What counts as “mathematics for engineers” and how can it be captured?

Daniela Velichová

Slovak University of Technology in Bratislava, Slovakia

SEFI Mathematics Special Interest Group

Slovak University of Technology in Bratislava, Slovakia

- Established in 1937 in former Czechoslovakia (85 years)
- 7 faculties + 1 institute
  - Faculty of Civil Engineering
  - Faculty of Mechanical Engineering
  - Faculty of Electrical Engineering and Information Technology
  - Faculty of Chemical and Food Technology
  - Faculty of Architecture and Design
  - Faculty of Materials Science and Technology
  - Faculty of Informatics and Information Technology
  - Institute of Management
- Almost 11 000 students
- 3 types of degrees - Bachelor, Master and Doctoral
- Lifelong learning and MBA programme in cooperation with TU Wien
- More than 700 research projects funded through EU grants and hundreds of research contracts commissioned by businesses

Bachelor programmes

Mathematics I (Linear algebra, Differential and Integral calculus, Sequences and series)

Mathematics II (Differential equations, Coordinate geometry in 3D, Multivariable calculus)

Mathematics III (Curve and surface integrals, Fourrier series)

- Numerical Analysis (Iteration methods, Interpolation and approximation, Numerical differentiation and integration, Numerical methods for ODR, Eigenvalues and eigenvectors)
- Construction Geometry (Projection methods, Geometry of curves and surfaces (free-form)
- Basics of Statistic Analysis (Probability, Discrete and continuous random variables and vectors, Covariance, correlation, distribution, Chebyshev inequality, Statistical induction, Central limit theorem, Statistical hypothesis testing)

Master programmes

- Vector Analysis
- Differential Equations
- Applied Mathematics
- Applied Algebra
- Statistical Analyses
- Differential Geometry

PhD programmes

Special Differential Equations

Optimisation mehods

Selected Parts of Mathematics

D. VELICHOVÁ

- Employed at STU from 1974
- Head of the Institute of Mathematics and Physics from 2011
- Lecturing for 46 years various subjects
  - Mathematics I
  - Mathematics II
  - Mathematics III
  - Numerical Analysis
  - Vector Analysis
  - Applied Mathematics
  - Applied Algebra
  - Construction Geometry
  - Differential Geometry

- Member of the SEFI MWG Steering committee from 1995
- Chair of the SEFI MWG – MSIG from 2014

SEFI Mathematics Special Interest Group - www.sefi.be

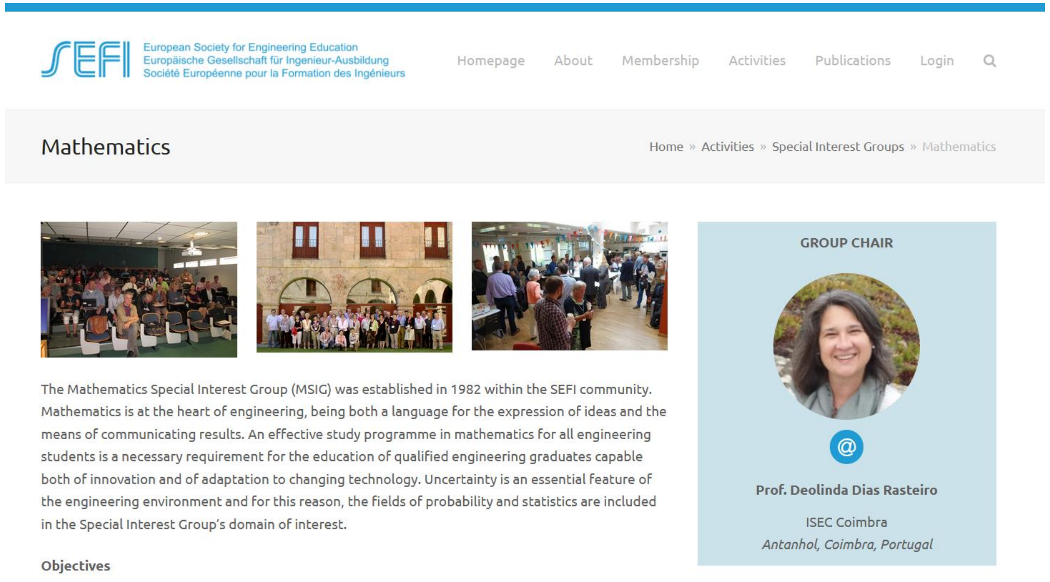
- Formed as SEFI Mathematics Working Group in 1982
  - activity of the mathematics lecturers around Lennart Råde,
    at the Chalmers University in Gothenburg, Sweden
- Member of the SEFI MWG Steering committee from 1995
- Chair of the SEFI MWG – MSIG for 7 years 2014 - 2021
- Aims of the Group include
  - to provide a forum for the exchange of views and ideas amongst those interested in engineering mathematics
  - to promote a fuller understanding of the role of mathematics in the engineering curriculum, and its relevance to industrial needs
  - to foster co-operation in the development of courses and support material, in collaboration with industry
  - to recognise and promote the role of mathematics in the continuing education of the European engineers

