Systemic Shifts in Instructional Technology: Findings of a Comparative Case Study of Two University Mathematics Departments

By Daniel H Jarvis[1], Zsolt Lavicza[2] and Chantal Buteau[3]

[1]Schulich School of Education, Nipissing University, 100 College Dr., North Bay, Ontario CANADA P1B 8L7
danj@nipissingu.ca

[2]Faculty of Education, University of Cambridge, Cambridge, UK CB2 8PQ
zl221@cam.ac.uk

[3]Department of Mathematics and Statistics, Brock University, St.Catharines, Ontario CANADA L2S 3A1
cbuteau@brocku.ca

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This paper reports on the findings of an international case study in which researchers examined two mathematics departments (Canada/UK) in which the sustained use of technology was strategically established in a mathematics degree program. This case study forms part of a larger research initiative which involved an extensive literature review (Marshall, Jarvis, Lavicza and Buteau, 2012) and a national survey of Canadian Mathematicians (Buteau, Jarvis and Lavicza, 2014). Findings from the case study indicate that sustained implementation at the departmental level requires a unique combination of key factors such as: a dedicated core group led by a committed advocate in a position of influence/power; a strong and shared incentive for change; strategic hiring processes; an administration which supports creative pedagogical reform and well-considered risk-taking; and, a continuous and determined revisiting of the original vision and purpose. Significant challenges to implementation and sustained program development, with specific examples, are also discussed.

1 INTRODUCTION

A growing number of international studies have shown that Computer Algebra Systems (CAS-based) instruction has the potential to positively affect the teaching and learning of mathematics at various levels of the education system, even though this has not been widely realised in schools and in higher education (Artigue, 2002; Bossé and Nandakumar, 2004; Kendal and Stacey, 2002; Lavicza, 2006; Keynes and Olson, 2001; Meagher, 2001; Pierce and Stacey, 2004;). In contrast to the growing body of research focusing on CAS technology use at the secondary school level (Kieran and Drijvers, 2006), there is a definite lack of parallel research at the post-secondary, or tertiary level (Martinovic, Muller and Buteau, 2013; Stewart, Thomas and Hannah, 2005). Furthermore, although substantial research has been conducted in the area of professional development for teachers (Darling-Hammond and McLaughlin, 1995; Guskey, 2002), as well as that relating specifically to the development of teachers of mathematics at the elementary and secondary school levels (Even and Ball, 2008; Jarvis and Franks, 2011; Loucks-Horsley and Matsumoto, 1999), relatively little has been published in the area of research surrounding instructional supports for university mathematics teaching.

School level studies suggest that beyond the availability of technology, teachers' beliefs and cultural influences are key factors in technology integration into mathematics teaching and learning. Lavicza's comprehensive study (2008a, b) featured an on-line survey of 1100 mathematicians as well as interviews with 22 mathematicians in three countries, namely, Hungary, United Kingdom, and United States, which examined mathematicians' beliefs/conceptions regarding CAS and its instructional potential. Findings showed some similarities, but also notable differences, between university- and school-level research findings (e.g., use of CAS in one's research being the greatest factor influencing the use of CAS in one's teaching).

Building on the findings of Lavicza's international work (2008a, b), the team of Jarvis, Lavicza, and Buteau planned a three-year, mixed-methods research study to examine individual and systemic CAS usage in undergraduate mathematics instruction. This research involved an extensive literature review, a national survey of Canadian mathematicians, a multi-site case study of two technology-enhanced mathematics departments (Canada and the United Kingdom), and the hosting of two national workshops at premier Canadian research institutes in both Quebec (in French) and Ontario (in English) (Buteau, Jarvis, and Lavicza, 2011). The goals of our research study included: documenting existing undergraduate mathematics teaching practices involving the use of CAS and other technologies; raising the amount of attention paid to tertiary mathematics teaching from both research and pragmatics perspectives; and elaborating on specific issues relating to, and strategies for, systemic, sustained integration of technology in undergraduate mathematics departments.

While the use of instructional technology for mathematics teaching and learning at the university level is often the prerogative of an enthusiastic individual instructor (see for example, Rosenzweig, 2007), the case of departmental or system-wide adoption appears to be much more rare, and complicated (Buteau, Jarvis and Lavicza, 2014). A thorough CAS-related literature review of journals and conference proceedings was conducted as part of our research study (Buteau, Lavicza, Jarvis and Marshall, 2009;

Buteau, Jarvis, Marshall and Lavicza, 2010). In these publications, we have already shown that faculty within mathematics departments believe that CAS and other software use in mathematics teaching has numerous benefits such as multiple representations in mathematical modeling, time-saving and unprecedented calculation power, the ability to tackle more authentic, "messier" real-world problems, and deeper student understanding of concepts (see for example, Sarvari, 2005; Schurrer and Mitchell, 1994; Weida, 1996). We have also been careful to document the expressed criticisms of CAS use such as the steep learning curve required for faculty/student use, the potential "blackbox" effect on student learning, the high cost of software, and issues of limited access to labs/laptops. Further, we have noted that university faculty members face formidable obstacles while attempting to persuade colleagues and administrators about the importance and perceived significance of technology-enhanced mathematics learning (Buteau, Jarvis and Lavicza, 2011).

Noss (1999) conducted a related research study in two UK university mathematics departments that had both received funding to implement a specific technology software (*Mathematica*) in their respective undergraduate mathematics programs. In his conclusion, Noss described how that the analysis of the two departments - that had approached the integration of the technology from very different epistemological and pedagogical starting points - lead to more universal insights regarding the shape and purpose of technology integration, as it related to teacher perceptions:

> [T]he opportunity to examine two different design decisions and their outcomes actually revealed fundamental differences in the way mathematical knowledge was conceived. This, perhaps is the main contribution of new technology in mathematical teaching and learning: it provides us with an opportunity to reassess not simply how we teach, or even how students learn, but what it is that we teach them and why. (p. 388)

These insights were helpful as we prepared to conduct our two case studies insofar as we were mindful of the fact that departmental change (or resistance to it) is closely linked to individual teacher beliefs, and that these beliefs are indeed predicated on the way in which instructors view the essence of mathematics content, the goals of mathematics teaching, and the role of instructional technology as it relates to these deeply-espoused beliefs. In other words, we were not only trying to tell the two departmental stories in terms of content, structure, and chronology, but rather we were also attempting to capture, through the wording of the interview questions and probes, the more nuanced realities of negotiated teacher beliefs and shared sensibilities regarding technology implementation that hindered or allowed for departmental reform.

In the Department of Mathematical Sciences at the United States Military Academy faculty has been incorporating technology in their mathematics instruction since the mid-1980s. Heidenberg and Huber (2006) claim that technology has "made a dramatic impact on both education and the role of the educator. Graphing calculators and computer algebra systems have provided the means for students to quickly and easily visualise the mathematics that once took effort, skill, and valuable classroom time" (p. 103). In their program, all cadets (students) receive laptop computers with a standard suite of software. The curriculum is heavily project-based wherein "students use technology to explore, discover, analyse, and understand the behavior of a mathematical model of a real world phenomenon" (p. 104). Two-day exams are experienced by cadets, with the first day featuring a traditional in-class exam for which students do not have access to technology, and that focuses on basic fundamental skills and concepts; and the second day wherein cadets tackle a rich, authentic (real-world) problem relating to a take-home problem scenario they had received the night before by way of background, and using technologies that were available throughout the term. In approaching our two case study sites, we were indeed looking for this type of fidelity in terms of assessment practices closely aligning with curricular experiences in undergraduate mathematics learning.

Oates (2011) contends that, "The effective integration of technology into the teaching and learning of mathematics remains one of the critical challenges facing contemporary tertiary mathematics" (p. 709). In his recent paper, *Sustaining Integrated Technology in Undergraduate Mathematics*, he reports on the technology implementation occurring at the University of Auckland, proposing a detailed taxonomy for describing and comparing technology use within individual courses and departments that identifies a complex range of factors, summarised under six defining characteristics (i.e., access, assessment, organisational factors, mathematical factors, staff factors, and student factors) of an "integrated technology mathematics curriculum (ITMC)". The survey on which his taxonomy was based drew upon the input of 56 colleagues from international tertiary institutions involved in the teaching of undergraduate mathematics. In conclusion, Oates highlights the urgent need to revisit curricular content and assessment practices in light of technological realities:

> Content and assessment issues were singled out for particular attention here, as they were seen as requiring continued attention for the effective and sustainable integration of technology. With respect to assessment, both pedagogical consistency, and the impact of CAS on examination questions, is seen as particularly significant issues. For content, the findings reported here support the complexity of assessing the values of topics, and support the overall conclusion that a re-examination of the changing pragmatic and epistemic values of specific topics, and the goals of mathematics education, within a rapidly evolving technological environment, remains a pressing challenge for undergraduate mathematics educators. (p. 720)

The ability to change curricular content and assessment practices, as a "negotiated piece" of the reform process, requires a long-term commitment by faculty within the mathematics department, as noted by Buteau and Muller (2013):

> The situations in which mathematics departments find themselves vary from one university to another, most importantly in their faculty who have the power to impact and change the way mathematics is taught When different approaches in the use of technology are implemented over significant time, their results will provide pointers as to 1) what technologies are most likely to enhance mathematics learning; 2) when and how they can be implemented; 3) for which students they are most beneficial; and 4) which faculty are most likely to integrate them in their teaching. From the experiences reported by faculty and from the experimental programs and initiatives developed by mathematics departments, a pedagogy of systemic technology integration may emerge. (para. 11).

In this paper, we specifically examine the results from the case studies conducted in two mathematics departments in the United Kingdom and Canada, highlighting the significant design elements of their respective programs, as well as the successes and challenges faced by both departments, as change was brought about over an extended period of time. We further compare the trajectories and significant similarities and differences of these two mathematics departments, in an attempt to provide meaningful insights into the complexity of sustained technology integration at the university level.

2 METHODOLOGY

In preparation for the case studies, we first consulted widely in the fields of mathematics and mathematics education at conferences and at our own respective universities and regions to ascertain what types of technology use were happening in different parts of the world. In this part of the research, we didn't restrict our focus to CAS-based technology only, but rather considered any digital technologies being used by mathematics departments. Over time, as a research team, we narrowed a list down to 5-10 possible institutions in North America and Europe where we could definitely see signs of unique, sustained technology-rich undergraduate mathematics instruction. We ultimately selected two such mathematics departments, one in Canada and one in the United Kingdom, for the comparative case study due in part to their long-term, technology-enhanced programs, and also due to the relative accessibility (i.e., researchers employed in these countries). The universities in which these two mathematics departments were located were then contacted, and agreements were drafted and signed at each of these institutions to allow for the research data gathering process to take place.

Two case studies were then carried out. Semi-structured interviews were conducted with key individuals (administrators and faculty) at both the UK and Canadian sites. The interview questions were semi-structured (i.e., open-ended in nature) and designed according to case study standards (Denzin and Lincoln, 2005; Yin, 2009). Participants were thereby encouraged to communicate their individual perceptions relating to their departmental structures, leadership, resources, and significant changes over time - particularly those involving the re-crafting of the undergraduate mathematics programs with a comprehensive use of digital technology (see Appendix A). Artifacts such as course schedules, sample assignments, marketing brochures, webpages, and meeting minutes were also collected for review. These items were helpful in ensuring the overall accuracy of the analysis of participants' statements, and also provided further information about the two undergraduate programs. Interviews were transcribed and checked for accuracy. Transcripts were then analyzed using qualitative research software and Thematic Analysis methods, i.e., familiarisation with data, generating initial codes, searching for emergent themes among codes, reviewing themes, defining and naming themes, and producing the final report.

The United Kingdom Mathematicss Group (i.e., department) was situated within a large-sized university (i.e., student population of approximately 34 000) in north-central England, United Kingdom. During several visits to the university site in early 2009, interviews were scheduled with nine individuals including mathematics professors and the department Head/Chair. Similar supporting artifacts were also collected at the UK site. The same two researchers who had conducted the Canadian interviews also conducted the UK interviews, and the interview schedule of questions was the same for each of the participants (see Appendix A).

The Canadian mathematics department was situated within a medium-sized university (i.e., student population of approximately 17 000) in Ontario, Canada. Over a number of days in late 2008, interviews were scheduled with 19 individuals at this university including mathematics professors, the department Chair, and a retired faculty member who had been instrumental in implementing the program. One further interview with a senior administrator took place by telephone several days following the original interviews. Similar type artifacts were also collected at the second site. Two researchers conducted the interviews together, taking turns asking questions from the same prepared interview schedule (Appendix A).

