Integrating Computer Algebra Systems in Post-Secondary Mathematics Education: Preliminary Results of a Literature Review

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We present results of a literature review pilot study (of 326 papers) regarding the use of Computer Algebra Systems (CAS) in tertiary mathematics education. Several themes that have emerged from the review are discussed: diverse uses of CAS, benefits to student learning, issues of integration and mathematics learning, common and innovative usage of CAS, and integration scope in university curricula. Our analysis suggests that, perhaps contrary to popular belief, CAS integration in tertiary mathematics teaching occurs most frequently in courses for mathematics majors as opposed to service courses designed for non-math majors. The types of paper contributions indicate that the theoretical framework proposed by Lagrange, Artigue, Laborde and Trouche (2003) for literature reviews on technology use in mathematics education needs to be adapted to better address tertiary education, in particular for use in our upcoming comprehensive literature review that will build upon the pilot study review reported herein.

1 INTRODUCTION

A growing number of international studies have shown that Computer Algebra System (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 institutions (Artigue, 2002; Lavicza, 2006; Pierce and Stacey, 2004). In contrast to the large body of research focusing on technology usage that exists at the secondary school level, there is a definite lack of parallel research at the tertiary, or post-secondary, level. However, Lavicza (2008a) highlights that university mathematicians use technology at least as much as school teachers, and that the innovative teaching practices involving technology that are already being implemented by mathematicians in their courses should be more fully researched and documented. Further, Lavicza found that within the research literature there existed only a small number of papers dealing with mathematicians and university-level, technology-assisted teaching. In addition, most of these papers are concerned with innovative teaching practices, whereas few deal with educational research on teaching with technology. These findings somewhat coincide with school-focused technology studies conducted by Lagrange et al. (2003) and Laborde (2008).

We aim to point out that it is particularly important to pay more attention to university-level teaching for several reasons (Lavicza, 2008b). Although universities are experiencing an overall increase in student enrolment, there is a declining interest and enrolment in Science, Technology, Engineering and Mathematics (STEM) subjects (Lavicza, 2010). Also in noticeable decline is students' mathematical preparedness for tertiary studies (Lavicza, 2010). Finally, the emergence of new technologies raises the expectations of secondary school students who anticipate using software and hardware in their further study of mathematics. Mathematicians must cope with these challenges on a daily basis and only a few studies have offered systematic review and recommendations in this area.

Our research program aims at both documenting post-secondary teaching practices involving technology, and formulating recommendations for individual and departmental change. We also would like to increase the amount of attention paid to tertiary mathematics teaching, from a research perspective, and to see more related articles published which elaborate on specific issues and strategies for systemic integration of technology in university mathematics curriculum. Based on the above-mentioned Lavicza (2008b) findings and recommendations, we have designed a mixed-methods research study that involves, among other components, a systematic review of existing literature regarding CAS use at the post-secondary level (i.e., university, community college, CEGEPs - Quebec collegiate institutions, technical institutes, etc.). Our goal is to conduct a comprehensive literature review that will involve approximately 1500 papers/theses. In order to achieve this objective, we needed to develop a theoretical framework as a basis for conducting such a large scale study. As a first step, we conducted a pilot study of 326 papers stemming from two peer-reviewed journals and proceedings from two selected conferences. The aim of this pilot study was to refine our data collection template and analytical framework, both of which were based on the theoretical framework proposed by Lagrange et al. (2003) for reviewing literature focusing on technology use in mathematics instruction. Lagrange's literature review focused mainly on secondary school mathematics, thus indicating to us that their proposed framework might need to be adapted for our specific focus on CAS-based technology use in tertiary, or post-secondary, mathematics education.

In this paper, we report on the findings of our literature review pilot study. In Section 2, we describe the methodology. Section 3 provides, in addition to some basic categorical results, details about different themes that emerged from the review. In Section 4, we discuss the review results, and we conclude in Section 5 with some final remarks, including comments on a short editorial exchange between two mathematicians with clearly opposing views on the use of technology in university mathematics instruction.

2 METHODOLOGY

The theoretical framework developed by Lagrange et al. (2003) involved several stages. They first reviewed a large number of relevant articles and then categorised these papers into five “types of problématique” (pp. 242-243):

1. “technical descriptions (53%)
2. innovative classroom activities (9%)
3. assumptions about improvement (12%)
4. questions about the use of technology (21%)
5. integration (5%)”

Based on these types and on the fact that, “Most of the papers of type 1 and 2 lack sufficient data and analysis and we could not integrate them into the [detailed analysis]” (p. 242), they then selected a sub-corpus of papers dealing specifically with educational research papers (types 3 to 5) focusing on technology use, mainly in the secondary school level. Through the careful analysis of this sub-corpus of papers, they further developed seven dimensions, each with key indicators, and then proceeded to identify and further analyse papers that best described each of these dimensions.

As mentioned above, it was decided to implement a pilot study for our large literature review in order to begin to work with the Lagrange et al. framework and to determine if it would be sufficient for our purposes, or may be in need of certain modifications. In the summer of 2008, we therefore began a pilot study focusing on 326 contributions dealing with CAS use in secondary/tertiary education and technology use in tertiary education. These papers were drawn from two well-regarded journals, namely the *International Journal for Computers in Mathematical Learning* (issues since its beginning in 1996) and the *Educational Studies in Mathematics* (since 1990). We also selected proceedings from two technology-focused conferences, namely the *Computer Algebra in Mathematics Education* (since its first meeting in 1999) and the *International Conference on Technology in Collegiate Mathematics* (since 1994 with first electronic proceedings). A sub-corpus of 204 papers that in whole or in part explicitly discuss CAS use at the post-secondary level was then identified to further focus the analysis.

