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Engineering Students Understanding Mathematics (ESUM) – research rigour and dissemination

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Abstract

The Engineering Students Understanding Mathematics (ESUM) project was a developmental research project aimed at enhancing the quality of mathematics learning of students of materials engineering in terms of their engagement and conceptual understanding. The initial phase of the project consisted of an innovation in mathematics teaching-learning which was designed, implemented and studied, with feedback and concomitant modification to practice. Details are reported in Jaworski (2011b). The second phase of the project, reported here, focused more overtly on the analysis of data in relation to theoretical perspectives. In particular, Activity Theory (AT) was used to make sense of emerging findings. A literature review was undertaken and showed evidence of so-called 'constructivist' methods being introduced to the teaching of mathematics in higher education (HE). Dissemination has taken place both internally within the institution and externally and is still ongoing. It has generated interest and activity beyond the local setting. Findings from the project include students' views on elements of the innovation, improved scores on tests and examinations compared with earlier cohorts and students' strategic approaches to their studies and ways in which this creates tensions with lecturers' aims in designing the innovatory approach. The gains from the projects can be seen in terms of developing knowledge of the complexities of achieving principles for more conceptual understandings of mathematics within the context and culture in which teaching and learning take place.

Keywords: Mathematical understanding, engineering students, innovation in teaching, inquiry-based activity, activity theory analyses, students strategic approaches

Background

The Mathematics Education Centre (MEC) at Loughborough University (LU) includes a group of developmental researchers who seek to improve the teaching of mathematics university-wide. The group is particularly renowned for its work in mathematics support. This case study reports on the second phase of the Engineering Students Understanding Mathematics (ESUM) project. The initial phase of the project consisted of an innovation in mathematics teaching-learning which was designed, implemented and studied, with feedback and concomitant modification to practice. Details of this are reported in the case study for phase one (Jaworski, 2011b).

The ESUM project worked with a first year cohort of 48 materials engineering students in the academic year 2010/11 during the first semester of a year-long module of 30 weeks with two lectures and one tutorial each week. An innovative, enquiry-based approach to teaching-learning mathematics was pioneered using mathematical software (GeoGebra) and specially designed enquiry-based questions and group projects aimed to enhance participation and understanding. Although aimed particularly at materials engineering students, its focus was generic, with the possibility to influence design of teaching broadly within LU and beyond. The innovation was designed to stimulate and challenge students and to encourage their involvement during lectures and tutorials. Design of teaching and its implementation were researched with data gathered from all phases of the project and analysis taking different forms at different stages. The second phase of ESUM encompassed a literature review, further analysis, dissemination and the relation of findings to theoretical perspectives.

Rationale

This programme has built upon collaborations between the departments of Mathematics and Materials Engineering at LU over three years. There is close liaison between colleagues, joint curriculum design and common goals in enhancing the learning experiences of students in mathematics. Mathematical understanding as it relates to engineering is a primary such goal. During this time the mathematics curriculum had been modified and styles of teaching developed. Materials engineering problems were sought to which mathematics could be related in order to motivate students. The software package GeoGebra¹, free software which allows both algebraic and graphical representations of a function to be displayed side by side on a screen, was used to provide a means for conceptual visualisation around key mathematical concepts. Associated enquiry-based questions were designed and used in tutorials to motivate students and encourage mathematical engagement (Jaworski, 2008b; 2010). An enquiry-based approach to learning engages students in collaborative exploratory activity through which they ask their own questions, take up their own lines of enquiry and hence develop a more conceptual understanding of mathematics (Jaworski, 1994; 2006; Wells, 1991). In ESUM, a decision was taken to cohere these various approaches in an innovative teaching schedule in which pedagogy was enquiry-based, students were required to work in groups in tutorials using GeoGebra and assessment was modified to include an enquiry-based group project.

