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COMMISSION INTERNATIONALE DE L'ENSEIGNEMENT MATHÉMATIQUE
(THE INTERNATIONAL COMMISSION ON MATHEMATICAL INSTRUCTION)

DISCUSSION DOCUMENT FOR THE SIXTEENTH ICMI STUDY

CHALLENGING MATHEMATICS IN AND BEYOND THE CLASSROOM

1. INTRODUCTION

Mathematics is engaging, useful, and creative. What can we do to make it accessible to more people ? Recent attempts to develop students' mathematical creativity include the use of investigations, problems, reflective logs, and a host of other devices. These can be seen as ways to attract students with material that challenges the mind.

Initiatives taken around the globe have varied in quality and have met with different degrees of success. New technologies have enabled us to refine our efforts and restructure our goals. It is time to assess what has been done, study conditions for success and determine some approaches for the future.

Accordingly, ICMI has embarked on its 16^{th} Study, to examine challenging mathematics in and beyond the classroom, and is planning a Conference to be held in Trondheim, Norway, from 27 June to 3 July 2006 at which an invited group of mathematicians and mathematics educators, drawn from around the world, will analyze this issue in detail and produce a report.

This document will suggest specific issues and invite those who might contribute to the discussion to submit a paper, so that the International Programme Committee can select those attending the Conference.

Finally, using the contributions to this Conference, a book (the Study Volume) will be produced. This book will reflect the state of the art in providing mathematics challenges in and beyond the classroom and suggest directions for future developments in research and practice.

The authors of this Discussion Document are the members of the International Programme Committee (IPC) for this ICMI Study. The committee comprises 13 people from different countries, listed at the end of this document. The structure of this Discussion Document is as follows. In Section 2 we define and discuss fundamental terms used in the Study. In Section 3 we look at the current context, list examples of current practice, observe changes in recent years and identify problems. In Section 4 we pose a number of critical questions leading to the results of the Study. In Section 5 we call for contributions and outline the process of the Study.

2. Description

(a) Challenge

What is a mathematical challenge? While this may be the topic of discussions during the Study Conference itself, we offer some preliminary thoughts to provide background to debate.

One answer is that a challenge occurs when people are faced with a problem whose resolution is not apparent and for which there seems to be no standard method of solution. So they are required to engage in some kind of reflection and analysis of the situation, possibly putting together diverse factors. Those meeting challenges have to take the initiative and respond to unforeseen eventualities with flexibility and imagination.

Note that the word 'challenge' denotes a relationship between a question or situation and an individual or a group. Finding the dimensions of a rectangle of given perimeter with greatest area is not a challenge for one familiar with the algorithms of the calculus, or with certain inequalities. But it is a challenge for a student who has come upon such a situation for the first time. A challenge has to be calibrated so that the audience is initially puzzled by it but has the resources to see it through. The analysis of a challenging situation may not necessarily be difficult, but it must be interesting and engaging.

We have some evidence that the process of bringing structure to a challenge situation can lead one to develop new, more powerful solution methods. One may or may not succeed in meeting a challenge, but the very process of grappling with its difficulties can result in fuller understanding. The presentation of mathematical challenges may provide the opportunity to experience independent discovery, through which one can acquire new insights and a sense of personal power. Thus, teaching through challenges can increase the level of the student's understanding of and engagement with mathematics.

We do note that there are several terms sometimes used to describe similar things, but which really have quite distinct meanings. These terms include the expressions 'challenge', 'problem solving' and 'enrichment'. We have discussed the term 'challenge' above. Problem solving would appear to refer to methodology, but problem solving is often associated with a challenging situation. Enrichment would be the process of extending one's mathematical experience beyond the curriculum. This might or might not happen in a challenging context.

(b) How do we provide challenges ?

Mathematics can challenge students both inside and outside the classroom. Learning takes place in many contexts. Mathematical circles, clubs, contests, exhibits, recreational materials, or simply conversations with peers can offer opportunities for students to meet challenging situations. It is our responsibility to provide these situations to students, so that they are exposed to challenges both in the classroom and beyond.

In this endeavour, the role of the teacher is critical. It is the teacher who is faced with the difficult task of keeping alive in the classroom the spontaneity and creativity students may exhibit outside the classroom.