Based on the Systematic Research Synthesis methodology developed by the EPPI Centre at the University of London (EPPI-Centre, 2007) and guided by the Lagrange et al. (2003) theoretical framework, we progressively developed our own framework. More precisely, while the descriptive themes found within the template (Lagrange et al., 2003; Laborde, personal communication, November 22, 2007) were helpful, we began to notice that some of them would need to be adapted and several other theme columns would be beneficial at this stage of the template development. We modified sub-themes of some themes, such as “technology used” (for a description, see first paragraph of Section 3.1) and “mathematical fields” (see Figure 1). We added the following themes: “computer/calculator”, “integration scope”, “instructional purposes”, “course level”, “examples of CAS use”, and “implementation issues”. For the theme involving instructional use of CAS, we used as sub-themes the eight purposes identified by Lavicza (2008b, p. 164) in his international (US, UK, Hungary) comparative survey. After the review was completed, we decided to add the theme of potential benefits of CAS. Using our notes that we made while reviewing papers, we were able to identify and summarise the advantages of using CAS perceived by instructors and researchers. Since this theme was added after the review was completed, Section 3.3 does not include a percentage analysis.

An important point to note here is that in contrast to the Lagrange study where a significant proportion (38%) of papers were those describing educational research results, our selection of papers revealed a majority that focused on practitioner innovations with very few involving educational research (10%; see Table 1).

It became clear that we could not set aside the 90% contributions from practitioners if we wanted to fairly report on CAS-based technology integration in post-secondary mathematics education. Thus, we herein present an initial analysis of the corpus of 204 selected contributions, including the 10% educational research papers, with the aim of describing the literature on practitioner reports of technology use. We will further develop the template and the related analysis for reviewing the 10% educational research papers in a forthcoming paper. We realise that in order to complete our template for reviewing the large number (1500) of papers in the research study proper, we will have to separate the practitioner report type papers from the educational research papers, and combine and further modify the template in both of these areas.

Practitioner Reports	Presentation of Examples	46%
	Examples with practitioner reflections	20%
	Classroom Study	6%
	Classroom Survey	3%
	Examinations of a specific issue	3%
	Abstract only	11%
Education Research Papers		10%
Editorial Journal Letters		1%

Table 1 Types of contributions

3 RESULTS

The corpus of 204 papers that discussed CAS use at the post-secondary level was used for our initial analysis. While proceeding with the literature review, five main themes emerged: diverse use of technology; benefits of technology use; issues of CAS-technology integration and mathematics learning with the use of CAS; common and innovative uses of CAS (reported examples); and, CAS integration scope in tertiary curriculum. Following a brief report on basic categorical results, we discuss the above-mentioned five themes in more detail.

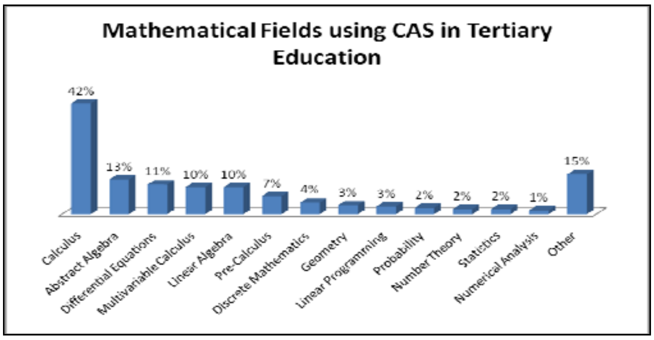

Figure 1 Mathematical fields identified in the lit review.

3.1 Basic Statistical Results

The analysed corpus was overwhelmingly American in origin, with 178 papers (88%) written in the United States, 9 (4%) from the United Kingdom, and 17 (8%) being from various other countries. In terms of the technology used, the literature review indicated that computer-based CAS was the most popular with 120 papers (59%). Only 61 (30%) solely featured the graphing calculator (with and without CAS) while twenty papers (10%) used both handheld and desktop technology. In addition, there were three (1%) papers that did not discuss a specific technology. *Maple* was the most common computer-based CAS in the tertiary literature sub-corpus with 52 references. *Mathematica* followed closely with 43 instances. *Derive* (21) and *Matlab* (11) were mentioned frequently, and less common CAS such as *MathCAD* (7), *Scientific Workplace* (4), *Study Works* (3), *TI-Interactive* (1), *GeoGebra* (1), and *Math Plus+* (1) were also included.

There was a considerable variety of mathematical fields that were identified in the analysed corpus (see Figure 1). Calculus was by far the most frequent mathematical field in which CAS was utilised in tertiary courses. Single-variable calculus was mentioned more than three times as much as Abstract Algebra, the second most widely mentioned topic. When papers dealing with first year calculus were combined with papers discussing pre-calculus and multivariable calculus courses, this accounted for over 55% of the corpus. Other areas of mathematics, such as Differential Equations and Linear Algebra were also commonly discussed in the sub-corpus. Number Theory, Discrete Mathematics, Numerical Analysis and Geometry were also pointed out as courses in which CAS was used.