SEFI Mathematics Special Interest Group - www.sefi.be

- New chair of the group from September 2021

  Dr. Deolinda Dias Rasteiro, ISEC Coimbra, Portugal

- Members of the Steering Committee
  - Burkhard Alpers, Aalen University, Germany
  - Marie Demlova, Czech Technical University in Prague, Czech Republic
  - Tommy Gustafsson, Chalmers University, Sweden
  - Duncan Lawson, Coventry University, UK
  - Brita Olsson-Lehtonnen, Espoo, Finland
  - Paul Robinson, DIT Dublin, Ireland
  - Morten Brekke, University of Agder, Norway
  - Daniela Velichová, STU in Bratislava, Slovakia



SEFI Mathematics Special Interest Group Activities

- Editions and update of the Core Curriculum document

"**Mathematics for the European Engineer. A Curriculum for the Twenty-First Century**"

the 2nd edition of the curriculum document in terms of learning outcomes

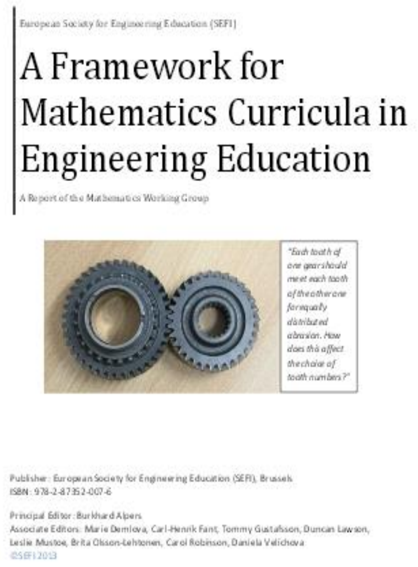
Leslie Mustoe at all., 2002

"**A Framework for Mathematics Curricula in Engineering Education**"

the 3rd edition, based on the concept of mathematical competence

(Mogens Niss: Danish KOM project)

Burkhard Alpers at all., 2013



"**Mathematics as a Service Subject at the Tertiary Level**"

State-of-the-Art Report of the SEFI MSIG

Burkhard Alpers, 2020

"**Making Sense of Engineering Workplace Mathematics to Inform Engineering Mathematics Education**"

the most recent report of the Mathematics Interest Group

Burkhard Alpers, 2021

SEFI Mathematics Special Interest Group Activities

- Group Information webpages
  - www.sefi.be/activities/special-interest-groups/mathematics/
  - sefi.htw-aalen.de/

Contacts and information about the group main role and activities:

- curriculum document updates
- information on SEFI MSIG seminars
- proceedings from past seminars (from 2004)
- overview of recognised important topics
- list of references for further reading
- list of contact persons in the European countries

Aim – to accumulate a sound body of knowledge on the mathematical education of engineers.

SEFI Mathematics Special Interest Group Activities

- Organisation of bi-annual European Seminars on Mathematics in Engineering Education

The **20th SEFI-MWG European Seminar on Mathematics in Engineering Education** took place as a virtual event on June 17-18, 2021 in Kristiansand, Norway.
It was jointly organized by the University of Agder and the MaTRIC centre of excellence.

Aim

– to promote a fuller understanding of the role of mathematics in engineering study and practise

– to share best examples and experience among practicing mathematics lecturers at the European TU.

Next seminar

The **21th SEFI-MSIG European Seminar on Mathematics in Engineering Education**
June 15 – 17, 2022 at the University of Brasov, Romania.

SEFI Mathematics Special Interest Group Activities

- Annual meetings of MSIG Steering Committee members

December 4-5, 2021, Czech Technical University in Prague, Czech Republic

Aims

– to prepare list of activities for the next period

– to manage organization of group seminars

– to discuss new challenges and important topics for the future of mathematics in engineering education and practise.