The innovation was designed to stimulate and challenge students and encourage a deeper engagement with mathematical concepts through participation in focused activity with their peers (Vygotsky, 1978). Enquiry was seen as both a tool and a 'way of being' in practice, designed to draw participants into a working relationship with mathematics within a community of mathematical practice related to becoming an engineer (Jaworski, 2004, 2008a; Wenger, 1998). It is possible to see university mathematics teaching as an established *community of practice* (CoP) (Wenger, 1998) of which, in this particular case, lectures and tutorials, mathematical curricula, university ethos and academic and student cultures each form a part. According to Wenger, learning is seen to arise through *participation* and *reification*: concepts emerge through participation in established practices and are reified, "congealed into thingness" (pp. 55-62). In this established CoP, the "mutual engagement, joint enterprise [and] shared repertoire" of which Wenger writes can be seen (pp. 73-84). Briefly, teachers and students together engage with mathematics, seek to fulfil teaching and learning goals, use resources and interact in ways that are in common practice. Identities that are formed can be seen through Wenger's constructs of "engagement, imagination [and] alignment" (pp. 174-181).

The concept of *alignment* is very important in a CoP, since it can foster ways of being and doing that may not be the most fruitful for effective learning. An example is relevant here. Traditional university mathematics teaching may foster *instrumental* learning/understanding rather than a desired *conceptual* or *relational* learning/understanding (e.g. Hiebert, 1986; Skemp, 1976). Instrumental learning can be seen to be reinforced through established norms of practice: teachers telling and explaining and students seeking the 'right' ways to tackle given questions and problems. Thus, conceptual learning, the deeper engagement with concepts and relationships between them, even though it may be desired, does not emerge. The concept of *critical alignment through enquiry* has been developed to address these issues (Jaworski, 2006, 2008a). This involves questioning the established practices while concurrently engaging in and with them. Such questioning can be seen as a form of critical enquiry into teaching practice which promotes instrumental learning.

The focus of this research is on one cohort of engineering students learning mathematics in a one-semester module taught by mathematicians. The students have come (in the main) directly from school and are *in transition* between two important phases of education (Hernandez-Martinez et al., 2011). Their previous school experiences and their first perceptions and expectations of the new environment, as well as youth culture and strategic goals for their higher education all contribute to their engagement in learning mathematics. Various 'cultures' are involved. Within a teaching culture, teachers design teaching to take into account students' previous experience and

¹ <http://www.geogebra.org/cms/>

offer a student-supportive mathematics learning opportunity. Teaching intentions are translated into action in meetings with students and resource provision. Students take part in designed events and interact with this provision. The goals of teaching translate into learning outcomes and the changing perceptions of students through their experience and interaction. Achievement of teaching goals can be discerned through observation of events and measures of attainment.

Activity (in Activity Theory terms) in this research encompasses all of the above and more. Thus the activity is everything, not just the sum of all the parts (Leont'ev, 1979). Activity Theory (AT) is used specifically to address issues that are seen *between* the intentions of the approaches to teaching and use of resources (in the innovation) *and* students' responses, engagement and performance. The context (as set out above) is central to analysis, but hard to factor in. One purpose of the use of AT is to try to make sense of the relationship *between* the purposes of the innovation and associated findings *and* the aspects of context in which the innovation is embedded.

In addition, there are two areas of theory which are important to ongoing work:

Documentational genesis, which deals with the growing awareness of the teacher(s) of the methods and resources being used and their schemes of utilisation. This was referred to in the initial case study and is used as a means of capturing the nature of learning as teachers. Reference to it can be seen in Jaworski and Matthews (2011a).

Constructivism, as a conceptualisation of knowledge and learning from which implications can be seen to arise for approaches to teaching. *Constructivism* has emerged as a description of pedagogies in the literature reviewed (see also Jaworski, 1994). This is at odds with its nature as a theory of knowledge and learning, of which more is said below.

Methodology

The main aim of the ESUM project was to engage first year engineering students in mathematics in a more conceptual way that prepares them for the use of mathematics in problem-solving situations in engineering. The programme involved *developmental* research: that is, research which actually influences the developmental process as well as charting the development (Jaworski, 2003). A programme of teaching and assessment was designed that incorporated 1) the use of enquiry-based questions and tasks, 2) the use of a dynamic algebra-geometry electronic environment (GeoGebra), 3) students' small group activity and 4) an assessed project that brought together elements 1, 2 and 3. This approach was researched using funding from The Royal Academy of Engineering/STEM first phase. Full details are provided in the case study relating to the first phase of ESUM (Jaworski, 2011b).