Mathematics Majors	First Year Maths Majors	32%
	Upper Year Maths Majors	24%
Engineering and Science Majors		4%
Teacher Education Majors		2%
Other Program Majors (e.g., Business Majors, Social Science Majors)		2%
Unstated Undergraduate Program		37%

Table 2 Student audience for CAS integration/instruction

The integration of CAS in tertiary teaching reported in the literature was aimed at different student audiences (see Table 2). The majority of reported CAS integration occurred within courses for mathematics majors (56%). Several papers specifically mentioned engineering and science majors, teacher education majors, or other program majors (total of 8%), whereas the remaining (37%) didn't explicitly specify any particular student program.

As noted earlier, diverse contribution types became apparent during the literature review (Table 1). The majority of the papers in the corpus were practice reports by practitioners (88%), whereas the education research papers were in a significant minority (10%). A rather passionate journal editorial letter exchange between two opposite views on the integration of the CAS graphing calculator completed the corpus (1%) and will be briefly commented in Section 5. Among the practice reports, different types of contributions were identified. Some (46%) were merely examples of CAS usage without any analysis or reflection. However, other papers (20%) did feature examples of CAS which included reflections by the practitioner. A few (6%) had the practitioners go further and included classroom data, upon which they performed some basic analysis. There were also papers (3%) that focused on classroom surveys and a small set (3%) that examined in detail a specific issue of CAS integration in the classroom. The remaining contributions (11%) were conference abstracts.

3.2 Diverse Uses of CAS-based Technology

Diverse instructional purposes of CAS were reported in the literature. These results are summarised in Table 3. The most widely reported purpose was tertiary-level practitioners using CAS to provide an experimental laboratory for students in which they could *explore mathematical objects*. Kunyosying (1998, p.1) reported that *Maple* can "be effectively used in the undergraduate abstract algebra course to encourage the discovery of mathematical ideas through guided experiments." At the University of Texas, Dogan-Dunlap, "has been implementing an online laboratory approach in a matrix algebra section." (2003, p. 4). He emphasised that an inquiry-based online approach allows students to "come to class better prepared for discussions on relevant topics, which seems to help students better understand the material covered in class" (p. 5).

Experimentation and Exploration	63%
Visualization	59%
Real and Complex Problems	50%
Instructor preparation for Homework and Assignments	16%
Group Work	9%
Conceptual Discussions	8%
Student Motivation	8%
Checking of solutions and problems by Instructor	3%

Table 3 Instructional Purposes of CAS-based technology

Cnop (2003, p. 2) argued that, "Mathematics has always been an experimental science and its foremost interest has been in the prediction of behavior of complex systems, from Babylonian astronomy to post-bubble finances." He links experimentation with the *exploration of "real-world" problems* reporting that, "Thanks to the introduction of technology this functionality is again possible. . . . Students can rephrase (simple) real-world problems, leave computing to the software and focus on the qualitative analysis of the result and understanding." Real world and complex problems constituted the third major purpose of CAS usage discussed in papers (50%) encountered in the review.

The second most widely reported use of CAS (59%) was *visualisation.* This can range from simply plotting graphs (e.g., Putz, 1995, p. 1) to producing more complex animations to illustrate a mathematical concept. Blyth (2004, p. 1) wrote, "We use the visualisation and animation capabilities of *Maple* throughout our courses. Animations are used in presentations in class from first year onwards." He reported that RMIT University uses these animations to explore many mathematical undergraduate topics, such as illustrating how slicing is used to generate the domain for double integration or to exploring Newton's Method.

3.3 Potential Benefits stemming from CAS usage in tertiary mathematics teaching and learning

The literature contained a diverse set of motivations and goals expressed by professors regarding the integration of CAS into the tertiary classroom. The emphasis by practitioners and researchers in the corpus was focused on *how CAS can benefit students pedagogically*, although concerns such as enrolment and student preparedness for courses were also noted. Some of the most common potential benefits of CAS usage identified in the review as follows: promoting a greater understanding of mathematics (in particular through an easy and quick shift between representations of mathematical objects or by refocusing instruction away from tedious calculations to more conceptual understanding); supporting students' development to achieve and learn independently; increasing student motivation to learn; facilitating harder and more realistic mathematics at earlier levels; and, being responsive to the 21st-century work place needs.

After integrating Derive into the calculus curriculum Weida wrote that "Students found having a second approach to the material aided their comprehension" (1996, p. 4). This increase in student comprehension can be linked to better student attendance/retention in STEM courses. Alexander (1996, p. 2) justified the implementation of a Mathcad-based open classroom setting: "Our philosophy is that college algebra should be a pump not a filter. Improvements in this course can broaden students' selection of majors and even remove obstacles to graduation."