- Participation at the SEFI annual conferences

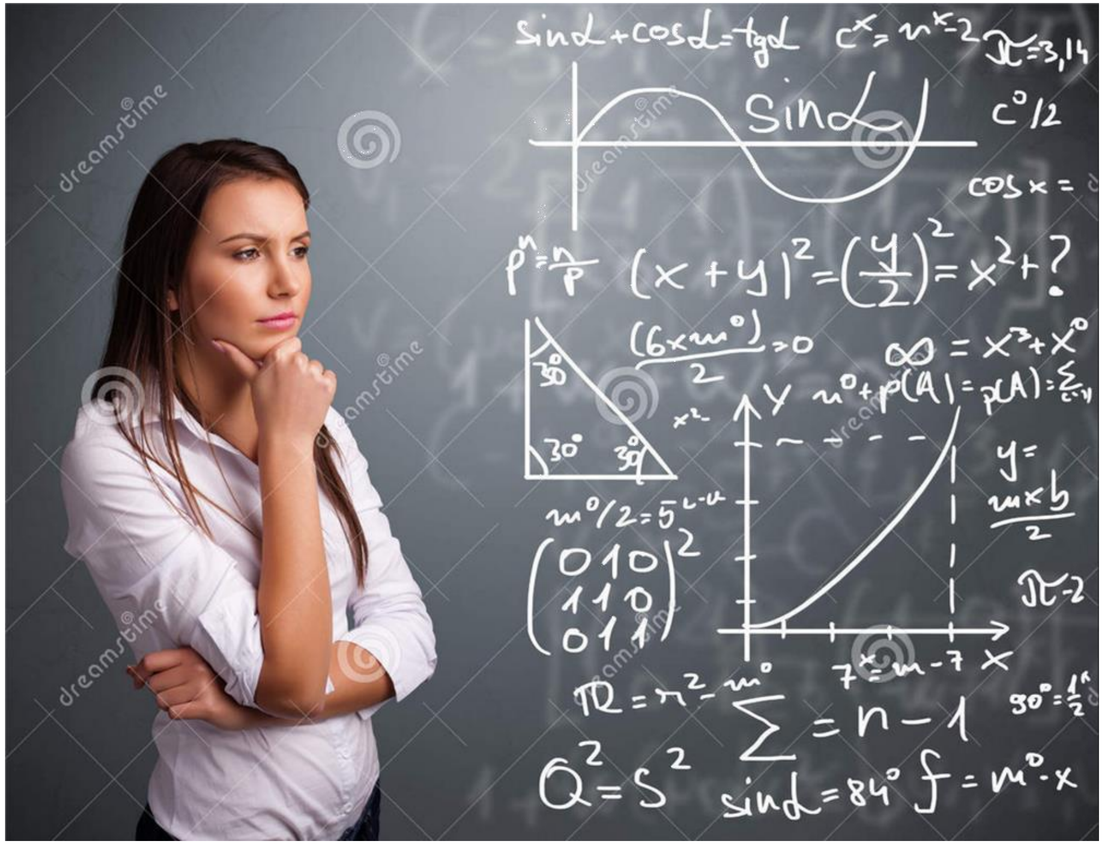
Aims

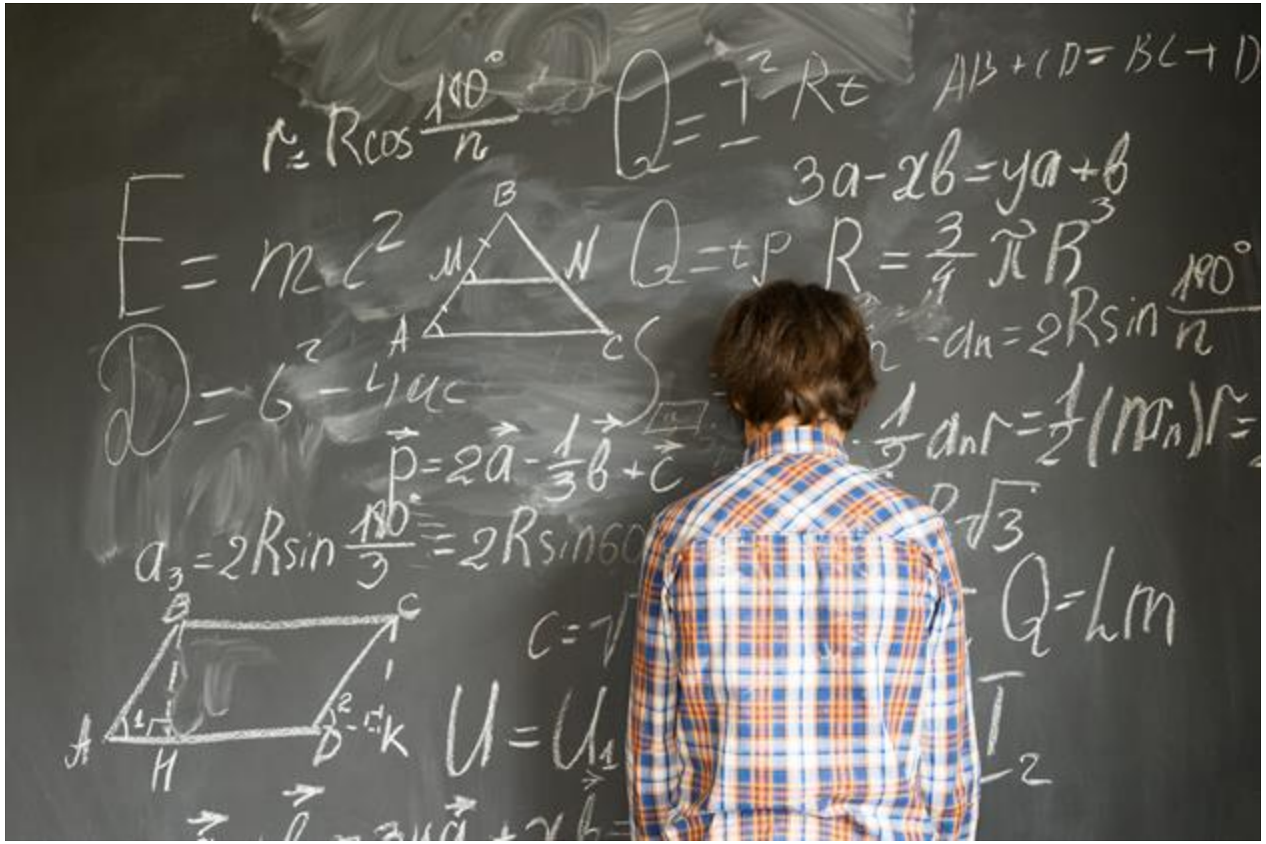
– to present activities of MSIG

– to organize workshops and special conference sessions on maths in engineering

– to develop and promote cooperation with other SIGs within SEFI.

Can I Become an Engineer if I am Bad at Math?





Can I Become an Engineer if I am Bad at Math?

According to the Bureau of Labor Statistics of USA

- Mathematics is a central component to the education engineers receive in all major specialties before they begin their careers.
- Engineers also use math extensively on the job. For these reasons, it is unlikely anyone would be successful in becoming an engineer with poor math skills. Math is a major part of engineering coursework, along with statistics, physics and life sciences, depending on what kind of engineering you study.
- Math skills are important for all kinds of jobs, from retail cashier to stockbroker, IT user to AI specialist, mechanical engineer to expert in applied mechanics, mechatronics or aerospace, civil engineer to architect, or from processing engineer in chemical plant to expert in macromolecular chemistry and biotechnology.