It should be noted that the number of mathematicians involved in the Canadian mathematics department was approximately the same size (around 20) as the UK site, but, based on the availability of faculty during the research schedule, over double the number of interviews (19) took place in Canada, as had taken place in the UK (9). Therefore, the group of mathematicians at the Canadian site likely represented a wider variety of backgrounds, specialties, and perceptions regarding the challenges and opportunities of technology use in university teaching. In both cases, most members of what could be considered the "core group" were interviewed.

3 FINDINGS

In this section we shall present each of the two mathematics programs in sequence, with a comparative focus on the following four key areas that emerged from our analysis: the history and rationale of the program; the structure, curriculum, and assessment of the program; the challenges faced in developing, implementing, and sustaining the program; and, successful strategies that have helped the two institutions to be successful in implementing and sustaining their revised, technology-based programs. For confidentiality, participant codes are used instead of participant names throughout the paper.

3.1 The UK Undergraduate Mathematics Degree Program

In what follows, we document, according to these four key areas, the opinions and past/present experiences of the UK faculty relating to the planning, implementation, and sustaining of their technology-rich program over time.

3.1.1 History and Rationale of the UK Mathematics Degree Program

The revised mathematics program at the UK site was launched in 1996. At this time, the "maths" (mathematics) program and the "maths education" program were together within the same department. Approximately two years later, the mathematics education program separated from the mathematics program and joined a newly formed School of Education. Reading through the transcripts, it becomes evident that this split was rather a painful and significant moment for many faculty, particularly because a number of the mathematicians had been trying to establish a pedagogical focus for the department in light of technology-enhanced learning and other innovations. The mathematics department Head shared this part of their history:

> We had a really good relationship with maths education and we were beginning to form some good ideas about trying to mould the kind of theoretical educational approaches that they would take to the kind of rough-and-ready curriculum development moves that we were making, and there was the beginnings of some thinking there, but politics and finance drove things in different directions, and that was unfortunate. . . . And part of the politics was that there was a School of Education, but when you've got a group of educationists who are explicitly mathematical educationists, then there's bound to be a kind of border dispute about whether they should be with mathematics or whether they should be with education. . . . So maths education went off and joined the School of Education. . . . And so it kind of took away our theoretical base, if you like. (AP1, PD3, para. 35)

Ironically, in retrospect, this forced split within the two programs ultimately bolstered the mathematics group's solidarity and desire to continue to offer this unique mathematics program that would focus on technology and student-centred learning. The Head recollects a significant personal encounter with a colleague that had a profound effect on his outlook at this time:

> She just looked me in the eye and she said, "You're as much an educationist as the rest of them are." That was one of those moments when you think, Hang on, yes actually, I don't have the theoretical training, I don't have the theoretical framework, but I've got a lot of experience of working as an industrial mathematician, I've got a lot of experience of actually teaching people mathematics and seeing how they respond to it, and so on. . . . And I think it was that kind of growing confidence that we could talk about educational things that made us start not only designing a programme, but turning to the outside world and saying, "Look, you know, this is what we've done." (AP1, PD3, para. 35)

Part of the rationale for establishing the technology-focus, as it related to undergraduate instruction, was the realisation that due to their size as a smaller department, and being a group of mathematicians many of whom had previously worked as engineers or in the applied sector, they would not realistically be able to compete with much larger UK institutions wherein pure mathematics research was often central. Rather than view this as a limitation, they looked upon it as an opportunity to showcase their unique collective strengths, particularly their ability to support "authentic" mathematics learning.

> We're a bunch of just over 20 people. . . . We have a very firm idea of the identity of the group. . . . Staying alive has been a real issue, and many other mathematics groups have closed down over the last 25 years. So, I guess I'm deeply relieved that we seem to have hit on a way of staying together and functioning and running courses and so on. . . . Anyway, my view of it when I was first becoming influential and then was put in charge, was that it was pointless going for a research rating in mathematics because there were people that were so many years ahead of us, we were never going to catch up with them. If we were going to survive as an independent mathematics group, then we needed to think very carefully about what was worth pouring our energy into. So my view was, we should become very interested in education and that we should pour our effort into curriculum development, and pedagogical development, and so on. (AP1, PD3, para. 7-151)

Survival as a department was another major driving factor at the point of the group's history when they began to discuss the possible creation of an entirely new mathematics degree:

> The survival of the department was such that we had to accept any [service teaching] work that was going. It wasn't until we put together a proposal to run a mathematics degree - because you weren't allowed to run a mathematics degree until about 10 years ago, and then we were allowed to run one, so we did. And

> this was when the graphing calculators came in, and the Internet, and people were realising computers were quite important, so then we wrote our course" (AP2, PD4, para. 247).

In both of the case study sites, three vitally important character types clearly emerged, and these three personalities, as well as their significant contributions to the departmental reform, can arguably be quite closely mapped from one location to the other. We shall refer to these three individuals as the *Long-term Leader*, the *Roving Radical*, and the *Pensive Politico*. In essence, they form the heart, the hands, and the head, respectively, of the prolonged and successful reform efforts.

In the case of the UK site, [AP1], having worked at the university for three decades and who was now the Head of the Mathematics Group (or department), was clearly recognised by his peers as one of the main forces behind the initiative: "I think [AP1] has obviously been a motivator for the degree since its inception - he became Head of the Mathematics Group, and that made a difference in so many other ways too" (AP5, PD11, para. 57). The *Long-term Leader* was described by another colleague as follows, "[AP1] is the completer - the finisher who writes everything up, and he is very, very good with words, and he can translate a snip of an argument or an idea into a paper" (AP2, PD4, para. 7). Yet another colleague highlighted [AP1]'s servant leadership skills, including his ability to organize without "managing," and to inspire:

> [AP1] I think is quite critical to the process. He is a very competent leader in the best sense of the word. If you've got a group of people, the leader goes in with a very clear view and sort of convinces everybody to follow the route. . . . Certainly the collective group had a collective ideology, and certainly [AP1] was committed to that ideology. He is certainly not seen as the manager, but when it comes to talking to management he is the one who does the job. (AP3, PD6, para. 63)

In both case study sites, one particular faculty member became extremely excited about the potential impact of new technologies, leading to a desire to "go out and explore" these new tools/strategies and then report back to the group. In the UK scenario, [AP2], the *Roving Radical*, travelled to the USA to specially target conferences where he knew certain educational technologies were being celebrated and promoted.

> I went in 1994, because a student in the back row was playing with a TI-85 and grinning. . . . He kept laughing at me - and I couldn't believe this, he was solving electronic circuits with complex numbers [with a calculator]. So I thought, "This is good, I must go find out about this." So [AP7], who was our acting Head said, "I'll give you the money, you can go to Ohio to see what's happening." Went there, saw [organizer], and saw the hub - one bloke running the kite for North America, and I thought, "This is good, this is good." So, I came back and forced everybody to do it. . . . The Americans gave us the impetus to go on - they were very strong. They came over and saw us once, and [AP1] got sucked into it, and he was busy defending my back because people were saying, "You're cheating, this is cheating, this is not proper mathematics, you can't do this, you're pressing buttons!" - you know, we had all that. And so, when we put the course together it was heavily technology-based, but also how to assess it. It's no use actually having technology unless it's actually embedded, and you know how to assess it properly - and people hadn't done that. (AP2, PD4, para. 267-275)

Another colleague remembers how [AP2] organised formal debates so that instructional technology could be discussed openly in public, thereby increasing the opportunities of positively influencing fellow faculty members and administration:

> I would say [AP2] was really critical to the process. He was quite important in saying, "New technology is here, let's go with it." There was not a vast amount of opposition, as I recall - we did have that form of debate and discussion and argument, and there was resistance to it, but the person who [was on] our side of the debates was a math educator, he wasn't a mathematician, and I think that's quite significant. (AP3, PD6, para. 23-25)

Although careful reflection and ongoing posturing, in terms of the timing and selected strategies for the reform, were participated in by all of the "core group" members throughout the reform process, one or two individuals seem to stand out as being particularly effective at providing experienced counsel to the group. In the UK case, [AP3] fits the description of a *Pensive Politico*, as noted by his colleague: "Then there's [AP3] who is a renegade - he was a pure mathematician, very classical mathematician - radical, great thinker, great organiser, and very, very political, and he really solves problems very, very well ranging from using technology to game theory" (AP2, PD4, para. 7).

The idea and significance of a dedicated "core group" was also clearly evident in both case study sites. Not only did this group "gel" professionally around a shared vision for the department, but they also enjoyed each other's company both on and off campus.

> We've got a list of people who actually feel called to the department, and people who have moved in to our department, all with different skills - and luckily we seem to be friends - the inner core are friends, we go away and enjoy each other's company, and we all bring to the table, the department, different skills. We all bring different skills, we all get on together, and we manage to survive. (AP2, PD4, para. 7)

Sometimes the Mathematics Group Head would request that faculty members, on special days or for focused planning sessions, attend weekend events at the university site. [AP3] described such occasions: "This thing takes awesome amounts of time and effort, and for people to give up their precious Saturdays - it's a commitment. Virtually the whole group comes in and gives up their time, and we all have a good laugh" (AP3, PD6, para. 55).

Although the core group shared a common vision and deep commitment to the technology-based mathematics degree program, this did not mean that they were always in agreement, or that they weren't prone to respectful arguments on many finer points: "I mean we do have debates - I would have a slightly different opinion than [AP2] about where exactly you use a calculator, for example, and that's natural, and I think, and healthy. I respect his opinion. But I think in terms of what we are trying to achieve by it, we are pretty much of one mind" (AP5, PD11, para. 57).

Apart from the "survival" rationale that we have already examined above, four other key factors are clearly evident in the transcripts and historical artifacts, namely, *employability* of students based on specific learned competencies; the recognition of a mathematics skills *deficiency* in many incoming undergraduates, coupled to the idea of making mathematics more *accessible* to these students; a perceived sense of higher *engagement* among the student population; and, a firm belief that *enhanced mathematics understanding* is the direct result of a more "balanced" approach (i.e., paper-and-pencil along with technology) in both curriculum and assessment.

The university, as an institution, had moved toward a strategic vision that emphasised student satisfaction and employability. The revised UK mathematics degree program meshed well with this institutional focus, albeit within a mathematics framework, i.e., the development of requisite technology-related skills that were deemed useful and in high demand in many of the student work placements (e.g., Excel spreadsheet proficiency), and the parallel development of interpersonal and communicative skills that were born out of multiple layers of collaborative groupwork participation and project sharing. The Head of the Mathematics Group explained this in detail:

> I mean if you look at where our people go - a lot of them go into finance, some go into IT, and quite a number go into education. But in terms of feedback from employers, typical comments are, "Yeah, Liz is very good, she's good at the mathematical and technological stuff, but she's been really good at working with the team, and when she talks to us we understand what she's got to say," and this kind of thing. There have been some SMEs [small and medium enterprises] where they say, "Yeah, he was terrific - he revolutionised our store's record keeping with the spreadsheet that he designed". Our aim has always been - not that the technology would de-skill people, so you don't use it as a black box. What you do is you use the technology which forces you to really understand what you're doing before you can use it. (AP1, PD3, para. 261-281)

In multiple interviews, participants linked the concept of "relevant mathematics" to the everyday work world. As [AP2] noted, this linkage bodes well for students in terms of both conceptual understanding and increased employability:

> We have certain people who we upset because we have a belief about what mathematics is all about for the 21st century, in a technological age. Underlying this is business and employability, and you ask people to go out there and they may not be the most brilliant mind - in terms of symbolic manipulator - but they'll always get the job, because they can talk and communicate, and this has happened quite a few times and, they can play with spreadsheets, very effectively. And it's awesome what they do, when you go and see them in industry - what the supervisors think of them, it's fantastic. (AP2, PD4, para. 115)

According to one participant at the UK site, mathematical literacy, that had once been deemed critical to the student experience by the institution, had more recently fallen into disregard. Unlike literacy skills, numeracy no longer mattered:

> I think there is another whole dimension - the debate that was happening around 10 years ago - What do we mean by people being graduates, and should they have any mathematical or numerical, you know, any broad numeric capacity, if we are saying they are graduates, in the same way that we would say that about the literacy skills and their written skills? And that perception around written skills is still there across the university, but it's shrunk around mathematics. (AP7, PD5, para. 53)

Add to this reality of not emphasising mathematical literacy at the university level the fact that many students now entering university were, according to almost all of those interviewed at the two sites, demonstrating increasingly weaker mathematical competency. So, with a top-down de-emphasis on numerical skills among graduates and a bottom-up deficit, in terms of student readiness entering first-year mathematics classes, it is perhaps little wonder that the mathematics department sought reform that would, in some ways, need to compensate for the apparent deterioration of mathematics skills as well as build student confidence through meaningful projects that allowed students to be successful. Enter a technology-based learning philosophy: easier access to higher, and more interesting mathematics, while at the same time providing a sense of renewed urgency around mathematical literacy, yet redefining this term to also include technological savvy along with more traditional paper-and-pencil skills.