In particular, a frequent idea was that since CAS facilitates student understanding by allowing students to *quickly shift between numeric, algebraic and graphical representations* of mathematical objects, it should be viewed as an important pedagogical tool. For example, Savari (2005, p. 2) noted that the "effectiveness of teaching for comprehension of mathematical concepts greatly depends on using the appropriate representation. On the basis of examining the mathematical learning process, we can say that the internal representations are greatly determined by the mathematical representations." He further argued that "The multifaceted illustration of concepts and their multiple representations clearly add to the process' epistemological value. It is essential to apply as much as possible descriptive, graphical, and numerical representations." Kent (2000, p. 2) noted that "the programmability of a CAS means that we can modify and extend the representation for the benefit of learner in a particular context. That is, it is possible to build mathematical structures . . . into the fabric of the medium, thus shaping the types of action that are possible: they do not only exist in the mind of the learner." At Sheffield Hallam, Challis (2001) observed that for his students, a CAS object;

> may be a computer-generated mathematical one, or it may be generated by gathering real or nearly real world data and attempting to abstract mathematical ideas from that. To have this wider possibility for expression acknowledges that with a more diverse range of students we need to have a variety of possibilities for motivation. (p. 8)

Another aspect of CAS promoting greater student understanding of the material, was that CAS can also be used as a means of *refocusing instruction away from tedious calculations to more conceptual understanding.* For example, Schlatter (1999, p. 8) noted in his calculus class that, "the main advantage of using CAS was in allowing myself and the students more time to focus on setting up the integrals. I felt more able to cover a wider variety of integrals in class, and the students who used CAS could focus more time on finding the limits of integration." Dreyfus and Hillel (1997, p. 108) agreed that CAS saved time, arguing that "without a system such as *Maple*, the computation of the definite integrals for the inner products would have been time-consuming, prone to errors and not very relevant to understanding the topic."

In describing the use of CAS as an experimental lab for mathematics, as contrasted with a more traditional lecture/tutorial format, Alexander (1998, p. 2) mentioned that CAS use supports the *development of independent learning*: "Students work in small groups of three with the instructor acting as a facilitator. . . . The StudyWorks lessons are exploratory, leading the students to discover facts by themselves." Dogan-Dunlop (2003, p. 1) argued that, "according to a constructivist view of learning, learners construct their own understanding of subject matter. To achieve the goal, learners will need learning environments supporting investigation, conjecture and discovery."

The CAS labs could also be beneficial to student mathematics learning by potentially *increasing their motivation to learn*. For example, Weida (1996) observed: "The laboratory format seemed to have the greatest impact on students who were struggling in the lecture format" (p. 2). He then provided an anecdote about an unmotivated student who, despite homework completion and attendance issues with lectures, would arrive early for a CAS lab and frequently stay after to continue "playing" with Derive. (1996, pp. 2-3)

There was also the idea that CAS allows for students to tackle *more complex mathematical objects sooner* and to explore *topics that are more relevant* to them. For example, while exploring parametric curves in *Maple* with his multivariable calculus class, Putz (1995, p. 2) commented that, "An advantage of using the CAS is that students can start analysing some interesting curves right away - much earlier than we would have expected them to do just plotting by hand." To address the student perception that his first few assignments on area and volumes of revolution were "abstract," not "real world," and perhaps only "irrelevant symbol manipulation," Lehmann (2006, p. 2) had his students estimate the volume and surface area of the Saint Louis Arch and complete an additional real-world consulting assignment, both of which emphasised the context, presentation, and analysis of results over the actual mathematical calculations involved.

Wu (1995) argues that CAS integration in tertiary math instruction is a vital part of *contemporary thinking*. Noting that the pressures of the information age add to the need for students developing creative and critical thinking skills to solve real world problems, she added that:

> It is our job to help students to gain the ability that will enable them to use mathematical methods and tools whenever they seem appropriate and helpful. To this end, computer-oriented mathematics courses, focusing on . . . problems solving, and investigative learning and writing are an important part of the education for our students. (p. 4)

Although many benefits of CAS use in tertiary instruction were highlighted in the literature, significant and difficult issues were also discussed within the analyzed papers.

3.4 Issues of CAS Integration and Mathematics Learning with CAS Use

Throughout the investigated literature, there were many issues identified by practitioners and researchers as being barriers to technology integration. We identified issues that were pedagogical in nature as well as those that were material (technical or financial) barriers to the implementation of CAS in tertiary mathematics teaching (see Figure 2). In what follows, we summarise the identified issues that are discussed in detail in (Buteau, Lavicza, Jarvis, and Marshall, 2009). There were four technical issues identified in the literature review. Practitioners emphasized difficulties with computer lab availability (Lab) and the need for adequate technical support (Tec). They also highlighted complications with ensuring that the system requirements (Sys) of their chosen CAS could be met by computers that were available, and a need for themselves to engage in troubleshooting various problems (TrS) with the CAS itself. In addition, there was also a concern regarding the cost of CAS (Cost) both from a student and from a departmental perspective.

Eleven of the sixteen identified issues were pedagogical in nature. For example, there was a concern about possible failure of students to achieve learning objectives (Obj), which then can place additional time pressures on practitioners. Krishanamani and Kimmons (1994, p. 4) noted that students failed to learn material assigned in labs and that they had to include this material in subsequent lectures. One particular type of student error that clashes with learning objectives is the assumption on the part of students that their methodology is correct if their paper-and-pencil calculations match up with results obtained from the computer. As Cazes, Gueudet, Hersant and Vandebrouck (2006 p. 342) wrote, "A correct answer does not mean the method is correct or is the best one. Teachers and students must be aware of such . . . pitfalls." Often students engaged in trial-and-error strategies, with students guessing the answer from CAS feedback without making a proper mathematical argument (p. 347). Instructors sometimes failed to ensure that students found an "optimal" solution to a particular problem rather than just having a "correct" answer (pp. 342-343).