- However, jobs vary in how much they depend on mathematical knowledge. For engineering jobs, using math - **from simple addition and subtraction to complex calculus** - is a daily part of the work, in the analysis, design and troubleshooting.

Can I Become an Engineer if I am Bad at Math?

Engineers design and develop various types of projects and systems, depending on their area of expertise.

- Civil engineers - roads, tunnels and bridges, ...
- Electrical engineers - electrical equipment, motors, navigation systems, power generators, ...

Becoming an civil or electrical engineer requires at least a bachelor's degree in this field, and coursework will include advanced mathematics, including advanced calculus.

- Architects – houses, office buildings, cultural, sport and industrial complexes, ...

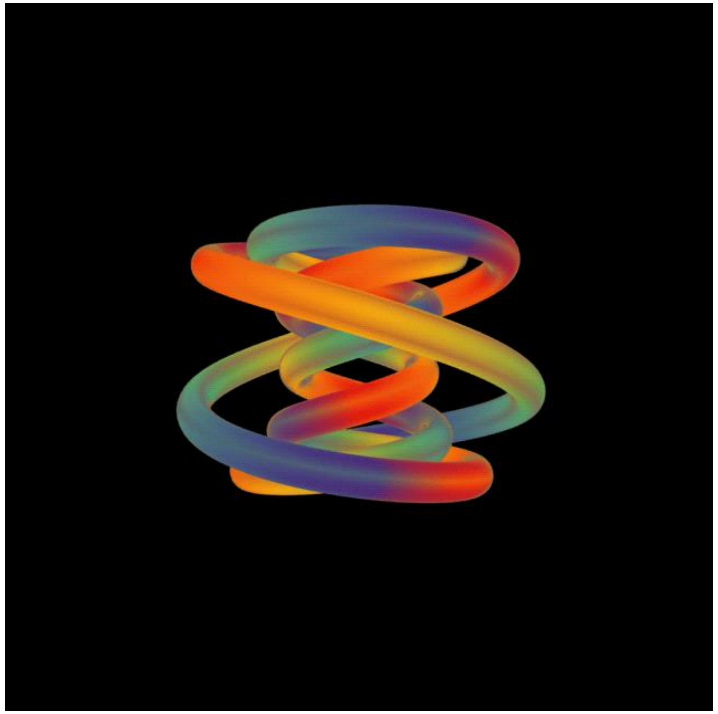
An in-depth knowledge of mathematics is essential for informed design of 3D structures. Becoming an architect requires at least a bachelor's degree in architecture, including courses on 3D geometry and projection methods.

