (Jordan & Henderson, 1995), a method for analyzing multimodal data that foregrounds analysis of the interactions between humans, their environment and the artefacts in it. Following an Interaction Analysis approach at least one pass of the interview recordings and observational videos was made in collaboration with another researcher. This process afforded an alternative perspective on the data and allowed generative discussions to take place regarding analytic decisions.

Throughout the process of repeatedly working with the data, I concentrated on ‘edge cases’ of interaction between teachers, students and TI-Nspire such as innovations, breakdowns and frustrations to identify stabilized practices within the networks of activity (Latour, 2007). To analyse these stabilized practices, I drew on the Actor-Network theoretic work of Akrich (1995) to describe ways that developers inscribe the technologies they create with representations of envisaged user activity. In this work she identified such methods as market surveys, consumer testing, user feedback, personal experience and expert consultants as ways that developers create and appropriate representations. Akrich only examined the process of initial configuration as developers create scripts out of which the future history of their technologies emerge and did not address reconfiguration through use. Her findings served as a starting point for analysing the ways developers inscribed TI-Nspire with a script. This analysis was then augmented by drawing on the work of Latour (1996, 2007), Pinch & Bijker (1984) and Suchman (2007) to investigate the activity of teachers and students who translated the developer’s script as they adapted and reconfigured the technology to their own needs.

Findings

The findings from this examination of the development of an educational technology can be divided into two distinct yet interrelated parts. The first part addresses the initial configuration of TI-Nspire and the second describes the ways that it continues to evolve as teachers and students adapt and reconfigure it through their mathematics education activities. Following discussion of these parts that are addressed separately for organisational purposes, their interrelatedness will be examined.

Configuration.

During the 1980s and 1990s *Texas Instruments* developed a series of graphing calculators that quickly took a dominant position in the mathematics education market. To build on this success, in late 2004 the company decided to begin development of a new device that would take advantage of recent advances in mobile computing technology, such as higher resolution screens and faster processors. This device eventually became TI-Nspire, but for it to emerge as the technology now used in schools a complex development process took place. This development drew on a well known software development model called *Agile XP* (Beck, 2000). Part of the family of *Agile Software Development* models, *Agile Extreme Programming* (XP) is an approach to creating software that rejects the more traditional waterfall style of development that follows a linear framework of milestones and checkpoints (Monochristou & Vlachpoulou, 2007). Instead, *Agile XP* and other similar software development models promote iterative approaches that tend to involve the participation of potential users throughout a technology's initial configuration.

Taking a participatory approach, *Texas Instruments* developers worked with members of the mathematics education community to develop representations of the potential ways teachers and students might use the imagined TI-Nspire. The ideas generated were then communicated

through a technique associated with *Agile XP* called ‘user stories’ (Cohen, 2004). Created through negotiations between developers and community members, user stories are short descriptions of envisaged scenarios of use that can be assembled together to form longer ‘epics’ that describe, for instance, a complete mathematics lesson. The result of this iterative process of developers and community members working together was representations of envisaged future teacher and student activity expressed as user stories that developers then used to create the features that form TI-Nspire.

Developer acumen and consultation with mathematics education researchers.

To create user stories and define requirements for the evolving TI-Nspire, developers used a variety of methods to construct and appropriate representations of envisaged teacher and student activity. A prominent method that developers and consultants described in their interviews involved the use of personal experiences or acumen. This approach was also identified in interviews with both *The Geometer’s Sketchpad*TM and *Cabri-Géomètre*TM developers (Goldenberg, Scher & Feurzeig, 2008). It entails developers who have a wide range of experiences including developing technologies for mathematics classrooms and knowledge of educational policy and research using their experience, knowledge and intuition to imagine teacher and student activity. In some cases, TI-Nspire developers had even worked as teachers before joining *Texas Instruments* and this experience contributed to their ability to envisage potential ways that teachers and students might use the imagined technology. One mathematics education researcher who took an extended leave of absence to work at *Texas Instruments* during development described his approach to thinking about himself as a user saying:

I’m always thinking about how would I present this idea to students. I mean it may sound hokey, but I tell people, they say where do you get your good ideas?

Sitting there with my book, I gotta teach this tomorrow and I'm laying it out and I'm thinking you know what could I do to make this clear. (Consultant One)

This development team member drew upon his experiences as an educator and mathematics education researcher to inform his imagining of the future activity of teachers and students. His comments illustrate the kind of important personal experiences that developers and consultants brought to the development of TI-Nspire and used to envisage the activity of teachers and students.

A related way that envisaged teacher and student activities with TI-Nspire were constructed and appropriated was through consultation with mathematics education experts. This approach that has also been mentioned by the creators of *Cabri-Géomètre*TM (Laborde & Laborde, 2008) involved professionals such as mathematics education researchers, teacher educators, and highly experienced classroom teachers participating in the development process. These contributors participated directly in the initial configuration of TI-Nspire by meeting with developers or indirectly through commissioned research projects (for an example see *TI-Nspire Math and Science Learning Handhelds: What Research Says and What Educators Can Do*, a report produced by the *Center for Technology in Learning* of *SRI International*, 2006). One consulting mathematics education researcher described his consultant role saying:

I think TI relies on people like [a colleague] and I and [another colleague] to give them that kind of feedback, to be able to say OK somebody's come up with this great idea of this kind of interface, wouldn't it be great you know to have in the classroom? And we step back and we say OK yeah in this way, in this way, in this way, but maybe here's a drawback you might want to think about based on the

research literature and that's one of the things that I try to do a lot is to give feedback based on what I know from research. (Consultant Two)

In addition to offering advice, consultants often contributed by acting as informed representatives of teachers and students. During his interview, one consultant developer described a session where he and other consultants were asked to examine the experience of introducing TI-Nspire to a class for the first time:

We sat down and [a developer] says we want you to describe the first three hours, we want to clean up the user interface so the first three hours is a little easier. So we start with the graphing and we started models about what you're going to do in a classroom. (Consultant One)

Both by acting as experts and informed representatives of teachers and students, mathematics education research consultants performed an important role in the development of TI-Nspire. Their expertise combined with the acumen of developers helped to construct representations of the ways that teachers and students might best make use of the emerging technology as it developed.

Interaction with classroom teachers.

Beyond relying on their own experience and consultation with mathematics education researchers, a more direct route developers had for creating and appropriating representations of envisaged teacher and student activities was by interacting with classroom teachers. Throughout their interviews, developers repeatedly emphasized working with educators as partners, observing classroom practice and talking with teachers. During his interview, one developer highlighted the highly participatory nature of the development process noting that, “our design

approach [is] really working closely with educators to design it.” (Developer One). Similar to the techniques identified by Akrich (1995), developers used approaches such as collecting feedback from users of previous generations of graphing calculators and conducting surveys to gather ideas and opinions from teachers. Beyond these indirect techniques, they also employed more direct approaches such as frequent workshops that invited teachers into the *Texas Instruments*’ offices where they could share ideas and talk directly to developers. The workshops particularly involved those teachers who participated in the pilot testing phases of development. These teachers were given class sets of pre-production versions of TI-Nspire as it evolved and were asked to give feedback based on their experiences. In addition to asking these educators to participate in workshops, developers also visited their classrooms to observe and talk. A senior engineer on the project spoke about the wide range of team members who visit classrooms saying:

Developers go periodically, at least yearly, to go watch a training site, go interact with teachers. You know team leads, key developers, system engineers, system architects, you know not just the people who's job quote un-quote it is to interact directly with customers. (Developer Four)

While all the developers interviewed characterized the programme of direct interaction with teachers positively, one issue with the approach was highlighted. In general only highly experienced teachers who are confident with technology agree to have their classrooms observed. This phenomenon challenged the developers to find ways to interact with teachers who are less comfortable with technology in their classrooms, so that their wants and needs could be incorporated in to TI-Nspire. To foster interactions with a broader range of teachers, developers draw on *Texas Instruments*’ support of a large community of both experienced and new

calculator users who participate in professional development at *Teachers Teaching with Technology*TM (T^3) conferences. These programs have an important role in helping to build a strong community of teachers who use TI-Nspire. For example, one of the teacher participants in this study spoke about the important role the T^3 programmes have had for his practice saying:

Teacher One: There wasn't a whole lot of PD [professional development] for high school math teachers other than the annual conference so the T^3 summer workshops were quite unique and they had quite a strong following so that drew me in like between the conference sessions, the being part of the T^3 culture.

Researcher: And you've been doing T^3 since the mid-nineties I guess?

Teacher One: I got involved with T^3 doing workshops during my time as a [school board mathematics] consultant, so I've been quite active and in the T^3 group for the last bunch of years now.

T^3 conferences are organised at regional and international levels and are attended by many teachers. They not only help to foster a thriving community of teachers using *Texas Instruments* products but also provide the development team with the opportunity to interact with a broad range of users.

Underscoring the importance of having a participatory development process with frequent interaction with teachers and students, when asked about the ways the team deals with

the tendency of developers to look inwards and fall back on designing for themselves, one developer noted that, “for the most part we overcome that by having so many avenues to educators and there's so many that are coming into this building and where they're going out to conferences or visits” (Developer One). As repeated highlighting in the developer interviews demonstrates there were frequent interactions with teachers and students during the initial configuration of TI-Nspire. This feature is one of the defining characteristics of the process and permeated as developers used their own acumen, worked with mathematics education consultants and interacted with classroom teachers to construct and appropriate representations of envisaged activity. These representations and their inscription into the technology though form the process by which TI-Nspire was initially configured as a tool for mathematical learning.

Reconfiguration.

While a process involving professional technology developers, mathematics education consultants and the participation of teachers and students led to the initial configuration of TI-Nspire, as a tool for mathematical learning it continues to evolve as teachers and students use it. Speaking about the importance of the innovative ways that teachers and students use technology, the creators of *Cabri-Géomètre*TM note that, “This is certainly one of the reasons for the on-going improvement and continuous evolution of the project” (Laborde & Laborde, 2008, p. 49). This reconfiguration is a reciprocal process through which users shape the technologies they use and in turn those technologies shape them (Oudshoorn & Pinch, 2005; Pinch & Bijker, 1984).

Exploiting explicit avenues for customization and authoring.

Developers not only acknowledged the role that teachers and students have in shaping TI-Nspire through use during their interviews, but also discussed approaches to supporting the phenomenon. Specifically, developers spoke about supporting teacher and student innovations by

creating avenues for customizing the technology. By offering features such as the ability to build and share files through what is known as the ‘document model’, developers provided mechanisms that afford teachers and students explicitly identified ways to customize TI-Nspire for their own needs:

The idea behind [TI-Nspire] and behind the document model as well is to give the teacher or publisher or author, well teacher, the most ability to customize it and personalize it for you know for his audience and for the level of students. I mean we can't here by ourselves provide the solution that's optimal for everybody. You have to give the possibility to customize it. (Developer Two)

This ‘document model’ is one of the major features that differentiates TI-Nspire from previous graphing calculators. It affords users avenues for creating, modifying and sharing complex files with wide latitude for shaping the technology’s functionality. One teacher participant compared the way his students use the feature to create and save documents to the use of earlier calculator models that lacked these features saying:

It’s more important I think when they're using the tool to have some record of it, because otherwise I mean the [previous calculator models], you used it, you turned it off and the record of everything you did with it was gone. Even the class set, I mean it’s not your own so there's multiple kids using them so, for instance, having a library of files that’s accumulated almost like an extension of your notebook becomes less sensible if its not your tool right? So the kids that have their own tool, its becoming an add-on to their notebook almost. Some kids

actually use it as their notebook which I find interesting. So they'll actually prefer to take their notes on there. (Teacher One)

The practice of using TI-Nspire as a digital notebook where a library of mathematical work can be saved and shared with others, illustrates one way the document model was used by students to customize the technology for their own needs.

Working in concert with the creation and sharing of files through the document model is another element of TI-Nspire - computer software that facilitates the authoring of documents. This software supports users in creating and modifying documents in ways beyond those possible on the handheld calculator, by using the greater capabilities of a personal computer. It provides teachers with the significant advantage of being able to work with TI-Nspire documents without being restricted to the relatively small screen and keypad of the calculator. Developers spoke about the intention to support teachers in authoring their own documents, modifying those created by others and sharing their work:

We want to have enough of a pool of documents out there that you don't have to create anything, but if you want to create everything we want to have enough authoring tools that you can create everything and if you want to be in-between you know then that's great too. (Developer Four)

The ability to create or modify documents to meet a specific instructional need was identified as being particularly important. It was described by developers as allowing teachers to take the comparatively complex multipurpose TI-Nspire and restrict the functions available to students to only those needed for a particular lesson or activity. Equally this ability was characterized as enabling teachers to create documents intended to support a more exploratory style of activity

such as providing large datasets to work on without restrictions. Speaking about how he works with the authoring software, one teacher participant discussed the way he took an activity he has used for years and adapted it for TI-Nspire. The activity that the teacher adapted for TI-Nspire is developed around data from Olympic sporting events and demonstrates some of the latitude that teachers have in shaping the technology for their own particular needs using the authoring software (see Figure 10).

| Olympic Discus | | A year | B mens | C womens | D |
|--|------|--------|--------|----------|---|
| The table on page 1.2 shows the winning distances for the discus event at the Olympic Summer Games from 1948 through 1996. | | | | | |
| Create a separate scatter plot each set of data, then answer the questions on the following pages. | | | | | |
| 1 | 1948 | 52.78 | 41.92 | | |
| 2 | 1952 | 55.03 | 51.42 | | |
| 3 | 1956 | 56.36 | 53.69 | | |
| 4 | 1960 | 59.18 | 55.1 | | |
| 5 | 1964 | 61. | 57.27 | | |
| 6 | 1968 | 64.78 | 58.28 | | |
| AI | 1948 | | | | |

Figure 10: Screens from Olympic sporting events activity

Describing ways he has adapted the activity for different technologies the teacher noted:

It was from their old textbook so it's one that I've used for years and if we looked in my files I've got that data set in an Excel file, I have it in a Fathom file, I have it in the TI-Nspire. So I've used it in a variety of ways. I have it in Word where, you know, in previous years I've just printed it for the kids and they've graphed it by hand. I have it in Word where there's an Excel graph in there as well, where I've said OK well we've done the graphing so here just take it, I've already plotted the points for them and I've used it just to draw the line of best fit, but in this case now I have them do the line of best fit on [TI-Nspire]. (Teacher Two)

Adapting the activity for TI-Nspire, the teacher was able to create a self-contained document that includes all instructions, necessary data, spaces for graphing and calculation and places for answers to be written. Once loaded on his students' calculators, TI-Nspire became less a general purpose mathematical tool and more a specific tool for the Olympic sporting events activity. This example illustrates the kinds of ways that using authoring software in combination with the document model to customize TI-Nspire, teachers and students reconfigure the technology by translating and adapting it to meet their needs.

Reconfiguring the technology in unexpected ways.

Beyond using features such as the document model and authoring software intended by developers to support customization and authoring, teacher and student participants also reconfigured the technology in unexpected ways to make it their own. Students, for instance, used the document model for 'off-topic' activities, such as creating complex drawings that can be saved, edited later and shared (see Figure 11).



Figure 11: Picture drawn by student using graphs and geometry features

While this ‘off-topic’ use of the graphs and geometry features of TI-Nspire had been observed with earlier graphing calculator models, developers provided no explicit support beyond the flexibility afforded by the document model:

One of the very common activities, I know we never thought of this with our original graphing calculator, works great on Nspire too is when they draw pictures using functions and they make the most amazing things. Actually Nspire's better at it, because it's easier to specify the domain of where you want the function to be defined and the [earlier graphing calculators] had some pretty bad user interface. You had to divide by zero to make it not show, so it wouldn't graph in that particular place or something. Nspire's actually mathematical. (Developer One)

Using features such as the ability to plot functions and build geometric constructions, students’ reconfigured TI-Nspire to create complex drawings. They worked with the mathematical language and concepts needed to operate the technology to repurpose it in ways beyond those supported by developers.

Similarly reconfiguring features of TI-Nspire in innovative ways, during an observed session one student developed what became known as the ‘box method’. In the session, the class had been working on an activity that included creating a line of best fit for some data that had been graphed as a scatter plot using TI-Nspire. As he often did, the teacher used a computer software TI-Nspire emulator projected onto an interactive whiteboard to take up the activity (see Figure 12).