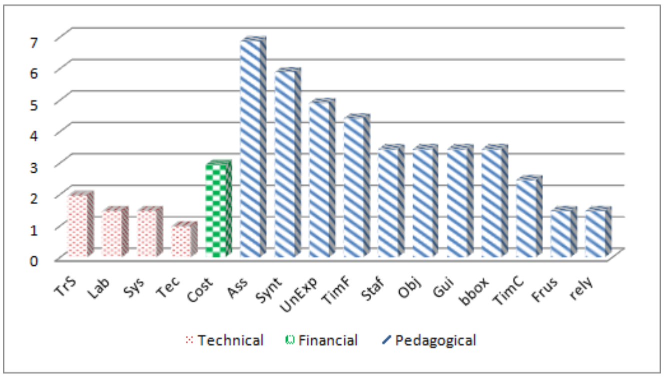

Figure 2 Issues of CAS integration and mathematics learning with CAS use in tertiary mathematics instruction.

Practitioners also worried about how much guidance (Gui) should be given to students engaged in complicated CAS-based projects. The idea of CAS as a "black box" (bbox) that can only provide answers with little mathematical appreciation of the underlying concepts was also a concern. This is possibly related to an uneasiness among instructors regarding student overreliance (rely) on CAS which might degrade their mathematical abilities in absence of the tool.

Syntax (Synt) is the second most frequent concern for both practitioners and students. Cherkas (2003) found this to be a source of student dissatisfaction. He quoted a student complaining that, "*Mathematica* would cause a lot of problems. If I make a mistake in the syntax, I couldn't do my work" (p. 31). Tiffany and Farley (2004) exclusively focused on common mistakes in *Maple*, emphasizing the hurdle for practitioners caused by syntax issues. Practitioners employ various schemes attempting to minimize this difficulty. Some instructors such as May (1999) design interactive workbooks that eliminate the need for formally teaching syntax. Others like Herwaarden and Gielen (2001, p. 2) provide *Maple* handouts with expected output to their students. Another instructor emphasized a palette-based CAS such as *Derive* (Weida, 1996, p. 1) because it is easier to learn and has, according to them, a more straightforward notation.

Student frustration (Frus) with using CAS was another concern. Although practitioners have to deal with unusual or unexpected behaviour of CAS (Unexp), this was occasionally shown to provide pedagogical opportunities. CAS integration also places a lot of time pressures on faculty, both within the course (TimC) and also outside the classroom to prepare CAS-based projects and lessons (TimF). In addition there was recognition that trained staff (Staf) including practitioners and teaching assistants are needed in order for successful integration of the CAS.

Finally, the most commonly examined issue encountered in the literature was that of assessment (Ass). Practitioners encounter problems in evaluation. For example, Schlatter (1999) allowed for CAS use during his exam for his multivariate calculus course, and reported that on a question designed to test student understanding of the divergence theorem, several students simply used the CAS capabilities to solve the integral in a "brute force" approach (pp. 8-9). A poorly designed assessment thus may lead to a failure to achieve learning objectives. Schlatter further noted that he expected "to spend more time during this semester . . . [to] more carefully design exam questions" (p. 8), pointing again to the issue of faculty time.

Interpreting CAS output was also discussed frequently. Many papers that discussed mathematical projects stressed the use of written reports (e.g., Westhoff, 1997, p. 1). Lehmann (2006, p. 3) wrote in his handout, "the important part of this assignment is the thought you put into it, the analysis you do and the presentation of your solution, not the answers themselves." Xu (1995, p. 1) found that students were finding derivatives of easy functions by hand on assignments, but using graphing calculators to solve the more difficult questions. To show students "that the calculator could not do everything for them" he purposefully found functions in the textbook that "were easy to handle by hand but could not be done easily on the calculator."

Although assessment does present certain significant challenges to CAS usage, many instructors have developed innovative uses of CAS relating to assessment and teaching.

3.5 Examples of Common and Innovative Uses of CAS

There were many common applications of CAS repeatedly featured in the corpus. For example, first-year calculus often explores the idea of integration by approximating area with finite Riemann Sums (e.g., Baildon 1999, pp. 5-11); Taylor series are regularly constructed one term at a time and the accuracy of the approximation observed through visual inspection (e.g., Hill and Roberts, 2001, pp. 2-3); the epsilon-delta formal definition of a limit is also often explored through visual experimentation (e.g., Sher and Wilkinson, 2002, p. 1) or examined through a table of values (e.g., Prevost, 1997, pp. 2-3). In multivariable calculus, CAS is regularly used to visualize complex 3-dimensional surfaces (e.g., Putz, 1997) or to explore the concept of Lagrange multipliers (e.g., Richardson, 2004, p. 218). Other areas of mathematics besides calculus have common applications of CAS use as well. For example, CAS is often used in Linear Algebra to solve systems of linear equations (e.g., Herwaarden and Gielen, 2001, p. 2).

Besides these common CAS usages identified in the investigated literature, there were also some unique applications reported that were implemented in the tertiary mathematics classroom or computer lab. We describe a select few of these innovative CAS uses. At Hollins University, Clark and Hammer (2003, pp. 4-8) discussed a distinctive applied project that involved the estimate of an American state's area using Simpson's rule and other approximation methods. In describing this final project, they wrote that, "Student solutions for this final project have been quite varied and creative" (p 6). A student even gained greater accuracy in approximating the area of California by calculating the areas of the map surrounding the state and subtracting, resulting in the need for far fewer sampling points (p. 7).