> So, we did develop new modules ... trying to deconstruct and reconstruct their [students] basic knowledge, if you like. That whole thing about kids repeating, and repeating, and repeating these techniques - they really do not understand. You have to break that cycle and maybe you need other tools to help you break that cycle, so that they build up a different conception. (AP7, PD5, para. 133-137)

We should be clear that we did not get a sense that the primary objective among the UK faculty was therefore to "dumb down" curriculum. Rather, it sounded much more like a restructuring, or refocusing of the curriculum on different kinds of mathematical explorations, tools, and skills-some of which, as is mentioned in the following quotation, were described as actually being more advanced in nature, as well as being more interesting to the average student.

> If we are taking students with very low P8 level grades, it's nor fair to them to present them with something they are not going to be able to do. If I want students to explore the different types of behaviours you can get out of the system, and yet every time they do it they've got to solve this algebraically, then half of the time they are not going to be getting to the point I want. So, in some ways I think I am trying to use technology as a way of getting them to do more interesting things, and sometimes more advanced things. (AP8, PD7, para. 51-60)

Not only has this changed the mathematics content, but also how it is taught: "So, the process of teaching has changed massively, and consciously. The using of the technology alters what we teach. So, I teach genetic algorithms and cellular automata, and you know, if we had a traditional approach forget it, you cannot teach them. So it alters the way we teach, and what we teach" (AP3, PD6, para. 43). Another participant expressed a similar idea, yet here focused on the enabling effect of technology on many students:

> But you realised what you could do then [with technology]. Otherwise, you were trying to teach people who didn't want to know, something that they couldn't do. But the technology enabled them to feel comfortable, to get an answer, what you have to do is show them how they know the answer is right, and what it is used for. And you enabled people, and anybody could be enabled to actually do mathematics. (AP2, PD4, para. 283)

In addition to employability and increased mathematical accessibility, another key rationale factor was that of a perceived sense of heightened student engagement with the curriculum.

> I have a friend who is a maths education researcher who did a few interviews with students here, just to assess something they had done for me. And I met her afterwards and she said, "You know, that's the first time I've ever interviewed students in the university where every single one of them was enthusiastic about what they are doing." . . . You know, we get our dropouts, we get those who really don't like it, and we get the ones who kind of whine about this or that aspect of it, but by in large they seem to be reasonably positive. (AP8, PD7, para. 115)

Finally, but perhaps most importantly, a frequent rationale for program change, shared by a majority of participants, was that of enhanced mathematical understanding. Technology-enhanced activities, assignments, and projects were viewed as promoting deeper and more meaningful mathematical learning via real-world context, "authentic" investigations.

> If we look at the final year students that we were looking at this morning, I think what they get out of that is an appreciation of where it's going, that's one thing. And the other thing is being able to experiment with it fairly quickly so that they can see the effect of the parameters they use in that case, or the case of the malaria model. So, I think it makes it a lot more real to them when they can do that. I think it enables slightly more complex procedures. Although you want them to be able to do the whole thing [by hand] if they have to, it can take some of the detail out, so you can concentrate on more important, bigger sections of it. (AP5, PD11, para. 23-31)

Participant [AP3] emphasised a "new balance" or pedagogical implementation wherein students learn to harness the power of technology, yet also continue to develop the ability to mentally check technology-generated answers for reasonableness:

> For mathematician students ... they have to know where it comes from, the skills that you develop for differentiating from first principles - these things carry over to too many other areas just to say the machine will do it. We are not training people to be purely just pressing buttons, but clearly the old balance was wrong too. I think we try always to do things two ways: "Always check your answer," and then, "Take a step back, and does the answer feel right?" All of that thinking got incorporated into the program. (AP3, PD6, para. 9)

In this section, we have looked at the history and rationale of the UK technology-based mathematics program. For reasons of survival, student employability, increased student access and motivation, and, enhanced mathematical learning, the new mathematics degree program was created in the mid-1990s. A core group of individuals formed the nucleus of the reform efforts, and within this committed central group three particular leaders, contributing various key skills/actions, were highlighted. We now turn to the structural features of the new program, with a specific focus on the revised curriculum and assessment.

3.1.2 Structure, Curriculum, and Assessment in the UK Mathematics Degree Program

In the UK BSc Mathematics program, a modular system was used in which certain courses were required in Years 1, 2, and 4 of the program, and other courses were to be selected from a list of extra mathematics topics/modules (see Appendix B for full details). At the UK site, first-year students took courses in which a variety of different kinds of software and calculators were introduced as a series of "tools of the trade" which were to be used throughout all four years of the program.

> We've got traditional mathematical elements of course, and we've got modeling elements where they are putting those into practice to try and simulate real world problems. And so that would be in the first year where they are learning how to use spreadsheets, and learning how to handle calculators, and learning to do a bit of programming - other software products. There is a range of tools out there which we want to bring to solving mathematics. And while it is important for people to understand what the process of, say, calculus is - how to actually do it - it is more important that they know what to do with the result, and understand what it means. Suddenly they see that in fact there is a whole lot more to it than just learning rules - the rote repetition of rules. (AP6, PD12, para. 15-17)

Students developed their own websites which became a digital portfolio of their various projects throughout the program: "Our students create their own websites, and part of the programming is how they can program their websites so they can run mathematical modules and deliver them over the web" (AP6, PD12, para. 17). Online learning logs were also used to help track student progress and to provide another means of open communication between faculty and students.

> We've got an on-line learning log system, which is a very important part of keeping the students rolling along ... we don't want it to be seen as an alternative to personal contact, because we do have this firm belief that the way you learn is by talking to people, and negotiating your way around your problems, and this kind of thing. It's partly trying to make them feel valued in a way. So it's not forming inappropriate relationships, it's not getting too buddy with the students, its' just acknowledging them as human beings. (AP1, PD3, para. 185-205)

A faculty member with a Teaching Fellow role/status within the Mathematics Group was specifically tasked with organising and monitoring the learning log system. He shares some of the challenges involved in trying to convince other colleagues:

> Students have logbooks they complete online every week for all of their modules, so that there is a lot of recorded e-communications taking place, and the staff are monitoring that all the time. Its part of the assessment in Years 1 and 2. We've probably got about six or seven people who wanted to engage with it right from the start, and there are probably another six or seven who occasionally engage with it. It's hard to get staff to get engaged with something - you can't tell them to do it, it won't work, but what you can do is to point out the benefits, and if they can see it working for their students - then that's an incentive. (AP6, PD12, para. 43-75)

The second year was a continuation of various mathematics courses that involved software and project-based learning. Further, students were heavily involved in applying for, and receiving employability training for potential third-year work placements.

> The degree is technologically-oriented, and that's one of the claims we make when students come to see us. The main bits of technology we use are the web, and the logbooks, ... and in terms of packages, we've made a lot of use of Derive. Excel is probably the thing I make most use of - there are just so many different things you can do with Excel, and so many different ways you can support the mathematics. (AP5, PD11, para. 7-11)

In their third year, students had the option and were all encouraged to take part in a full-year "sandwich," or cooperative work placement. According to one instructor, himself a father of a son who was currently in the program and involved in the work placement process: "They work quite hard, actually, to get sandwich placements and quite a wide range of sandwich placements, if you look at their website" (AP7, PD5, para. 73). The positive, character-building effects of these third-year placements on returning students was frequently mentioned.

> The history of this institution is that ... the whole place has been centered around relations with local employers - getting people into work placements. You learn skills in Years 1 and 2 that you are going to take into account in industry. And the industry placement here provides people with a lot of maturity. As a result of a year's working, they have to conform to a completely different style of approach to work, and suddenly they realise it's important to be there at 9 o'clock in the morning, they learn how to deliver to deadlines, they learn how to work as part of a team in a company. A typical student doesn't get up until midday and, you know, walk around - looks like a mess. But when they come back, that's a changed person. You can see they've got a professional approach to what they are doing. (AP6, PD12, para. 15-116)

When asked about whether or not this third year placement was always optional rather than mandatory, [AP6] noted:

> We don't want to make it compulsory for several reasons. One is that when people join the course, we think it might hit recruitment if we say, "You must do one of these." During the first year we tell them it's going to be very useful to them, that they should consider applying for it. In the second year we put a lot of effort behind that. They are given training in job application skills, interview skills, and self-presentation skills, so they can hopefully get an interview first, and then once they got an interview, they can succeed at it. (AP6, PD12, para. 117-127)

While student placement numbers had seen somewhat of a decline in recent years, [AP6] noted that employers are usually extremely pleased with the undergraduates on placement, often offering them jobs either on the spot, or upon return.

> I think they are very happy with the skills our students have. And the evidence for that would be that in many cases [students] are being offered jobs, there and then. And they are not being given a low-level job while they are there, but they are taking full part in the organization, and they are doing everything a full-time employee would do, and sometimes more. And a lot of them are doing work analysing data, or writing computer programs, developing software that the company is using after they leave. (AP6, PD12, para. 103)

In their fourth and final year of the program (for some, this would be their third year if they did not choose to do the work placement), students returned to the university to complete their final mathematics courses, which were also heavily saturated with technology-based applications and projects. One of the fourth year instructors describes the final year details:

> In the final year we have a large 30-credit project module and many of them do a lot of programming. It starts in May of their second year when students will look and see what projects are available [for their fourth year project]. We present them with a list of projects ... 80 or 90 projects to choose from. And if they want to propose one of their own, that's fine, we'll talk to them about that. They pick a project and they get assigned a supervisor and a moderator. So, the supervisor and the student will agree on a time to meet, and how frequently - it's very much according to what the student needs. (AP6, PD12, para. 31-45)

Among the variety of technologies being used in required and elective courses at the UK site, clearly the one form of technology that was held in the highest regard, supported by a number of instructors who were very proficient with this particular software, was Microsoft Excel (Challis, Jarvis, Lavicza and Monaghan, 2011). Advanced spreadsheet skills were often noted as contributing to the success on placements.

> And that's why I like the spreadsheet so much, because you've got to understand what the inter-relationship is, and you really need to think about patterns and relationships between data. So they're learning a tool which is widely used in the industry, but they're also using it to enhance what they're learning mathematically as well. And that's always been my aim, and you can do it more easily in some areas than in others, but modeling is a terrific area for doing this kind of stuff. (AP1, PD3, para. 281)

Clearly the modeling of mathematical problems had figured centrally in the entire UK mathematics program, as well as the constant awareness and use of newsworthy current events that lent themselves to mathematical modeling and analysis.

> We do a lot of case studies with the students. We did sub-prime mortgages and risk analysis last year. We had a lot of Avian flu in the news, and so we actually got models for what happens if it happens in Dover, or, we try and relate it to the great flu which was in the First World War. Modeling can be applied to pure mathematics, it can be applied to cryptography, it can be applied to discrete models, it can be applied to money, it can be applied to pictures, image processing, and so it goes on. You need technology to handle mathematical models. The nice thing about modelling is that it's got everything there - you've got to talk about it, you've got to have the skills you need to write it up. We go through SNOG'n - Symbols, Numbers, Oral, Graphics. (AP2, PD4, para. 55-59)

Another colleague explained the tenuous balance that needed to be struck between learning traditional calculation skills and the ability to understand why/when certain mathematical skills are necessary, and which technology might be useful.