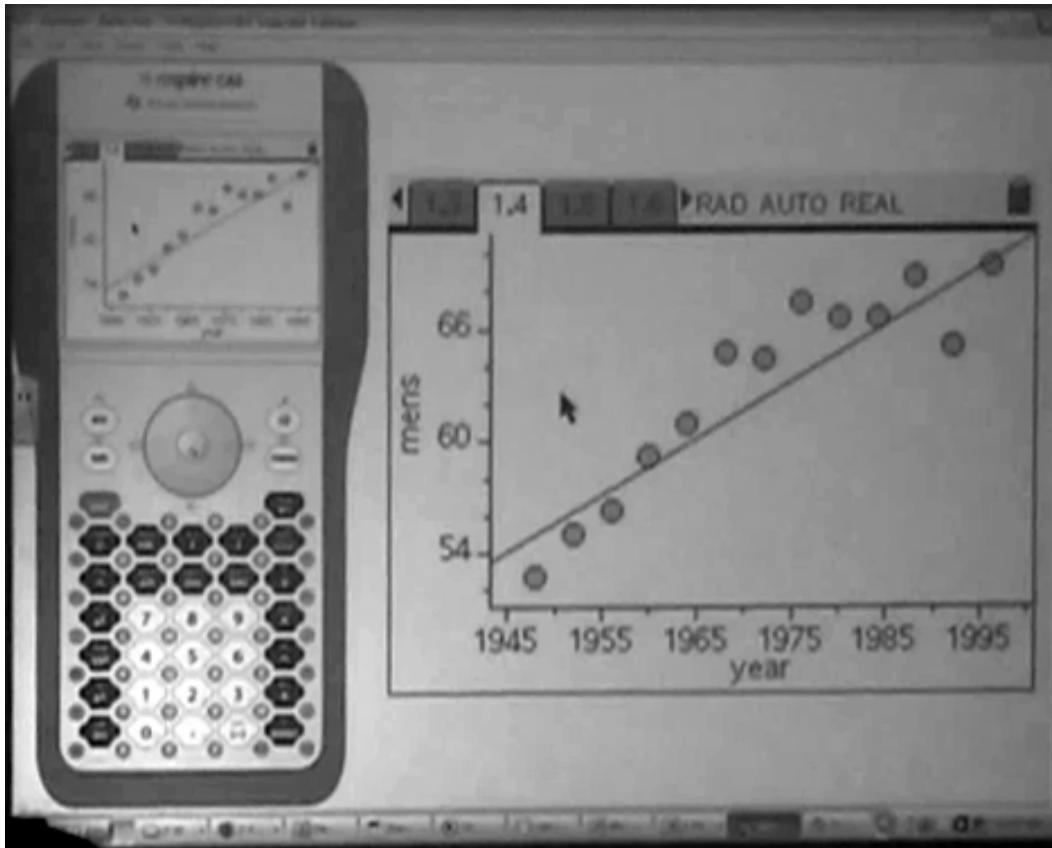


Figure 12: Scatter plot on TI-Nspire emulator projected onto an interactive whiteboard

While this arrangement allowed the teacher to use all the same features the students had been working with on their calculators, it also afforded him the option to sketch freehand on top of the TI-Nspire screen, using features specific to the interactive whiteboard. When it came time to find the values for a particular point on a line of best fit, the teacher drew freehand lines of intersection from the point to the corresponding values on each axis of the graph. He then noted to the class that it was the interactive whiteboard that allowed him to sketch on top of the graph to find the values of the point and that they could not perform the same operation on their calculators. One student, however, had found an innovative way to work around the problem and he shared it with the class:

Teacher Two: Now we don't have the luxury of doing that on the graph. We can't just draw those lines there can we?

Student: Kind of.

Teacher Two: Kind of? Did you draw lines on there?

Student: Yeah, you can make a square.

Teacher Two: You can make a square?

Student: Yeah.

Teacher Two: You want to show us what you did then there,
[Student]?

Student: You have to, like, click on the [interactive whiteboard] and then, like, drag.

Teacher Two: So I need to click and drag like this?

Student: Put it on, like, the different points.

Teacher Two: Oh! OK. So what you're saying is if I clicked here around 2012 and dragged up to my line and go across, it will tell me roughly what that value is.

Student: Yep.

Teacher Two: So what value would it be? According to my graph it would be 82. That's a neat way of doing it! I didn't know about that!

The method that the student explained uses the selection tool built into TI-Nspire to create the lines of intersection needed to read the corresponding values for a particular point on the line of best fit. As with most computer systems, the selection tool on TI-Nspire allows users to select a number of elements such as folders, files or points by clicking and dragging the cursor across the screen. As the cursor is dragged, a box appears showing the area bounding the elements that will be selected. In this case, a student repurposed the feature to serve their need to quickly and visually find the values for a point on a line of best fit. This repurposed use was identified and named as the 'box method' by the teacher and quickly became a legitimate feature of TI-Nspire in the context of that classroom. This example illustrates the kinds of ways that teachers and students find ways beyond those avenues for customization created explicitly and deliberately by developers to reconfigure TI-Nspire as they use it.

Whether it be through features like the document model and authoring software intended specifically to support user customization or through the adaptation and repurposing of other aspects of TI-Nspire, the teachers and students who participated in this study showed ways that they work to make the technology their own. Both through overt practices (such as authoring documents) and through unexpected activity, they reconfigure TI-Nspire within their contexts. Such, often innovative, ways of working with the technology do not go unnoticed by the developers and consultants at *Texas Instruments*. As they prepare updates and new versions of

TI-Nspire, developers use the configuration methods discussed earlier to interact with teachers and students and modify their representations of envisaged activity. They work to understand the ways that teachers and students are using existing versions of the technology so that they can improve it. Speaking about the practice of examining teacher authored TI-Nspire documents to see what is being created, one developer noted that, “when you look at some of the documents I guess you just say wow we didn't think you could do that!” (Developer One). Through their constant contact with educators, developers and consultants have many opportunities to witness the innovative ways that teachers and students reconfigure TI-Nspire. This affords them the chance to incorporate user innovations into new versions of the technology and provides an avenue through which teachers and students contribute to the continued configuration of new versions TI-Nspire. Asked about the innovative ways that teachers and students work with the technology, the same developer noted that:

Some of the things we see that people go to great lengths to do, we're kind of like well we can make that easier [so] regular people could do it. And also it makes it a little more reliable because sometimes they are workarounds and then they might be brittle for a user you know if the user does the wrong thing. So we want to make it more robust for some of the document authoring and things like that. So yeah we pay a lot of attention to what the authors are doing and things that they're running into. (Developer One)

Illustrating this process of taking teacher and student innovations and incorporating them in new versions of the technology, one consultant discussed a particularly salient example during his interview, saying:

You know when [TI-Nspire] first came out it couldn't do histograms, it couldn't do box-and-whisker plots, any of that. So people came up with ways to do it. They created their own little files, but then it started to become so clumsy that you know [Texas Instruments staff] of course then went straight to [the development team] and had them work on it. (Consultant Two)

As this example demonstrates, the reconfiguration process that teachers and students engage in as they translate and adapt TI-Nspire for their own needs and context feeds into new versions of the technology. This feedback cycle ensures that the configuration of new versions of TI-Nspire has an on-going interaction with teacher and student reconfigurations.

Discussion and Conclusion

This paper has examined the development and use of *Texas Instruments'* TI-Nspire to help grow understanding of the reflexive and iterative ways that educational technologies are created and become part of mathematics classrooms. The findings illuminate the configuration and reconfiguration processes that shape educational technologies as those technologies shape the activities of the developers, consultants, teachers, and students who create them. By revealing an on-going and iterative process of co-construction, the findings expand on the accounts of technology development for mathematics education offered by the creators of dynamic geometry environments (Goldenberg, Scher & Feurzeig, 2008; Laborde & Laborde, 2008; Roschelle & Jackiw, 1999). Developers, consultants, teachers, and students shape TI-Nspire as it, in turn, shapes their activity through a process of reflexive co-construction that is similar to those described by researchers in the field of Science and Technology Studies (Bijker, 1997; Akrich,

1995; Latour, 1996a; Suchman, 2007). This process involves the innovations of teachers and students throughout and bears little resemblance to traditional linear models of technology development such as those described by Monochristou and Vlachpoulou (2007).

The findings in this paper identify a highly participatory space from which a technology designed not only to acknowledge but also to support potentially original reconfigurations continues to evolve. Within this space, teachers and students are provided explicitly created avenues for authoring modular documents and customizing, features that have been identified as important for supporting rich mathematical learning with technology (Roschelle & Jackiw, 1999; Roschelle, Kaput, Stroup & Khan, 1998). In addition, teachers and students find ways to reconfigure the technology beyond the ways explicitly supported by developers and in doing so make it their own and influence future versions in similar ways to those suggested by researchers investigating the broader world of technology use (Bijker, 1997; Lindsay, 2005).

While configuration and reconfiguration processes were discussed separately for organisational purposes in this paper, the data collected for this study shows that they are highly interrelated (see Figure 13).

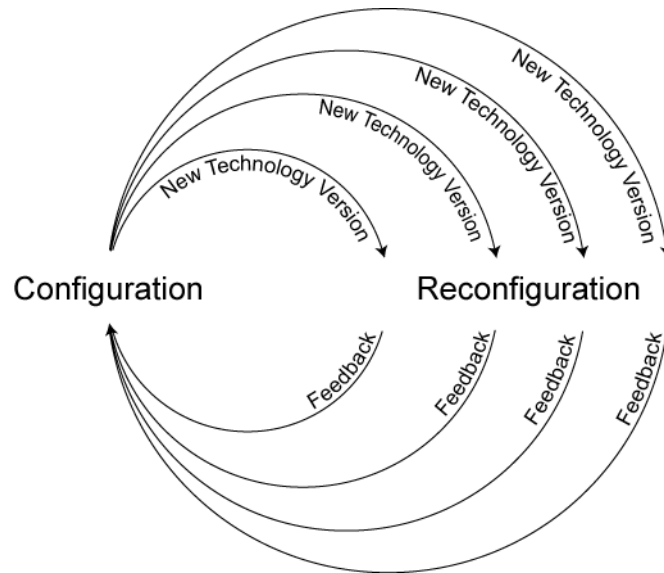


Figure 13: (Re)configuration process

In the case of TI-Nspire, both processes are parts of a single emergent movement as teacher and student reconfiguration feeds into the participatory configuration of new versions of the technology.

In many ways a parallel can be drawn between the co-constructive process of interrelated development from which TI-Nspire continues to evolve and the mathematical learning that the technology is intended to support. Students and teachers work in the context of existing formal mathematical and mathematics education practices to make meaning for themselves. As they make meaning, they translate these mathematical practices and shape school mathematics itself (Ernest, 1999; Noss, Healey & Hoyles, 1997). This on-going generative process is similar to the way the TI-Nspire configuration and reconfiguration processes interact. Far from being a coincidence, this similarity may be a result of the context from which TI-Nspire emerges. As the highly participatory nature of its development indicates, TI-Nspire is an educational technology born from an educational context. The participation of members of the mathematics education

community along with the educational acumen of the professional developers involved ensures that mathematics education ideas are central to the initial configuration of TI-Nspire. Equally, the conceptions of mathematics and mathematical learning of teachers and students profoundly mediate the ways they reconfigure the technology as they adapt and translate it in innovative ways.

Chapter 8. A Geography of Connections: Networks of Humans and Materials in Mathematics Classrooms Using Handheld Technology

Submitted to *Forum: Qualitative Social Research*

Abstract

This paper examines the role of materials in education by investigating the inclusion of a handheld digital technology in mathematics classrooms. By drawing on Actor-Network theory to understand the relationships between materials and humans and Activity-Theory to conceptualize learning with technology, the use of *Texas Instruments'* TI-Nspire graphing calculator in two secondary school mathematics classrooms is investigated. This investigation maps the patterns of relations between humans and materials as the classroom sociotechnical networks adapt to the inclusion of TI-Nspire. The results suggest that sociotechnical networks in classrooms using handheld technology operate as an interconnected whole and illuminate the complex interactions between humans and materials.

Introduction

In the field of educational research, the dominant discourse is squarely focused on the practices of humans such as teachers and students (Sørensen, 2007b). This makes a great deal of sense since education is primarily concerned with human learning. In some cases, however, this focus on human practices may mask the roles that materials play and limit the richness of understanding about learning situations (Shaffer & Clinton, 2006). In mathematics education, for example, some researchers have gone as far as to suggest that materials are transparent until

made meaningful in the context of human practices (Meira, 1998; Pimm, 1995). Such approaches privilege the role of humans to the point of obscuring important aspects of the mediational role that materials have in mathematical learning and any intrinsic educational value they might have (Shaffer & Clinton, 2005, 2006).

In this paper, I focus on the role of materials in education by investigating the inclusion of a handheld digital technology in mathematics classrooms. As a particular technological case, I examine the use of *Texas Instruments'* TI-Nspire (see Figure 14).

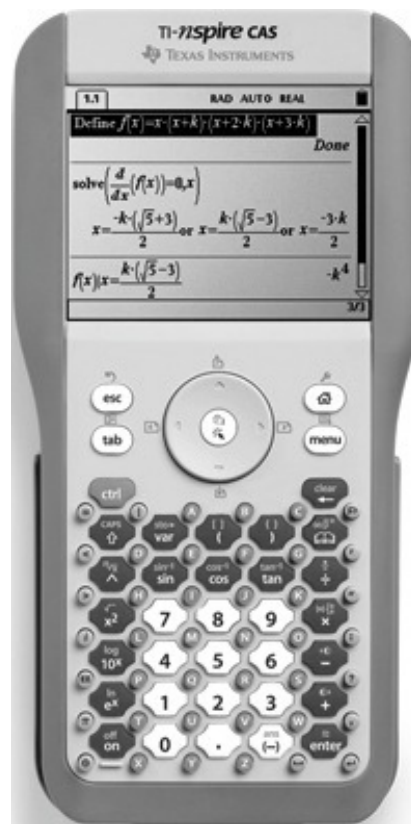


Figure 14: TI-Nspire CAS

Part of the latest generation of graphing calculators to be created specifically for educational use, devices like TI-Nspire have closed the gap between what might be considered a calculator and

what might be considered a computer (Drijvers & Weigand, 2010; Kaput & Schorr, 2008). These new technologies use advances in mobile computer processors and displays to offer a range of software applications such as spreadsheet tools, dynamic geometry software (DGS) and computer algebra systems (CAS) on relatively inexpensive handheld devices (Drijvers & Weigand, 2010).

To investigate the role of TI-Nspire in mathematics classrooms, I draw on educational research related to the use of educational technology in mathematical learning, but I also draw on the field of Science and Technology Studies and in particular Actor-Network theory (Callon, 1986; Latour, 2007; Law, 2002; Law & Mol, 2001). Specifically, I use the theoretical tools of Actor-Network theory (ANT) to understand the relationship between humans and materials without overtly obscuring the role that materials play and without discounting their potential intrinsic educational value. Taking the Actor-Network theory (ANT) idea that the social is comprised of networks of both humans and non-humans, I map the formation of sociotechnical networks in two mathematics classrooms where *Texas Instruments'* TI-Nspire is used.

Understanding the Role of Materials in Mathematics Classrooms

Within the mathematics education research community, several researchers looking specifically at educational technology such as TI-Nspire have suggested approaches to understanding the relationship between technology, teachers and students that avoid masking its potential role (Borba & Villarreal, 2006; Drijvers & Trouche, 2008; Hegedus & Moreno-Armella, 2010; Shaffer & Clinton 2006; Trouche & Drijvers, 2010; Verillon & Rabardel, 1995). One particularly prominent view is known as the instrumental approach (Drijvers & Trouche,

2008; Lagrange, 1999; Trouche & Drijvers, 2010; Verillon & Rabardel, 1995). From this perspective, learner and technology are considered to have a reciprocal relationship and the process by which a technology becomes useful is conceptualized as a movement from tool to instrument as the learner develops schema associated with the mathematical task they use the technology to complete. Research drawing on the instrumental approach focuses on the ways that teachers organize the technologies available to them in the classroom for pedagogical purposes and the ways technologies become meaningful in the context of mathematical activity (Drijvers *et al.*, 2010; Trouche, 2004). While the instrumental approach foregrounds the important relationship between learner and technology, it reduces the role of the technology to that of a mere object waiting to be made an instrument by learners. This understanding moves away from the view that materials are transparent until made useful in the context of human practice, but still obscures much of the intrinsic educational value that a material may potentially bring to an interaction with a learner.

Addressing the problem of obscuring the potential role and intrinsic value of materials in investigations of mathematical learning, Shaffer and Clinton (2005, 2006) have suggested another approach that draws on elements of Actor-Network theory (ANT) to conceptualize the relationship between learners and materials. In particular, Shaffer and Clinton (2006) take the ANT concept that when agents whether human or non-human act within sociotechnical networks, the capacity to act is not located in either party but instead emerges from their interaction (Suchman, 2006; Latour, 2007; Law, 2002). Drawing on this notion, they assert that in relation to computing technologies such as TI-Nspire, an overt focus on the human side of human-technology relationships may limit understanding of the role technology plays in learning. They note that while “this may not be a problem in a theoretic culture of static

inscriptional systems. In a virtual culture based on offloading of symbolic processing, however, using human action to analyse activity obscures the active role tools play” (Shaffer & Clinton, 2006, p. 289).

While the use of ANT is relatively rare in educational research, Shaffer and Clinton’s approach shares a number of communalities with a small group of researchers drawing on ANT to investigate a wide range of educational topics (Edwards *et al.*, 2009; Emad & Roth, 2009; Fenwick and Edwards, 2010; Fountain, 1999; Roth, 2002; Samarawickrema & Stacey, 2007; Sørensen, 2007a, 2007b). A key communality amongst the approaches of these researchers is a focus on the materiality of learning situations without assuming the agency or role of any actors (whether human or non-human) before examining their local interactions. Sørensen (2007a, 2007b) for example, examined physical and virtual materials in primary school classrooms by considering the activity between humans and materials to be a relational effect rather than focusing on the agency of any individual or group of actors. Her analysis describes a situation where both space and time within the classroom are emergent phenomena of the relationships among students, teachers and materials (Sørensen, 2007a).