We note that many teachers do not select problems for lessons on their own, but just follow what is given in a textbook. In this context the role of good textbooks and books of problems is very important. To provide challenge one needs not only to include challenging problems, but also, which is often more helpful, to construct small groups of problems, leading a student from very simple and basic facts and examples to deeper and challenging ones. By carefully selecting problems and organising the structure of textbooks the authors can very much help teachers in providing challenge. It can happen that a student with a good book may develop an interest in the subject even without any help from a teacher.

The support of the general public is likewise critical. Since children are products of their entire social environment, they need the support of the adults around them in acquiring an understanding and appreciation of mathematics. And, in supporting the new generation, the engagement of citizens in mathematics will open new opportunities for their own personal growth and the public good.

It is important for us to challenge students of every level of motivation, background or ability. Highly motivated students need challenges so that they don't turn their active minds away from mathematics and towards endeavours they find more appealing. Mathematical challenges can serve to attract students who come to school with less motivation, and such students learn from challenging material more than they can learn from the mastery of algorithms or routine methods.

It is particularly important, albeit difficult, to provide challenges for students who struggle to learn mathematics. It is all too easy for students with learning difficulties to content themselves with competence at, or mastery of, algorithmic mathematics, and not attempt to think more deeply about mathematics. However, some practitioners have found that even the learning of routine material is improved when taking place in a challenging environment.

Particularly valuable are situations that can be used to challenge all students, regardless of their background, or motivational level.

The process of providing students with challenging situations itself presents challenges for educators. Some of these challenges are mathematical. Teachers must have a wide and deep knowledge of the mathematics they teach, in order to support students who are working on non-standard material. Other challenges to the teacher are pedagogical. In expanding the kinds of experiences students have, teachers must likewise expand their knowledge of student learning, and their ability to interpret what students say. It is the responsibility of the mathematics and mathematics education community to support teachers in these aspects of their growth.

(c) WHERE ARE CHALLENGES FOUND ?

• Challenge situations provide an opportunity to do mathematics, and to think mathematically. Some are similar to the activities of professional mathematicians. These include: solving non-routine problems, posing problems, working on problems without achieving a complete solution, individual investigations, collaborative investigations in teams, projects, historical investigations, organizing whole-class discussions searching for ways to solve a problem, a puzzle or a sophism.

• Other challenges are less like formal mathematics. These attract in a different way, leading into mathematics from other contexts. Some of these are: games, puzzles, construction of models, manipulation of hands-on devices.

• Still other challenges connect mathematics with other fields. Some examples are: mathematics and other sciences, mathematics and the humanities, mathematics and the arts, real-world problems.

• Challenges can be found in a variety of venues and vehicles, including: classrooms, competitions, mathematics clubs, circles or houses, independent study, expository lectures, books, papers, journals, web sites, science centres, exhibits, festivals, such as mathematics days, mathematics camps.

3. CURRENT CONTEXT

(a) PRACTICES AND EXAMPLES

There are many ways that students are currently being challenged. These challenges occur both within and outside of school and include students as well as general members of the public. They can also be classified in several categories such as competitions, problem solving, exhibitions, publications, and what may be roughly called 'mathematics assemblies'. Below we refer to some particular cases where challenge is organised. To illustrate this we have used examples which are familiar to members of the International Programme Committee.

Competitions

EXCLUSIVE AND INCLUSIVE COMPETITIONS. There are many well known competitions such as the *International Mathematical Olympiad (IMO)* and *Le Kangourou des Mathématiques*. The former involves small groups of students from many countries (an example of an exclusive competition) while the latter involves thousands of students in France and Europe (an example of an inclusive competition). Details of these and many other competitions can be found on their web sites as well as in the World Federation of National Mathematics Competitions' journal *Mathematics Competitions*.

The word 'competitions' may initially conjure up an image of rivalry between individual students with 'winners' and 'losers'. While this may be so in certain situations it is not always the case. Even in the IMO, where medals and prestige are at stake, there is more cooperation than rivalry outside the competition room. In all competitions, though, students work 'against the problem' as much as they work 'against each other' and there are situations where completing the questions is the main aim rather than 'winning'. And there are competitions where the students have to compose questions for other students to solve rather than having the questions imposed by the competition organizers. Below we give examples of two competitions that are different in some way from the traditional competition where students are essentially submitted to an examination.