> Obviously we have a syllabus, but it's not [the] kind ... containing such and such abstract ideas. If you were to quiz other universities about that they'll likely say, "What's important about maths is that you can think logically and abstractly, and solve problems" and all those things, but I don't think it is always reflected in what they are actually doing. So, they will cram in a huge amount of content, which can detract from developing some key skills. Students are under pressure to learn new stuff, so they never have time to dig into the stuff they are learning about. I don't think we've got it perfect by a long way, but I think we've stepped a little bit further back from a list of syllabus topics ... saying, "What are the skills, and attitudes, and ways of working that you should have as a mathematician?" (AP8, PD7, para. 35-47)

Allowing students (at any level of formal schooling) to use technology during assessment activities in mathematics has always been a very controversial topic (see for example, Fey, Cuoco, Kieran, McMullin and Zbiek, 2003). In some jurisdictions "tiered assessment" is used, where part of final exams are written by hand only, with other parts completed using a scientific, graphing, or CAS-based calculator, depending on the grade level and course. In many universities, even when technology is permitted during the term, both in class and even on tests, calculators are often disallowed on final examinations. The following instructor shared his belief in the necessity of technology accessibility during some forms of assessment, where appropriate:

> For a lot of the assessment, it depends on the course, and the individual bits of the course. So, for example, I teach genetic algorithms and there is no way that I am going to teach that without computers, and there is no way I can set an assignment for them to do something without computers. [I]n assessment, one ... has to be using the technology. There are practical problems using technology in exams - the bloody thing can collapse or you know, all sorts of things can

> go wrong on a day, but nevertheless, I would defend their use. (AP3, PD6, para. 11-19)

In this section, we have examined the structure of the UK Mathematics degree program, noting the optional and unique "sandwich" work placements in Year 3, for which participating students were thoroughly prepared in Year 2. We have seen the heavy emphasis on Excel spreadsheet technology, particularly in the fourth and final year; the use of contemporary events from which interesting phenomena was modeled and examined mathematically; the debate regarding black box and deeper mathematical understanding/checking; and, the use of technology in assessment as well instructional practice. We now turn our attention to several perceived challenges experienced by the UK Mathematics Group as they designed, implemented, and strove to sustain the technology-based mathematics degree program over time.

3.1.3 Challenges Faced in Developing, Implementing, and Sustaining the UK Mathematics Degree Program

Challenges to such a revision of curriculum design and purpose were certainly not few in number or kind. The UK mathematics group encountered obstacles both external to the university, as well as internal to the department. In this section, we will examine several of the more difficult challenges as shared by case study participants during the research interviews.

Certain external challenges were noted such as centralised changes to national curriculum policies in the UK. More specifically, participants mentioned the "Curriculum 2000" changes that occurred in England in the year 2000 wherein the secondary school curriculum was rewritten, resulting in an unexpected spike in mathematics failure rates, and by extension, a severe downturn in post-secondary mathematics enrolment in years directly subsequent. We have mentioned already that the average student readiness in terms of mathematical competency was in decline, but here we had the added challenge of fewer students successfully completing A Level secondary school mathematics courses in order to even apply to the program.

> We started the [programme] with 16 ... then the numbers started rising a bit after that and we pretty soon started feeling a little bit more secure, actually, because you began to see maybe these numbers are going to be alright. We had to paddle very hard around about 2002, you know, with the Curriculum 2000 mess. We nearly went under then, our numbers dropped to low 20s. Basically, the government, or the QCA re-wrote the A-Level syllabi for mathematics and split it into AS and A Level, and the first year of AS there was something like about a 30% failure rate. So, it was a mess but we've worked away - last year we had 80 people. (AP1, PD3, para. 123-131)

Within the university proper, another major challenge described by participants was the central management itself, insofar as it related to, and frequently tried to regulate certain aspects of the Mathematics Group and the larger unit to which it belonged within the university structure. Control of the website was the most commonly shared example:

> Maths is exceptional in having an academic coherence to it, whereas some of the other subject groups are part of a line management structure, but not particularly the driving force academically. Tied in with that is the fact that, for instance, the prospectus is a university-produced thing, it's centrally produced by the corporation. They come to us and ask us for words, and we put those words in, but they're filtered before they finally get through. So, we live in quite a centralized, corporate environment. Everything has to be uniform, pounded, the edges have to be chopped off, as you see, and you're thinking, "We have no say in that." But what we have done over a period of time, we have managed to maintain our own website. (AP1/AP2, PD2, para. 482-526)

In trying to establish a more technology-rich program in mathematics, there were times when colleagues from other faculties, or discipline-based university groups, did not appreciate the direction in which the Mathematics Group was headed, pedagogically speaking. Many debates, for example, took place around the perceived effects of the increased use of technology on "basic" computational skills, which were viewed as essential for success in the various professional programs.

> We ran seminars for our engineering colleagues and came up against terrific opposition because they were saying you know, "de-skilling," and so on, and we were saying, "No, no, if anything, it is going to enhance the skills." So, we got into all those arguments about the role technology can play. If you're going to use the technology, everybody's got to acknowledge that it's going to introduce some good things, and maybe you're going to have to change the way you do some other things. (AP1, PD3, para. 115-119)

Some of the Mathematics Group faculty were still apparently struggling on a personal level, not so much with the inclusion of, and focus on, technology per se, but rather on how to balance the more traditional mathematical computational skills, including standard proofs, with the more exploratory aspects of the new paradigm. One instructor, for example, noted: "I am not a big technology person but obviously I am [competent] with it. I don't think we should use technology too much because it does disempower students sometimes, because if they just learn how to do something with a technology, then they can't adapt it, and they don't really understand it" (AP14, PD10, para. 27). Hence, insofar as some of their own faculty members had doubts about the overall direction of the program, and the more specific ramifications of technology on curriculum, learning, and assessment, one can consider this a form of ongoing, internal challenge.

Finally, one other obstacle to achieving the successful establishment and prolongation of the mathematics degree was the more general stereotype of the mathematics major that participants indicated still existed in society at large. By focusing on new technologies and current events as sources of rich modeling exercises, and by emphasising the importance of third year work placements, participants indicated that much of this negative mathematics connotation was thereby avoided.

> Most of us came to the view that mathematics is an "alive subject," it's not dead, you know, and that new technologies have opened up new branches of mathematics. When our students go out to get jobs they will be using technology, and so we have to incorporate that at a very fundamental level into what we teach. Mathematics has a terrible perception in the outside world - that it's a nerdy thing, and this leads to a whole range of problems for recruiting. So, I think it was the jobs that people were doing, and the new technology - they were genuinely excited about what you can do with a mathematical approach using technology. (AP3, PD6, para. 9)

Challenges were certainly not insignificant as the core group prepared to design the new mathematics program in the mid-1990s, and then grow and protect the fledgling program throughout the subsequent decade. As we have seen, formidable external obstacles existed such as national education policy changes, institutional governance regulations, and departmental concerns from other quarters. Internally, the biggest challenge appears to have been the ability of the core group to maintain clear messaging around the shared vision and rationale for the program, as well as open lines of communication among all faculty, including the opportunity to openly discuss the "new balance" required for the ultimate success of the program. In the final section, we will now focus on successful strategies that, even amidst these challenges, allowed the program to thrive.

3.1.4 Successful Strategies in Developing, Implementing, and Sustaining the UK Mathematics Degree Program

There were at least four key focus clusters shared by the various UK participants in terms of perceived successful strategies that allowed their new mathematics degree program to flourish during the decade preceding our research: a focus on maintaining a shared meaning and camaraderie among core group members; a focus on student satisfaction; a focus on the validation of and participation in classroom-based research; and, a focus on strategic hiring, where possible.

A naturally emerging core group of committed members played a foundational role in the establishment and sustaining of the new mathematics program. This social network was fostered by the group's leadership, understanding the vital importance of this unofficial body to the future of the program.

> There is a core in this mathematics group that are very - we all see through the same sunshield basically, and we do a lot of talking. So, there is a social network, we've gone away for weekends and things like that, and I think that's important, and people would say what they were thinking. And I think that the philosophy is very, very coherent and I'd suspect there's, you know, a vast bulk of the [larger] group that are absolutely committed to that technology, and to that philosophical approach. (AP3, PD6, para. 51)

Aligning well with the university's over-arching mandate, a focus on student engagement and satisfaction was something that the mathematics group had been successfully maintaining for nearly a decade. One administrator noted:

> We have a new corporate plan and it emphasises one thing really ... student experience. So the number one goal in this university is to provide an experience for students second-to-none, and one that meets their expectations. The maths group within the Department of Engineering, in their teaching, implement that plan and, as you know, have started on that because they have scored very highly on student satisfaction. (AP9, PD1, para. 77)

The Head of the Mathematics Group highlights the open-door policy and positive space with which the program is characterised:

> Our emphasis is on supporting people. Word gets out about the fact that, for instance, we've got an open-door policy so that students can come and see us at any time. We've got a very good community atmosphere with them. People are here because they're interested in maths, and we're interested in maths. They're interested in getting a job, we're interested in helping them to get a job. By the end of the three or four years, you get to know people pretty well. (AP1, PD3, para. 165)

One specific strategy that was adopted early in the program's development was that of a drop-in Mathematics Help Centre:

> I am a first year tutor and instructor, and I am in charge of math support and Math Help throughout the university. . . . a general mom to all the students [laughter], which is getting more and more difficult. I mean, we used to have about 25 students, but now we have 80. It's a lot of children to have, especially when a lot of them are 18-year-old boys . . . trying to help them to do some work, which we largely succeed in doing. (AP4, PD10, para. 7)

A third focus that became apparent in many of the interviews was that of classroom-based research. As opposed to more pure mathematics research, many of the professors in the UK mathematics faculty had been involved in exploring new approaches to teaching and learning, often involving technology, and then documenting and publishing these experiences at through various publications and conference presentations.

> We try things and share good practice, like you do in any decent profession. We don't do heavy-duty research, we do research that we think is useful, and we try and share it, and we've been very popular. We've established a reputation for doing lots of interesting stuff and publishing it. We also go to certain conferences every year and, having taught engineers, we always go to the engineering maths conference. (AP2, PD4, para. 35-39)

A final focus that was discussed by UK participants was that of strategic hiring in light of the Mathematics group's shared vision for the program. At the time of the research, an imminent hiring wave due to upcoming retirements was anticipated.

> We have not had a turnover of staff, really. This is one of our problems in that we've got people who've been here for many years, and most recent members of staff probably joined about eight years ago. The problem is going to be how we cope to keep this going. We've got imminent retirements - next year, I think, we'll have to make a bid for new staff on the grounds that we are loosing too many existing staff. (AP6, PD12, para. 91)

As we have seen, the UK Mathematics degree program, despite many external and internal obstacles, had been successful in creating a technology-based, employability-focused mathematics degree program. Certain strategies were adopted to help maintain the shared enthusiasm and to regularly revisit the common core beliefs held among faculty members who were teaching and doing related research within the program. Our focus now turns to the Canadian case study context, as we seek to recognise and understand some of the significant similarities and differences to be found within their comparable journey.

3.2 The Canadian TECH Mathematics Degree Program

In what follows, we now similarly document the history and rationale of the Canadian TECH mathematics degree program; the structure, curriculum, and assessment of the program; the challenges faced in developing, implementing and sustaining the program; and, successful strategies that were adopted by the Canadian "core group" in order to ensure the sustained growth of their technology-rich program over time. Please note that the technology-based undergraduate mathematics program's acronym has been changed to "TECH" for the sake of institutional confidentiality, and the name of a key software program that was developed by one of the faculty within the institution will be referred to simply as "interactive calculus software," for similar reasons.

3.2.1 History and Rationale of the Canadian Undergraduate Mathematics Program TECH

The TECH mathematics degree program was formally launched in 2001, although serious research and planning for the new program had begun at least five years earlier. As opposed to the UK site where a new Mathematics degree program had been created for the first time in 1996, at the Canadian site there had already existed a mathematics degree within the faculty, but in this case it was being completely revised according to new objectives and principles, one of which directly involved the comprehensive use of technology: "to develop mathematical concepts hand in hand with computers and applications."