Beyond conceptualizing the relationships between humans and non-humans without making a priori assumptions about the agency of any actor, another key commonality amongst studies of learning and educational settings that draw on ANT is the combination of theoretical perspectives. Since by design ANT is more a loose set of ideas than a well-defined theory, many researchers choose to simultaneously draw on other theories to inform their work. This reflects the evolving nature of ANT as a perspective on networks of social activity (Fenwick and Edwards, 2010). Samarawickrema and Stacey (2007), for example, drew on Rogers’ (2003) theory of diffusion of innovations in combination with ANT to investigate the adoption of web-

based distance learning technologies by university level instructors. Using Rogers' theory to examine the individual motivations and actions of the instructors and ANT to understand the networks of humans and technology, they analysed the cases of six Australian universities as they adopted web-based learning technologies. Their finding that successful adoption of technology by instructors had little to do with general comfort with digital technology and was instead influenced by such factors as funding grants and faculty politics illustrates the broad range of inquiries that ANT can be implicated in through careful combination with other theory.

Samarawickrema and Stacey's (2007) choice to work with a combination of theoretical perspectives is common amongst educational researchers who draw on ANT (Fenwick and Edwards, 2010). Returning to Shaffer and Clinton's (2005, 2006) approach to conceptualizing the relationship between humans and technology in learning situations, they also combine ANT with other theory. In this case, they draw on ANT together with Activity-Theory (Cole, 1998; Engeström, 2001; Leon'tev, 1978; Nardi, 1995; Roth & Lee, 2007; Vygotsky, 1978). This approach addresses the major criticism that ANT lacks tools for conceptualizing the internal properties of agents within social networks (Engeström, 2001). To address this limitation, Shaffer and Clinton (2006) draw particularly on the Activity-Theory notion that all human action including cognition takes place within activity systems that are mediated by tools, whether psychological or technical (Leont'ev, 1978; Vygotsky, 1978, 1986). With this conceptualisation, learning is considered to be an integral aspect of all human activity that necessarily involves tools whether or not technical tools such as educational technologies are involved (Säljö, Eklund & Mäkitalo, 2006).

Theoretical Perspective

As a theoretical perspective for this study, I follow Shaffer and Clinton's (2006) approach by drawing on Actor-Network theory (ANT) in combination with Activity-Theory. Originating with the ideas of Vygotsky (1978, 1986) and Leont'ev (1978), Activity-Theory is a psychological approach that is particularly concerned with the socially and culturally situated nature of cognition. As a sociocultural approach to understanding cognition, it, "takes as its point of departure the *mediated* nature of human knowledge and action" (Säljö, 1999, p. 151). The theory contends that all human activity takes place within systems that are mediated by cultural tools. These tools can be both internal and external of the learner yielding the notion that all learning involves tools (Säljö, Eklund & Mäkitalo, 2006; Wertsch, 1991). From this sociocultural perspective, tools are understood to mediate all human activity whether we notice them or not and are recognized as the resources through which we make meaning (Wertsch, 1998). This conception of tools, including technologies such as TI-Nspire, as the crucial resources with which we make meaning is an important part of the way learning is conceptualized in this study as tool mediated activity.

While both Activity-Theory and ANT are concerned with the mediation of systems of activity, Activity-Theory refers to systems of human activity mediated by tools while ANT describes networks of humans and non-humans all mediating each other's activity. From an ANT perspective, the properties of technologies in learning situations cannot simply be ignored or considered transparent since they and the humans that use them both mediate each other (Latour, 2007; Law, 2002; Shaffer & Clinton, 2006). Instead, ANT focuses on the ways sociotechnical networks form as humans and non-humans interact and their practices stabilize (Latour, 2007). These networks are composed of relations of network-objects themselves enacted by nested

networks of humans and non-humans (Law, 2002; Law & Mol, 2001). In the case of this study, for example, TI-Nspire is treated as both a material object and a network-object. As a network-object it is an element of classroom sociotechnical networks that is enacted through nested networks that include its developers, the teachers and students who use it, electronics, software, and mathematical knowledge. Network-objects such as TI-Nspire become what Latour (1990) refers to as ‘immutable’ as the networks that form them become stable. While network-objects stabilize in the context of patterns of relations, the networks themselves remain fluid. In this fluid space, the relations between network-objects constantly adapt as new elements emerge or existing elements reconfigure but throughout this fluidity, there is necessarily continuity. Otherwise, networks cease to remain intact, “If everything is taken apart at the same time the result is rupture, the loss of shape-continuity, the loss of identity. The result is more likely to be the creation of an alternative object” (Law, 2002, p. 99). In these cases, network-objects become new entities such as a phonebook being repurposed as a doorstop or a bolt dissolving into the car it holds together. Drawing on ANT conceptions of sociotechnical networks of humans and non-humans, and the Activity-Theory understanding of cognition as tool mediated activity, in this study I examine classrooms using TI-Nspire. This examination is at a scale in which the technology is viewed as a network-object while recognizing that it and other implicated network-objects are themselves enacted through complex nested networks.

Method

To develop an understanding of the ways TI-Nspire is used in classrooms, I interviewed two teachers who regularly include the technology as part of their instructional practices. This process involved audio-recorded interviews that focused on the teachers’ use of TI-Nspire and

their experiences with technology in the classroom. Following these initial interviews, a series of five sessions in a ninth grade class taught by each teacher were observed. While observing the classes, I focused on the teacher's practices with TI-Nspire and recorded the activity with a video camera. To help unpack the events of the sessions, I invited the teachers to participate in debriefing interviews after each class. In addition, I also invited students from the two observed classrooms to volunteer for a lunchtime mathematical activity. These sessions involved pairs of students working on a mathematical activity with a TI-Nspire available. The activity, which was similar to those the students were familiar with from their classes, was created in collaboration with an experienced school mathematics teacher and mathematics education researcher. Following the completion of the activity, each student pair participated in a debriefing interview that provided insight into both their practices during the activity and more generally with TI-Nspire.

Once interviews and observation had been completed, I transcribed and added the interview recordings and the observational videos to the qualitative analysis software package *Transana* that allows efficient organisation and analysis of multiple media sources (Woods & Fassnacht, 2009). Within *Transana*, each recording and transcript pair was synchronized so that sections identified in one medium would automatically correspond to the same sections in the other. This freedom to move between recording and transcript while maintaining synchronisation afforded flexibility to the analytic process during which multiple passes of each interview and video-recording were made. While I analysed the interviews and observational videos, I also examined artefacts such as digital documents created by the teachers to load on TI-Nspire and worksheets collected from the observed classrooms.

As an approach to the analysis of the collected multimodal data, I drew on Interaction Analysis (Jordan & Henderson, 1995). This approach shares many of the same or similar theoretical assumptions that are drawn on in this study. In particular, the approach assumes “that knowledge and action are fundamentally social in origin, organization, and use, and are situated in particular social and material ecologies” (p. 41). This basic assumption is shared by both Activity-Theory and Actor-Network theory (ANT) and forms a key element of the theoretical perspective of this study. From this underlying assumption, Interaction Analysis suggests a number of ways of working with particularly video recordings to analyse ethnographic data. These methods include creating content logs that outline the activity on a recording as soon as possible having recorded an observational session and conducting collaborative viewings with other researchers (Jordan & Henderson, 1995). Drawing on these suggestions, I assembled content logs following each interview or observed session and at least one viewing of the recordings was made in collaboration with another researcher.

Drawing on Interaction Analysis procedures in concert with the theoretical perspective developed by the combination of ANT and Activity-Theory, I examined the interviews with teachers and students for discussion of the ways they perceive their practices to have changed in relation to TI-Nspire. Using the themes identified from this analysis, I then examined the classroom and lunchtime activity session video-recordings along with collected artefacts for patterns of relations between human and non-human agents that relate to the use of TI-Nspire. This analysis drew on the work of several ANT researchers concerned with the spatiality of sociotechnical networks (Law, 2002; Law & Mol, 2001; Sørensen, 2007b). These researchers describe the sociotechnical networks that are enacted through the practices of human and non-human agents in terms of ‘fluid spatiality’. They suggest that the shape of sociotechnical

networks is constantly adapting and is never fixed but, importantly, “while the connections which make a shape invariant in fluid space change shape, they do so *gradually* and incrementally” (Law & Mol, 2001, p. 6). Paying attention to the continuity of network-objects within fluid sociotechnical networks, I attended to the patterns of relations in the classrooms looking specifically for gradual formations involving TI-Nspire. I then mapped these patterns of relations to produce a snapshot of the fluid networks as they were enacted through the activity of the human and non-human agents in the classrooms.

Findings

From the analysis of the interviews, observational recordings and artefacts I identified and mapped patterns of sociotechnical relations involving TI-Nspire. This mapping resulted in a geography of connections with three key areas representing different aspects of the classroom sociotechnical networks that were identified by participants as having adapted in relation to TI-Nspire.

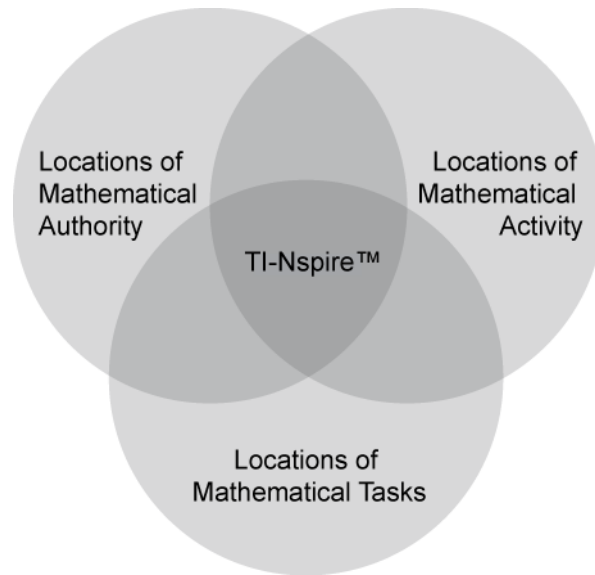


Figure 15: Key sociotechnical network areas

These areas, locations of mathematical authority, locations of mathematical tasks, and locations of mathematical activity are illustrated in Figure 15. In the following sections, each network area will be addressed and patterns of relations between implicated network-objects in the classrooms will be discussed.

Locations of mathematical authority.

One key area of the classroom sociotechnical networks in relation to TI-Nspire that was identified during interviews involves locations of mathematical authority in the classrooms. Both teacher and student participants spoke about the role of TI-Nspire as a source of mathematical guidance and way of checking answers. In particular, teacher participants described students' asking TI-Nspire to answer questions rather than coming to them, a phenomenon that they encouraged and has been observed by a number of researchers in relation to other technologies (Monaghan, 2004; Pierce, Stacey & Wander, 2010). During a debriefing session, for example, one teacher spoke about how he had encouraged students to go to their TI-Nspire when they

were stuck on a problem involving the application of a formula to determine the volume of a solid:

So the minute [the student] writes down the volume formula he's like 'oh is that the right one?' Like he wants to ask me, is that the right one, am I right? And we started to make some progress at the beginning of the year, like I said 'when solving equations don't ask me, check [TI-Nspire], it'll tell you if it's right or not.'

(Teacher Two)

This practice of suggesting to students that the technology could be a source of mathematical help and verification was also apparent during the observed classes. Typifying the phenomenon, in one lesson that involved a period devoted to completing a worksheet in pairs, the other teacher participant instructed the class to, "Work through it, talk with each other, use the handheld to check what you're thinking to see if it's giving you what you expect" (Teacher One). As this teacher often did, he reminds the class that TI-Nspire can give them definitive answers and help them to find misconceptions in their mathematical thinking.

These practices reveal new patterns of relations between teacher and students in terms of the sources of mathematical authority in the classroom. Speaking in an interview about the resources students have for checking their mathematical reasoning, one teacher noted, "They do see this [TI-Nspire] as being in the hierarchy of who you trust. Like they'll trust the textbook, they'll trust the teacher, they'll trust the handheld, right? They'll be a little sceptical of their partners, but willing to listen" (Teacher One). With the introduction of a technology that can provide trusted answers to a broad range of mathematical questions, the role of the teacher as a

source of mathematical authority an change as students can turn to the technology to resolve mathematical problems or disagreements with others.

A network-object that directly relates to the role of the teacher and TI-Nspire in terms of locations of mathematical authority is the textbook. Similar to the way students were encouraged to use TI-Nspire to check answers before asking their teacher, they also tended to use the technology instead of the answer pages at the back of their textbook. Speaking about this behaviour in an interview, one of the teachers offered, “They've realized the limitations with the textbooks, that there are answers wrong in the back of the book. Well there's a certainty and a trust to this [TI-Nspire] - kind of that the answers are right” (Teacher One). The teacher indicates that he has noticed his students choosing to verify answers with TI-Nspire because it is more reliable than the back of their textbook. This practice was observed in the classrooms with both teachers encouraging the use of the technology to check answers by verifying each component operation used in a solution. During one class, the same teacher described some benefits of using TI-Nspire to verify answers telling his students:

The back of the book lets you know if your answer is right. It doesn't necessarily know where your thinking went wrong, OK? So you're not totally lost in space if you don't have a TI-Nspire. If you're understanding this stuff and you're confident and you're not making silly numeric mistakes. I want you-, Each question you do check the back of the book. I don't want you doing 15 questions all wrong and then realising after 15 you did them all wrong, OK? Those of you with TI-Nspires, you don't need the back of the book. You check each transformational move that you make, so each equivalence transformation, write it down, put it in

your handheld and see what you get OK? So you'll know not only if your answer is right, you'll know if each move is appropriate. (Teacher One)

By drawing attention to the possibility of checking each step of a solution to a problem, the teacher asserts that TI-Nspire affords students much more support than simply the correct answer in isolation at the back of a textbook can provide. It can act more as a guide than as a simple arbiter of correct answers. Reflecting this advantage, both teachers encouraged their students to work with the technology and their textbook by taking questions from the book but turning to TI-Nspire for guidance about mathematical concepts and procedures. Speaking about the benefits of this practice during an interview, one teacher explained:

I think the TI-Nspire allows them to play around with partial understandings much more comfortably than the textbook. You need to fit yourself into the correct ways that the textbook proposes you do things and some kids just can't find it in themselves to do that. So they can still be incorrect and playing around with their ideas and trying to resolve them with the TI-Nspire with feedback all the time. The only feedback you get with the textbook is 'I'm wrong.' (Teacher One)

This teacher notes that like the back of the textbook TI-Nspire can be used to check if an answer is correct. He asserts that unlike the back of the textbook, however, TI-Nspire is more flexible giving students more latitude to explore mathematical ideas. The teacher suggests that when students are working on questions from their textbook, the technology becomes a partner in the activity. Similar to the relationship between teacher, student and TI-Nspire in terms of locations

of mathematical authority, the sociotechnical network of student, textbook and TI-Nspire affords new possibilities for learning that would be difficult to realise with student and textbook alone.

Locations of mathematical tasks.

Similar to the way new patterns of relations formed with TI-Nspire as a location of mathematical authority in the classrooms, the ways that mathematical tasks were assigned to students also adapted. Speaking to such changing practices, teacher one noted that by affording students a more flexible way to work through problems, TI-Nspire had changed the types of questions he felt comfortable assigning. Talking specifically about assigning homework, he suggested:

It's changed the nature of the homework that I give, because if I'm assuming a kid has access to this [TI-Nspire] at home what I can envision them doing is very different than if all they have is their textbook and a notebook. (Teacher One)

Similarly, the technology also changed the way the other teacher gave assignments. Instead of handing out a paper worksheet or assigning questions from the textbook, teacher two often created self-contained digital documents that he then distributed to each student's TI-Nspire (see Figure 16).

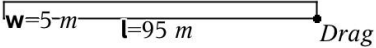
| | |
|--|--|
| <p><u>Option 1: Free-Standing Enclosure</u></p> <p>Use the model on page 1.4 to create different rectangles. Try to determine the dimensions (length & width) that produce the maximum area. You may use the diagram, the data table (page 1.5) or the graph (page 1.6).</p> | <p style="text-align: right;">Perimeter=200 A=475</p>  |
|--|--|

Figure 16: Two pages from a teacher created TI-Nspire digital document

These digital documents contained pages such as those presented in Figure 16. Each page contained different elements of an activity such as instructions, questions, calculation, tables, graphing, and space for recording answers. Once students had completed all the pages of an activity, the teacher could digitally collect their work so that he could examine it on his own TI-Nspire or using a computer-based version of the technology. During an interview, the teacher expressed a preference for this approach over the more traditional worksheet or questions from the textbook, saying:

I kind of actually prefer to have [digital documents] cause I can open them up. I don't have to cart around like this stack of papers. I can just cart around the files, they're fairly small so whether it be on the handheld or on the computer, I can just look at what they've done. (Teacher Two)

While here the teacher focuses on pragmatic reasons for assigning digital documents, instead of using worksheets or the textbook, during a debrief after an observed class he spoke about how using digital documents changed his instructional practice. Discussing a session in which students were given class time to work with a data set that described life expectancy for males

and females based on year of birth, the teacher spoke about how he had approached the activity before TI-Nspire:

What I've done before is I would have given them an instruction sheet. It's a double-sided sheet of paper. There's a graph of the men's data, so they didn't actually plot the data or use the table of values. There was the graph, it asked them to draw the line of best fit, it asked them to make the predictions on the data. The back side was the women's, draw the line of best fit, make the predictions in the data like the years or whatever that I've used and then the end of that activity I actually had them do it on [an earlier graphing calculator model], graph it and have the calculator determine the line of best fit and then we just compared the answers. So we said OK well this is the answer you got, the line the calculator gave us, are they close, are they different? And then we actually from there went about talking about how to create the line and come up with the equation using a couple of the data points. (Teacher Two)

When assigning the activity before having access to TI-Nspire, the teacher asked students to graph the male and female life expectancy data sets on paper and then draw lines of best fit. Then he had students enter the data into older graphing calculators that do not have all the features of TI-Nspire. With these more basic calculators, the students then used linear regression to produce lines of best fit. The students could then compare their drawn lines of best fit with those produced by the calculators. Since class time was limited and the teacher's goal was to have students explore the concept of modelling trends in data through lines of best fit, he did not see the approach as ideal. Graphing the data on paper took a long time, but allowed students to interpret and draw their own lines of best fit, while using the older calculators for graphing took

less time, but did not afford students the chance to create their own lines of best fit. TI-Nspire, however, allows much of the manual work of data entry to be eliminated while still providing students the opportunity to create their own graphs and lines of best fit using its graphical functionality. By providing students with a digital document containing all the necessary data and instructions, the teacher was able to make what he considered to be much better use of the available class time, while still focusing the activity on the interpretation of data. Particularly by reducing the time required for students to perform tasks, the relationship between student and TI-Nspire opens up new instructional possibilities that allow teachers and learners to focus on mathematical concepts. In response to these possibilities, new patterns of relations were found in the two classrooms between such network-objects as the textbook and TI-Nspire that showed ways that the classroom sociotechnical networks adapted in terms of locations of mathematical tasks.