The project team consisted of three academics, experienced in teaching mathematics at various levels and comprising the teaching team, and one research officer, employed specifically to undertake elements of the research. The teaching team variously designed questions and tasks, planned the group project and organised the research. One member was the lecturer in the first semester. Two PhD students contributed to designing questions and tasks. Design and planning were documented, lectures were observed and audio-recorded, students were surveyed twice during the first semester and interviewed during the second semester and the lecturer in the first semester wrote reflective notes after each week of the teaching. Analysis was ongoing during the first semester and involved an informal level of reflective conversations between the lecturer, the researcher and a graduate assistant and analysis of the two surveys.

In the second phase, reported here, funding was sought for further analysis and to support a deeper (that is, more theory-related) level of analysis. During the second semester two individual and two focus group interviews were conducted by the researcher and one member of the teaching team and subsequently analysed. Analysis from the second student survey and from these interviews provided information relating to students' experiences of the module. These are reported on below. A literature search was conducted to reveal findings in engineering, mathematics and science teaching that related to this programme. A theoretical base was sought that would fit well with ongoing practice and support the analysis of data. There was an expectation

that this would be contrasted with theory propounded in the related literature in the higher education (HE) sector and at school level.

In addition, this phase would:

- feed back findings to inform teaching of the next cohort of students in the first semester of 2011/12. Post-module analysis would be conducted with the new cohort in mind, with modifications to teaching and assessment practice as indicated
- extend dissemination overtly to groups of professionals and researchers and report its findings. The first phase of the ESUM project was written up as a conference paper and presented at the Mathematics Education of Engineers Conference (a subgroup of the European Society for Engineering Education (SEFI)) in 2011. It has subsequently been rewritten as a journal paper and is now published (Jaworski and Matthews, 2011)
- start to consider the wider applicability of what was being learned and seek perspectives of colleagues in other branches of engineering education and possibilities to influence practice in design and implementation of learning and teaching.

Review of literature

The literature review was conducted by a post-doctoral fellow in the Engineering Centre for Excellence in Teaching and Learning (engCETL) at LU. This was subsequently written up as a conference paper and submitted to the SEFI conference, for which it was accepted (Abdulwahed et al., 2011).

The findings from the literature review provide a snapshot of emerging trends in approaches to mathematics instruction for STEM subjects in HE. Calls for reforms of mathematics instruction have been stressed in a number of studies and responses to these calls have embraced, in general, novel 'constructivist' methods for implementing changes in the learning and teaching of mathematics. A number of trends have been observed and were categorised in six groups:

- 1.The use of student-centred learning methods
- 2.Contextualisation of mathematics using real-world examples
- 3.Bridging the gap in previous mathematical knowledge
- 4.Encouraging discourse in the classroom and amongst students
- 5.Enhancement of students' motivation, engagement and self-efficacy
- 6.Consideration of differences in learning styles.

Thus, methods for facilitating conceptual understanding include novel pedagogies (e.g. collaborative learning, enquiry/problem/project/discovery-based learning), contextualising with real-world examples and the use of documentary movies for stimulating motivation and self-efficacy beliefs. In addition, and alongside many of the approaches, mathematical software packages (e.g. GeoGebra, Matlab/Simulink, LabVIEW, Mathematica, Maple and MapleTA, etc.) and online tools (wikis and web-based courses) are increasingly being used to support learning of mathematics. Most of the studies in this review were from the USA, with a few papers from the UK, Australia and Malaysia. Most were published in the last few years.

Hence, there is evidence of a trend towards developing new approaches to teaching mathematics in STEM subjects in HE of which the ESUM project might be seen to be a part. These new approaches are motivated by a desire to achieve more conceptual or in-depth understanding of mathematics by students. The methods/pedagogies in ESUM (enquiry-based questions and tasks, small group collaborative enquiry, use of GeoGebra, etc.) fit well with those described in the literature.