For his multivariable calculus class, Westoff (1997) assigned a project that simulates the lighting and shading of a 3-dimensional surface. He approached the problem from the perspective that the students "were working for a computer graphics company which was designing a program that would allow a user to build 3-D models and then light the models in a number of ways." (p. 1). Westoff noted that "The mathematics involved in this project is interesting but not beyond the level of a typical calculus student." (p. 1). He also wrote that by its completion the project had provided his students with "an interesting nontrivial application of the calculus they were learning as well as the opportunity to work together as a team." (p. 6).

Schiffman (2007, pp. 188-191) reported on how the *Voyage 200* graphing calculator could be used as a tool to explore two open problems in Number Theory: Goldbach's Conjecture and the Twin Prime Conjecture. Instructions were provided to program the calculator to find prime numbers and view the data in an easy-to-interpret format. As a final activity Schiffman reported that one student attempted "to find the next largest pair of twin primes after 140737488353699 and 140737488353701, the largest known twin prime pair in 1975" (p. 191).

3.6 CAS Integration Scope in Tertiary Curricula

There were different scopes, or levels, of CAS-based technology integration in tertiary mathematics curricula and in teaching practices reported in the literature (see Table 4). A large majority (67%) of the corpus focusing on practice reports discussed CAS usage with regards to one course, or in other words, CAS integration by one practitioner (e.g., Xie, 1994). While 16% had a scope that reached across a series of courses (e.g., calculus courses, Putz, 1995), 11% discussed a CAS implementation with a grouping of courses by year (e.g., all first year courses, Monteferrante, 1993), and only 6% discussed a program-wide implementation within a department (Sárvári, 2005). In what follows, we briefly report on these particular contexts.

One Course	67%
Series of Courses	16%
Grouping of courses	11%
Program-wide implementation	6%

Table 4 Technology implementation scope in tertiary mathematics instruction

Challis (2001) described motivations for the full technological integration at Sheffield Hallam:

> Employability of our graduates is high on our list of aims, and so key or transferable skills are important. . . . Students come to do a degree in mathematics for a variety of reasons, and finding the essence of their motivation is a key issue when deciding what approaches to teaching will and will not work. As access to university education widens . . . students' motivations and interests will be increasingly diverse, both from one anothers' and from our own. Thus we implement a rich approach, combining Symbolic, Oral, Numerical and Graphical aspects (SONG), and integrating use of technology. (pp. 1-2)

The University of Northern Iowa also featured a program-wide integration. Schrurrer and Mitchell (1994) reported that:

> Over the past 10 years it has become evident that to change the mathematics curriculum and make it relevant and useful as well as accessible to a larger portion of the student population would involve the incorporation of current technology. Using the available technology to apply mathematics in a meaningful way requires a revision of the current curriculum as well as a modification of the method of delivery. (p. 1)

What begins as a relatively small CAS integration scope can lead to something much more extensive. For example, after a successful attempt in incorporating *Derive* into the calculus curriculum, Weida (1996, p. 4) commented, "I am definitely glad that we added the computer labs to PreCalculus, Calculus I, and Calculus II. I hope we expand the use of Computer Algebra Systems to our other courses, at least on an informal basis" (Weida, 1996, p. 4).

4 ANALYSIS OF RESULTS

Our results have to be understood in light of the pilot study context, i.e., a small sample of 326 papers in total, with 204 papers analyzed when restricted to CAS use in tertiary education. Our subsequent comprehensive literature review may confirm, as well as inform, the trends we have noticed in the pilot study. Also, due to the choice of journals and conferences, the majority of papers were from the US, which no doubt influenced our results. We will ensure that our comprehensive study will better reflect international (at least Occidental) practices by a careful and broader selection of journals and conferences. We also must stress, albeit rhetorically, that we are summarising what has been reported in the literature, thus not necessarily providing an accurate representative of what is actually being implemented in tertiary education. The possibility exists that some subjects may have gone unreported in the literature. It also highly depends on who is writing the papers - no doubt there are relatively few mathematicians publishing works based on their teaching practices. Finally, our analysis deals primarily with reports and points of view of CAS users; those advocating against technology are rarely present in our analysis due to the study parameters, thus again limiting our study overview. The results of this literature review pilot study will be compared with an international survey (US, UK, HU) regarding mathematician practices in a separate paper (Marshall, Lavicza, Buteau and Jarvis, forthcoming).

If one examines the types of tertiary mathematics courses in which CAS was implemented (Table 2), one observes, perhaps contrary to popular belief, that CAS integration in tertiary mathematics teaching occurs most frequently in courses for mathematics majors, as opposed to service courses designed for non-math majors. This popular view was supported by participants of a closing discussion of the Working Group 7 on "technologies and resources in mathematical education" during the Sixth Conference of the European Research in Mathematics Education" held January 28 - February 1, 2009.

This is true also of any technology use, not just the CAS. Also noteworthy is the fact that CAS is not only used in first-year mathematics courses, and that the most frequently reported use of CAS was in 1st-year calculus.

In comparing contribution types with the framework developed by Lagrange et al. (2003) and which focused on secondary school mathematics, several things became apparent: (i) practitioner reports (as opposed to formal educational research studies) are more prominent at the tertiary level and therefore must be analyzed with greater detail; (ii) the Lagrange framework must be adapted to reflect this difference; and, (iii) this situation underscores the need for research in tertiary education, particularly in terms of technology use. We have decided to treat conference abstracts (i.e., where no full paper is available) separately, i.e., as a minor focus, in our comprehensive literature review.