Locations of mathematical activity.

While TI-Nspire may open up new instructional possibilities and ways of working, it was not the only location of mathematical activity observed in the classrooms. It was not even the only digital technology used. In the school in which this study was conducted, the teachers had dynamic geometry software such as *The Geometers Sketchpad*TM, and statistical and graphing software such as *Fathom*TM and *Tinkerplots*TM at their disposal. As is the case in many schools, however, this software was hosted on computers in a lab that required classes to move classrooms. By contrast, TI-Nspire is a mobile handheld device that can be used in any classroom, but has drawbacks particularly in terms of the limited size of its screen and keyboard. These factors meant that the teacher participants had to choose when to use TI-Nspire and when

to use the computer lab. Discussing this relationship, one teacher talked about how TI-Nspire relates to the computer lab:

It's nice that there's a single tool that the kids can use for pretty much all the math that we're doing right now. So if I can't get into the computer lab we can still do Fathom or Tinkerplots things with [TI-Nspire]. Or if we can't get in the lab and use Sketchpad there are dynamic geometry things we can do with [TI-Nspire]. So the fact that you've always got a computer lab at the ready without having to book it, march the kids into a different location is really nice. So that this fits itself to the lesson rather than the lesson having to fit itself to the technology. (Teacher One)

Because TI-Nspire is a handheld technology, it is inherently more flexible than a fixed computer lab in terms of where and when it can be used. As the teacher notes, it does not necessarily need to be booked and unlike computer labs, which require moving the class to another location, can be used for a short part of a lesson. During the observed classes, both teachers used TI-Nspire at times for short periods of focused activity that might have been impractical with a computer lab. For example, guiding the class through the simplification of a polynomial by writing on the blackboard and describing his actions, one teacher turned to TI-Nspire during a discussion with two students about what the next operation should be. The students had different views of how the expression could be operated upon and the teacher asked them to put it in to the technology saying, "For those of you with TI-Nspires, just try putting that in and hit enter and see what it gives you back" (Teacher One). This kind of quick use of the technology would not be practical if the class had to move to a computer lab.

Beyond having the flexibility of a handheld device that can be easily transported and used on an *ad hoc* basis during a lesson, TI-Nspire was also seen by the teachers as supporting richer mathematical conversation than traditional computer labs. One teacher in particular indicated that part of his decision when choosing TI-Nspire over taking his class to the computer lab was informed by the idea that its handheld nature lent itself to supporting or at least not hampering conversation between students. He noted that, “The computer lab is a hideous setup where kids are facing the wall around the outside and it’s a bad setup for learning, it’s all about computers. The nice thing about [TI-Nspire] is it’s not all about the handhelds” (Teacher One). Despite the perceived beneficial attributes of TI-Nspire, such as those the teacher refers to, many of its functions such as dynamic geometry and graphing overlap with features of software often found in school computer labs. The very size and portability of TI-Nspire that makes it useful in some situations may render it clumsy and difficult to use in others. The opinions and practices of the teachers show that a relationship exists between TI-Nspire and the computer lab. While in many cases TI-Nspire was chosen over the computer lab, it did not totally replace it and the sociotechnical networks in the classrooms adapted to accommodate both technologies.

Another digital technology in the classroom that has a relationship with TI-Nspire in terms of locations of mathematical activity is the interactive whiteboard. It displays a projected computer screen and allows users to interact by touching and writing directly on the image. Teachers can project a computer software emulator version of TI-Nspire onto an interactive whiteboard and then manipulate a large image of the handheld (see Figure 17).

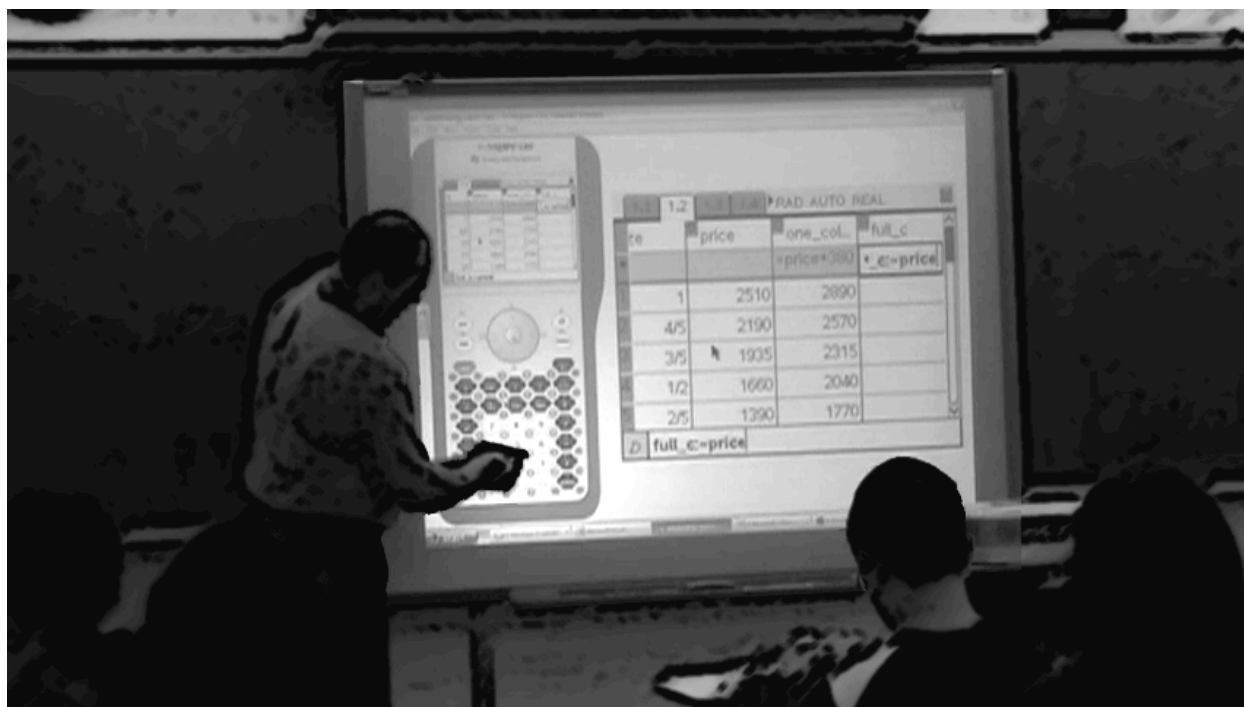


Figure 17: Teacher using interactive whiteboard with TI-Nspire

Despite this feature of interactive whiteboards that allows users to manipulate a large projected version of TI-Nspire, in one of the observed classrooms the teacher preferred to use a blackboard as the primary location of shared mathematical activity. In this classroom, the blackboard was used in combination with TI-Nspire and the translation of mathematical notation between the technology and blackboard was a key component of most of the observed sessions. This teacher described how he had at first frequently used an interactive whiteboard when he first introduced TI-Nspire to his classes but then changed his practice saying, “I used it a lot at first. I quite enjoyed using it, I use it less now. I don’t like to use it as demo, because as soon as the lights go off its like it’s a movie and the kids are just like this [sits back in chair and folds arms]” (Teacher One).

In the other classroom, an interactive whiteboard was often used in combination with TI-Nspire instead of the blackboard. It was the primary location of shared mathematical activity in this classroom and was integral to the way TI-Nspire was used. Describing his rationale for the arrangement, the teacher observed, “It is so important for them [the students] to be able to have access to it [the interactive whiteboard] to be able to follow along. It just makes it a lot smoother” (Teacher Two). By using an interactive whiteboard in combination with TI-Nspire, the teacher demonstrated ways of working and discussed activities that in his class were almost always assigned as self-contained digital documents. In addition, students could and often did come up to the front of the class and share ways they had approached problems or ways of working with TI-Nspire. For example, during an observed session the teacher asked a student to use the interactive whiteboard to show the class how she arrived at a solution to a problem:

Teacher says: Go ahead, punch it in on my calculator. As [student] punches it in, I'm going to describe what she's doing.

Student inputs: $100 = \frac{\pi \cdot r^2 \cdot 6}{3}$

TI-Nspire returns: $100 = 2 \cdot \pi \cdot r^2$

Teacher says: All right so the very first thing is just to enter the formula and again it did simplify for us, because six divided by three is two.

Student inputs: $Ans / 2$

TI-Nspire returns: $50 = \pi \cdot r^2$

Teacher says: So the next step [student] did was to divide by two and she's got fifty is equal to pi times r squared.

Thus, using the TI-Nspire projected on the interactive whiteboard, the student was able to replicate the work she had done on her handheld. This allowed the class to discuss her approach to solving the problem without having to work with a mediator such as a blackboard that would require them to translate between TI-Nspire mathematical representations and hand-written forms.

A theme that runs through the patterns of relations between TI-Nspire and other network-objects such as the blackboard and interactive whiteboard in terms of locations of mathematical activity is the crucial connection between the technology and paper/pencil work. The importance of this relationship is also indicated by the large amount of mathematics education research that focuses upon the interaction between technological and paper/pencil mathematical activity (Artigue, 2002; Chappell & Kilpatrick, 2003; Drijvers & Kieran, 2006; Kieran & Saldana, 2005; Tall, Smith & Piez, 2008). In the observed classrooms, students worked with both paper/pencil and TI-Nspire collaboratively. There were, however, marked differences between classes that relate directly to the use of such network-objects as paper worksheets, textbooks, self-contained digital documents, blackboards, and interactive whiteboards. In the class where assignments were most often given via paper worksheets and the blackboard was the primary medium for sharing with the group, students tended to work predominately with paper/pencil with TI-Nspire acting as a partner in their activities. In the class where most assignments involved self-contained digital documents and sharing with the group took place on an interactive whiteboard, TI-Nspire tended to be the focus of student mathematical activity.

Each teacher had distinct impressions of how TI-Nspire and paper/pencil could be useful as parts of their instructional practices. As is the case with many of the pedagogical views teachers have, these intentions shaped the role the technology had in their classrooms (Pierce, Ball & Stacey, 2009). During interviews, one teacher in particular spoke often about resisting the technology becoming the focus during lessons. Discussing his choice not to find or create digital documents and distribute them to his students, he explained:

The documents I haven't used as much as I thought I would. And I don't think its because there aren't documents out there that are good. It's just that I don't want it to be about the documents, the lessons or the handheld. You know I would prefer it to be in the background and the kids grab it when they need it. (Teacher One)

This teacher believed strongly that TI-Nspire should be one of many tools available to students but that most mathematical activity should be on paper/pencil. Sharing the view of a number of mathematics education researchers (Drijvers, 2000; Pimm, 1995; Stacey, 1997), that handing off procedural tasks to technology may actually make conceptualizing mathematical concepts more difficult, the teacher also expressed concern about TI-Nspire becoming a black-box. He described his fear of TI-Nspire becoming an opaque computational machine into which problems go and solutions come out, without any indication of the processes that have been performed. This motivated him to de-emphasise the importance of the technology in his classroom, instead choosing to focus mathematical activity on paper/pencil.

The other teacher whose class was observed had a distinctly different view and spoke most often about the advantages of TI-Nspire being the primary location of mathematical

activity. Speaking during a debriefing session about a class in which he had asked students to create a number of graphs so that they could be compared, he offered:

I don't think I would have got that discussion necessarily about the different points of intersection for the male and female [datasets] today if I didn't have the technology. Cause what would have happened is with, I don't know what did we have there 20 data points, some of the kids it would take them half an hour to graph 20 data points. So by the time they get the one graph created and we get that line drawn that's almost the entire period, right? So you can spend a period let's say creating graphs, but now if you want to get through the graphs and just do talking about it and analysing it and comparing it, it's so much easier to do in an instant have the graph and now let's discuss. (Teacher Two)

For this teacher, TI-Nspire made it possible to have more discussion and to address more concepts than would be possible with paper/pencil. He saw these advantages as outweighing concerns of black-box effects or the technology becoming the focus of mathematical activity. In his classroom, the primary location of mathematical activity was TI-Nspire, with the role of paper/pencil greatly reduced even to the point that students often took notes on the technology. This arrangement of the technology and paper/pencil is distinctly different from the arrangement preferred in the other teacher's class and shows some of the range of ways that sociotechnical networks form in relation to TI-Nspire and locations of mathematical activity.

Discussion and Conclusion

By examining the activity in classrooms using TI-Nspire, the findings of this study illuminate ways that patterns of relations among teachers, students and classroom materials adapt with the introduction of handheld technologies. While only those adapted relations that participants expressed in their interviews were discussed, this subset of the enormously complex set of mediators in classrooms where handheld technologies are used shows the interconnectedness of network-objects such as the teacher, the textbook, worksheets, the computer lab, the board, paper/pencil, handheld technology and students. In Figure 18, the connections between these network-objects that were identified as having formed in relation to TI-Nspire are illustrated.

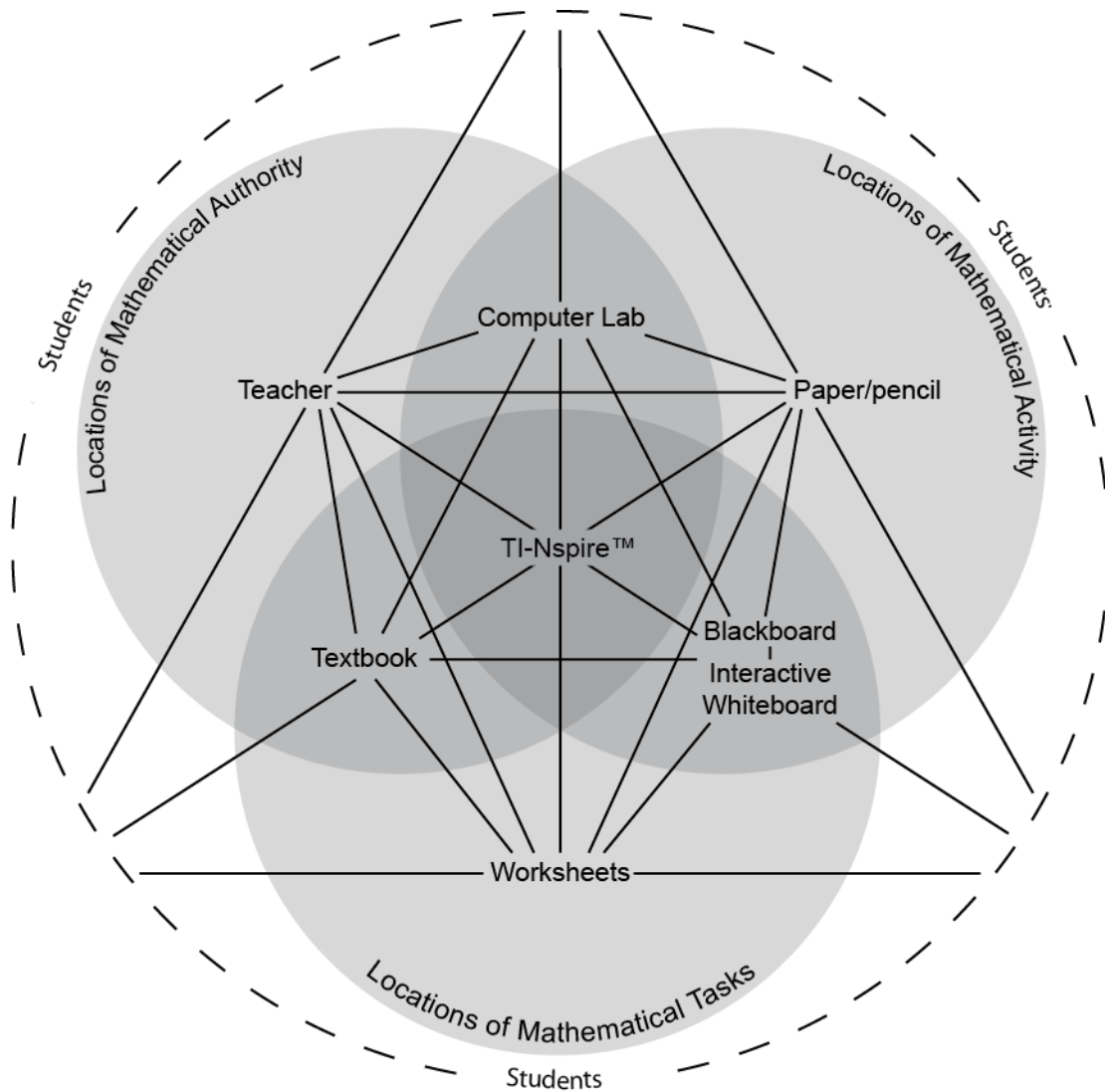


Figure 18: Geography of classroom sociotechnical networks involving TI-Nspire

This diagram represents a snapshot of the fluid networks in the two classrooms and the network-objects within them. It shows not only the interconnectedness of the sociotechnical networks but also the overlapping roles of the network-objects within them. The humans and materials identified in the diagram fall within three overlapping areas that represent the roles they play in classrooms. While an agent such as the teacher, for example, plays a much greater role within the

classroom than solely as a location of mathematical authority, this is the role identified in terms of the networks formed in the two classrooms in relation to TI-Nspire.