Many of the interviewed participants indicated that they regularly used technology in their own independent mathematical research. A list of such technology uses for mathematics included: simulation for statistics, number zeroing and cryptography, solving non-linear equations, mathematical music theory, solving differential equations by symmetry groups, solving large polynomial algebraic systems, discrete data microsystems, and functional analysis. While a majority of those interviewed indicated that technology was essential to their own research pursuits, there were a few exceptions where it did not figure so predominantly, or at all, in the work of certain colleagues, such as in the following case: "I'm a traditional mathematician, so, I don't use much technology. I use my computer for basic typewriting, or for searching Internet, to find information, you know, those kind of things" (BP9, PD24, para. 12). One interviewee provided us with an insightful overview statement regarding his perceptions of the composition of his department:

> When I realise what is happening here [with technology] it makes sense. I think it's because most departments are probably pure math oriented. They basically consist of pure mathematicians who do seem to have some sort of resistance towards the technology. Our department is unique in the sense that most of us are physicists - most of us are either physicists, or people who came from very applied areas. Our math department ... never acquired this kind of orientation, where pure mathematicians would ... basically run the place. (BP5, PD30, para. 106)

The history of the TECH program actually begins much earlier by virtue of the longstanding commitment of the "patriarch" character found in [BP11], who had not long retired prior to our research study. As described by another colleague, "Even before [BP11] became the Chair, we had a very nice department - it always was supportive ... we miss him. He was so dedicated, high quality, excellent, always really, really nice. I think he played a major role" (BP10, PD21, para. 100-116). In the early 1980s, [BP11] had begun advocating for technology adoption at the university, and one of his early key strategies had been to invite all members of the mathematics faculty to informally drop in to a computer lab to observe students working on simple prescribed assignments.

> We were able to convince the university to develop a Mac lab to run Maple - we had 450 students on Macs in 1982, or '84, doing fairly substantial questions. I asked faculty to volunteer in the labs and I said, "I want you to look at the interaction between the students and the work that they're doing, and the

> kinds of questions that they're raising. There will always be a teaching assistant there for any questions about technology. You can just sit back and listen." . Every faculty member went into the lab. There was some discussion in the department meetings. There were things which fascinated people. Then for some of the faculty, we started talking about doing it in class, first for the service courses. [P]eople were asked to teach a minimum amount of Maple in their classes, and I gave them examples of things that they could just run. (BP11, PD27, para. 78-118)

Another colleague further described the prominent role that [BP11] had played in the slow but steady investigation of new technologies for mathematics instruction that would lay the foundational groundwork for the major changes to come.

> We had, first and foremost, [BP11] who ... is so dedicated to making the world better mathematically. ... a real visionary - he really saw that we needed to do something different in mathematics - that technology was beginning to come on the scene, and that mathematicians had better begin to cope with those issues and grapple with them. And he was one of the very first to do it. He is the progenitor of all this - he really is. Because he would ask questions in department meetings like, "Why are you teaching derivatives when Maple can do it? That really upset everybody, because basically he was saying, "What you're doing is invalid. What's the point of it?" So, that was a constant confrontation, but that really got me thinking as well. (BP15, PD28, para. 336-340)

Introducing Maple (CAS) technology into the computer lab for the service courses was one thing; moving it into the mathematics major courses - the traditionally pure mathematics domain - was described as quite another challenge:

> The transition to the majors was a bit more difficult, and required faculty support. Even though I said I'd be happy to come and participate in their courses, most faculty didn't like that. So I said, "What I can do is show you what I've done. I've got this little sub-routine here, and all you have to do is click on here. I had a strong individual who became interested in linear algebra. That helped a lot because that was an area that I had not touched, because I stayed with statistics and analysis. So, here we had one major course which was technology-bound, and all we needed was a decision on the major calculus courses. People were prepared first of all to have a lab. Some of the faculty said, "If you want a lab, that's fine, but don't ask me to set the labs, or to get involved with the labs.". So, we had teaching assistants who were quite versatile. (BP11, PD27, para. 120-175)

If [BP11] represented the parallel *Long-term Leader* at the Canadian site, then [BP15] would clearly assume the parallel role of the *Roving Radical*. This individual, like [AP2] in the UK site, made a significant journey to the USA, but in this case not to attend a particular technology conference and report back, but rather to take a 2-year sabbatical leave to work with a publisher and design team to produce an interactive calculus software DVD. This software would form the essence of the introductory (i.e., first contact) Fall term course in the new TECH degree program. As [BP11] explained:

> [BP15] then became quite interested, and was approached to develop the DVD idea for calculus. So he took a 2-year leave of absence to do that. We've used it here from that time on. [BP15] saw a different role for technology. We started working with learning objects, and we had a summer project with students and teachers, after he came back, to see what would be the best way to proceed, if we were to make a radical change to our program. That was a fundamental event. So, [BP15] came back and said, "You know what, people, they don't use computer algebra systems as much as you think they do - they use simulation." He didn't need to talk to me very long before I was convinced ... it was a huge amount of work - it took two years. (BP11, PD27, para. 176-210)

The third parallel character at the Canadian site, our *Pensive Politico*, would arguably be [BP16], who was once again serving as Chair of the department at the time that our research took place. He recollected the same era and events:

> There was some resistance in the department, because at that time most of the professors of the place were senior. So we asked to form a committee of eight people out of twelve. I needed two thirds of the department to revise the program, because if you have a majority consensus then it becomes the business of the department, and not the business of a person. And then we put the first part of the document together, there was a great picture of the situation in terms of the [declining] enrolment, and you know the "dying program." And once we presented it to the department, we did not find a resistance to convince our colleagues that we needed an overhaul. We made it a point to consult with [other departments] every step of the way - this was very important. Some voices objected, but as a unit they did not. The entire math department was agreeing to this. (BP16, PD15, para. 101-124)

The "roving radical" reflected on the key role of the then Department Chair [BP16] in paving the way politically within the institution for the new TECH program to be conceptualized and developed at the turn of the millennium:

> We had [BP16] who's also very strong - not as interested in technology, but when he came back as Chair, he basically said, "We're going to build a new program here - I don't know what it is, but we're going to build it." And so he pointed to me and said, "You are going to build it. You are the new Chair of the Curriculum Committee." I had no clue, but I was up for it. You know, I've always been interested in

> education issues. There was a feeling in the department that it was possible - that they were ready. (BP15, PD28, para. 341-345)

As in the UK site, there were four similar rationale clusters that emerged from the various discussions, namely, *survival* of the program, student *employability*, increased *student engagement* in light of an increased *accessibility* of the mathematics content using technology, and *enhanced student learning* of mathematical content and relationships.

Survival of the mathematics program was not an obscure or non-significant concern at the time the core group began to seriously contemplate a major program restructuring. As [BP15] recounted, it was indeed a central driving force.

> Our [student] numbers were down, so there was motivation. We started by looking at some of the more famous programs in the US like West Point and Purdue University. We tried to identify emerging programs - things that were more current, more relevant, not just the classical programs. And we tried to listen to what was actually working - who's getting good feedback? Who's actually thinking about mathematics in the 21st century? We'd have them spread out in front of us, and we'd just sit in a committee meeting and read through the curriculum. It was a really long process. So, out of that came the idea for a philosophy of TECH built around technology. So, linear algebra would have a lab with the computers, using Maple. We identified several courses like that, and then we decided we needed to have a new stream that would really encapsulate all of our thinking about TECH - those were the TECH I, TECH II, TECH III courses - where we could really, fully go in that brand new direction and begin to substantiate everything that we'd learned from these other programs. (BP15, PD28, para. 346-352)

Although not as prominent a theme as in the UK site, where the third year work placement certainly solidified this point, student employability was still commonly shared as a contributing rationale factor in the Canadian case site.

> I would think a technology-rich program should be a better draw because it's easier to make the line between the training they're going to get at the university and career options for the students. Unfortunately, far too many students don't consider mathematics because they don't perceive that it leads them to a career. There are careers in academia, but also in many applied areas, most of which they don't even know about. Certainly in biology sciences, and neural science, and in chemistry, there are a fair bit of computations. In the case of physics, all of what they do now is computational-based. There's still a lot of traditional thinking that, "They need calculus, you know, because they still have to be able to understand the classical work that was done," and calculus is essential for a lot of what they do, but in my opinion, it's necessary, but in many sub-disciplines it's no longer sufficient. (BP7, PD25, pra. 16-32)

A young faculty who had been hired to replace the iconic [BP11], and specifically to teach much of the innovative TECH courses, also spoke clearly on the need for mathematicians to realise the importance of technology in many sectors - a fact that should, according to her philosophy - bolster the need for the departmental shift.

> I think that technology is here, and we cannot deny technology any more. And even if mathematicians want to leave it on the side, mathematicians somehow cannot deny that technology has changed our practices as mathematicians. I'm talking about, What is it "to do mathematics"? What does it mean? And I think all mathematicians, even pure applied mathematicians, at some point they use technology. What is the mathematics that we teach, and what is the mathematics that we need to teach? How is mathematics now used outside the mathematics discipline, right? The mathematics that is needed in chemistry and biology is not necessarily the mathematics that we now teach. When we deal with that kind of complexity we need the computational power. (BP18, PD17, para. 194)

Future mathematics teachers who were being educated at the Canadian university also benefitted from a technology-rich mathematics degree preparation insofar as the Ontario Curriculum heavily emphasises the use of many forms of technology in K-12 schooling. [BP19] described how the new program is beneficial for future school level educators: "TECH really lends itself very well to training young people so that they can go back into the school system and find a resonance with the kids there for mathematics. And I think it can be made to fit within the Ontario curriculum" (BP19, PD16, para. 101).

Tied to employability, the second rationale factor is the reported success of students entering graduate programs after successfully completing the TECH degree. Though not many in number, several such examples were shared by faculty in the interviews:

> The feedback that we get from our graduate students from [other large research institutions], I mean, the three of them this year told us that they are really well ahead of many other students because of the training they had in TECH with programming in C, and C++, and in Visual Basic, and in Maple - this gave them an edge over the other students. And they are doing very well in graduate schools. Two of them completed MSC, the other one a PhD. These are the type of things that are always very, very pleasing to me. (BP16, PD15, para. 281)

A third major rationale factor was that of a decrease in mathematical competency among incoming students, coupled with a desire to make mathematics more accessible to students via technology-related explorations and modeling. One instructor noted: "On the one hand, we had students more comfortable using computers. But it got so that their mathematical background when they came out of high school wasn't as good, and so the computer was getting to be like a black box" (BP3, PD29, para. 10-12). Another colleague shared the changes he had made in his teaching in light of these realities:

> I came more and more of the opinion that for the newer generations, the reality of knowledge, and the reality of what capabilities must be there to succeed in life were not necessarily based on your skills to know the derivative, or to carry out complex computations by hand. So I gave up a little bit on the proficiency that students should have doing things by hand on the premise that if they know the fundamentals, and if they are good with technology, they will be very productive, and they will meet whatever is required. (BP16, PD15, para. 69-89)

Student engagement with the mathematics learning was yet another important factor in the decision to develop the TECH mathematics program at the Canadian site. How were students best motivated to learn and to be more fully engaged?

> What is a university? A university to me is that you offer to your students the most recent information and knowledge that you have, and certainly if I'm going to develop a guy that's going to dig ditches, I'm not going to say to him, "I'm sorry. You can't use this new tool to dig ditches, you still have to use a shovel." No, you offer them the dynamic environment of learning mathematics. People use it in their research, and it's part of the mathematics landscape. And to say you can't use [technology], I think that's irresponsible. It's not giving them the latest tools that are available in mathematics. (BP11, PD27, para. 280)

The Dean of the Faculty of Mathematics and Science explained how he, even as an outsider to the TECH program, could clearly see the added value of the technology for student motivation and engagement:

> I think what it really opens up a window that was not there before, which is the application of computers to mathematics. And so, I think what it does is to capture a constituency, if you will, of students who would normally find the sort of traditional way of going through mathematics of formulas, and proofs, and things like that a bit either daunting or boring. I know that what they are involved with really puts them very much in contact with the real world. Engagement with the development of learning objects, using the combination of mathematics and computers fits very well. (BP19, PD16, para. 101)

The final major rationale factor that was shared by a number of Canadian site mathematicians was that of increased student understanding of *important, authentic mathematics learning*. By this we mean mathematics problems that actually reflect the "messiness" of real-world scenarios, as opposed to the secondary school calculus or linear algebra problems that always seemed to end up with nice, simple, non-decimal answers after the algebraic manipulation had taken place by hand.

> [In traditional instruction] every problem that you set has one solution, and you'll never get a problem that doesn't have a solution. You can do each one based upon the chapter that you've just looked at. Everything is parceled off into little bits. Faculty prefer to teach in that way. They prefer to really have command of everything that goes on in that class. You've refined it. It's like a poem, and you're living in that poem. It's the most beautiful thing. Applied math is much more difficult to handle. There are many more variables. Math can be set up in a most linear fashion, physics follows very closely to that, and then chemistry, then slowly it dissipates and becomes more and more chaotic. But if you want your students to work in this chaotic world, you're going to have to provide them with some experience, either in modeling or using computers, which is much richer. Part of the TECH philosophy was to provide a broader breadth of experience in mathematics. (BP11, PD27, para. 260-264)

One of the participants who indicated to us that he was actually quite tentative about moving towards technology integration in his own teaching, nonetheless shared a rather poignant and elaborate metaphor for mathematics education, as he explained his perceptions regarding the inadequacies of the longstanding, traditional mathematical approach.