AN EXCLUSIVE COMPETITION OF INTERACTIVE STYLE. The competition *Euromath* is a European cup of mathematics. Each team is composed of 7 people: students from primary school to university and one adult. The six best teams are chosen to participate in the final competition by the results of their work on logical games. In the final, these teams work in front of spectators. To win, a team needs to be quick and to have good mathematical knowledge but the most important thing is 'l'esprit d'équipe'.

ANOTHER MODEL OF AN INCLUSIVE COMPETITION. *KappAbel* is a Nordic competition for 14 year olds in which whole classes participate as a group. The first two rounds consist of problems distributed on the Internet and downloaded by the teacher. Within a 90 minute time limit, the class discusses the problems and decides how to answer each problem. The third round is divided into two parts: a class project with a given theme (that ends with a report, a presentation and an exhibition), and a problem solving session run as a relay where two boys and two girls represent the class. Recent themes have been Mathematics and local handicraft traditions (2000), Mathematics in games and play (2001), Mathematics and sports (2002), Mathematics and technology (2003) and Mathematics and music (2004). The three best teams from the third round meet on the following day for the final, which is a problem solving session with the teams that did not make it to the final as audience.

REFERENCES. A web site for IMO: olympiads.win.tue.nl/imo/, web site for *Le Kangourou*: www.mathkang.org/, mathematics competitions reference: via WFNMC site www.amt.edu.au/wfnmc.html

Classroom use of challenge

PROBLEM SOLVING. The words 'problem solving' have been used to cover a variety of experiences but by the words here we mean allowing students to work on closed questions that they are not immediately able to solve. Hence they need to apply their mathematical content knowledge as well as ingenuity, intuition and a range of metacognitive skills in order to obtain an answer.

Problem solving is often used in classrooms as a one-off exercise that may or may not be connected to the main mathematical curriculum. It can be seen as a 'filler' that many students enjoy but it is not always viewed as central to the mathematics classroom.

Investigations and projects may be extended problem solving exercises where students look into more difficult problems over more than one period of class time. They frequently involve a written report.

Teachers who use problems to develop students' ideas, knowledge and understanding of curriculum material can be considered as taking a 'problem solving approach' to the topic. This approach can reflect the creative nature of mathematics and give students some feel for the way that mathematics is developed by research mathematicians. Examples of both problem solving lessons and lessons which take a problem solving approach can be found on the web site www.nzmaths.co.nz.

CHALLENGE IN TRADITIONAL EDUCATION: AN EXAMPLE. A traditional method in Japanese elementary school is to solve a problem through full-class discussion. With a skilful teacher, the children can learn more than the curriculum intends. For example, suppose that they are given the problem of dividing 4/5 by 2/3. One student might observe that 6 is the least common multiple of 2 and 3, and write

$$\begin{aligned}(4/5)/(2/3) &= (4 \times (6/2))/(5 \times (6/3)) \\ &= (4 \times 3)/(5 \times 2) \\ &= 12/10.\end{aligned}$$

The children can come to realise that this method is equivalent to the standard algorithm and can be used with other choices of fractions. From the teacher's point of view, this dynamic is unpredictable, and so the teacher requires deep mathematical understanding and sure skills in order to handle the situation. But when the approach succeeds, the children deepen their mathematical experience.

Exhibitions

Exhibitions, in the sense of gathering material together for people to view or interact with, are becoming increasingly common. These are generally outside of the classroom and may be aimed as much at the general public as they are at students. They can also take place in a variety of settings from schools to museums to shopping malls to the open air. We mention several examples.

The idea of a science centre is to present scientific phenomena in a hands-on way. This means that the visitors are challenged by a real experiment and then try to understand it. Some science centres have mathematical experiments, but there are also science centres devoted exclusively to mathematics, for instance the *Mathematikum* in Germany or *Il giardino di Archimede* in Italy. These permanent centres, best visited with a guide, attract tens and hundreds of thousands of visitors per year.

There are also annual exhibitions, varying in content from year to year. An example of this which attracts tens of thousands of visitors per day is *Le Salon de la Culture Mathématique et des Jeux* in Paris. Further, there are also occasional exhibitions, such as the international exhibition *Experiencing Mathematics* sponsored by UNESCO and ICMI jointly with other bodies and presented in 2004 at the European Congress of Mathematics and the 10th International Congress on Mathematical Education.