The teacher was not the only agent of the sociotechnical networks in the two observed classrooms that acted as a location of mathematical authority. The answers at the back of the textbook, software in the computer lab and TI-Nspire also acted as locations of mathematical authority for students to draw on. This changed the relationship between teacher and student, allowing students to explore their thinking further before asking the teacher for help. Pierce, Stacey and Wander (2010) also found evidence of shifts in locations of mathematical authority in relation to the introduction of TI-Nspire. They assert that technology capable of being a source of mathematical authority changes the didactic contract between teacher and student and shifts socio-mathematical norms in the classroom (Pierce, Stacey & Wander, 2010). While they speak to the changed relationship between teacher and student in terms of locations of mathematical authority with the introduction of TI-Nspire, the present study adds to this work by identifying other important relationships within classroom sociotechnical networks that are also implicated. The textbook in particular, was identified as also acting as a location of mathematical authority whose relationship with students shifted in relation to TI-Nspire.

While the textbook was identified as a location of mathematical authority in the two observed classrooms, it also served as a location of mathematical tasks. Along with paper worksheets, the blackboard and interactive whiteboard and digital documents on TI-Nspire, the textbook acted as a way mathematical tasks were assigned to students. Each of these network-objects afforded the teachers different possibilities in terms of the kinds of tasks they could assign with the network of TI-Nspire and student having distinctly different properties to student and textbook. Drijvers and Kieran (2006) have also spoken to the relationship between

technology and the kinds of tasks assigned to students. They assert that when a student undertakes a mathematical task with a computer algebra system there exists a dialectical relationship between that task and the technique they use from which mathematical theorizing emerges (Drijvers & Kieran, 2006; see also Kieran & Saldana, 2005). This indicates the interrelated nature of materials available to students and the kinds of tasks that can be assigned. Findings drawn from the two observed classrooms in this study support Drijvers and Kieran's assertion by suggesting the introduction of TI-Nspire certainly influences the kinds of tasks assigned to students but, in addition, suggest that it influences the relationships between teacher, student and other network elements such as paper worksheets and the blackboard and interactive whiteboard.

Apart from being implicated as a medium for assigning tasks, the blackboard and interactive whiteboard also acted as a location of mathematical activity in the classrooms. Together with the computer lab, paper/pencil and TI-Nspire handhelds, the blackboard and interactive whiteboard served as locations of both individual and shared mathematical activity. While none of these locations replaced any of the others, they were all involved to greater or lesser extents in the mathematical activity of each classroom. The student, teacher, board, paper/pencil, computer software, and TI-Nspire were arranged in different ways with each configuration supporting different activity. As several researchers have suggested, in terms of learning perhaps what is most important is that multiple locations of mathematical activity were available for students to work and share with (Drijvers & Kieran, 2006; Kieran & Saldana, 2005).

Particularly by adopting an Actor-Network theory perspective on the many agents and connections that exist within classrooms, the findings of this study indicate that sociotechnical

networks in classrooms using handheld technology operate as a complex interconnected whole. In the two observed classrooms, it was particularly evident that the effects of the teachers' decisions to include TI-Nspire as part of their instructional practices were not limited to, for instance, the local patterns of relations between student and technology while completing an activity. They were instead extremely broad, influencing practices as diverse as homework and the use of the computer lab. The findings of this study show as Drijvers *et al.* (2010) suggest, that the didactical configuration of technologies in mathematics classrooms has a profound effect on the mathematical practices within them, but also suggest that this is far from a one-way phenomenon. While teachers have enormous influence through their choices of what technological arrangements to use, other agents both human and non-human in the classroom mediate these configurations and are highly interrelated. For instance, the choice to assign activities as digital documents rather than as questions from the textbook may influence the decision to share mathematical activity as a class with an interactive whiteboard and may influence the decision to create digital notes rather than work with paper/pencil. Each pattern of sociotechnical relations mediates the others and together they reciprocally shape the geography of the classroom.

Chapter 9. Tracing Mathematical Activity with Handheld Digital Technology: From Development to Classroom Use

Submitted to the *Mathematics Education Research Journal*

Abstract

This article examines mathematical activity with digital technology by tracing it from its development through its use in classrooms. Drawing on Actor-Network theory, it examines the visions of mathematical activity that *Texas Instruments* developers have for their TI-Nspire graphing calculator. It then follows the technology into classrooms and examines the ways teachers include it within their instructional practices and the ways students work with it to perform mathematical tasks. The findings of this genetic analysis of the relationship between a technology and mathematical activity illuminate important links between the ways developers envisage features supporting mathematical activity, the ways teachers choose to situate those features in their classrooms and the ways students choose to work with them.

Introduction

Evidence from numerous researchers shows that handheld digital technologies have the potential to help learners make connections with and between mathematical concepts and enrich their mathematical thinking (Kaput, 1998; Kaput & Schorr, 2008; Noss, Healey & Hoyles, 1997). Digital technologies including graphing calculators, dynamic geometry software (DGS) and computer algebra systems (CAS) have been reported to encourage learners to make mathematical conjectures, investigate those conjectures, and engage in mathematical reasoning

as they make meaning of mathematical concepts (Harvey, Waits & Demana, 1995; Heid & Edwards, 2001; Hollar & Norwood, 1999; Knuth & Hartmann, 2005; Laborde *et al.*, 2006; Yerushalmy, 2006). Drawing on this research, technology use in mathematics classrooms is broadly encouraged in many curriculum and policy documents (cf. National Council of Teachers of Mathematics, 2000; Ontario Ministry of Education, 2005). In the Canadian province of Ontario, for instance, the grade nine and ten mathematics curriculum describes the potential of digital technology, saying:

Information and communication technology (ICT) provides a range of tools that can significantly extend and enrich teachers' instructional strategies and support students' learning in mathematics. Teachers can use ICT tools and resources both for whole-class instruction and to design programs that meet diverse student needs. Technology can help to reduce the time spent on routine mathematical tasks and to allow students to devote more of their efforts to thinking and concept development. (OME, 2005, p. 27)

This support for the use of digital technology can be found throughout the Ontario curriculum in both broad framing statements and specific content to be covered (OME, 2005). For example, in a section describing the specific analytic geometry concepts to be covered in ninth grade mathematics, the curriculum document states:

By the end of the course, students will determine the equation of a line from information about the line (e.g., the slope and y -intercept; the slope and a point; two points). (Sample problem: Compare the equations of the lines parallel to and

perpendicular to $y = 2x - 4$, and with the same x -intercept as $3x - 4y = 12$.

Verify using dynamic geometry software). (OME, 2005, p. 34)

With strong support for their use in educational policy and evidence of their benefits for learners such as offering new ways to represent and engage with mathematical concepts from many researchers, more investigation of the complex dynamic ways that digital technologies mediate mathematical learning is warranted. In this paper, I unpack the relationship between technology and mathematical activity in classrooms as a number of researchers have done (cf. Lagrange, 1999; Meira, 1998; Trouche & Drijvers, 2010; Pimm, 1995; Verillon & Rabardel, 1995). Expanding on the work of these researchers, I draw inspiration from Vygotsky's genetic analysis. Vygotsky's work suggests that it is not enough to examine learning situations *in situ* and proposes that we must also seek to understand their history (1978, 1986). In the case of educational technology, its history mediates how it comes to be used the ways it does in the hands of learners and this history begins with its development. This indicates that without examining the intentions of developers, our understanding of why a technology is used the ways it is in classrooms may be limited. Taking a genetic analysis approach to investigating the relationship between digital handheld technology and mathematical activities such as calculation, problem solving and exploring relationships between mathematical concepts, I draw on Actor-Network theory (ANT) to conceptualize the links between technology development, technologies themselves and the humans that use them. From an ANT perspective, humans and technologies form sociotechnical ensembles as they interact and it is from their interactions that activity emerges (Latour, 2007). Working with this conception and the premise that handheld digital technologies are complex actors in learning situations that have a history and have been created

with purpose, I examine ways that mathematical activity is mediated as technology developers, teachers and students work with technology.

Handheld Digital Technology and Mathematical Learning

Recent innovations in mobile computer processors and screens have allowed mathematics software to move from desktop computers to handheld technologies like graphing calculators. With this movement, sophisticated software that supports a variety of ways of working with mathematical concepts is now available on portable and relatively inexpensive devices. Two of the most widely used and researched types of software that have made the move to handheld devices are dynamic geometry software (DGS) and computer algebra systems (CAS).

Perhaps the key feature of dynamic geometry software (DGS) is that it allows learners to create geometric constructions that can be modified by selecting them and dragging the cursor. As a point or line in a construction is selected and dragged, it responds by adapting while constrained by the geometric rules that define it. Taking a simple construction such as a triangle for example, students can draw lines to construct an equilateral triangle and then drag one of the vertices while the others remain fixed. This allows them to watch as their movement changes the triangle from equilateral to isosceles and scalene. It was this power to represent concepts in dynamic new ways that led much of the excitement about the technology as it emerged in the late 1980s (Laborde & Laborde, 2008; Moreno-Armella, Hegedus & Kaput, 2008). Educational researchers quickly became interested in the potential of DGS and its gradual introduction into schools coincided with the spread of the idea that access to multiple-representations of mathematical concepts is pedagogically important (Sträßer, 2002). Early studies revealed a

technology that takes advantage of the graphical features of computers to offer learners the ability to engage with geometric constructions in a dynamic fashion all the while supporting new ways of thinking about geometric properties (Hölzl, 1996; Laborde, 1992; Laborde & Sträßer, 1990). Later, researchers began to investigate detailed aspects of DGS use in classrooms along with both its pedagogical benefits and limits. Ethnographic research that examines teachers' integration of DGS into mathematical tasks, for instance, shows that teachers often ask students to exploit the dynamic visualizations that DGS provides but seldom suggest that it be used to help construct mathematical proof (Christou, Mousoulides, Pittalis, & Pitta-Pantazi, 2004; Chazan, 1993; Guven, Cekmez, & Karatas, 2010; Hadas, Hershkowitz, & Schwarz, 2000; Jones, 2000; Mariotti, 2000; Laborde, 2001). This finding suggests that there is a disconnect between the inductive approach to developing evidence for a mathematical concept supported by DGS and the deductive approach of formal mathematical proof. Some researchers have expressed concern that students using DGS to explore geometric properties would only use empirical experience to support their assertions and never move to producing a formal proof (Chazan, 1993). Others suggest that while DGS does disrupt the classical notion of what constitutes proof in mathematics, there is a relationship between the kind of inductive exploration that the software promotes and the deductive reasoning needed to construct a formal proof (Christou, Mousoulides, Pittalis, & Pitta-Pantazi, 2004; Edwards, 1997; Guven, Cekmez, & Karatas, 2010; Jones, 2000).

Like DGS, computer algebra systems (CAS) have also taken a prominent position in many mathematics classrooms. Its ability to manipulate algebraic symbols in addition to numbers has been shown by a number of researchers to be useful in helping students learn to manipulate symbols and perform operations such as factoring binomials or solving equations

(Drijvers & Kieran, 2006; Heid, 1988; Jakucyn & Kerr, 2002). Early experimental studies showed that undergraduate university students who used CAS to perform computational tasks had improved conceptual knowledge of calculus over those who had used more traditional paper and pencil approaches (Beckmann, 1988; Heid, 1988; Palmiter, 1991). Later research, however, has suggested that while handing off procedural mathematical tasks to the technology may appear to free learners to conceptualise the broader concepts of mathematics, it risks creating black boxes into which problems go and solutions come out without any indication of the processes that have been performed (Drijvers, 2000; Pimm, 1995; Stacey, 1997). Reflecting this concern, several researchers have examined CAS use in concert with other approaches such as more traditional paper and pencil work (Drijvers & Kieran, 2006; Jakucyn & Kerr, 2002; Kieran & Damboise, 2007; Kieran & Saldana, 2005). Based on findings from a study of several tenth grade classrooms, for example, Drijvers and Kieran (2006) suggest that students benefit from the interaction of different approaches to factoring equations. They highlight the advantages of CAS in providing learners a means for quickly verifying their mathematical theorizing but caution that the technology should not replace paper and pencil work.

Research involving the use of digital technologies for mathematical learning indicates that learners benefit from a rich array of tools that encourage them to engage with a variety of ways of approaching mathematical concepts. This research indicates that while digital technologies may have advantages they mediate the mathematical activity in classrooms in complex ways (Drijvers & Kieran, 2006; Laborde, 2001; Monaghan, 2004; Pierce *et al.*, 2010). Addressing this complexity, a number of researchers have examined the interactions between technology and mathematical learners seeking ways to characterize the relationship (Shaffer & Clinton 2006; Trouche & Drijvers, 2010). A particularly prominent instance of this work is

research that draws on the notion of instrumentalization (Drijvers & Trouche, 2008; Lagrange, 1999; Trouche & Drijvers, 2010; Verillon & Rabardel, 1995). This research draws on the Piagetian concept of schema to describe the learning of mathematical concepts and on an anthropological approach to describing the relationship between technology and learners (Monaghan, 2004). It conceptualizes educational technologies as tools that become instruments as learners develop schema associated with mathematical tasks. With this understanding, the work of researchers drawing on instrumental genesis examines the ways teachers guide their students to make technology meaningful in the context of mathematical activity (Drijvers *et al.*, 2010; Trouche, 2004).

Similar to the instrumental approach to understanding the relationship between technology and learner, Shaffer and Clinton (2005, 2006) have proposed their own theorization. Their ‘toolforthoughts’ approach also recognizes the reciprocal relationship between learner and technology, but does not limit the role of the technology to that of a mere object waiting to be made an instrument by learners. Drawing on a combination of Actor-Network theory (Latour, 2007) and Activity-Theory (Leont’ev, 1978), they argue that while theorizing that understands technology solely as a servant to human activity may have served researchers well when investigating analogue objects, such as linking-cubes in a mathematics classroom, complex computational technologies such as computer software have a much more active role in their interactions with humans. They note that while focusing solely on humans as actors in learning situations, “may not be a problem in a theoretic culture of static inscriptional systems. In a virtual culture based on offloading of symbolic processing, however, using human action to analyse activity obscures the active role tools play” (2006, p. 289). Based on this view, they suggest that researchers examining learning with computational technology may be better served by

conceptualizing technologies as active partners in mathematical learning (Shaffer & Clinton 2006). Like research drawing on an instrumental conception of the relationship between learners and technology, Shaffer and Clinton's (2006) approach opens up new ways of understanding the role technology has in mathematical learning. These recent theoretical approaches speak to the need for research that supports the development of a richer understanding of the kinds of complex computational technology typified by the latest generation of handheld digital devices.

Theoretical Perspective

To examine ways that mathematical activity is mediated as technology developers, teachers and students work with technology, I also draw on Actor-Network theory (ANT) in combination with elements of Activity-Theory as Shaffer and Clinton (2006) propose. Since my aim is to examine both the history and the *in situ* use of technology, however, I draw more broadly on ANT to help conceptualize the relationship between technology development and use. This combination of theories provides a framework for examining the reciprocal relationship between humans and technology in the context of mathematics learning while offering ways of understanding the development of technology that are of significant advantage to this study.

Activity-Theory, a key element of the theoretical perspective of this study, is particularly concerned with the socially and culturally situated nature of cognition (Leont'ev, 1978; Vygotsky, 1978, 1986). The theory contends that cultural tools mediate all human activity. These tools can be both internal and external yielding the notion that all learning involves tools (Säljö, Eklund & Mäkitalo, 2006; Wertsch, 1991). As Roth and Lee describe, Activity-Theory's "inherently dialectical unit of analysis allows for an embodied mind, itself an aspect of the

material world, stretching across social and material environments” (2007, p. 189). From this perspective, all learning is activity that takes place simultaneously inside and outside of the learner thus suggesting that understanding the mediation of tools including technologies is vital to understanding learning itself.

While Activity-Theory foregrounds the important role of tools in human activity, it considers technical tools and humans to have an asymmetrical relationship. In this relationship, humans are assumed to act and tools are not (Shaffer & Clinton, 2006; Wertsch, 1991). This assumption may obscure the important role that particularly complex digital technologies can have in mathematical learning. Seeking to address this issue, I follow Shaffer and Clinton’s approach by turning to ANT which conceptualizes the relationships between humans and technology as part of social networks of humans and non-humans all mediating each other’s activity (Latour, 2007). Within these sociotechnical networks, ANT conceptualizes the relationship between actors, both human and non-human, in reciprocal terms offering the notion that when interacting, the capacity to act cannot be located in either party but instead emerges from their interaction (Latour, 2007; Suchman, 2006). With this in mind, the development of technologies used in learning situations cannot be ignored since the resulting technologies and the humans that use them mediate each other and the activity that emerges from their interaction (Akrich, 1992, 1995; Latour, 2007; Shaffer & Clinton, 2006).