> Let's suppose you want to learn how to paint, and you go to an art gallery. But not just one, you visit many, many art galleries over four years. In fact you have courses, you know, where one course is modern art, another course is abstract art, French Impressionism, etc. And at the end of the four years you come out, and are you an artist? No, you've just seen painting. And that's more or less what we do in math. I mean we show people finished products, and we don't let them make mistakes - we penalize them for making mistakes. So we end up graduating anxious people, who after 14 or 18 years of education - counting high school and everything - they are just concerned about not making a mistake. And it's very rules-oriented, so you come out with a totally distorted picture of mathematics. You've never done mathematics - you can't even imagine what its like to do mathematics, or don't have any concept of what math really is. How is it used? Why was it developed? Nothing. So the great thing, to me, about TECH is that you get some of that sense. (BP6, PD18, para. 134)

To summarise, both case study sites developed, or in the case of the Canadian team restructured their new mathematics programs involving rich and varied uses of multiple forms of technology, based on a rationale that included among other factors: an urgent sense of program survival, student employability, increased student engagement, more accessible and authentic mathematics, and, a desire for deeper mathematical understanding among students by using a variety of tools.

3.2.2 Structure, Curriculum, and Assessment of the Canadian TECH Program

The TECH program was first presented by an ad hoc Program Task Force Committee to the department, and subsequently the faculty, in the form of a substantial, confidential report in June of 2000. Excerpts from this artifact provide insight into the original vision and projected structure and format of the unique program that was being proposed:

> The TECH program is an innovative mathematics program that fully incorporates computers and applications into its course content. With its special attention to the role of technology, the TECH program will be unique in Canada and of particular interest to students looking for careers involving applications of mathematics and computing. We predict that graduates of the program will be in demand for their ability to apply, interpret, and present mathematics using modern tools. Our new graduates will meet the need for mathematicians who are computer literate and we anticipate that they will make significant contributions to the practice, creation, and teaching of mathematics. The distinctive new courses in the program will be TECH I, II, and III. These three courses are dedicated to the TECH philosophy of using technology as a tool to solve mathematical problems. In addition, the TECH required core consists of a 3-term calculus sequence, Linear Algebra, courses in Statistics and Optimization, and courses in Differential Equations and Numerical Methods. Students can take additional math credits to create areas of concentration in Applications of Math, Education, Pure Math, and Statistics. (2000, p. 1)

The proposal goes on to list six guiding principles of the new curriculum: (i) create upward mobility, (ii) encourage creativity and intellectual independence, (iii) guarantee prerequisites, (iv) develop mathematical concepts hand in hand with computers and applications, (v) strengthen preparation for graduate school, and, (vi) strengthen ties with other departments (pp. 2-3). In a section regarding "Teaching Philosophy," the committee clearly outlines in the proposal the kind of learning atmosphere such a program would seek to foster, and the types of learning activities in which students would be engaged.

> The pedagogical goal of the TECH program is to help students internalize a unified framework of mathematical concepts by interpreting them numerically, visually and computationally. Lectures will focus on motivating and applying mathematical concepts as much as possible. Students will have the opportunity to work closely with professors. To encourage creativity, the three TECH courses will challenge students with difficult projects that require them to develop their own strategies for handling complex real world mathematics problems. As part of the TECH program, students will be expected to master at least one programming language (JAVA) along with programs like MAPLE and statistical packages like SAS. We expect to graduate mathematicians who are curious and continue to create and apply mathematics throughout their careers. (p. 4)

The new program was approved shortly thereafter with the first set of TECH program students beginning in September 2001 (see Appendix B for details of the required courses for the Honours TECH degree program with four possible streams). The first year fall calculus course was taught by [BP15], and was based primarily on the interactive calculus software package that he had developed while on sabbatical leave in United States. This course provided students with rich, diverse experiences of mathematics learning through the use of this software. It extended into the Winter term with a second calculus course. Year 1 students also took a Linear Algebra course in the fall term, followed by the TECH I course in the Winter term, in which they learned to design and program (on desktop computers) interactive learning objects to investigate conjectures and complex real-world problems. This represented the students' second such exposure to a project-based approach to mathematics learning and assessment, the first being the use of the interactive calculus software during the first term. [BP18] described the nature of the TECH I course that she had begun to teach.

> In the class, it's very interactive … you're trying to help students to have some confidence to conjecture, to raise questions. It can't be at the same pace as our traditional math university courses, so it slows it down. So, we start with a real world situation that they have to research, they have to decide on a strategy. How will you test that? What do you want to do?" If the model has too many parameters, if it is too complex, then I will say, "Okay, let's fix this parameter, let's use a constant here. What is important is that the students have to have an idea of how to use the computational and visualization potentiality of the programming language with the interface, in order to address the question - the real world situation. It's exploration of a self-stated conjecture. Some students are more independent learners than others. This personalized aspect, which is new to them for a mathematics project, I think it has a positive impact on the student. (BP18, PD17, para. 42-166)

The designer of the interactive calculus software further described the TECH I course by stressing that students at this point begin to program their own interactive creations.

> They already had a really fun experience with interactive objects [interactive calculus DVD in Fall term], and so we find that it's really no leap from that experience to, "Go and make your own," with a few clear guidelines. It begins with basic programming. When you're doing any kind of creative work, it's so

> important that you are completely positive. In fact, no one can ask a bad question in my class. When you ask a student to take this kind of risk you had better be there and saying, "This is amazing - what a neat idea!" And then the questions come, "Well, I want to test this, but how would I do that?" Then you start working through strategies. Students are willing to invest in this in a way I've never seen before. It's a different kind of mathematics. In five to six weeks we've got everybody up to speed on the [programming] basics. They're learning Visual Basic in the lab, but at the same time we're trying to create a universe of interesting problems that they can explore using their programming knowledge. (BP15, PD28, para. 110-280)

In Years 2 and 3, students took the TECH II and III courses, respectively, alongside other more traditional mathematics electives. [BP15] described the TECH II course that was heavily focused on modeling.

> TECH II is more independent. We don't teach any programming. What do we cover? Every kind of simulation and modeling you could think of, we do in that course. I teach it with [BP14] right now. We teach it independently. I mean, because he has his favourite models, and I have mine. So, we generally team teach it. It's really great. The first project is about data fitting so they have to write a program. Everything here is programmed in Visual Basic, and it always has a visual component, so there's usually a graph or graphics attached to the text field. Ten projects by the end, and two final projects - one at the end of each term. (BP15, PD28, para. 154-280)

The second instructor of TECH II highlighted his similar but different course components and associated assessments:

> I teach TECH II integrated technology. In the first term, they use Visual Basic and in the second term, I mainly use Maple. The reason for that is that in the first term we concentrate more on discrete mathematics, I would say, and do a little bit of simulations. So, it's quick, fast execution. In the second term I do models based on differential equations, so the power of Maple is useful. I give them about five mini-projects and five assignments per term. I try also to teach them how to use computers to do exactly what I'm doing in my research, to do experimental mathematics - to analyze certain systems, and see how they behave, and to try to draw some conclusions built on conjectures about that system. They do have small tests, but they are worth not too much, only 20%, and 80% are the project assignments, and there is no final exam. (BP14, PD20, para. 20-36)

The third year TECH III course was very ambitious in its original design, yet somewhat problematic in its implementation.

> The purpose of the course was to be a finishing course in modeling that would enable the student to go into any environment - scientific, industrial, or commercial. It was to give them an enormous background in simulation, modeling, and computation. The problem with our design was you have to have people that can teach that course. The recommended books were there, but who had the expertise for that? A third-year course that is really visionary that really hits everything - that was beyond any of us. And so a couple of people took over the course, and I think they did their best. One of them used Maple, the other one used a lot of C++. They were not done, I would say, in the spirit of the first two courses. They didn't have that same sort of investigatory approach, you know, thinking about mathematics and creating interactive experiences. And in fact, the last several years here people have been trying to pull our programs out of that course, and in my opinion, this has hurt our program. For the TECH program to be viable, we really need that finishing course. (BP15, PD28, para. 304-388)

In their fourth and final year of the TECH program, according to the handbook, students were to be exposed to more advanced mathematics courses such as real and complex analysis, as well as participating in a 1-year honours thesis project. Unlike the UK site where the culminating fourth year was described in some detail, very few comments were made regarding the fourth year of the Canadian program, perhaps since few of those interviewed were actually involved in teaching the Year 4 courses, or simply owing to the fact that we as researchers did not sufficiently probe this area during the interviews.

3.2.3 Challenges Faced in Developing and Implementing the Canadian TECH Program

The challenges, both external and internal in nature, that were experienced at the Canadian site, were similar in certain respects to those discussed in the UK scenario. We will focus on four main areas in this section: (i) a Ministry of Education change that had far-reaching implications on university mathematics departments; (ii) university tenure and promotion practices that tended to favour research over teaching; (iii) debate among mathematics faculty as to the balance between traditional, abstract mathematics and the use of technology for instruction; and, (iv) the ability to maintain a cohesive vision within an expanding department in which new hires may or may not agree with the TECH philosophy.

As we saw in the UK scenario where a national educational change in 2000 involving secondary school mathematics program structures had widespread, ripple-effect ramifications for university mathematics programs, so too in Ontario where the (then) Ministry of Education and Training had phased out the longstanding fifth year of secondary school first by canceling Grade 13 in 1984, then by eliminating the subsequent Ontario Academic Credit (OAC) system completely in 2003. Although many students would still choose to complete a "victory lap" (5th year), the overall effect on mathematical skills was noticeable: "It use to be in Ontario there was Grade 13, and about '90 or '91 I think they changed it. OAC was supposed to be more challenging, but actually I think it was the other way around. That seemed to be the start, and from then on they gradually slid" (BP3, PD29, para. 13-15). According to another participant, the weak student skills came "mostly from the omission of Grade 13, because they've lost an entire year of math. I think probably math is hardest hit by that change. And now it can't possibly make that up in four years, I don't think" (BP17, PD23, para. 24-36).

Another external challenge was the fact that university administration was seen as not adequately valuing teaching practice or related research, in terms of existing tenure/promotion policies, whereas "pure" research was clearly rewarded. As [BP16] noted, "I think that the administration will have to understand that the way you value research in promoting someone, you have to also value good practices in teaching. And also faculty who want to engage in a solid way in the implementation of technology must be given incentives to do it, in terms of course release - that is not happening, and it's a huge part of the problem" (BP16, PD15, para. 225). Not only were universities seen as being guilty of not encouraging a focus on teaching or related research, but [BP11] also noted that part of the problem hinges on the way in which mathematicians often prefer to work in isolation, rather than as part of a team.

> That's the problem with mathematics departments, in the sense that a PhD is very individualistic. Once you've completed your PhD, you come into a department and you're now expected to work with other people. Mathematicians are not very good at that. People are not driven to work together, and so developing a systemic change is a really major problem. Mathematicians are not good at developing philosophies of education at all because they have their [focus on] research. Even though universities say they value teaching ... they haven't found a means to engage faculty in teaching in the same way as they are engaged in research. The kinds of things that they offer for improving teaching seem fairly artificial. (BP11, PD27, para. 26-38)

With multiple hires over the past few years and an expanding program, it became increasingly difficult for the department to ensure that those hired would be sympathetic to the special technology focus of the TECH program. For example, as we interviewed the 19 participants it became quite clear that individual faculty members held quite different views about the role of technology in teaching and learning, as well as about how and if traditional mathematics teaching should be balanced with a more technology-based approach.