Exhibitions can have a special theme, such as the one at the University of Modena and Reggio Emilia featuring mathematical machines. These machines are copies of historical instruments that include curve drawing devices, instruments for perspective drawing and instruments for solving problems.

Instruments for museums, laboratories or mathematics centres may be very expensive. For classroom use small cheaper kits may be available with information about possible classroom use.

REFERENCES. *Mathematikum* www.mathematikum.de, *Il giardino di Archimede* www.math.unifi.it/archimede/, *Le Salon de la culture mathématique et des jeux* www.cijm.org, *Mathematical machines* www.mmlab.unimo.it

Publications, including internet

Publications cover at least books, journals, web sites, CDs, games and software. They are generally accessible to a wide audience.

SCHOOL MATHEMATICS JOURNALS. There are many examples around the world of journals designed to stimulate student interest in mathematics. These journals contain historical articles, articles exposing issues with current research, such as the four colour theorem and Fermat's Last Theorem, and Problem corners, where new problems are posed, other current problems from Olympiads are discussed and students may submit their own solutions. Examples of such journals in the Eastern Bloc, where the traditions are older, are *Kömal* (Hungary) and *Kvant* (Russia). In the West outstanding examples are *Crux Mathematicorum* (Canada), *Mathematics Magazine* and *Mathematics Spectrum* (UK).

BOOKS. There are many publications which enrich and challenge the student's interest in mathematics. In the English language the Mathematical Association of America has a massive catalogue and the Australian Mathematics Trust has a significant number of publications. In Russian there is also a very rich resource, traditionally published through Mir. In the French language the *Kangourou* and other publishers have a prodigious catalogue, as does the Chiu Chang Mathematics Education Foundation in the Chinese language. This just refers to major languages. It is expected to be impossible to try to list individual references in this Study. We expect it will be difficult enough to identify the major publishers.

INTERNET. There are a number of examples in which people can join a classroom by internet. The 'e-classroom' conducted by Noriko Arai is a virtual classroom in which everybody interested in mathematics can join by registration. The classroom is run and supervised by a few mathematicians called moderators. Usually one of them gives a problem such as 'characterise a fraction which is a finite decimal'. Then, discussions start. A student gives a vague idea to solve the problem, a partial answer or a question, and other students give comments on it or improve former ideas. Moderators encourage the discussions, giving hints if necessary. Usually the discussions end with a complete answer. Sometimes a new problem arises from discussions. Otherwise, another problem will be given by a moderator. N. Arai developed software so that only students of the classroom can have access to the discussions. In this environment a shy child or an older person who is not so strong in mathematics may feel more comfortable in joining discussions.

"Mathematics assemblies"

These activities are aimed at groups of people who generally assemble together in one place to be educated by an expert or group of experts. We have in mind here such activities as mathematics clubs, mathematics days, summer schools, master classes, mathematics camps, mathematics festivals and so on. Five specific examples are given below that refer to mathematics days, research classes, and industry classes.

SCHOOL MATHEMATICS DAYS. There are many examples around the world of mathematics days in which teams of students from various schools in a district come together. During the day they will participate in various individual and team events in an enjoyable atmosphere, and there may be expository lectures.

MATHEMATICS CLUBS. The world has many examples of mathematics clubs (or circles as they are sometimes known) of students who meet at regular intervals in their town to solve new problems. Often these clubs use a correspondence competition such as the *International Mathematics Tournament of Towns* as a focus for their activity. These clubs are usually coordinated by local academics, research students or teachers who do so in a voluntary capacity.

MATHEMATICS HOUSES. In Iran, a team of teachers and university staff have established what are called *Mathematics Houses* throughout the country. The Houses are meant to provide opportunities for students and teachers at all levels to experience team work by being involved in a deeper understanding of mathematics through the use of information technology and independent studies. Team competitions, e-competitions, using mathematics in the real world, studies on the history of mathematics, the connections between mathematics and other subjects such as art and science, general expository lectures, exhibitions, workshops, summer camps and annual festivals are some of the non-classic mathematical activities of these Houses (see www.mathhouse.org).