A key feature of ANT that is of particular importance to this study is the notion of translation. This concept describes the connections within networks of semiotic mediation that are made up of both human and non-human actors (Fenwick & Edwards, 2010). It refers specifically to the reflexive mediation that connects two actors as “a relation that does not transport causality but induces two mediators into coexisting” (Latour, 2007, p. 108). Applying

this concept to the development and use of educational technology, the vision developers have for a technology is translated into its features. Then users, such as teachers and students, translate these features as they use the technology in their own unique ways (Akrich, 1995; Akrich & Latour, 1992). Often developers then seek out these innovative practices by consulting with users and they are translated into new versions of the technology. Throughout, the semiotic relationships that connect the activities of developers, users and the technology are a matter of translation and not of direct causation.

Despite providing a frame for conceptualizing the interactions of human and non-human agents, one criticism of ANT is that it does not offer conceptual tools for investigating the internal properties of actors within social networks (Engeström, 2001). In combination however, the sociocultural approach to cognition offered by Activity-Theory and the sociotechnical approach to networks of humans and technology offered by ANT develop a useful perspective from which to investigate both the interactions of actors within a system and their internal properties (Shaffer & Clinton, 2006). This combination affords a lens through which to investigate mathematical learning with technology while providing ways to understand the relationship between technology development and use. It conceptualizes the roles of humans and technology in learning processes without overtly restricting the focus of inquiry to one or the other.

Method

As a technology to focus on in this study I chose *Texas Instruments'* TI-Nspire. This handheld computing device has evolved from a line of graphing calculators reaching back to the

mid 1980s (Hamrick, 1996; Kidwell, Ackerberg-Hastings and Roberts, 2008). It has many features including spreadsheets, graphing tools, dynamic geometry, and computer algebra (CAS), all hosted as a single interconnected mathematical environment that has been designed specifically for educational use.

Data collection.

To examine the emerging relationship between educational technology and mathematical activity through its development and use, data was collected in two major phases. One phase involved the participation of TI-Nspire development team members and the other involved secondary school mathematics teachers, their classrooms and their students (see Table 6).

Table 6

Participants

| Phase | Participants | Background | Instruments |
|-------|---------------------------------------|--|--|
| 1 | Four developers | Amongst the four developers were a senior manager, an engineer, a former teacher, and mathematician turned developer. | In-depth interviews Artefacts |
| | Two mathematics education consultants | Each of the two mathematics education consultants is an educational researcher and teacher educator. They are both involved in professional development for mathematics teachers and have worked on several <i>Texas Instruments</i> projects | In-depth interviews |
| 2 | Two teachers | One teacher has a long history of classroom technology use and has worked as a school board mathematics consultant. The other teacher trained as a mathematics teacher but spent several years teaching computers and programming only recently returning to mathematics teaching. | In-depth interviews Classroom observation Debriefing interviews Artefacts |
| | Four students | Four students participated in mathematical activity sessions during a lunch period. Each of these students owned a TI-Nspire and had used it for one semester at the time of the study. In the case of one of the classes, two students could not be found who would volunteer to participate. Instead one student invited a friend who had taken the same mathematics class in the previous semester. | Classroom observation Mathematics activity sessions Debriefing interviews Artefacts |

One of the key ideas guiding this study is the notion that technologies in classrooms come from somewhere and have been designed with the specific purpose of supporting learning. To understand how and why TI-Nspire emerged as the technology now sold to schools and learners, I interviewed members of the team who developed it. I conducted interviews with a total of six development team members who are either professional developers working at *Texas Instruments* or mathematics education consultants who were directly involved in the project.









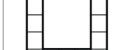
Each team member participated in an in-depth, semi-structured interview of between one and two hours in length that focused on the TI-Nspire development process. These interviews were audio-recorded and took place in person at the offices of the participants.

The other phase of data collection involved two teachers and their ninth grade mathematics students. Both teachers taught at a large suburban secondary school in the Canadian province of Ontario and regularly used TI-Nspire. First, I interviewed the teachers about their use of TI-Nspire and their experiences with technology in the classroom. These interviews provided me an opportunity to learn about the participants' backgrounds, their goals and their feelings about teaching mathematics and the role of technology in their practices. Following these initial interviews, I observed a series of five sessions of each teacher's class. These sessions were recorded with multiple microphones and a single video camera that was focused on the activity of the teachers. While focusing on teacher activity, I made efforts to use panning and zooming sparingly so that a wide view of the overall classroom context could be maintained (Derry *et al.*, 2010). Following each observed class, the teachers were invited to participate in retrospective debriefing interviews that helped to unpack the events of the session. In addition, these sessions provided me with an opportunity to collect any material artefacts that had been used in the class such as handouts or digital TI-Nspire files.

In addition to focusing on the teacher participants in order to obtain a more detailed view of student activity with TI-Nspire I also invited the students in the observed classes to participate in mathematical activity sessions during lunchtime. The activity deliberately avoided requiring the use of TI-Nspire. Instead, students were provided with linking-blocks to manipulate, paper and pencils, and TI-Nspire, thus allowing me to observe *when* they chose to use the technology in addition to *how* they used it.

Block Patterns Activity

Each of these three groups of shapes built from blocks represents the beginning of a pattern.

| | | Step | | | |
|---------|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| Pattern | A |  |  |  | |
| | B |  |  |  | |
| | C |  |  |  | |

1. Using the extra blocks, build the 4th step in each of the three patterns...
2. Looking at the relationships between step number and number of blocks, which of the three patterns have relationships that are linear? Show how you know...
3. How many blocks would be needed to make the 50th step in pattern A? Show how you know...
4. Show how patterns A and C are similar and different...

Figure 19: Activity sheet and instructions

As can be seen in Figure 19, the activity involved a series of three shape patterns provided to the students as diagrams and as linking-block models. With the first three steps in each pattern provided, the students were asked to perform a series of tasks that related to the number of blocks required to make each step in the patterns. For each of the three patterns, a shape grew over a series of three steps and the student pairs were asked to create the fourth step and determine whether or not the change in number of blocks between steps was linear. Two of the patterns grew in linear relations while the third grew non-linearly. This focus on linear and non-linear patterns was chosen due to the focus on similar topics in the Ontario ninth grade mathematics curriculum (OME, 2005). Having determined the linearity of the patterns, the

students were then asked to determine how many blocks it would take to build the 50th step in pattern A and asked to compare patterns A and C for similarities and differences.

To best record the students' activity while completing the tasks, two video cameras and two microphones were used. I placed one camera facing the pair and a second camera above and behind them to record their activity. In addition, a computer recorded the screen of the students' TI-Nspire using screen-capture software. Following the completion of the activity, each student pair participated in a retrospective debriefing interview that provided insight into both their practices while completing the task and more generally with TI-Nspire.

Data analysis.

Soon after each interview or observation session, I listened to or watched the recording to verify its quality and so that I could make content logs while the experience was still fresh in my mind. I then transcribed the interviews and mathematical activity sessions and added the recordings and transcriptions to *Transana*, qualitative analysis software that allows efficient organisation and analysis of multiple media sources (Woods & Fassnacht, 2009). Using *Transana*, I was able to synchronize audio and video recordings with transcripts so that sections identified in the different media would automatically correspond. This allowed me to transcribe sections of the classroom videos as needed and gave me the flexibility to select a passage in either a transcript or a recording and have the same section in the other media automatically linked. While I analysed the interviews and observational videos, I also examined artefacts such as digital documents created by the teachers for use on TI-Nspire and handouts collected from the classrooms.

As an approach to analysing the collected multimodal data, I drew on Interaction Analysis (Jordan & Henderson, 1995). Theoretically, this approach aligns well with the key assumptions made in this study by assuming “that knowledge and action are fundamentally social in origin, organization, and use, and are situated in particular social and material ecologies” (p. 41). This basic assumption is shared by both Activity-Theory and Actor-Network theory (ANT) and forms a key element of the theoretical perspective of this study. With this key assumption, Interaction Analysis suggests a number of basic methods of working with video recordings. These include, assembling content logs directly following each interview or observed session and viewing recordings with other researchers (Jordan & Henderson, 1995).

While working with the data, I used *Transana* to mark instances where participants spoke about or used TI-Nspire. Following this initial sorting, I added descriptive keywords to each marked instance. These keywords identified activities such as a developer describing the ways he imagined a feature of TI-Nspire being used or a teacher demonstrating a way of working to a class. Following this recursive process of adding keywords and repeatedly working with instances, I was able to search across all the interviews, artefacts and observational recordings to find similar activity. This allowed me to examine the relationships between developers, teachers, TI-Nspire, and their mathematical activity while maintaining a broad perspective on the corpus as a whole. Having organised and sorted the data, I traced the relationship between TI-Nspire and mathematical activity across the participants and settings. This involved examining the data for what Latour (2007) refers to as stabilized networks of sociotechnical activity. Looking specifically at instances where participants used or referred to TI-Nspire, I examined the mathematical activity as stabilized practices with the technology formed. In particular, I drew on the work of Akrich (1995) to analyse ways that the developers inscribed TI-Nspire with their

vision of future mathematical activity and on the work of Latour (2007) and Suchman (2006) to analyse ways those inscriptions were translated within the context of teacher and student mathematical activity.

Findings

Tracing the mediation of mathematical activity through the interactions of humans and TI-Nspire, I examined the practices of developers, teachers and students. Reflecting this process, the findings of this study are presented in three sections. The first discusses the ways the developers' envisaged mathematical activity with TI-Nspire and how they inscribed their vision through the features of the emerging technology. The second section speaks to the mathematical activity in the two mathematics classrooms that participated in this study; and the third section addresses the mathematical activity of the two student pairs who worked with TI-Nspire to complete a series of tasks during lunchtime activity sessions.

Setting the stage for future mathematical activity.

During their interviews, the developers described the mathematical activity they envisaged happening with TI-Nspire and discussed how their ideas are inscribed in the features of the technology. From the beginning of development, they envisaged TI-Nspire as an environment for open and exploratory mathematical activity. This vision was highly influenced by the mathematics education researchers who were involved in setting the initial framework of the project. An international group of mathematics education researchers were invited to consult with developers through meetings, workshops and written reports that helped to guide the development process. In an example of a publically available document prepared by consultants

for *Texas Instruments*, the *Center for Technology in Learning* at *SRI International* offers a review of the educational research literature that describes the vision for TI-Nspire. It is divided into three major sections. The first section describes evidence supporting the use of graphing calculators in general and discusses the ways TI-Nspire builds on existing features with an emphasis on problem solving and formative assessment. The second section speaks to a focus on enhancing ways to represent and communicate mathematical concepts through key features such as interlinked multiple representations; and the third section discusses ways of creating richer learning opportunities by, for example, encouraging collaboration and giving learners space to test conjectures (SRI International, 2006). The document depicts a technology intended to help promote exploration of mathematical concepts, a vision that permeated its development. As one developer noted:

If you go look at our visions and principles it's right in there, you know? One of our main visions and principles in there is that concept of allowing students to be without fear to be able to go have open exploration of the concepts. (Developer Four)

In light of this conception of mathematical activity with the future TI-Nspire, developers created features that inscribed their ideas into the technology. One such feature, the ability to save and share work through digital documents in particular, is one of the major features that differentiates TI-Nspire from previous graphing calculators. It supports user customization and affords avenues for modifying and sharing work created with the technology. Using this feature teachers' can, for instance, create an environment for an entire activity including resources such as instructions, questions, calculation spaces, places to create tables, and spaces for graphing. Similarly, teachers and students can share documents with each other or download pre-made activities from the

Internet. This feature allows users to work with mathematical concepts, save their work, return to it later, and share it with others thus supporting collaboration and exploration.

While the ability to create and share documents is a complex feature that inscribes the vision developers had for TI-Nspire, many much simpler and less immediately evident features play an important role. A good example of this is the seemingly simple undo command. One developer spoke about the importance of this feature for their vision of mathematical activity with TI-Nspire:

One of our guiding principles throughout the system is we want to have open exploration available. So some of the things we do plan for is, you know, some of it's just as simple as being able to do an undo. It's like you don't have to worry about oh I'm going to break it, you know if I do something it'll break uh oh, well you can just hit the undo button and you go back to where you were. (Developer Four)

As this developer describes, the vision that TI-Nspire support open and free exploration is inscribed in the undo feature. The command provided enables users to move back through a history of many actions rather than, as commonly found on graphing calculators, only undo their most recent action. This seemingly simple feature allows users to try operations without fear of making mistakes that ruin the work they have done to that point and encourages open mathematical activity.

The developers and mathematics education consultants spoke about their vision for an environment that supports open and exploratory mathematical activity but they also described changes to this vision as the project evolved. For example, developers had initially downplayed

the idea that TI-Nspire be used as a calculation tool, but as early versions of the technology were released to the public they had to reevaluate this decision. One senior manager spoke about the change saying:

I think maybe what teachers' say and what they do or maybe how we interpreted it, we thought they were doing more exploration maybe than they really were doing and so we aimed [TI-Nspire] a-, maybe didn't pay as much attention to the computation part as maybe we should have. (Developer One)

Faced with initially slow sales (Dicolo, 2009) and feedback from educators that TI-Nspire did not meet their needs for a calculation tool, developers changed the kinds of mathematical activity that they envisaged TI-Nspire supporting and began to add features and change the technology's software to reflect this new view. The developers spoke about ways in which this new vision changed the technology. They described a move away from the creation and promotion of largely exploratory problem-based downloadable documents for teachers to use in their classes. Instead, document-authoring efforts were shifted to include the creation of tightly organised activities based around clearly defined chains of actions and consequences that could be compared to paper worksheets. One developer in particular spoke specifically about a newly created series of downloadable documents called *Algebra Nspired™*, developed to meet the need to also support a more directed style of mathematical activity, saying:

TI-Nspire is this open platform that's open exploration. Students can do incredible things. So can teachers and that advanced teacher can create incredible environments and do incredible stuff with it. But if you're on the other side of the coin, go to some place like Algebra Nspired and what Algebra Nspired will

provide you is right there on the activity page. Not only an explanation of the activity but it'll give you the questions to ask the students, the possible student answers. [It] will provide movies of exactly what kind of technical tasks you need to understand how to do with Nspire, how its tied to your textbook. I mean basically we provide everything for that teacher, so that they can pick it up, they can grab what they need to grab and they can teach this thing without having high technology knowledge and enough support instructionally that they can deliver this thing. And so that's really I think kind of the beauty of introducing the document. The document allows some set environments but also allows this open exploration, so I think it's trying to bridge the two. (Developer Three)

As this developer's comments on the *Algebra Nspired*TM series of digital documents demonstrate, conceptions of the kinds of mathematical activity that might take place with TI-Nspire changed during the course of its development. The developers and mathematics education consultants' spoke of a technology that was at first envisaged as an environment for open and exploratory mathematical activity and as less calculation oriented than previous graphing calculator models. Later, as early versions of TI-Nspire were released and sold, however, factors such as market forces and feedback from educators influenced the developers to expand the ways they envisaged the technology supporting mathematical activity to include a more directed style with more support for calculation tasks. Developers inscribed this expanded vision in revisions to the technology that continue to evolve.

Mathematical activity in the classrooms.

Following TI-Nspire from development to use, I examined mathematical activity in two ninth grade classrooms where the technology forms an important part of the instructional

context. To trace ways that the mathematical activity was mediated as the teachers and students worked with TI-Nspire, I spent a week observing with a video camera in each class. During the week that I observed classes in the first classroom, mathematical activity focused on algebraic operations such as operating on like and unlike terms, simplifying expressions and solving equations. While working in pairs during class time, the teacher often encouraged students to make use of TI-Nspire by first conjecturing the result of an algebraic operation and then verifying it using the computer algebra system (CAS) on the technology. Following this sequence students working in pairs discussed the solutions to tasks, recorded their conjectures and then finally turned to TI-Nspire for verification. This procedure ensured that the students worked with both written symbolic notation and the technology's representational forms. In addition, it encouraged students to explore the algebraic operations needed to complete a task while being supported by the technology's ability to verify each step they made.

In the second classroom, I observed the class working on several project-style activities, which all involved the use of TI-Nspire. Most of the activities included plotting datasets, determining a line of best fit and then working with the resulting functions to answer questions. The teacher distributed these projects as self-contained digital TI-Nspire document files that were loaded on each student's calculator. Having distributed an activity as a digital document, the teacher often spoke about the advantages of using TI-Nspire to perform tedious tasks. Working with this advantage, the teacher designed his digital documents to have all the elements students would need to complete them. These elements included all instructions and spaces for graphing, calculation, tables and geometric construction. For instance, creating a digital document allowed the teacher to distribute a dataset instead of having students manually enter it

into a table or distribute an identical geometric construction to each student without the need for them to recreate it.

In both classrooms, once students had been given time to work through an activity the teacher most often led a whole-class discussion. Students were encouraged to offer their solutions and the teachers often recorded them or asked students to share their work on the blackboard or on the interactive whiteboard so that they could be referred to and discussed in detail. This practice bridged the mathematical activity the students had been engaged in while working individually or in pairs with TI-Nspire, with the more teacher-directed activity of whole-class discussion. It also provided opportunities for students to translate between the representational forms of the technology and written symbolic notation. For example, on one occasion in the first class students were asked to write an algebraic expression on the blackboard that they had created for homework. The assignment was to create three expressions equivalent to $-18x^2y^3$. This activity offered the students wide latitude to work with algebraic operations while knowing that TI-Nspire could not only check the equivalence of their expressions, but also help them unpack the operations needed to prove that equivalence. As the students shared their created expressions on the blackboard, the teacher typed them into a computer software emulator version of TI-Nspire that allows users to work with an on-screen version of the handheld calculator. Once he was finished, the teacher projected the students' work onto a screen (see Figure 20).