- Mechanical engineers - various mechanisms, motor engines for vehicles and planes, robots manipulators, mechatronic devices, ...

Good understanding and knowledge on solving differential equations is essential to obtain bachelor's degree in mechanical engineering.

- Obtaining an engineering degree requires you to successfully complete a multitude of engineering mathematics courses.
- In the days before computers, engineers used slide rules and pencils to work out math problems, such as determining the stresses a dam must withstand, or the most efficient operating weight of an airplane.
- Although today computers can solve many of these math problems, engineers still need a solid foundation in maths and a good steady understanding of mathematical principles.
- Each university develops its own degree plan and course catalogue, but certain types of engineering math courses are typically required.

- Take Algebra Courses
- Trigonometry is essential
- You will also need Analytic Geometry
- Calculus is a Must
- Engineers should understand Differential Equations
- Do not forget Probability and Statistics
- Numerical Methods and Analysis is a necessity



- Take other suggested and required Courses
  - Vector Algebra
  - Discrete Mathematics
  - Graph Theory
  - Differential Geometry
  - Complex Analysis
  - Fuzzy Logic Systems
  - Neural Networks
  - Etc.

Demanding and Ambitious

University of Bristol, UK
promotes Bachelor and Master
Engineering Mathematics Courses

Engineering mathematics is the art of

- applying maths to complex real-world problems
- combining mathematical theory, practical engineering and scientific computing

to address today’s technological challenges.

How can all this be captured?

First things first

- One should not expect university education to deliver ‘full grown’ engineers.
- Engineering student, performing well at examinations in various maths and professional courses, is not „right away“ a good practising engineer.
- An ability to do engineering work comes from the “experience of working in an engineering environment” watching other engineers estimate, work out real problems, and experience how they view “the bigger picture”.
- University education can provide opportunities to experience the different aspects of theoretical sciences, work on projects in team, and to induce meta-cognitive thoughts about the processes involved, but

it cannot anticipate years of experience in real engineering projects.

But what university education can do is to contribute significantly

to building and developing competencies.

3 aspects of mathematics engineering education

- **Technological issues**

ICT supported education, distance learning, on-line courses and assessment, instructional materials and resources

- **Didactical issues**

Various learning arrangements and scenarios, active learning methods, motivation, content and learning outcomes

- **Mathematical understanding**

Conceptual understanding versus calculation skills, epistemological and hermeneutic understanding

Some of ideas born, discussed and addressed at MSIG seminars

Technological issues

- Everlasting topics for discussions (before 2000)

  - How to settle the proper proportion balancing usage of traditional methods and ICT?

  - New role of teachers as instructors, and no more the main “bearers of knowledge“!?

  - Computer assisted assessment versus traditional paper-and-pencil tests!?

  - What web-based learning resources are well designed, and how to restrict or improve ill-considered computer aided teaching and assessment?

  - Should be all calculation skills left to computers?

  - May/does computer-based learning environment cause an unexpected transmission of the bases of “traditional mathematical culture”?

  - How to recognise a stable amount of the core mathematical knowledge and ideas, having a strong impact on the overall reasoning, that was always considered by engineers as **natural**?

Technological issues

- Various ways how ICT can be utilised in maths education

Direct methods - usage in educational process and assessments

- CAS and dynamic maths software as powerful demonstration tool for lecturer
- CAS for exploring and calculations during maths lessons and practicals
- Pocket / graphing calculators
- CAS utilised by students in solving mathematical problems and projects
- E-learning solutions for maths courses
- Computer based assessment

Indirect methods – additional study resources for self-study and evaluation

- On-line maths courses
- On-line maths databases with electronic resources
- Mathematics support centres
- Usage of web-based materials (applets, videos, on-line stack exercises)
- Tutorials by e-mails
- Maths chats on Internet

CURRENTLY ESPECIALLY APPRECIATED AS ALMOST THE ONLY POSSIBLE SOLUTION LEFT!

Technological issues

- Students´ approach, reactions and their attitude to the utilization of new technologies

There is strong evidence that students enjoy well designed web-based learning resources.