Three main reported uses of CAS for classroom instruction were as follows (Table 3): (i) *experimentation/exploration* in which an individual or small group of students use the software to do mathematics; (ii) *visualization* in which students use CAS as a tool for creating/viewing/modifying graphical renderings of mathematical functions/objects; and, (iii) for use in analyzing *real-world and/or complex problems* in which students use CAS to model and interpret mathematical phenomena. These three uses of CAS, which are also the main uses of any technology use reported in our review, can be viewed as strongly supporting student *intellectual independence*, insofar as they empower students to independently, or cooperatively, use CAS as a thinking/learning tool within the prescribed curriculum.

Our literature review pilot study coincides closely with the results of Lavicza's (2008b) doctoral study examining CAS usage in research and teaching. Based on his survey of mathematics professors in US, UK, and Hungary, Lavicza found that "projecting images (visualization), experimenting with CAS (exploration), and use of CAS in homework (authentic/complex problems)" were reported as the top uses of CAS in university mathematics instruction.

At the secondary school level, motivation or student engagement has been cited as a key factor influencing technology use by teachers (Lagrange et al., 2003). However, at the post-secondary level this factor was rarely (8%) reported in the reviewed literature, with more attention paid to other factors such as the use of technology as a computational tool, for checking solutions, for individual/group explorations, and/or for enhancing conceptual discussions. While it may be possible that university/college instructors are concerned about student motivation, they appear to be more preoccupied with the effects of the technology (CAS and other tools) on mathematical learning/understanding, at least insofar as the shared rationales for technology use. Notwithstanding this expressed focus on the impact of CAS on learning, we observed in our literature review that only a few authors, among the 10% education research papers and practitioner reports/classroom studies (see Table 1), presented a demonstration of improved student mathematical learning and understanding based on CAS use, or CAS use together with a different teaching practice. Most of these papers were based on student performance (e.g., final grade) wherein the same assessment tool was used with both the control group (without CAS) and an experimental group (with CAS), in the context of one instructor's teaching assignment. Although these studies mostly did show positive results in terms of increased student achievement following CAS-based instruction, they are obviously limited in number and scope.

The potential benefits of CAS use in teaching - and most probably of any well-designed technology - are naturally linked to the reported uses and purposes of the technology. To the extent that CAS was used to enhance conceptual discussions and support visualizations, it was reported as promoting greater understanding of mathematics. One such specific and commonly-mentioned example was the ability of students using CAS to quickly and easily shift between various representations of mathematical objects (i.e., numeric, algebraic, graphic models). CAS also allowed for the refocusing of instruction (and student practice) away from tedious calculations to more conceptual understanding. The exploration of authentic, or “real-world,” mathematical problems with CAS not only increased student interest/motivation, but the computational power made available through the CAS software facilitated the tackling of harder problems at earlier levels in a student’s university/college experience. On numerous occasions, the authors note that, in their opinion, the inclusion of CAS in mathematics teaching/learning represents a natural change in keeping with the perceived future of mathematical instruction and with the demands and realities of contemporary life.

As is evident in Figure 2, there appears to be less concern among mathematics instructors about technical and financial issues than there is for pedagogical issues. This may be a combined function of at least several factors: (i) lab availability (for CAS software) being reportedly more problematic at the secondary school level than at the post-secondary level, and (ii) the increased availability of freeware/open-source software options (e.g., XCas, Maxima) which provide alternatives to expensive software packages; and, (iii) the expressed concern of many post-secondary instructors regarding the perceived changes in assessment practices needed to support parallel changes in instructional practices, particularly in light of huge class sizes and the extra time/energy these changes would ultimately require.

In many instances within the reviewed corpus of papers, instructors would refer to common uses of CAS described in their work as being “new.” This fact may underline a deficient rigor by journals in accepting and editing papers. It also emphasizes the need for better communication and shared materials/resources between mathematicians. As mentioned in Section 3.4, preparing well-designed instructional materials that include the use of technology is time-consuming and requires a certain level of both technological and pedagogical expertise. The reality of additional pressure (i.e., time, expertise, bureaucracy) on instructors is a factor shown to impede technology integration in university teaching (Assude, Buteau and Forgasz, 2009). If CAS-based instructional resources were to be shared, perhaps via interactive, on-line repositories/wikis (e.g., *GeoGebra* Wiki/UserForum), then perhaps more mathematicians would be willing to use technology in the classroom. Certainly, the increased availability of these types of shared resources and a safe, positive, interactive web space/forum would at least make the idea of implementing technology-rich learning experiences more inviting for post-secondary instructors, given their busy research, teaching, and service schedules.

Change involving technology in tertiary curriculum, like in its secondary school counterpart, seems to remain very slow (Ruthven and Hennessy, 2002). Policy making regarding the curriculum in tertiary education is rather different than in school education. Hodgson and Muller (1992) note that school mathematics curricula are in general developed by Ministries or Boards of Education and then implemented in the classroom by teachers, whereas tertiary mathematics curricula are developed and implemented by the same individuals, i.e., faculty within departments of mathematics. Lavicza (2006) argued that due to academic freedom, “Mathematicians have better opportunities than school teachers to experiment with technology integration in their teaching.” This ad hoc basis for technology integration was strongly reflected in our literature review as 67% of the reported CAS-based technology integration was linked to use in a single course, or in other words, by a single practitioner (See Table 4). In contrast, very little indication of program-wide, or systemic, CAS use was reported in the papers examined. Such a systemic integration in the curriculum would require, among other factors, an initial consensus among colleagues in a mathematics department - a major step representing a significant challenge in itself.