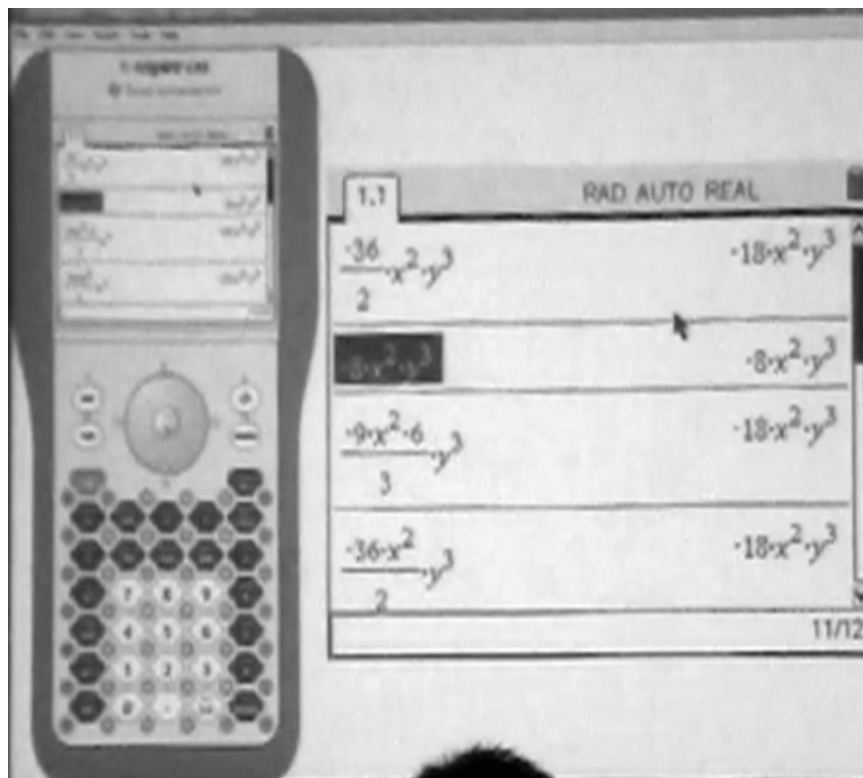


Figure 20: Student created equivalent expressions projected using TI-Nspire software

By projecting onto a screen, the teacher was able to use TI-Nspire to verify the equivalence of the students' expressions in real time. This allowed the students to compare each other's expressions in the same representational form in which they had created their own and discuss the ways the technology determined equivalence based on their own experiences of working with it. As was the case in the other classroom, during whole-class discussion of activities, TI-Nspire often served as a means of checking calculations and verifying mathematical conjectures that was similar to its role when students worked individually or in groups. Frequently while taking up an activity, when students gave differing or problematic answers, the teachers would ask the class to try the operation on TI-Nspire instead of directly giving an answer. For example, after an activity in the first classroom that asked students to simplify a series of binomials, several students disagreed about the operations that could legally be performed on $(6y^3)(-3x^2)$. Instead

of directly resolving the disagreement by reminding the students about the rules of working with coefficients and variables, the teacher deconstructed the expression by asking the class to put the terms into TI-Nspire to see how it would interpret them:

Teacher: Do me a favour, put six y cubed into your TI-Nspire. What does it give you back?

Student: It gave me 6 times y cubed

Teacher: Oh OK. So it dumps a little times symbol there eh? Now put negative three x squared into your calculator and what does it [do]?

Student: Negative three times x squared

Teacher: Interesting. So even though, and this [Pointing to $(-3x^2)$ on the blackboard] was really bothering, who was bothered by the fact that this was a term and we couldn't split off the coefficient?

Student: Kevin

Teacher: Kevin. It's almost forcing you to think of this as a term right with the brackets, negative $3x$ squared, that it somehow belongs together.

When TI-Nspire interpreted $(6y^3)(-3x^2)$, it represented it as $(6 \cdot y^3)(-3 \cdot x^2)$, making the multiplication relationships between coefficients and variables explicit, where as before they had

been implied. Discussion of such instances where differences between the ways the technology uses symbolic notation to represent expressions and ways the same expressions are most often represented in written work was a key feature of the mathematical activity in the classrooms during individual work, group work and whole-class discussion. The technology challenged students to translate between representations, while providing a means of quickly checking calculations, verifying conjectures and unpacking mathematical operations.

In addition to acting as a means of unpacking mathematical operations, TI-Nspire also acted in the observed classrooms to reduce the burden of doing calculations and creating representations. The teachers supported this role by highlighting ways the technology could perform tedious tasks. For example, during one observed session the teacher in the second classroom demonstrated working with TI-Nspire to create a table of values to represent the cost of holding a banquet relative to attendance. The teacher manually calculated the cost for three different attendance levels based on the rules set out in the task that dictated a banquet would always cost \$1000 plus \$25 per person. Having calculated these three values, the teacher decided to show the class how TI-Nspire could be used to speed up the process, saying:

That starts to become a little bit repetitive because we're doing the same calculation over and over again and that really doesn't take advantage of the technology. Yes, it will do the math for us, but the fact that we have this here, it should be able to save us from having to retype all of those calculations. (Teacher Two)

The teacher then directed the class in a discussion that resulted in a formula that represented the banquet cost based on the rules set out in the task. He then entered this formula into one of the

columns in the table and TI-Nspire computed the cost for all the remaining attendance levels required by the task. In this example, working with the mathematical environment of TI-Nspire, the teacher offloaded calculation tasks to the technology and suggested that his students do the same. This role for TI-Nspire is linked to its role as a means of checking calculations. Situated by the teachers as a means of offloading calculation and representation tasks, or as a means of checking calculations and verifying conjectures, in both cases the technology supports learners in exploring and unpacking mathematical concepts.

Student mathematical activity.

To examine ensembles of TI-Nspire and students in more detail than was possible during classroom observation, I organised activity sessions with a pair of students from each observed class. The activity I asked the students to complete four tasks that involved working with a series of linear and non-linear patterns. The first task asked the students to represent the next step in each of the three patterns. Reflecting the many ways the activity could be approached, the student pairs began with distinctly different methods. One pair started by working physically with the extra linking-blocks to expand the existing shapes. The other pair began by determining a formula to represent each rate of growth. These students approached the task by first counting the number of blocks in each step and working by trial and error to find formulae to represent the change between steps. They proceeded in this fashion to find a formula to represent the change in number of blocks for each of the three patterns and used these formulas to answer questions about the linearity of the patterns and as proof for their assertions. Throughout this process, the students worked with TI-Nspire to check calculations and unpack aspects of the formulae as they were created.

For the second task, the students were asked to show which of the three patterns grew in a linear fashion, the student pair who had been working with TI-Nspire to find formulae continued this approach using their formulae as evidence of linearity by asserting that it had the same $y = mx + b$ form as a standard linear equation. The other pair who had chosen to work with the blocks to solve the first task now turned to the technology. Their approach was to create tables in the spreadsheet environment of TI-Nspire so that they could then use the technology to graph the relationships for each pattern. This involved counting the number of linking-blocks used for each step and entering the values in tables. From the tables, the students generated graphs that plotted step number in relation to the number of blocks required. They then examined the graphs as they discussed whether or not the relationship for a pattern was linear and used them as evidence to support their assertions. Working in this fashion, the students determined that the relationship for two of the patterns was linear and that for the third pattern the relationship was non-linear. In this ensemble, TI-Nspire served as a means of verifying conjectures but this time also acted as the primary location of mathematical activity.

The third task of the activity asked the students to determine the number of blocks required for the 50th step in one of the patterns. To solve this problem both pairs chose to work with TI-Nspire by building on the ways they had used the technology for the first two tasks. One pair used the formulae they had created to solve the first task while the other pair used the tables they had developed for the second task. For the first pair who had found the formula $n = 4s + 4$ to represent the number of blocks needed for each step in the pattern, finding the number needed for the 50th step only required substituting in the value 50. They verified their formula one more time by testing its results against the number of blocks used in the first four steps and then used it to find a solution. Similarly working with TI-Nspire to build on their existing solutions to

develop a formula to represent the number of blocks required for each step in the pattern, the other pair turned to the table and graph they had created with the technology to solve the second task. The pair used the computer algebra system (CAS) features of TI-Nspire to type a formula directly into the table they had created to test if it would produce the same number of blocks for the four steps they had manually counted earlier. With this successful verification of the formula, they used it to determine the number of blocks needed for the fiftieth step and referred to the table and formula as proof of their solution:

Student Three: I got it, I got it. Times 4 plus 1, times 4 plus 1, times 4 plus 1.

Student Four: Well, do this one [points at the diagram of the third step].

Student Three: 50 then you do... [types a formula into TI-Nspire]

Student Four: No, times.

Student Three: 50?

Student Four: No this. OK wait check this one. Times-, I need the TI. [Picks up TI-Nspire and types while speaking] times 4 equals 2.

Student Three: Oh my God!

Student Four: Hmm I see. [Reading TI-Nspire screen] times 4 plus 1. It works.

Student Three: Ahhh. I know, I know, here's an easy way. [Takes TI-Nspire, closes an open window and types $blocks = step \times 4 + 1$ into an empty column in the table] close, equals, step, step times 4 plus 1.

Student Four: 50 times 4 is 200 plus 1, 201!

To complete this task, these students again worked directly on TI-Nspire using it as their primary workspace while, by contrast, the other pair chose to work with paper and pencil. Despite this difference, TI-Nspire continued to act as a means of verifying conjectures in both ensembles.

For the fourth task, the student pairs were asked to compare and contrast two of the three patterns. Based on their work for the earlier tasks, both pairs identified that the number of blocks required to build each step in the two patterns grew in a linear fashion. One pair worked with the tables and graphs they had created earlier, while the other worked with the formulae they had used to represent each pattern. Despite working with different representational forms, both pairs again primarily worked with TI-Nspire to verify their mathematical conjectures. For the pair working with formulae, the technology served as a way to check calculations while they constructed proof for their assertions. For the pair working with tables and graphs, the technology served as the workspace in which they directly compared the values in the tables and the graphs, referring to them as proof for their assertions. Examining the tables and graphs they had created with TI-Nspire, they observed that the change in number of blocks needed to create the steps for the two patterns increased at a constant rate but started from different numbers. They noted that each pattern started with a shape requiring a different number of blocks resulting in every step in one pattern requiring an odd number and the other always requiring an even

number. While the other pair of students chose to work with the formulae they had created earlier to compare the two patterns, they arrived at largely the same conclusions with TI-Nspire again acting primarily as a way of verifying conjectures and as support for assertions in both ensembles.

Discussion and Conclusion

Handheld digital educational technologies such as TI-Nspire have a distinct influence on the mathematical activity of the classrooms they are used in, but began life outside schools with technology developers who have specific visions for them. Following the premise that it is important to understand both the history of a technology and its *in situ* use in learning situations, this study has examined the visions of a technology's developers and then followed that technology into classrooms where teachers and students negotiated it for their contexts. By following the technology from its development to its use, the findings shed light on the evolving ways that mathematical activity is mediated as developers, teachers and students interact with educational technology.

Developer participants described a changing vision of the mathematical activity that TI-Nspire is intended to support. This vision was inscribed in the features of the technology and was initially focused on encouraging open and exploratory mathematical activity with less emphasis on calculation features than previous graphing calculators. Later, in response to feedback on early releases of TI-Nspire they expanded their vision to support a more calculation-oriented role and more directed styles of mathematical activity. This finding highlights some of the challenges of producing educational technology. The developers' envisaged future mathematical activity in

classrooms but ultimately could only provide features to support the ways teachers and students themselves choose to use TI-Nspire. As findings from studies of the development of other types of technology also indicate, technologies like TI-Nspire continue to emerge through interaction with users and are not defined by their developers alone (Akrich, 1992, 1995; Bijker, 1997; Latour, 1996a; Lindsay, 2005; Suchman, 2006).

Reflecting the role users have in shaping technologies through use, the teacher and student participants engaged with TI-Nspire for mathematical activity in a variety of ways. The teachers situated the technology as way of reducing the burden of performing calculations and creating representations, and as way of checking calculations, verifying conjectures and supporting assertions. The students approached the mathematical tasks I asked them to complete by sometimes working with TI-Nspire as their primary mathematical environment and at other times as a calculation tool. In both cases, however, similar to the way their teachers had situated the technology, they repeatedly worked with it to verify conjectures and as evidence for assertions. This pattern of use is similar to patterns observed by a number of researchers who have examined computer algebra systems and dynamic geometry software (Drijvers & Kieran, 2006; Hadas, Hershkowitz, & Schwarz, 2000).

In addition, as other researchers have found (Drijvers & Trouche, 2008; Drijvers *et al.*, 2010), the findings of this study suggest that the way teachers situate technologies for students is an important aspect of how mathematical activity with those technologies unfolds in classrooms. Adding to this understanding, however, the findings of this study illuminate the relationship between the ways teachers situate technology, the mathematical activity in their classrooms, and the visions developers have for mathematical activity with their creations. While the developers envisaged the exploratory environment and calculation tool aspects of TI-Nspire as related but

distinct, the teachers situated both aspects in open exploratory and in more directed mathematical activity. For instance, the teachers often only encouraged their students to use the technology to perform calculations while they worked on open-ended activities that promoted exploration. In these cases, the explicitly exploration-oriented features of the technology's environment of interlinked mathematical representations were not being used. While the technology may have had a less central role in the activity of such situations than it would have if more of its exploration-oriented mathematical environment had been involved, the ensemble of student and technology was still engaged in mathematical exploration. This suggests that the pedagogical conceptions of teachers have a profound influence on the ways they integrate technology into their practices, but also suggests that the instantiation of these conceptions is mediated by technologies themselves as teachers translate them to their own contexts

Similarly during the activity sessions, the students worked with a wide variety of the features of TI-Nspire and these features mediated the approaches they took to completing the tasks. In addition, the approaches the student pairs took were well aligned with the ways TI-Nspire was situated by their teachers. The pair who worked primarily with the technology to check calculations and verify conjectures while they created formulae to represent each linking-block pattern attended the class where I observed the teacher most often positioning TI-Nspire as a partner in paper-and-pencil focused mathematical activity. The pair that worked with TI-Nspire to create tables and graphs attended the class where the teacher tended to assign tasks as self-contained digital documents and emphasised offloading tedious calculation and representation tasks to the device. Despite these different approaches to mathematical activity with TI-Nspire, both student pairs engaged in the exploration of mathematical concepts throughout the activity sessions. This again highlights the profound role that teachers have in situating technologies for

their students but also suggests that similar to the vision of mathematical activity developers have, the ways teachers situate technologies does not directly dictate the ways students work with them.

The findings of this study show that the vision developers had for TI-Nspire mediated teacher and student practices, and the ways teachers positioned the technology mediated student practices even outside the classroom. By offering a genetic analysis of an educational technology, the findings suggest that while this mediation does not dictate mathematical activity with a technology, there are important links between the ways developers envisage features supporting mathematical activity, the ways teachers choose to situate those features in their classrooms and the ways students choose to work with them.

Chapter 10. Discussion and Conclusion

I began this project with the conviction that educational technologies have an important role in learning and that their design is neither insignificant nor able to dictate human activity. My own professional experience as a designer of technologies suggested that without examining how and with what purpose an educational technology is created, our understanding of why it is used the ways it is in classrooms is limited. This idea was further strengthened by reading the genetic analysis work of Vygotsky (1978, 1986) which suggests that to understand a learning situation it is not enough to examine it *in situ* and that we must also examine the history from which it emerges, or in the case of educational technologies, develops. Looking for ways to conceptualize the relationship between the development and use of technology, I came across the work of several researchers in the field of Science and Technology Studies (Akrich, 1992; Bijker, 1997; Latour, 2007; Pinch & Bijker, 1984; Suchman, 2006). Their work and Actor-Network theory (ANT) in particular offered me a way of reconsidering the relationships between humans and technology and between design and use that avoids essentialist positions and foregrounds the socially and culturally situated nature of these relationships. This research helped me understand the relationship between humans and technology but my interest in technology and learning required that I find ways to understand that relationship as well. In my reading in the field of mathematics education, I found Shaffer and Clinton's (2006) approach that combines elements of ANT with Activity-Theory. Following their suggestion, I turned to Activity-Theory to help me conceptualize learning with technology and found the notion that all cognition including learning is mediated by cultural tools to be particularly helpful.

While Shaffer and Clinton's (2006) approach of drawing on elements of ANT and Activity-Theory primarily focuses on the ANT position that both humans and non-humans are actors in social networks, I found that ANT and other research in the field of Science and Technology Studies has much more to offer an investigation into educational technology development and use. Drawing on the research of Akrich (1995), Bijker, 1997 and Suchman (2007), I found theoretical tools to help me holistically understand the development and use of technology and its relationships with humans. This understanding combined with an Activity-Theoretic conception of tool-mediated learning oriented my view of the development and use of educational technology and of mathematical learning. Working from this perspective, the findings of this study offer a genetic analysis of the development and use of one technology that illuminates the ways educational technologies are co-constructed by developers, teachers and students, and the ways this co-construction mediates and is mediated by mathematical activity. These findings enrich *in situ* examinations of learning with technology by providing a historical perspective on how technologies come to be used the ways they are in classrooms.