- Many of students have a job in addition to their studies, therefore they prefer net based education, since they do not have to leave their job and family.
- An easy way to get an answer to some problems with basic terms and concepts.
- Electronic courses on Internet can be very useful for a particularly easy access to various resources, discussion boards, other sources of information if necessary (the links to other sites), etc.
- Each student can work at his/her own place: at home, in Internet cafe, in the school computer lab, wherever, and at its own comfortable pace.
- Lot of additional explanatory material— graphs, dynamic illustrations and visualisations, exercises and solved problems, applications, maths stories, puzzles, maths games, etc.

More demands on teachers = less expected from students?!

Technological issues

- Students´ approach, reactions and their attitude to the utilization of new technologies

Ill-considered computer aided teaching and assessment may produce frustration and anxiety.

- Explanations need to be very clear, simple and easy to use, as without the “human touch“, students can often get confused and frustrated.
- Students are concerned about the communication with other students and teachers.
- Students find it important to have real meetings and software that makes communication and collaboration easier and more enjoyable.
- Students mostly did not like the idea of a net-based course without real classes.
- Many students were not sure they could understand the mathematics well without face-to-face explanation and discussion with the teacher.
- Students were not sure if they would prefer to apply for an Internet e-learning course on Mathematics, probably yes, but only for enhancing the traditional courses.

Covid -19 impact: Great degree of forced social isolation among university staff and students!

Technological issues

- Summary and what can be expected in the future

- Information and communication technologies have created many new possibilities in teaching.
- Special facilities provided by computers need new approach to teaching mathematical subjects.
- Accumulation of necessary mathematical knowledge of an engineer has to be performed consistently and in various ways, by using computers from the very first year of the engineering study.
- In some topics computer animation can greatly increase the effectiveness of the teaching process.
- Computer visualisations and modelling, computational capacity of available computer algebra systems and rapidly expanding applications of mathematical models in many different areas, technical sciences in particular, led to a new specific character of teaching mathematics.
- Introduction of ICT supported education cannot be ignored, neglected or rejected.
- ICT should be used on a widest possible scope, but **not on the expense of face-to-face experience**.

The latest development shows increasing demands on complex hybrid solutions!

Didactical issues

- Content and learning outcomes

- B. Alpers at all. (2013) **A Framework for Mathematics Curricula in Engineering Education**

the 3rd edition of Core curriculum based on the concept of mathematical competence

- The main message of this new edition is that although content remains important, knowledge should be embedded in a broader view of mathematical competencies.
- This document adapts the competence concept to the mathematical education of engineers and explains and illustrates it by giving examples.
- It does not prescribe a particular level of progress for competence acquisition in engineering education.
- In a competence-based approach the mathematical education must be integrated in the surrounding engineering study course to really achieve the ability to use mathematics in engineering contexts.
- The competence framework serves as an analytical framework for thinking about the current state in one’s own institution and also as a design framework for specifying the intended profile.

Didactical issues

- Mathematical competencies – learning outcomes

1. Thinking mathematically
   To understand what is the role, scope and recognise limitations of mathematics
2. Reasoning mathematically
   To accept and actively use the way of mathematical argumentation
3. Posing and solving mathematical problems
   To identify mathematical problems, and specify ways how to solve them
4. Modelling mathematically
   To set and formulate problems in terms and symbols of mathematics
5. Handling mathematical symbols and formalism
   To use and manipulate symbolic statements and expressions according to the rules
6. Communicating in, with, and about mathematics
   To understand mathematical statements and to express oneself in terms of mathematics
7. Making use of aids and tools
   To know about available aids an tools and to use them efficiently

Didactical issues

- Which learning arrangements are adequate for preparing engineers for making proper use of mathematics at later workplaces?

- Lectures for large groups in traditional way

The goal is to give students a first glimpse and familiarity with the material; subsequent individual or group activities, carried out by the learners, are necessary to deeper understanding. A good lecture should motivate the material, relate it to previous concepts and provide an overall picture.

- Tutorials

Tutor (teaching assistant or student) works with smaller groups of students in order to improve their understanding related to a lecture.

- Formative assessments

All kinds of smaller tasks that students have to undertake on their own. These include standard computational tasks that serve to develop more familiarity with notation, formalism and procedures but also more open and investigative assignments, with or without technology.

Didactical issues

- Work on projects

Students work, mostly in groups, on problems which are larger, more open and investigative in nature. At the end they provide a project document and present their work.

- Mathematical laboratories

Students work in a PC laboratory on tasks requiring the use of mathematical software such as numerical programs or various CAS to practise their usage in solving computationally demanding tasks and experimenting with more open tasks of an investigative nature.

- Technology enhanced learning

Many different scenarios are available: e-learning platforms, blended learning, on-line learning courses, which often suggest that the learning activity may be carried out remotely from the presence of a member of academic staff. Presentation material, potentially using multimedia, can be made available for students to use to re-visit certain content in order to gain better understanding.