RESEARCH CLASSES. In Germany for many years the prize for the winners of a mathematical competition is an invitation to a 'Modellierungswoche'. In this, groups of 8 students together with two teachers work on a real application problem posed by local industry. Many of the problems are optimisation problems. The solution normally requires modelling, mathematical analysis and making a computer program (see zfm.mathematik.tu-darmstadt.de/).

As another example, in *Maths en jeans* each team works in collaboration with a university researcher who has proposed a problem, ideally connected to his/her research, on which the students work for a long period (often up to a full school year).

(b) TRENDS

It seems that, with few exceptions, the overall trends are positive. For example, there are many new competitions that cater for a wider range of students than the more traditional Olympiad-style competition and include younger children than before. Many competitions now involve groups of students rather than just individuals.

In recent years too, problem solving has been added to the curricula of a number of countries. However, without some professional development for teachers, it may not appear in the actual curriculum delivered in class.

In the same vein, there appears to be an increasing number of mathematical exhibitions. For a while, mathematical exhibits generally appeared in science centres but now there are more exhibitions devoted solely to mathematics. And, instead of being held in museum-like settings, mathematics exhibitions exist that are portable or appear in such unusual settings as shopping centres, subways, and the open air.

As for publications, there recently seems to have been an increasing number of books and films of a mathematical nature for the general public. Some of these, such as *Fermat's Last Theorem* and *A Beautiful Mind*, have been extremely successful. On the book side though, there may be a trend away from classical problem books to books that discuss mathematical topics and are meant to be read rather than worked on. These books may attempt to convey deep and complicated mathematics but they do so by creating an impression rather than going into great details.

In recent years the Moscow Centre for Continuous Mathematical Education has published a series of books, *The library of mathematical education.* These are small books (20–30 pages) written by professional mathematicians and addressed to interested high school students. They include popular explanations of various areas of mathematics, challenging problems for students and history. The small size of the volumes, good illustrations, and popular style of writing attract a lot of readers.

It appears that magazines and newspapers are currently carrying more mathematics, both with stories about contemporary mathematics and with problems or puzzles.

Mathematics can be found in many sites on the internet. These sites range from discussions of specific topics to problem sites, to the history of mathematics, to teacher professional development, to games (including sites that claim to read your mind), to emergency rooms where you can ask for mathematical help. There are even more and varied sites that all help to make mathematics more accessible, if not popular.

(c) Problems identified

The difficulties that these contexts produce fall into two categories: development and applications. In the former category most new initiatives depend on a small number of people for their success. This makes them fragile. It often seems easier to find money to begin new projects than to find continuing support for them.

By applications we mean applications in schools. It is not clear that much of the new material available is being used successfully by great numbers of teachers in the regular classroom. This may be for a variety of reasons. First, teachers are frequently plagued with time constraints as more material, especially involving new subjects outside of mathematics, enters the school curriculum. These subjects reduce the time available for mathematics. Second, especially in senior secondary school, high stakes examinations force teachers into teaching for the examination rather than developing mathematical ideas. And third, teachers may lack the confidence to deal with the new material that was not part of their undergraduate training. They may also be uncomfortable with the more open pedagogy required for challenging situations which are, by their nature, less structured than the traditional pedagogy.

4. Questions arising

One goal for the Study Conference will be to get a good picture of what is the state of the art. Here are some examples of issues that may be considered in the context of this Study.

Impact of teaching and learning in the classroom:

- How do challenges contribute to the learning process?
- How can challenges be used in the classroom?
- How much challenge is provided in current curricula?
- What further opportunities to challenge would enhance teaching and learning in the regular classroom?