Across the findings presented in the three articles that report on this project, the active role teachers and students play in shaping educational technology and the influence that shaping has on mathematical activity in classrooms is the key theme. When I began this project, I expected to find some evidence of teachers and students adapting TI-Nspire to their own needs, but I was surprised to find so many formal and informal avenues for their innovative practices to shape the technology. As described in the first article presented, I found that the development of TI-Nspire is an on-going co-constructive process with its configuration by developers and reconfiguration by teachers and students forming a single emergent movement. In fact, while I refer to the development process as configuration, this too is a form of reconfiguration as

developers build on the ideas of existing technologies. Building on earlier technologies, TI-Nspire emerged from a participatory process that involved members of the mathematics education community throughout. Then, it was reconfigured as mathematics teachers and students translated it in innovative ways that then fed into the participatory configuration of new versions of the technology.

Focusing on the co-construction of TI-Nspire in classrooms in the second article, I found that as teachers and students reconfigured the technology a wide variety of relationships among other human and material actors were influenced. These findings indicate that sociotechnical networks in classrooms using technology operate as a complex interconnected whole and show as Drijvers *et al.* (2010) suggest, that the didactical configuration of technologies in mathematics classrooms has a profound effect on the mathematical practices within them but also suggest that this is far from a one-way phenomenon. They indicate that each pattern of sociotechnical relations in a classroom mediates the others and that with the introduction of a technology such as TI-Nspire, adaptations within the network are not limited to local interactions between teacher, students and technology, but rather spread throughout the human and material relations.

In particular, I found that the relationships between teachers and TI-Nspire have wide reaching influence on the mathematical activity in classrooms and, as reported in the first article, comprise an especially important aspect of the co-construction process. Other researchers investigating the use of technology in mathematics classrooms (Drijvers & Trouche, 2008; Drijvers *et al.*, 2010) have also highlighted the important role teachers play in situating technology for their students, but the findings of this study strengthen this notion by indicating that the ways teachers configure technology influences the mathematical activity beyond their classrooms and whether their students are using the technology or not. The findings presented in

the third article show that the ways teachers situate a technology in their classrooms are part of a co-constructive process that involves the visions of mathematical activity inscribed by developers in a technology and the mathematical activity students engage in. I found that while the developers in this study envisaged the exploratory environment and calculation tool aspects of TI-Nspire as related but distinct, the teachers situated both aspects in open exploratory and in more directed mathematical activity. Similarly, I found that the students worked with a wide variety of the features of TI-Nspire, such as computer algebra, spreadsheets and graphing, and all were reconfigured for the exploration of mathematical concepts, regardless of whether they were designed as exploration or calculation features. This illustrates that while the vision developers had for TI-Nspire mediated teacher and student practices, and the ways teachers reconfigured and positioned the technology mediated student practices even outside their classrooms, neither mediation dictated mathematical activity with the technology. It does suggest, however, that while the technology is constantly reconfigured through use, an important link between the ways developers envisage features supporting mathematical activity, the ways teachers choose to situate those features in their classrooms and the ways students choose to work with them exists.

With its reflexive nature, the configuration and reconfiguration I identify as part of the TI-Nspire co-construction process is similar to processes associated with other technologies that have been investigated by researchers in the field of Science and Technology Studies, such as Bijker's (1997) study of the evolution of bicycles. However, TI-Nspire is an educational technology and, as such, has been developed with the specific purpose of supporting learning. This purpose renders the relationships among TI-Nspire, developers and users different to those implicated with other types of technology that only require users to learn about their own operation to achieve the goals of developers. The configuration and reconfiguration process by

which TI-Nspire is co-constructed is particularly significant as it mediates the ways the technology is used in classrooms, the mathematical activity it participates in and, ultimately, learning.

Implications of This Study

Within the field of educational research, relatively little attention has been paid to understanding the processes by which technologies are developed and the influence these processes have on the mathematical activity in classrooms. Those approaches that do exist for understanding the relationship between technology and human action often take essentialist positions, either over-emphasising a technology's role or largely ignoring it (Miettinen, 1999; Shaffer & Clinton, 2006; Suchman, 2006). The approach I have taken in this study offers a balanced alternative that allows for the influence the design of a technology may have, without suggesting that it can prescribe human activity. By drawing on ANT and conceptualizing learning as activity mediated by cultural tools, this study illustrates a way of unpacking the influence technologies can have in mathematics classrooms and how examining the development of an educational technology can shed light on the ways it is used. The approach has implications for the study of technology's role in learning. It shows that the local interactions between technology and learner are part of complex networks of activity that reach far beyond the classroom. This opens a wide variety of avenues of investigation and suggests that to unpack the richness of technological mediation in learning situations, researchers must expand the focus of their studies to include the actors that are implicated by the seemingly simple use of a technology.

In addition, this study also has implications for the practice of developing technologies for mathematical learning. The highly interrelated nature of the development and use of educational technology illustrated in this study shows the need for technology developers to invite teachers and students to participate in the design of new tools. To be effective, this participation must be on-going and involve more than just collecting input while the requirements for a project are defined and testing prototypes prior to release. Instead the findings of this study indicate that development benefits from the input of teachers and students throughout. It has been my experience that, perhaps due to the culture of education, teachers are often particularly attentive to their own practices and may be able to offer developers insights into detailed aspects of a technology's design well before it is committed to physical or software form.

Beyond the initial configuration of a technology, the findings of this study indicate that teachers and students constantly reconfigure the technologies they use and that these reconfigurations change the ways tools mediate learning. While the on-going relationship among TI-Nspire developers, teachers and students allow for reconfigurations to feed back into the configuration of new versions, based on the findings of this study and studies of other technologies (Bijker, 1997; Lindsay, 2005) it is reasonable to expect that even if there were no direct feedback process user reconfigurations would still occur. This has significant implications for technology developers who design their creations with specific educational intentions. The findings of this study suggest that developers should recognize that they cannot dictate the learning that goes on with their technologies, but can support teachers and students in creating rich learning environments. To serve teachers and students best, they should be responsive to reconfigurations and support them rather than restricting them. To illustrate this suggestion, I

draw an analogy between the design of an educational technology and the design of a pathway through a park. In parks, landscape architects often design paths with beautiful curves that follow the lines of ponds and flowerbeds. People then visit the park and some chose to ignore the curving pathways and instead walk directly across the grass. Over time, the grass is worn away and new unofficial pathways appear. The landscape architect now has many options, including putting a fence around the pathways to restrict visitors to the official routes, ignoring the problem leaving the unsightly unofficial routes, and formalizing the new routes as part of the network of pathways in the park. In much the same way, developers of educational technologies can choose to restrict or ignore the reconfigurations of teachers and students, or they can incorporate them and support these new ways of working. The findings of this study suggest that including new ways of working and developing technologies to support teacher and student reconfigurations is important to creating useful tools for learning. While the landscape architect may frustrate park visitors by limiting the ways they can use a park, in the case of educational technology it is ways of learning that may be constrained by restrictive designs.

The findings of this study also have implications for the practice of education. Specifically, they highlight the profound role teachers have in situating technologies for their students. They show that the way a teacher situates a technology within the classroom has a distinct influence on their students' mathematical activity with that technology, even outside class-time. They also show that both teachers and students are influenced by the visions of mathematical activity inscribed by developers in a technology, but that this mediation has a complex relationship with the ways teachers and students reconfigure it. The findings suggest that the vision of mathematical activity inscribed by developers is translated by teachers who reconfigure it within their instructional practices and then both are translated by students as they

use the technology as part of their mathematical activity. This complex process indicates that just as developers should support the reconfigurations of users, teachers should support the reconfigurations of their students. Instead of being situated in a restrictive way as a tool with certain specific uses, the findings of this study indicate that students may be better served if they are supported in making technologies their own and finding innovative ways to use them. In addition, this study suggests that teachers and students feel empowered to explore working with technologies in innovative and even unorthodox ways. The findings show that there are ways for such innovations to feed back to developers and that teacher and student exploration can be an important part of how educational technologies are improved.

Future Directions

This study points to a number of areas for further research. With greater access to developers and consultants from the earliest stages of the development process, more detailed investigation of their processes and choices could be made. Using a similar approach to the one taken in this study, attention to detailed aspects of the relationship between development decisions and activity in classrooms, while recognizing the important roles that teachers and students play, would help to unpack the ways specific technological features mediate learning. Then, following the introduction of a new technology into a school - from the teachers' initial contact with it, through professional development workshops, planning lessons and finally in-class use - would also help build understanding of the ways specific aspects of technologies mediate learning. Such a long-term examination that follows a technology in detail from genesis to classroom use would expand the understanding of the co-constructive nature of educational technology development highlighted in this study.

In addition, particularly by taking an ANT approach that required me to attend to the interactions between humans and non-humans in the classrooms while consciously trying to limit *a priori* judgements about their roles and agency, I found a number of relationships that I believe deserve further investigation. One such relationship is the connection between private and public locations of mathematical activity. During the course of this study, I was struck by the relationship between the activity students engage in individually and activity shared by the whole class by means of a blackboard or interactive whiteboard. I found that the materials that participate in this relationship have a distinct role in mediating mathematical activity and that the interaction between students and materials in one location had a particular influence on the other and *vice versa*. In the case of this study, the materials were most often paper and pencil and TI-Nspire for private activity, and blackboard and interactive whiteboard for public activity. The complexity of the relationships among these materials, students and teachers as they engaged in mathematical activity that I found in this study indicates that more focused research with other materials and in other settings would help to further our understanding of this important aspect of classroom practice.

Another relationship that is highlighted by the findings of this study is the relationship between the calculation features of a technology like TI-Nspire and exploratory mathematical activity. I found that on numerous occasions the teachers situated the calculation features of TI-Nspire within exploration-oriented mathematical activities and the students used those features while exploring mathematical concepts. Many technologies sold for use in mathematics classrooms, however, are marketed as *either* calculation tools or exploration tools. The marketing and development of calculation tools may not acknowledge the possibility that they can be a useful part of exploratory mathematical activity, leaving this style of activity

exclusively for what are framed as exploration tools. Further research on the role of calculation tools would expand on the findings of this study that shows teachers and students actually do use them as part of exploratory activity. This research might help to disrupt the unnecessary dichotomy between calculation and exploration tools.

Conclusion

Together, the findings presented in the three articles of this study illuminate the complex relationships between the development and use of TI-Nspire, among humans, materials and the technology in classrooms, and between TI-Nspire and mathematical activity. They suggest that educational technologies do not become part of the instructional context in classrooms through a linear process of development and use, but rather continuously emerge through a reflexive process of co-construction. They suggest that the introduction of new technology has wide ranging effects on the relationships between the human and material actors in classroom networks of activity. They further suggest that technologies for mathematical learning are neither neutral objects waiting to be made significant through mathematical activity nor do they dictate the course of that activity. The findings of this study illustrate how the development and use of educational technologies such as TI-Nspire are not separate processes but are instead an interrelated, reflexive and on-going process that mediates and is mediated by mathematical activity throughout.

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Appendix A: Interview Guides

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Developer Interview Guide

This guide is intended for use in interviews of between 1-2 hours in length. It contains questions on general themes that will be addressed through the course of the interview, but additional questions will likely emerge in relation to the responses of participants.

The development process:

- Could you please describe your role in the development of TI-Nspire?
- How would you characterise the TI-Nspire development process? Please elaborate on that process?
- How do you envisage teachers and students using TI-Nspire? Please describe how you imagine teachers incorporating the tool into their lessons and how students work with it.
- What role have teachers and students had in the development of TI-Nspire? Do they continue to have a role?

Mathematical thinking and technology for mathematical learning:

- Could you please describe your views on the role of technology in mathematics classes?
What are the benefits to your mind of tools like TI-Nspire?
- How do you think that your own mathematical thinking or the thinking of other developers shaped the development of TI-Nspire?
- Please describe how you think that TI-Nspire shapes the mathematical thinking of those that use it?

Initial Teacher Interview Guide

This guide is intended for use in interviews of between 1-2 hours in length. It contains questions on general themes that will be addressed through the course of the interview, but additional questions will likely emerge in relation to the responses of participants.

The role of teachers in co-constructing technology for mathematics education:

- Could you please describe the ways that you incorporate TI-Nspire into your lessons?
- How do you prepare lessons that involve TI-Nspire? Please describe your process.
- How did you learn to use TI-Nspire? Please describe any formal or informal training you have participated in.
- How much experience have you had using and teaching with other graphing calculators and computer based tools such as CAS and dynamic geometry environments? How do you think these experiences have influenced your approach to using TI-Nspire?

Mathematical thinking and technology for mathematical learning:

- Could you please describe your views on the role of technology in mathematics classes?
- Do you think that using TI-Nspire has shaped the ways you think mathematically? If so how and have you seen a similar effect in your students?
- When you plan a lesson that uses TI-Nspire how do you balance the need for technical skills to use the tool and the mathematical thinking you would like your students to engage in?

After-class Debriefing Interview Guide

These questions are intended to serve as a general guide for short (approximately 30 minute) debriefing conversations that will follow classroom observation sessions. It contains questions on general themes that will be addressed, but additional questions will likely emerge in relation to specific classroom observations and from the responses of participants.

- Could you describe your goals for how the TI-Nspire would be used in this last lesson?
Was the tool useful in the way you had expected?
- Did the students use the TI-Nspire in the ways you expected them to or were there any surprises? Could you describe any unintended ways the tool was used?
- In this last lesson how did you balance the need for technical skills to use the TI-Nspire with the mathematical thinking goals you had for your students?

Mathematical Activity Debriefing Interview Guide

These questions are intended to serve as a guide for short (approximately 15 minute) debriefing conversations at the end of mathematical activity sessions, in which pairs of students are asked to work on mathematical tasks that involve the use of TI-Nspire. It contains questions on general themes, but additional questions will likely emerge in relation to the specifics of the particular session and from the responses of participants.

- Could you talk me through how you used the TI-Nspire to work on the problems? How was it useful to you?
- Did you discover any new ways to use the TI-Nspire or had you already tried the ways you used it before?
- Do you think the TI-Nspire influenced the ways you worked on the problems? Could you describe that influence?

Appendix B: Letters of Permission

University of Ottawa Research Ethics Board Approval.....198

Texas Instruments Letter of Support.....200

University of Ottawa Research Ethics Board Approval

File Number: 03-09-04

Date (mm/dd/yyyy): 04/09/2009



Université d'Ottawa **University of Ottawa**
 Service de subventions de recherche et déontologie Research Grants and Ethics Services

Ethics Approval Notice Social Science and Humanities REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

| <u>First Name</u> | <u>Last Name</u> | <u>Affiliation</u> | <u>Role</u> |
|-------------------|------------------|-----------------------|--------------------|
| Barbara | Graves | Education / Education | Supervisor |
| Thomas | Hillman | Education / Education | Student Researcher |

File Number: 03-09-04

Type of Project: PhD Thesis

Title: Redesign for Learning: Reconceptualising the Development and Use of Technology for Mathematics Education

| Approval Date (mm/dd/yyyy) | Expiry Date (mm/dd/yyyy) | Approval Type |
|-----------------------------------|---------------------------------|----------------------|
| 04/09/2009 | 04/08/2010 | Ia |

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:

N/A

File Number: 03-09-04



Date (mm/dd/yyyy): 04/09/2009

Université d'Ottawa **University of Ottawa**
Service de subventions de recherche et déontologie Research Grants and Ethics Services

This is to confirm that the University of Ottawa Research Ethics Board identified above, which operates in accordance with the Tri-Council Policy Statement and other applicable laws and regulations in Ontario, has examined and approved the application for ethical approval for the above named research project as of the Ethics Approval Date indicated for the period above and subject to the conditions listed the section above entitled "Special Conditions / Comments".

During the course of the study the protocol may not be modified without prior written approval from the REB except when necessary to remove subjects from immediate endangerment or when the modification(s) pertain to only administrative or logistical components of the study (e.g. change of telephone number). Investigators must also promptly alert the REB of any changes which increase the risk to participant(s), any changes which considerably affect the conduct of the project, all unanticipated and harmful events that occur, and new information that may negatively affect the conduct of the project and safety of the participant(s). Modifications to the project, information/consent documentation, and/or recruitment documentation, should be submitted to this office for approval using the "Modification to research project" form available at:
http://www.rges.uottawa.ca/ethics/application_dwn.asp

Please submit an annual status report to the Protocol Officer 4 weeks before the above-referenced expiry date to either close the file or request a renewal of ethics approval. This document can be found at:
http://www.rges.uottawa.ca/ethics/application_dwn.asp

If you have any questions, please do not hesitate to contact the Ethics Office at extension 5841 or by e-mail at: ethics@uOttawa.ca.

Pierre Ndoumaï
Protocol Officer for Ethics in Research
For Dr Daniel Lazarec. Chair of the Health Sciences and Sciences REB

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Texas Instruments Letter of Support



Your Passion. Our Technology. Student Success.™

April 2, 2009

Thomas Hillman

Dear Mr. Hillman:

Congratulations on your research project! Texas Instruments is pleased to be of assistance.

The Education Technology Group of Texas Instruments places research at the center of its strategic vision. Consequently, our policy is to support and collaborate with research efforts relevant to our strategy. This may include information sharing, such as making our employees available for interviews on non-proprietary topics. We ask only that we receive access to the completed research.

Best regards,

Rob Foshay