- Collaborative virtual classrooms

Synchronous and asynchronous communication on available eLearning platform

Didactical issues

- Active learning methods and motivation

- Problem learning
  Solving small applied problems – individually or in project teams
- Learning by teaching
  Prepare and teach short lessons to fellow students on some basic maths concepts
- Flipped classrooms
  Self-study outside the class with presentation in a classroom environment
- EduScrum method
  Work in small teams guided by chosen scrum master from the team
- Jigsaw technique
  Collaborative learning via solving mathematical puzzles
- Gamification
  Learning by playing

Didactical issues

- Techno-mathematical literacy

- technology affords specific working styles of “trial and error “
- new problem solving strategies were recognised, as “guess and verify” and “separate larger problems into smaller ones”
- “technical creativity” is supported by innovative technology and tools
- “sense of numbers” is developed as aspect related to various interpretations of solution
- “sense of error” is fostered, meaning that an engineer should be able to “check and verify data and detect errors”
- “decision making, estimation and confirmation of solution” could be developed as a consequence of the competency based teaching approach
- “big picture thinking“ ability evolved as a goal of quality engineering education outcome

Mathematical understanding

- Conceptual understanding versus calculation skills

- calculation skills as one of the previously highly evaluated „engineering skills“ are becoming less important due to powerful ICT available
- technical skills how to use various available CAS, CAD and simulations are not sufficient to enable engineers to solve applied problems represented as mathematical models
- engineers today need a good steady understanding of mathematical principles and basic concepts to apply these reasonably to solve applied problems
- they must be aware of advanced and newly developing mathematical theories, to be able to apply these in mathematical modelling to solve challenging engineering problems
- essential skills are: estimation of the forms and values expected as results from computer, predict the results of calculations, i.e. be aware of limits and restrictions of mathematical modelling in terms of practical needs
- accuracy plays an important role in many advanced technical branches

Mathematical understanding

- Epistemological and hermeneutic understanding

- **Epistemological understanding** is acquisitional. In epistemology, understanding is a deliberate process whereby knowledge is developed. New knowledge is produced by the logic deduction or the transformation of formal systems. By knowing this process, we can say that we understand the result.
- Pure mathematician explores mathematics in its abstract form to reveal new insights. This is a creative role, which requires deep understanding of mathematical concepts and their relations, while no understanding of the physical world or its relations to mathematics is required.
- **Hermeneutic understanding** is transformational. Hermeneutics is concerned with what or who the learner is, rather than with what she/he knows. Understanding thus changes how the learners see and relate to the world around them.
- As an engineer, one has to see the mathematical model as if it is the real gadget being designed, in order to assess if it is good for real people. Computing the behaviour of the gadget is not sufficient, it is the meaning of the gadget that is important to its users.

Mathematical understanding

- Efficient learning depends on pre-understanding and meaning, both of which are highly personal and individual.
- Each student has their own unique background, and their own visions and motivations for the future. They need freedom to search for meaning within their own personal context and within their existing cognitive schemata.
- Understanding is the natural state of the mind when it is left free to explore the world, and it cannot be forced nor passed to. Some concepts and techniques have to be learnt, but student needs some freedom to find their meaning.
- Mathematics in itself studies necessary truths, about things which could not be otherwise. Learning therefore may be considered as creative imitation. Teacher is an authority and a good example for imitation, thus the students may be right when learning by heart simply to copy teacher´s solutions.

Mathematical understanding

- Understanding makes sense of the world, and it incorporates sense-experience with academic knowledge in one consistent whole.
- Meaning is personal, and has to be found by the learner, and not given by the teacher. This shifts agency from the teacher to the learner.
- This attention on meaning and agency, might possibly solve some of the known problems in mathematics education.
- Problem solving is trial and error, and each student will have to make sense of the problem as a free agent, and not as a copy of the teacher.
- If comprehension of the real world is out of scope of the taught module, and the student does not see himself as a mathematician, it makes sense not to aim for other understanding **just to understand how to succeed in the exam**.
- This can be seen as constructive misalignment - teaching was aiming for learning outcomes that the exam did not encourage.

4 general recommendations

- Workshop on Mathematics in Engineering, Imperial College London, April 25-26, 2006
- Presented by Jörg Waldvogel, ETH Zurich
- Teaching Mathematics to Engineering Students at ETH: Coping with the Diversity of Engineering Studies

1. Stress linear algebra, if necessary at the cost of analysis!

The operations of calculus are defined as limits of algebraic operations acting on discrete data.

This leads to the extremely useful and elegant concepts of mathematical analysis.

Unfortunately, most problems of analysis do not have explicit solutions, i.e. solutions in terms of known functions.