Lessons learned

Data from the individual interviews and focus groups were analysed by the researchers and two members of the teaching team. It had proved difficult to persuade students to attend individual interviews, so the two focus groups each involved four students. Students were asked for their perceptions of the various aspects of the innovation and their learning of mathematics in the

module. A first level of analysis involved a data reduction process in which the audio recordings were summarised in a chronological factual form to capture the main elements of discussion and in an associated synoptic account with relevant quotations. From this, the researchers sought key ideas and relationships. It appeared that, while they valued many aspects of the innovation, students were motivated largely by a strategic approach to their learning, having very much in mind what was needed in terms of assessment and what they had to achieve in order to pass the course. This led to some apparent contradictions in the evidence discerned. For example, in group projects, in response to a question on their use of GeoGebra, comments were largely positive, such as: "As a group we looked at many different functions using GeoGebra and found that having a visual representation of graphs in front of us gave a better understanding of the functions and how they worked. In this project the ability to be able to see the graphs that were talked about helped us to spot patterns and trends that would have been impossible to spot without the use of GeoGebra" (Group F). However, when asked explicitly about GeoGebra in focus groups, comments were less positive. Although students appreciated many of the qualities of GeoGebra (especially visual representation and the use of 'sliders'), they questioned its use more globally. It was suggested that GeoGebra does not involve doing mathematics, just plugging numbers into a computer. Several students felt that too much time was spent in its use and several agreed that, although this use helped their understanding, they did not feel that it helped their ability to do well in the exam:

"Understanding maths – that was the point of GeoGebra wasn't it? Just because I understand maths better doesn't mean I'll do better in the exam. I have done less past paper practice."

The time taken up by GeoGebra was seen as cutting short the time available for the lecturer to solve problems or for practising past exam papers. For many of the students, the most important consideration was passing the exam:

"Once you pass the exam, like, you know you can learn more about [example given relating to understanding of partial fractions] [...] [but] as long as I can get the marks that's fine, the understanding just comes with applying it to greater things."

Several students said that they did not use GeoGebra outside tutorials, except for the assessed group work. These students claimed that they did no work outside of taught sessions except for the group project and revision for CAA tests.

What is shown here is possibly both a reflection on students' past experience (school experience and A-levels² directly preceding their first year at university) and the nature of student epistemology. They perceive that they need to do well in the exam and in other forms of assessment in order to pass the module and focus on this strategically. Since A-level is a very high-stakes exam affecting a student's entire academic future, teachers spend considerable time tutoring their students to be successful with exam questions (Hernandez-Martinez et al., 2011). Thus students favour what they perceive will help with the exam and see their 'understanding' in relation to this; understanding functions through visualisation with GeoGebra is not, as they see it, directly usable in the exam, so it is not the kind of understanding they value. They believe the lecturer should spend more time working through problems and preparing them directly for tests and the exam.

A similar perspective is reflected by their views on enquiry-based questioning. Students were surprised to be asked questions in lectures; they said that they expected to go to a lecture to take notes. They recognised that such questions can be useful because "sometimes it shows you what you don't understand so you might think you know how to do something, but then you don't so it does come in handy." However, one commented that the questions were "a bit of a waste of time [...] would rather move on to [not clear in the recording] past examples." Again, a conflict is observed between the teaching intentions and students' aims. Are students being lazy here (too

² The General Certificate of Education Advanced Level (GCE A-Level) is an examination in individual subjects, taken usually at age 18, through which students qualify for higher education.

much effort required to engage) or are they focused on taking notes rather than trying to understand? Or is this again their strategic perspective (there is only a certain amount of time and they feel that it would be best spent on things such as past exam papers)? Regarding enquiry-based questions in tutorials (designed to promote engagement and understanding through use of GeoGebra with exploration and discussion), they were unhappy with the format of tutorials. Having computers was distracting (it was too easy to access social networking sites). They did not find exploratory work and discussion to be a good use of their time and did not appreciate the opportunity to talk with other students with whom they might not otherwise have conversations.

In order to make sense of these apparent dichotomies between student and teaching perspectives, an AT analysis was imposed onto the analysis to date. For this, Engeström's expanded mediational triangle (1999) and Leont'ev's three levels of activity (1979) were used as tools and the analysis was written up in a paper submitted to the ATATEMLO symposium held in Paris in November 2011 (Jaworski et al., 2011). Table 1 shows the presentation of ESUM findings in relation to Leont'ev's three levels of activity.