- How can teachers be made aware of the existence of the different types of challenges ?
- How can we ensure that these challenges are compatible with the mandated syllabus ?
- How can time constraints in the classroom be handled ?
- How can challenges be evaluated ?
- How can students be evaluated in challenges ?
- How can the effectiveness of using challenging materials be supported by the grading system ?
- What sorts of challenges are appropriate for remedial and struggling students ?
- What are the implications for teacher training of challenges which are in the classroom ?
- What are the implications for teacher training for challenges which exist outside of the classroom ?
- What background do students need to handle challenging material and how can this be introduced into the classroom ? This includes familiarity with mathematical notation and conventions, ability to reason and draw conclusions, ability to observe and classify and skill at communication.
- How can 'beyond classroom activities' like competitions, exhibitions, clubs, maths fairs etc influence the classroom activities and learning in such a way that all students in the class are challenged and motivated ?
- How can teachers, parents and students be made aware that these kinds of activities and challenges also will strengthen the learning and understanding of basic concepts and skills in mathematics ?
- Can experience with competitions, maths fairs etc be part of teacher training and in service teacher education ? And will this help to engage teachers in 'beyond classroom activities' or implement these kinds of activities in classroom practice ?
- How can textbooks be written so that challenging activities is the philosophy and leading idea behind the textbook, and not only fragmental parts of the content of the book ?
- How can technology be used by teachers and students to create challenging environments ?

Beyond classroom activities

- What is the effect on the visitors of exhibitions, festivals etc where they have only a short meeting with mathematical challenges ? How can parents, teachers, students and others be helped to go deeper into the mathematics beyond these short meetings ?
- How can one make visible the mathematics behind everyday technological devices, and how can this be put into a context that is accessible and mathematically challenging for different groups of people ?

Research

- What research has been done to evaluate the role of challenge ?
- What can research into the use of challenge tell us about the teaching and learning of mathematics ?
- What questions require further research ?

MORE GENERAL QUESTIONS

- How can the mathematics and mathematics education community be involved in this kind of challenging activity that goes beyond their own research interests?
- Are there some branches of mathematics that are more suitable for producing challenging problems and situations?
- How can different designs of challenging activities, in particular competitions, attract different groups of people (the very able students, gender, cultural differences, different achievement etc)?
- What can be done to identify, stimulate and encourage the mathematically talented students?

5. CALL FOR CONTRIBUTIONS

The work of this Study will take place in two parts. The first consists of a Conference to take place in Trondheim, Norway, from 27 June to 3 July 2006. The Conference will be a working one. Every participant will be expected to be active. Participation is by invitation only, based on a submitted contribution. Among the attendees, it is planned to represent a diversity of expertise, experience, nationality and philosophy. Such attendance should be drawn broadly from the mathematics and mathematics education community. It is hoped that the Conference will attract not only long term workers in the field but also newcomers with interesting and refreshing ideas or promising work in progress. In the past, ICMI Study Conferences have included about 80 participants.

The IPC hereby invites individuals or groups to submit contributions on specific questions, problems or issues related to the theme of the Study for consideration by the Committee. Those who would like to participate should prepare (a) a one-page listing of their current position and contact information, as well as of their past and present publications and activities pertinent to the theme of the Study; (b) a paper of 6–10 pages addressing matters raised in this document or other issues related to the theme of the Study. Proposals for research that is on its way, or still to be carried out, are also welcome. Research questions should be carefully stated and a sketch of the outcome – actual or hoped for – should be presented, if possible with reference to earlier and related studies.

These documents should be submitted no later than August 31, 2005, to both co-chairs of the Study either by post, by facsimile or (preferably) by e-mail. All such documents will be regarded as input to the planning of the Study Conference and will assist the IPC in issuing invitations no later than January 31, 2006. All submissions must be in English, the language of the Conference.

The contributions of those invited to the Conference will be made available to other participants beforehand as preparation material. Participants should not expect to present their papers orally at the Conference, as the IPC may decide to organize it in other ways that facilitate the Study's effectiveness and productivity.

Unfortunately an invitation to participate in the Conference does not imply financial support from the organizers, and participants should finance their own attendance at the Conference. Funds are being sought to provide partial support to enable participants from non-affluent countries to attend the Conference, but the number of such grants will be limited.

The second part of the Study is a publication which will appear in the ICMI Study Series. This Study Volume will be based on selected contributions submitted as well as on the outcomes of the Conference. The exact format of the Study Volume has not yet been decided but it is expected to be an edited coherent book which it is hoped will be a standard reference in the field for some time.

INTERNATIONAL PROGRAMME COMMITTEE

Co-chair: Edward J. BARBEAU (University of Toronto, Canada)

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INQUIRIES

Inquiries on all aspects of the Study, suggestions concerning the content of the Study Conference and submission of contributions should be sent to *both* co-chairs:

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The official website for the Study is http://www.amt.edu.au/icmis16.html