> Overall, it seems the by-hand part has been downgraded. Like, are you just going to do a few integrals by hand, and a few integrals by Maple, and that's it? Or are you going to do them by hand, and then by Maple, then compare the answers, that sort of thing. Even how much Maple is going to be in the courses seems to be a personal preference. That was my hope, that they still learn it by hand. Then you get, "Okay, I know it by hand, now I'll just save time and use the computer to do it." But that really hasn't happened. It's sort of like, we've got the computer, so why bother teaching them by hand? (BP3, PD29, para. 78-82)

Other faculty sounded much more torn in terms of their beliefs about both mathematics learning and the role of technology:

> It's not so easy to combine both. First of all, with the help of technology we can, I think, attack some problems which we were not able to attack before. We can think about insight into complex systems which are not accessible by traditional pen-and-paper mathematics. But I have a feeling, sometimes, that if you just do that, if you just show them simulations, experiments, and nice graphics they do like it, but I'm not sure they get too much from it. In mathematics you could say that computers are amplifiers of skills that students have. But if they have no skills, computers don't amplify them because there is nothing to amplify. After eight years of teaching, I realize that it's hard making use of technology effectively. (BP14, PD20, para. 44-72)

Another professor, while admitting that modeling was essential for most math-related occupations, seemed to equate only traditional paper-and-pencil calculations with "hard work," "proficiency," and "understanding."

> Right from the start, I thought this was a good idea. The only thing I'm disappointed in - I envisioned it just as a tool, I didn't envision it as an end in itself. [Technology] is only as good as what the mathematician does in incorporating it into the model. The computer allows us to do something that we couldn't do before, because it would take too long. I get the impression that some people ... are thinking that there's something magical about having a computer. I just view them as tools. They're not a substitute for hard work, for understanding, or for reading. Computers are getting to be a great distraction for students. (BP3, PD29, para. 30-172)

Tied to the challenge of mixed opinions among faculty as to the place of technology in mathematics learning, is the ability of a department to strategically hire faculty members who would share the original vision of the new program. At the time of the interviews, following the retirement of [BP11], the "father figure" of the TECH program, even with the hiring of his enthusiastic replacement, [BP18], it was clear in interviews with both newer faculty and with those from among the core group, that it was getting harder to maintain the original vision and program structure with the changing faculty attitudes.

> It's harder to teach with media and technology because there's pedagogy around it. You have to believe in it, and you have to know how to integrate it. These are all people of great integrity and ability

> but, you know, everybody has different ideas. It's not that they're bad, it's all good. What's amazing about TECH is that we had enough people going in the same direction at one time. It's like a fluke, right? To have all these people say, "Let's do this," and then have a department vote it in. It was amazing. But now we have, you know, more applied mathematicians, statisticians, pure mathematicians, and TECH isn't in their thinking, and I understand why not. So, we may be just down to the two courses [TECH I, II], and there have been the initial questions now about the second year course. Should our students have to take it? That's come from the pure mathematicians, asking, Why are they doing a course in simulation modeling? It's a fair question. (BP15, PD28, para. 110-112, 396)

At the time of the interviews, the department had just voted to remove the third-year TECH III course from the list of the core/required courses. The department Chair who had politically helped make TECH possible sympathized with these needed changes as he further explained:

> So, in my view we cannot impose a core course, which is surely a TECH course, but is basically PDEs [Partial Differential Equations]. I was very, very sad that it not remain a core course, but the reality of the course imposed that. It's compulsory for the students in the applied and computational math stream, and it is recommended for the students in the pure math stream, but it's not "core" anymore. (BP16, PD15, para. 181)

Another internal challenge had been the changing attitudes of the students themselves regarding technology, in terms of both increased access via portable laptops/devices, and a desire for Internet access and the new forms of technology.

> In terms of using computers, though, back in 1988 when we started, the labs used to be packed. We use to run labs in every course when we first brought in the technology. Now we don't, and those courses are our math major courses mostly, because we found the attendance was dropping. People were using their own computers, using the technology on their own. It use to be a novelty. Yes, the labs now have Internet. That [social media distraction] certainly has become an issue. We still run labs in our first-year calculus course, but we've seen a pretty steady decline in attendance there as well. (BP17, PD23, para. 24-36)

In summary, both external and internal challenges were encountered such as Ministry of Education changes to secondary school curriculum; university tenure/promotion policies that valued research over teaching; instructor beliefs about "proper" pedagogy (i.e., the "balance" between traditional mathematical skills and technology use); and, the changing nature of technology access and student expectations regarding the newest products and services. Finally, we now turn our attention to some of the successful strategies that were adopted by members of the core group within the revised TECH program.

3.2.4 Successful Strategies in Developing and Implementing the Canadian TECH Program

In terms of successful strategies for implementation and growth, we noted a similar set of four cluster areas that had also been evident in the UK site, namely, a focus on revisiting program and curriculum issues via the regular meeting of a Curriculum Committee; a focus on student satisfaction and student-teacher interaction (with the creation of a Mathematics Help Centre); a focus on classroom-based faculty research and publications/presentations; and, a focus on strategic hiring, where possible.

One successful strategy was the creation of a Curriculum Committee which had originally been struck by the Chair to undertake to plan for the new program, but in more recent years had served as a mechanism to revisit original goals and monitor the implementation successes and difficulties as the program had continued to grow. [BP18] described the active nature of the committee and also the difficult discussions that had gone on within the meetings, and within the department.

> Every year that I have been there we've been reviewing courses. When we revise a course - we're revising a course, we're not revising a colleague's teaching practices. But for some people that may be confusing. And it happens that some of my colleagues are uncomfortable with that, and they will confuse the two, and they will be a bit defensive. We're very close to academic freedom here, right? So, that's always the dangerous zone. Our core courses all have a [description] that says there's use of technology in the course. So, it is no longer dependent on the instructor - it is part of the course. But I could use Maple in two very different ways in the same course, and [students] would not at all get the same experience using that technology. It's not easy. Really, there's some discussion sometimes where you think the room is going to explode. (BP18, PD17, para. 176-180)

Similar to the UK site, the Canadian mathematics department considered the focus on student satisfaction and positive student experience to be critical. One faculty member describes her open door policy with students, which seemed to be a familiar practice among faculty at both case study sites: "I think students come to [our institution] from everywhere. The advantage is that it is friendlier and that individually we spend more time with students. I have my office with an open door policy - anytime they can come in and talk to me - like friends" (BP9, PD24, para. 64). One of the central characters from the Canadian program revision, [BP15], described what he felt were the essential qualities of a student-centred pedagogy that would best support the technology-based mathematics program, given the nature of today's students:

> I think the most important thing I want to say is that teaching, for me, is a very human thing. And when you're teaching a program like TECH, you've got to be working one-on-one with the students, and you have to be truly interested in their work. You can't just throw a theory up on the board, run away back to your office. We're constantly sitting down beside them at the computer saying, "Whatcha doing?" and "Where are you stuck? I am troubled by the fact that we're teaching a group of people who … learn differently than we do. These students don't say, "Oh, where is it in the book? - just let me read it." They don't learn like that. They want to play with it, work with it, talk about it, and do it in a group. (BP15, PD28, para. 400-410)

Students were also supported with a Mathematics Help Centre, much akin to the similar one described at the UK site: "It was decided that the department would offer a Help Centre where the students could go on a daily basis and ask questions for their learning" (BP18, PD17, para. 86). Another method that they had used to help focus on student satisfaction was a comprehensive exit survey of the first set of TECH graduates. The Chair noted: "Our first glimpse is quite encouraging. For the first cohort that we started in 2001-02, and completed in 2005, we conducted quite a comprehensive survey" (BP16, PD14, para. 277).

In both the UK and Canadian sites, participants shared that university policies on tenure and promotion often were perceived as favouring faculty work done in the area of pure mathematics research over that done in teaching-related areas. Notwithstanding, mathematicians at both sites still chose to pursue active research projects relating to teaching practices and the use of instructional technology. The dissemination of such research by way of publications and conference presentations served to further the goals of the TECH program. [BP18] described how, as a newly-hired, tenure-track faculty member, she found the support received from colleagues for early teaching and research endeavours to be positive and essential.

> I would say that support is crucial, especially for newly arriving faculty members. You're still tenure-track, then you have so much to do, so much pressure to accomplish, to publish, and so on. And I guess if you don't have the support of your colleagues, you won't. And especially if your colleagues think that time spent on teaching is wasted time, I don't see how you can focus on it. Of course, when someone is tenured, then they can decide if they want to spend more time on teaching, or not. In my case, it was in the job description, and it was clear during the whole interview that they were looking for an instructor of TECH courses. (BP18, PD17, para. 98-118)

Strategic hiring, while arguably an important part of building a cohesive department, also has its inherent limitations. The Dean noted his support of a focused effort to maintain the TECH vision regarding the "teaching modality":

> I think the successes really come down to how [BP15] continues to teach in the department. [BP18] came on board as the department's replacement for [BP11], when he retired. And so I think one of the hiring triumphs was the recognition by the department that having this stream in the department was a valuable contribution. From my perspective as Dean, I think it's important for the health of that department to make sure that modality of teaching mathematics continues. (BP19, PD16, para. 36)

The recently retired professor, [BP11], who had tirelessly prepared the way for the new TECH program for over two decades, offered his own insights into the importance of, yet also the difficulties inherent to, the hiring process:

> Hiring in specific areas is important. It's a divisive thing. This person has no experience, he's coming, and he's told you he's not interested in teaching technology, and yet some people are attracted because of his research, and so on. It's all right if he's coming into a research group, but it's not all right if he's coming into the TECH system. You need to have Chairs that are sufficiently strong, who are going to defend and provide the support. It grows slowly. (BP11, para. 218-252)

In this section, we have looked at several of the more successful strategies employed by the Canadian mathematics department to foster the technology-rich TECH mathematics program. A focus on student-centred learning, especially in the TECH courses, had led to positive student feedback. Members of the mathematics department had made major strides in introducing a rich, unique pedagogical approach to technology-enhanced teaching, especially within the innovative TECH courses, often sharing their successes through publications and conference proceedings. Despite best efforts and the strong leadership of the Curriculum Committee, it was clear that by the time of our research, proponents of the program were indeed struggling to defend the original vision and related course structures of the TECH initiative amidst a growing number of new faculty, some of whom questioned the relevance of the technology-based curriculum. The reality and challenge of this ongoing struggle is instructive, in that it shows us how truly difficult it is to maintain departmental reform at the post-secondary level.

4 DISCUSSION

In this section, we directly compare and contrast the two case study sites according to the various categories that we have already visited independently throughout the paper.

Whereas the UK program was created as a newly designed mathematics degree in 1996, the Canadian TECH program represented a drastic revision of an existing mathematics degree in 2001. Both programs involved a core group of individuals highly committed to a central vision that involved the inclusion of multiple forms of available technologies in all aspects of the mathematics curriculum.

Modeling and exploration of real-world (i.e., messy yet relevant) problems would form the heart of both programs, complementing the more traditional mathematics focus on paper-and-pencil calculations and proof.

Rationales for change at both sites included the following factors: *survival* as a program/department, *employability* of students based on specific learned competencies; the recognition of a mathematics skills *deficiency* in many incoming undergraduates, and an accompanying desire for increased mathematical *accessibility* via technology for these students; a perceived sense of higher intellectual *engagement* among the student population; and, a firm belief that *enhanced mathematics understanding* was the direct result of a more "balanced" approach to both curriculum and assessment.

Within this core group, we were able to identify three archetypical characters that each played critical roles in the preparation, implementation, and maintenance of the new/revised degree programs, and we have referred to these individuals as the *Long-term Leader,* the *Roving Radical*, and, the *Pensive Politico.* Basically, a dedicated patriarch or "father figure"; an intrepid researcher of technological advances that ventured beyond the university to bring back new and relevant ideas to the committee; and, a wise, politically-savvy individual who was able to provide sage advice and/or direct intervention in order to see the reform effort successfully dribbled (UK), or stick-handled (Canada), through the various obstacles involved.

Due to the strengths and interests of senior teaching faculty, the UK program clearly favoured Microsoft Excel spreadsheet software as the main focus of mathematical explorations, particularly in the final year of the program. At the Canadian site, a combination of Maple software for CAS manipulation and calculation, and programming languages such as Visual Basic, C++, and Java were all used depending on the course content and instructor preference. The UK site focused heavily on the preparation of Year 2 students, via special lectures and individual support, for an optional third year "sandwich" work placement outside of the university. Although presented as optional at point of entry to the program, this workplace component was participated in by many of the UK students, and, according to faculty, resulted in several major benefits among which were a marked difference in student attitudes/maturity upon return for the final year of the program; and, an opportunity for the department to consistently check program/course content against the realities of the workplace. In the Canadian site, where the designing, programming, and use of interactive learning objects for the investigation of conjectures and complex real-world problems became a central focus, students were intended to graduate as expert modelers of a wide variety of "authentic" mathematical problems, as well as proficient users of CAS (e.g., Maple) and other technologies.