What has been observed and evidenced through analyses are fundamental differences in how teachers and students perceive and conceive of the knowledge to be learned and the learning process. It has been demonstrated that a variety of cultures influence these perceptions and conceptions. The use of the two models (from Engeström and Leont'ev) allow situation and context to be characterised through juxtaposing key elements of the areas of conflict. Work continues with a new cohort of students and the cycles repeat themselves. Under consideration are what has been learned and how this learning may promote a clearer knowledge of the issues in order to inform ongoing design and organisation. These questions are still under discussion and relate to the use of the theory of documentational genesis as mentioned above.

Table 1. Leont'ev's three levels of activity applied to ESUM analysis of focus group data
activity <--> motive, actions <--> goals, and operations<--> conditions.

Level	Teaching	Students
1	<i>Activity</i> is mathematics teaching-learning, <i>motivated</i> by the desire for students to gain a deep conceptual-relational understanding of mathematics. This may be called 'teaching-for-learning'.	For students the <i>activity</i> is learning within the teaching environment and with respect to external factors (youth culture, school-based expectations of university etc.) and is (probably) <i>motivated</i> by the desire to get a degree in the most student-effective way possible.
2	<i>Actions</i> are design of tasks and enquiry-based questions, with <i>goals</i> of student engagement, exploration and getting beyond a superficial and/or instrumental view of mathematics. <i>Actions</i> include use of GeoGebra with the <i>goal</i> of providing an alternative environment for representation of functions offering ways of visualising functions and gaining insights into function properties and relationships. <i>Actions</i> include forming students into small groups and setting group tasks with the <i>goals</i> to provide opportunity for sharing of ideas, learning from each other and articulating mathematical ideas.	For students, <i>actions</i> involve taking part in the module: attending lectures and tutorials, using the LEARN* page, using the HELM [†] books, etc., with <i>goals</i> related to student epistemology. So <i>goals</i> might include attending lectures and tutorials because this is where you are offered what you need to pass the module, clear views on what ought to be on offer and what you expect from your participation, wanting to know what to do and how to do it, wanting to do the minimum amount of work to succeed, wanting to understand and wanting to pass the year's work.

3	These are <i>operations</i> such as the kinds of interactions used in lectures to get students to engage and respond, the ways in which questions are used, the operation of group work in tutorials and interactions between teachers and students. The conditions include all the factors of the university environment that enable and constrain what is possible – for example, if some tutorials need to be in a computer lab, then they all have to be; lectures in tiered lecture theatres constrain conversations between lecturer and students when tasks are set.	<i>Operations</i> include degrees of participation: listening in a lecture, talking with other students about mathematics, reading a HELM book to understand some bit of mathematics, using the LEARN page to access a lecture PowerPoint. The conditions in which this takes place include timetable pressure, fitting in pieces of coursework from different modules around given deadlines, balancing the academic and the social. They also include the organisation of lectures and tutorials and participating within modes of activity which do not fit with your own images of what should be on offer.
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*LEARN is the VLE used for all learning-teaching at LU. †HELM (Helping Engineers Learn Mathematics) is a series of booklets addressing key mathematical concepts related to engineering studies.

Evaluation

In evaluating this phase of the project, it is important to acknowledge what was reported in the first case study. The following six points present a summary of that evaluation and further details can be found in the case study itself. The findings presented there, together with results from survey analysis and module assessment, suggest that areas of achievement in the project are:

1. Greater participation (mathematical engagement) by students in lectures possibly responding to greater effort (than in previous years) by the lecturer to include students through frequent questioning and inviting students to respond, comment and ask their own questions.
2. Higher student attendance in lectures and tutorials than in previous cohorts.
3. Pleasing (to the lecturer) response by students to group work in tutorials and to project work. Enhanced engagement in particular was commented on by the graduate student who has helped in tutorials over two years. VERY pleasing participation in design of a poster.
4. A good average mark for the projects.
5. CAA scores at about the same level as for previous cohorts, despite each CAA test having almost twice the number of questions for the same amount of time.
6. A considerably higher exam average on the module as a whole and on individual questions relating to learning in the first semester.

In moving to the evaluation of the second phase, it seems worth stating that the results summarised above are largely positive regarding students' participation in the module and their achievement in the formal assessment. They come from analysis of data from the ongoing progress of the module and from quantitative analyses from surveys and assessments. The analysis conducted in the second phase was largely of qualitative data from project reports and interviews held in the second half of the module after the intervention. Students were reflecting on their past experience and thinking towards the final examination. Overall scores in this examination were much higher than those of previous cohorts.