5 CONCLUDING REMARKS

There is obviously a need to develop a framework for the review of literature on the use of CAS in tertiary education that will integrate specificities of tertiary-level education and technology integration. A significant majority of papers in our study stemmed from practitioner use (88%), as compared to Lagrange et al.’s (2003) study (60%) in which they state: “Most of the [practitioner] papers lack sufficient data and analysis and we could not integrate them into the detailed analysis" (p.242). Our selection of journals and conferences for our pilot study may have influenced the above percentage. Nevertheless, this reality will clearly and henceforth influence the development of our modified analytical framework. Lagrange et al. (2003) further stated:

> [Practitioner] papers offer a wealth of ideas and propositions that are stimulating, but diffusion is problematic because they give little consideration to possible difficulties. Didactical research has to deal with more established uses of technology in order to gain insights that are better supported by experimentation and reflection. We have then to think of these two trends as complementary rather than in opposition. (p.256)

They continued, describing their metaphor of a "three stroke cycle" as found in the literature:

> Innovation produces situations of use. Comparative research papers investigate these situations in order to get evidence about their benefits. These benefits - or more accurately potentialities - of technology provide material for research studies focusing on the understanding of learning situations or on long term effects. (p.256)

We aim at elaborating upon these complementary trends at the post-secondary level by both analyzing existing instructional practices and scrutinizing problematic issues within implementation.

Most of the publications about tertiary mathematics education come from mathematicians whose research activities are in the domain of mathematics, and therefore, may have relatively little interest and/or time to acquire the knowledge/skills needed for the creation of educational research publications. We therefore suggest that more collaboration between mathematicians and mathematics educators is necessary, and that this change would serve to increase the number, quality, and depth of such publications written by practitioners. However, we also acknowledge that such collaboration is difficult to facilitate, can be costly, and that it happens far too rarely (Even and Ball, 2003).

Lagrange et al. (2003) further state that the "integration into school institutions progresses very slowly compared with what could be expected from the literature" (pp. 237-8). This might be the case for school education, but perhaps less so for tertiary education where, contrary to popular belief, integration may actually be happening more frequently (Lavicza, 2008b). The research literature about school mathematics and technology seems to pay less than adequate attention to the issues surrounding classroom implementation. Contrariwise, the literature about tertiary mathematics and technology tends to inform us more about classroom implementation (67% discussed an individual instructor's initiative) than related didactical issues and benefits. This suggests that there may be a need for more educational research focusing on the integration of technology in tertiary education. It also points to the need for resources and shared strategies in mathematics departments, as suggested by Table 4, to facilitate the systemic integration of technology in teaching. At the recent ICME 11 conference in Mexico, the results of a special survey highlighted concerns about the international trend of disinterest in university mathematics (Holton, 2008). Departments of mathematics have a responsibility to question current teaching and assessment practices. We contend that part of this responsibility includes the careful consideration of the role and relevance of technology within the curriculum.

In closing, we would like to briefly comment on an editorial exchange, found in the journal *Educational Studies in Mathematics*, between pro-CAS/technology and anti-CAS mathematicians. Wilson and Naiman (2004) argued in a brief paper that their students at the prestigious Johns Hopkins University (USA) had greater success with little/no calculator use in their school mathematics education (based on a survey they did one year with 776 students). In Tunis' (2004, p. 145) response to Wilson and Naiman, he raised interesting questions regarding the use of technology (e.g., How can my examinations build upon my students' ability to select the appropriate technologies (during the exam) while still getting at their understanding of mathematics?), and also provided a strong rationale for its implementation in education.

Wilson subsequently responded (2005) to Tunis' rebuttal, once again articulating strong opposition to the integration of technology. For example, he maintained that assessment should not be revised since, "You cannot redefine mathematics!" (p. 416); that mathematicians teach mathematics (in service courses) as requested by other disciplines, and that these colleagues do not ask for technology, nor for change; that many mathematicians agree with him (based on answers on an electronic forum); that school teachers should talk to tertiary educators in order to know what is actually needed 'after' Grade 12 (he doesn't seem to be much concerned about the other communication direction); and, that since technology is "not used" in post-secondary classrooms, secondary teachers should cease using technology in their own classrooms. He concluded, "Tunis's questions indicate a lack of understanding of what mathematics is and what students need to learn about mathematics" (p.420). Both sides (and the many like-minded educators they represent) are equally passionate about their beliefs, fears, and visions of the future of mathematics.

As demonstrated in the above-mentioned intellectual skirmish, we maintain that there is a definite need for our research agenda which seeks as its foci the raising of *awareness* and *collaboration* among and between these two groups of professionals (i.e., mathematicians and mathematics educators). Given the paucity of didactic / systemic research at the tertiary level, and the related scarcity of practitioner-based research at the secondary level, we propose that such conversation is both timely and crucial. Like Euclid of old, we perceive a need to collect and organize (or at least facilitate these activities online) the instructional experiments, research, and technology-based resources that already exist in education so that instructors can begin to share and modify, rather than continually reinvent. We believe that mathematicians will, at some future point, need to rethink the tertiary curriculum vis-à-vis the growing ubiquity and computational power of technological learning tools.

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