Challenges in both the Canadian and UK mathematics departments were shown to include elements that were both external and internal in nature. National and provincial changes to public school curriculum policies were discussed as leading to significant ripple-effect ramifications for university mathematics departments, such as was noted in the "Curriculum 2000" changes in the UK, and the 1984/2003 termination of the fifth year of highschool in Ontario, Canada. University-level challenges took the form of administrative policies that reportedly handicapped the mathematics department at the UK site in terms of website control, course assessment policies, and marketing limitations. At both sites, the Deans and Department Head/Chair clearly supported the technology-enhanced undergraduate mathematics program initiatives.

The internal challenge of maintaining open communication and debate among mathematics faculty, many of whom shared with us their own uncertainties as to the best place/role of technology within a mathematics program, was shown to be significant and increasingly difficult in both the UK and Canadian departments. Even those within the original core group at both sites had certain reservations or questions about what an ideal "balance" of traditional and technological mathematics programming might/should look like, and what effect the new curriculum was ultimately having on student learning. Clearly, as increased hiring of new faculty at the Canadian site took place over time, the ability of the TECH leadership to defend the original rationale and vision of the technology-based program was continually under fire, or being quietly undermined.

Finally, the changing nature of new technology itself represented an ongoing challenge for both the UK and the Canadian mathematics departments. Flexibility and forward-looking vision on the part of the core group leadership was shown to be very significant in terms of the longevity of both programs. As laptop computers and hand-held devices became more readily available to students, the once critical computer lab experiences at both sites tended to dwindle in terms of student participation, sometimes leading to lab cancellations or at least modifications. The advent of the Internet, Web 2.0, and wireless connectivity was shown to bring about both advantages and new challenges, allowing students to communicate (with instructors and among themselves), upload/download files, and conduct web-based research at distance. Certain efforts to continually tailor the mathematics degree programs to these new technological advances were successful, while others proved to be too expensive, expansive, or unpopular among voting departmental faculty members.

Successful strategies at both sites included a focus on: (i) the maintenance of the core group, (ii) student engagement and satisfaction, (iii) research and publications based on teaching innovations and classroom practices, and, (iv) strategic hiring, where possible. In the UK, the small core group not only met professionally on a regular basis, but also enjoyed socializing together off-campus, often times discussing elements of the program reform during these less formal gatherings. At the Canadian site, where the numbers of full-time faculty had swelled, and the *"Long-term Leader"* had recently retired, the cohesion of the core group, although persistently nurtured through the regular meetings of the Curriculum Committee, was noticeably fragmenting.

Upcoming retirements and related new hires to take place at the UK site made core members anxious about the possible ramifications to the program, as they would soon move through a similar demographic cycle.

Both the UK and Canadian course instructors (i.e., of the technology-based courses) highlighted the essential one-on-one nature (i.e., teacher-to-student) of a project-based, technology-rich curriculum, a model described as standing in stark contrast to the more traditional blackboard "lecture and leave" approach. Students at both sites were encouraged to avail themselves of the existing open-door policy that were held by many of the core faculty involved, and both sites offered a Mathematics Help drop-in Centre for students. At the UK site, online learning logs were adopted to increase the communication between faculty and students, although this initiative was used in varying degrees by faculty and became more difficult to administer as numbers grew. Both sites made use of the Internet in terms of creating instructor websites for posting files and announcements, as well as student websites where digital assignments could be showcased for assessment and peer sharing.

Rather than being restricted to more "pure mathematics" research and dissemination, faculty who were proponents of the technology-based programs at both the UK and Canadian sites frequently published research relating to the scholarship of teaching, particularly with technology, and likewise regularly presented their ideas at conferences. While these efforts were recognized and celebrated as vital and significant at both the departmental and faculty levels, the university tenure and promotion processes were described as not always valuing these efforts in the same way that "pure" research was rewarded.

Although strategic hiring of new faculty who would continue to promote the technology-focused programs at both the UK and Canadian sites was recognised as an important goal for sustaining the initiatives, the difficulties inherent in this process, such as urgent needs for faculty replacements (often for non-tech courses), and the fact that promises made during interviews did not necessarily, in the light of academic freedom, result in equivalent post-hire classroom practices, sometimes led to divisive departmental discussions and to unsatisfactory results over time.

5 CLOSING THOUGHTS

Technology has changed the world in which we live. A cell phone today can perform more complex calculations than the first city block-sized computers. Technology permeates our society, affecting nearly all aspects of our lives. We submit that now is the time to further examine both the potentialities and ramifications of large-scale technology integration in mathematics education at the tertiary level. As we have seen in the two detailed analyses of both case study sites, certain areas of overlap and similarity have been evident within the areas of program rationale, curriculum and assessment practices, obstacles that must be overcome in planning and implementation, and key strategies that were found to be particularly successful.

What has emerged from the data analysis of the interview transcripts and artifact analysis from the two sites is that sustained long-term shifts in departmental technology use in mathematics instruction appear to require the following components for successful implementation: a key proponent in a position of influence/power (e.g., Head/Chair, often supported by one or more energetic, technology-savvy radicals and well-seasoned politicos); a strong and shared incentive for change; strategic hiring practices, where possible; an administration which supports creative pedagogical reform and well-considered risk-taking; and, a continuous and determined revisiting of the original program vision. We have also learned that despite the best and tireless efforts of the core group leadership, the growth in faculty numbers and program scope within a healthy department, the implications of academic freedom on teaching practices, and the inevitable retirement of key players, makes the process of program maintenance and long-term coherence much more challenging at the university level.

Although we can offer no simple algorithm for a successful transition to a technology-enhanced mathematics degree program, the following four activities may prove beneficial for a department that is serious about systemic change: (i) conduct some form of departmental self-analysis regarding existing practices, resources, and instructor beliefs/goals; (ii) arrange for a professor who is based within a technology-rich environment, like the ones described in the paper, to visit your faculty for a series of talks/workshops, and/or arrange to send your own representative(s) to such a mathematics faculty in order to observe both the teaching and the student learning; (iii) make it a point to obtain and share key articles, in order that current trends can be shared and discussed at departmental meetings; and, (iv) in order to sustain changes, include in the criteria for hiring new faculty the technology-enhanced teaching direction/philosophy that the department has taken.

We trust that our case study research will potentially assist other mathematics departments in the difficult, yet meaningful and perhaps long-overdue reform of mathematics departments in light of 21st century technology and trends.

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BIOGRAPHICAL NOTES

Dr. Daniel Jarvis is Full Professor of Education in the Schulich School of Education at Nipissing University, Ontario, Canada where he teaches in the graduate and undergraduate programs. His research interests include instructional technology, integrated curricula, teacher professional learning, and educational leadership.

Dr. Zsolt Lavicza is an Educational Researcher, teaching research methods and mathematics education in the Faculty of Education, University of Cambridge, UK. In addition, he is the Director of Research for the International GeoGebra Institute and the GEOMATECH Project. His research interests include educational technology, quantitative research methods, and teacher professional learning.

Dr. Chantal Buteau is Associate Professor in Mathematics at Brock University, Ontario, Canada. While her first research area is Mathematical Music Theory, she has become progressively involved in mathematics education research. Chantal has collaborated with mathematics educators on a number of research projects focusing on instructional technology, university mathematics teaching/learning, and the education of future mathematics teachers.

Appendix A: Guide for Case Study Interviews with Mathematics Faculty and Administration

Mathematics Professors at the Case Study Institution

1. How do you use technology in your own research? Which technology do you use and why? Do you think that technology has changed mathematics, if so, how?
2. How do you use technology in your university teaching? How do you choose which technology to use in your teaching? According to you, what are the benefits of using technology with respect to student mathematics learning? What are the pitfalls? Are/were there issues when integrating technology in your teaching?
3. Describe your involvement in the integration/use of technology in your undergraduate mathematics program.
4. What do you perceive as the benefits of the systemic integration of technology in your mathematics program for student mathematics learning?
5. What do you perceive as historical/current obstacles or drawbacks of this systematic integration?
6. Do you have any other comments or recommendations pertaining to this systemic integration?

Administration at the Case Study Institution (Dean/Chair/VP?)

1. Describe your involvement in the systemic integration of the technology in mathematics education at your institution. According to you, what technology or technology use has the greatest impact on student mathematics learning? In what ways?
2. From an administrator's point of view, what do you perceive as the benefits to this approach to mathematics learning? Has this change affected your programs and enrolment? If so, how?
3. What do you perceive as historical/current obstacles or drawbacks of this systemic integration of technology?
4. Do you have any other comments or recommendations pertaining to this systemic integration of technology?

Appendix B: Program Course Requirements for the UK and Canadian Case Study Sites

United Kingdom BSc Mathematics Degree Program

Note: To obtain a BSc, students must accumulate 360 credits, 120 at each of levels 4, 5 and 6.

Year 1 (Level 4): All modules 20 credits, except where stated

Semester 1	Semester 2
Mathematical Modeling; Mathematical Technology; Number and Structure; Mathematical Methods; and, Statistics and Probability	
Elective 1: Maths Workshop 2 (10); History of Maths (10); Exploring the Universe (10); or, a Modern Language course	**Elective 2:** Basic Computer Programming (10); Dynamic Geometry (10); or, a Modern Language course

Year 2 (Level 5): All modules 20 credits

Semester 1	Semester 2
Modelling 2; Linear and Discrete Mathematics; Dynamical Systems and Fourier Analysis; and, Statistical Methods	
Elective (choose one): Analytical Research Methods; Business Mathematics; Optimisation Methods; Programming for Excel and the Web; C and C++ Programming; or, a Modern Language course	

Year 3 (Industrial Placement)

Year 4 (Level 6): All modules 20 credits, except where stated

Semester 1	Semester 2
Project (30); Advanced Mathematical Case Studies	
Professional Development (10)	
Elective (choose three): Digital Signal Processing; Modelling with Partial Differential Equations; Fluid Flow; Tensors; Control Theory; Multivariate Statistics and Data Mining; Statistics for Business; Scheduling Applications; Advanced Web Programming and Parallel Computational Mathematics; or, a Modern Language course	

Canadian BSc Combined TECH and Math Specialization Honours Degree Program

Note: At the time of the research data collection in 2009, the TECH III course was no longer listed as a required course.

Year 1

Term 1	Term 2
Linear Algebra I; Calculus I	TECH I; Calculus II

Year 2

Required by all math students: TECH II (full year); Linear Algebra II; Calculus III; Ordinary Differential Equations; Probability; Statistics I
Pure Math Stream: Intro to Analysis; Abstract Linear Algebra; Discrete Optimization
Applied Math Stream: Intro to Analysis; Discrete Optimization
Statistics Stream: Experimental Design; Euclidean and Non-Euclidian Geometry I; Intro to Financial Math
Education Stream: Intro to Combinatorics; Euclidean and Non-Euclidean Geometry I; Great Moments in Mathematics I; Mathematics and Music

Year 3

Pure Math Stream: Intro to Combinatorics; Real Analysis; Complex Analysis; Group Theory; Abstract Algebra; Game Theory; Intro to Topology
Applied Math Stream: Complex Analysis; Advanced Differential Equations; Partial Differential Equations; Group Theory; Numerical Methods; Continuous Optimization; Theory of Financial Math
Statistics Stream: Experimental Design; Regression Analysis; Statistics II; Applied Multivariate Statistics; Advanced Differential Equations; Partial Differential Equations
Education Stream: Group Theory; Euclidean and Non-Euclidean Geometry II; Math at the Junior/Intermediate/Senior Level; Great Moments in Mathematics II; Abstract Algebra

Year 4

Pure Math Stream: Advanced Real Analysis; Topics in Groups; Combinatorics; Topics in Number Theory and Cryptography; Topics in Topology and Dynamical Systems; Topics in Rings and Modules; Honours Project
Applied Math Stream: Intro to Wavelets; Topics in Differential Equations; Solutions and Integrability of Nonlinear Evolution Equations; Topics in Stochastic Processes and Models; Topics in Advanced Statistics; Honours Project
Statistics Stream: Sampling Theory; Nonparametric Statistics; Topics in Stochastic Processes and Models; Topics in Advanced Statistics; Honours Project
Education Stream: Combinatorics; Topics in Groups; Topics in Rings and Modules; Advanced Mathematical Structures; Honours Project

Notes: *Courses are subject to availability; additional courses are required in order to complete degree requirements, as listed in the Academic Calendar*