A major part of the innovation was the change to assessment reflected in the project (a reduction of 20% in CAA tests in order to award 20% to the project report and poster). Students took the project seriously because it affected their assessment and their responses showed that they gained in aspects commensurate with the principles behind the project. This fits with educational wisdom, which suggests that changes to teaching must be reflected in assessment if they are to be successful.

However, the qualitative analysis of the interview data revealed the dichotomy expressed above. This challenges a re-think of perspectives at the design and implementation stages of the project. The innovation was designed to create deeper levels of engagement and understanding than was

experienced with previous cohorts. While there was evidence of degrees of engagement and understanding as reflected in the projects, posters and exam results, it was clear that students had not been persuaded of the value of seeking enquiry-based engagement or an appreciation of the conceptual nature of understanding. It was also recognised that better (more objective) ways of judging conceptual understanding and its development were required. To this end, work is being conducted with colleagues in Dublin³ to design and test an instrument to assess an increase in conceptual understanding. Perceptions of what is meant by conceptual understanding and how it may be recognised and tested for, together with theoretical considerations, are being challenged.

Discussion, summary

The innovation has shown considerable promise in engaging students and suggesting alternatives to an instrumental view of learning mathematics. The principles underpinning the innovation (regarding enquiry-based learning, small group activity and use of computer software as a learning resource) are sound (well evidenced in research at different levels). It is the detail that needs attention, particularly with respect to the context and culture in which the innovation is employed. The Smith report on education at the 16-19 level referred to a need for new pedagogies and culture change, both in the classroom and in the training of teachers (Smith, 2004). Students arrive from an A-level culture that values instrumental learning. They are introduced to a university culture in which lecturers offer material which students have to make sense of and reproduce appropriately. In addition, their motivation to end their studies with a good degree (possibly with the most economical approach in terms of time and effort expended) can be seen as the basis of a strategic approach to studying which has extrinsic rewards. The intrinsic rewards of deep conceptual understanding and the value this brings to studies remain largely outside their thinking and culture.

Teachers can accept the *status quo* and teach in a way that is commensurate with it, or can seek ways to gradually affect (and ultimately change) expectations and ways of being. In terms of Communities of Practice and Enquiry, the description above may be seen to apply to a community of practice in learning in the university as things stand and a community of enquiry as the goal through which ways of being change. It seems important to go on working towards a community of enquiry; however, the ways to do this are not straightforward, and it has been shown that a direct approach has not achieved its aims. The research has revealed the issues and the complexities that are involved. The challenges revealed by the literature review must also be addressed.

As a start with the new cohort this year, small changes have been made to the curriculum, the style of teaching and the project assessment in order to accommodate students' views as expressed in their feedback. However, the big questions still remain: how to teach in a way that results in students' deep engagement with mathematics and corresponding conceptual understanding, and what these things mean. The research with Dublin colleagues is a step towards this. Discussion and presentation of findings with engineering colleagues at LU is under way in order to engage them in the bigger questions. The teaching is ongoing, as reflects the academic cycle. Through an increased awareness of principles, issues and outcomes promoted through the two phases of ESUM (the documentational genesis), reflection on day to day practice and work with students is increasing knowledge of their perceptions and expectations.

Further development

In summary from the above discussion:

1. Innovation is ongoing with minor changes in response to feedback.
2. Reflection on practice to develop our knowledge of students, their perceptions and expectations continues.
3. Findings and the associated issues will be discussed with engineering colleagues. It is likely that some changes will result from these talks.

³ At CASTeL, St Patrick's College, Drumcondra and the National University of Ireland Maynooth.

4. Module assessment is an important consideration. Methods of assessment and how these relate to aims in the module need consideration.
5. Research with Dublin colleagues is designed to find out more about what it means to develop a more conceptual understanding of mathematics and how this may be recognised. Insights will help address the big questions.

New ways of thinking and acting have been set in process which may improve teaching and learning. These, alongside other initiatives in the MEC at LU, contribute to changing the current culture. The developmental research process is ongoing and is itself a form of adaptation in which ways of being and thinking develop alongside practice. There is much theoretical work also to be done.

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Further reading/bibliography

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Other publications are listed above.



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