TUHH
Hamburg
University of
Technology

# Module Manual

Master of Science (M.Sc.)

# Computer Science in Engineering

Cohort: Winter Term 2022

Updated: 21st June 2022

# Table of Contents

# Program description

## Content

The master's program in Computer Science in Engineering consistently continues the focus on cyber-physical systems, i.e. networked computing systems in their physical environment, from the bachelor's program. This is done through in-depth computer science education related to engineering disciplines, especially electrical engineering. Students acquire in-depth competencies up to the latest research in computer science, such as on machine learning or data science, with the goal of successfully applying them in engineering applications.

The master's program in Computer Science in Engineering builds on the three pillars of mathematics, computer science, and engineering. Corresponding elective catalogs guarantee that in-depth knowledge is acquired in these three specializations. In engineering, the focus is on electrical engineering. In addition, the curriculum offers a great deal of freedom to choose courses from the TUHH's other technical offerings. In this way, students set their own accents in order to build interdisciplinary bridges in specific engineering fields. Likewise, advanced knowledge in business administration and management as well as in non-technical subjects is acquired in order to form the competencies for the implementation of extensive IT projects. This includes, in particular, the ability to independently acquire complex areas of knowledge and to work independently on complex technical issues.

The study plans for (N) networked embedded systems, (D) reliable and secure systems, (A) algorithms for data engineering, and (M) medical technology show exemplary orientations of high practical relevance.

## Career prospects

Graduates can take up scientific activities at universities and research institutes, in particular with the aim of obtaining a doctorate, or decide to enter industry directly. They possess a wide range of methodological and interface knowledge that enables them to work across disciplines.

## Learning target

The learning objectives of the program are based on the objectives listed above. All of the learning objectives listed represent competencies that are required in both corporate and research environments. In distinction to the Bachelor's program in Computer Science in Engineering, the competencies listed here refer to complex problems, to the consideration of uncertainty and to working under given boundary conditions from application fields. In the following, the learning objectives are divided into the categories of knowledge, skills, social competence and independence.

**Knowledge**

- Engineering Sciences: Graduates have an in-depth understanding of mathematical, scientific, and systems engineering contexts with a focus in electrical engineering. This knowledge is underpinned by a broad theoretical and methodological foundation.
- Computer Science: Graduates have an in-depth knowledge of methods and procedures for model building and problem solving in theoretical, practical and technical computer science.
- Mathematics: Graduates have in-depth knowledge of mathematical methods for optimization, image processing, randomized algorithms, or neural networks.
- Economics: Graduates know the basics of business and management and related subjects such as patents and their relationship to their subject.
- Bridging the gap between computer science and engineering: Graduates have in-depth knowledge of methods and procedures to describe interfaces between engineering applications on the one hand and computer science models on the other hand. Graduates are familiar with the latest information and communication technology systems that interact with the real world - so-called cyber-physical systems.

**Skills**

- Engineering: Graduates are able to apply their engineering judgment to work with, recognize contradictions in, and deal with complex, potentially incomplete information.
- Computer Science: Graduates are able to develop instances of comprehensive formal models of computer science using advanced modeling approaches, determine their computability and complexity, and implement them in a technical framework using appropriate programming tools. Graduates will be able to design and implement software solutions. This includes complex software systems in which distributed realization, reliability or correctness play a special role.
- Mathematics: Graduates can solve optimization problems, apply mathematical methods of image processing or randomized algorithms.
- Bridging computer science and engineering: Graduates can scientifically analyze and solve engineering problems, develop a suitable formalization for information technology treatment, and implement a software solution. Graduates can realize cyber-physical systems that are distributed and networked.

**Social competence**

- Graduates are able to present the scientific approach and the results of their work in a written and oral way.
- Graduates are able to communicate about scientific contents and problems of computer science with experts from engineering fields and laymen. They can respond appropriately to inquiries, additions and comments.

**Independence**

- Graduates are able to obtain necessary information and place it in the context of their knowledge.
- Graduates can realistically assess their existing competencies, compensate for deficits independently and acquire additional competencies independently.
- Graduates are able to develop research areas in a self-organized and self-motivated manner and to find and define new problems (lifelong research).

## Program structure

The curriculum of the master's degree program in Computer Science in Engineering is structured as follows. A minimum number of credits must be earned in each of the three core areas of computer science, engineering and mathematics:

1. Computer Science: 18 credits
2. Engineering sciences: 12 credit points
3. Mathematics: 12 credit points

To deepen their studies, students can choose lectures from a catalogue of technical courses offered by TUHH. A total of 24 credit points must be achieved. Practical knowledge and skills are taught in a research project (12 credit points). A further 12 credit points must be earned in the courses

Operation & Management and a non-technical supplementary course. The master thesis is assessed with 30 credit points. This results in a total effort of 120 credit points. The curriculum contains a mobility window in such a way that students can spend the third semester abroad.

The following four study plans describe special characteristics of the master's programme in Computer Science and Engineering.