Therefore, engineers – in need of concrete solutions – are forced to use discrete approximations: e.g. sums instead of integrals, systems of algebraic equations instead of PDEs, etc.

A shortcut, partially circumventing calculus: directly solve the discrete problem by methods of linear algebra. Example: finite element method

2. Teach numerical analysis along with calculus!

- Numerical analysis is essential for every engineer.
- The practical engineering problems are rarely solvable in closed form.
- Combining calculus and numerical analysis saves time!
- The capability of efficiently solving difficult maths problems (and visualizing the results) increases the motivation of the engineering students.
- Problem is to find teachers willing to teach such complex courses.

  Possible solution: cooperation of mathematician and numerical analyst

3. Appropriate use of modern mathematical software

- Mathematical software cannot replace basic understanding.
- Mathematical software, in particular symbolic computation, is very useful in many situations, e.g. for checking the correctness, for shortening lengthy calculations, etc.
- Closed-form solutions – if they exist – are often too long to be useful.
- Canned solutions lack transparency. The user is often reduced to a typist: Key to the problem solution is the syntax of the software system and just to type – solve!
- The numerical approach (e.g. with the help of CAS) is often more transparent and more versatile.

4. Improve connection with specific engineering topics

- Topics of the advanced maths courses should be chosen in agreement with the engineering departments.
- Students always love examples. Primarily use examples from particular engineering fields. This requires intensive contact between the maths teachers and the engineering departments.
- Danger: the mathematician’s ideas about an engineering example: “Consider a practical example: Let *f* be a Hölder-continuous function defined on R^+ . . . ” will hardly address our students.

Last comments based on personal experience

- Mathematical skills are essential in STEM careers not just because they are required, or because they are utilized frequently, but because

❖ maths helps to analyze and solve problems with a methodical approach,

❖ while paying attention to detail, and

❖ thinking abstractly.

These are skills that all of us will greatly value when making key life decisions.

- Mathematical skills will not be rendered obsolete with time, so we can continue to use them in a meaningful way over the course of our lives, both professional and private personal.

Last comments based on personal experience

- Mathematics is teaching us

❖ to seek the truth,

❖ to solve problems prudently and rationally,

❖ to take objective views and

❖ never give up.

Often even a negative answer is an acceptable solution in mathematics.

However, engineers make impossible possible!

Last comments based on personal experience

- Mathematics gives us a way

❖ to understand patterns

❖ to quantify relationships, and

❖ to predict the future.

Mathematics helps us understand the world — and we use the world to understand mathematics.

It can also predict such issues as

- profits and growth, or loss and bankruptcy,
- how ideas or Covid-19 pandemic spread,
- how previously endangered animals might repopulate,
- how our Universe is going to behave and evolve.

Last comments based on personal experience

- Mathematics is going to become more important, not less.

Computational skill will become and already is far less important. If you only know how to mechanically do some calculations, that does not count for much.

Problem-solving ability and knowledge of how to take abstract mathematical ideas and apply them to real world situations is going to become far more important.

- Currently, the price of the physical labor is relatively high, but automation is killing most industrial jobs.
- Mathematical competency and understanding is the guarantee of future success; it will never become irrelevant.

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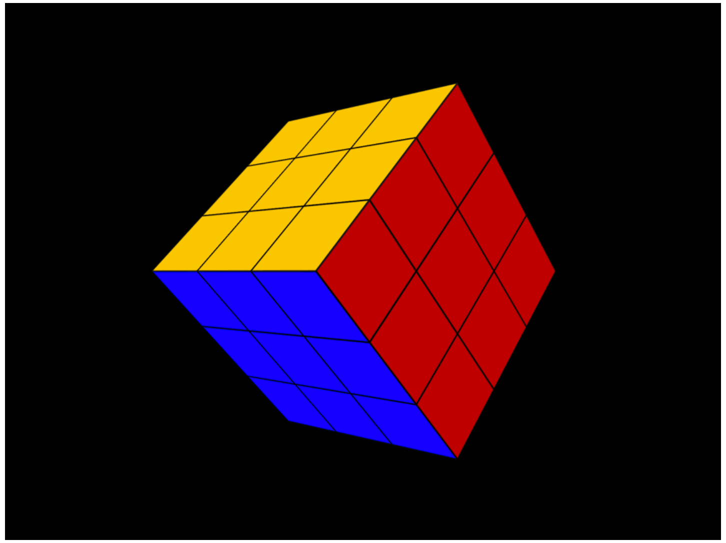
Mathematics is a fun game for those who accept its weird rules.
Game teaching us to accept the insurmountable boundaries,
and to wait patiently,
while tirelessly seeking and finding solutions of unsolvable tasks,
for the right time when we will be able to cross them.



Many thanks for your attention!