**N. Networked Embedded Systems**

1. Core subjects computer science

- Software security

- Design of Dependable Systems

- Communication networks

2. Core subjects engineering sciences

- Digital communications

- Information theory and coding

3. Core subjects mathematics

- Linear and nonlinear optimization

- Randomized algorithms and random graphs

4. Supplementary technical courses

- Software for embedded systems

- Simulation of communication networks

- Wirless sensor networks

- Operating system construction

**D. Dependable and Secure Systems**

1. Core subjects computer science

- Software security

- Software verification

- Design of Dependable Systems

2. Core subjects engineering sciences

- Digital signal processing and filters

- Electrical Power Systems II: Operation and Information Systems of Electrical Power Grids

3. Core subjects mathematics

- Linear and non-linear optimization

- Numerical mathematics II

4. Supplementary technical courses

- Robotics & navigation in medicine

- Data science for cyber security

- Security of cyber physical systems

- Industrial process automation

**A. Algorithms for Data Engineering**

1. Core subjects computer science

- Software verification

- Algorithmic game theory

- Advanced internet computing

2. Core subjects engineering sciences

- Information theory and coding

- Machine learning in electrical engineering and information technology

3. Core subjects mathematics

- Mathematical image processing

- Mathematics of neuronal networks

4. Supplementary technical courses

- Massively Parallel Systems: Architecture and Programming

- Numerical mathematics II

- Approximation and stability

- Hierarchical algorithms

**M. Medical technology**

1. Core subjects computer science

- Software verification
- Medical imaging
- Security of cyber physical systems

2. Core subjects engineering sciences

- Intelligent systems project
- Digital signal processing and filters

3. Core subjects mathematics

- Mathematical image processing
- Numerical mathematics II

4. Supplementary technical courses

- Probability theory
- Intelligent systems in medicine
- Robotics & navigation in medicine
- Feedback Control in Medical Technology

# Core Qualification

## Module M0523: Business & Management

| | |
|---|---|
| **Module Responsible** | Prof. Matthias Meyer |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | None |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | • Students are able to find their way around selected special areas of management within the scope of business management.<br>• Students are able to explain basic theories, categories, and models in selected special areas of business management.<br>• Students are able to interrelate technical and management knowledge. |
| *Skills* | • Students are able to apply basic methods in selected areas of business management.<br>• Students are able to explain and give reasons for decision proposals on practical issues in areas of business management. |
| **Personal Competence** | |
| *Social Competence* | • Students are able to communicate in small interdisciplinary groups and to jointly develop solutions for complex problems |
| *Autonomy* | • Students are capable of acquiring necessary knowledge independently by means of research and preparation of material. |
| **Workload in Hours** | Depends on choice of courses |
| **Credit points** | 6 |

| **Courses** |
|---|
| **Information regarding lectures and courses can be found in the corresponding module handbook published separately.** |

## Module M0524: Non-technical Courses for Master

| | |
|---|---|
| **Module Responsible** | Dagmar Richter |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | None |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | **The Nontechnical Academic Programms (NTA)**<br><br>imparts skills that, in view of the TUHH's training profile, professional engineering studies require but are not able to cover fully. Self-reliance, self-management, collaboration and professional and personnel management competences. The department implements these training objectives in its **teaching architecture**, in its **teaching and learning arrangements**, in **teaching areas** and by means of teaching offerings in which students can qualify by opting for **specific competences** and a **competence level** at the Bachelor's or Master's level. The teaching offerings are pooled in two different catalogues for nontechnical complementary courses.<br><br>**The Learning Architecture**<br><br>consists of a cross-disciplinarily study offering. The centrally designed teaching offering ensures that courses in the nontechnical academic programms follow the specific profiling of TUHH degree courses.<br><br>The learning architecture demands and trains independent educational planning as regards the individual development of competences. It also provides orientation knowledge in the form of "profiles".<br><br>The subjects that can be studied in parallel throughout the student's entire study program - if need be, it can be studied in one to two semesters. In view of the adaptation problems that individuals commonly face in their first semesters after making the transition from school to university and in order to encourage individually planned semesters abroad, there is no obligation to study these subjects in one or two specific semesters during the course of studies.<br><br>**Teaching and Learning Arrangements**<br><br>provide for students, separated into B.Sc. and M.Sc., to learn with and from each other across semesters. The challenge of dealing with interdisciplinarity and a variety of stages of learning in courses are part of the learning architecture and are deliberately encouraged in specific courses.<br><br>**Fields of Teaching**<br><br>are based on research findings from the academic disciplines cultural studies, social studies, arts, historical studies, communication studies, migration studies and sustainability research, and from engineering didactics. In addition, from the winter semester 2014/15 students on all Bachelor's courses will have the opportunity to learn about business management and start-ups in a goal-oriented way.<br><br>The fields of teaching are augmented by soft skills offers and a foreign language offer. Here, the focus is on encouraging goal-oriented communication skills, e.g. the skills required by outgoing engineers in international and intercultural situations.<br><br>**The Competence Level**<br><br>of the courses offered in this area is different as regards the basic training objective in the Bachelor's and Master's fields. These differences are reflected in the practical examples used, in content topics that refer to different professional application contexts, and in the higher scientific and theoretical level of abstraction in the B.Sc.<br><br>This is also reflected in the different quality of soft skills, which relate to the different team positions and different group leadership functions of Bachelor's and Master's graduates in their future working life.<br><br>**Specialized Competence (Knowledge)**<br><br>Students can<br><br>• explain specialized areas in context of the relevant non-technical disciplines,<br>• outline basic theories, categories, terminology, models, concepts or artistic techniques in the disciplines represented in the learning area,<br>• different specialist disciplines relate to their own discipline and differentiate it as well as make connections,<br>• sketch the basic outlines of how scientific disciplines, paradigms, models, instruments, methods and forms of representation in the specialized sciences are subject to individual and socio-cultural interpretation and historicity,<br>• Can communicate in a foreign language in a manner appropriate to the subject. |
| *Skills* | **Professional Competence (Skills)**<br><br>In selected sub-areas students can<br><br>• apply basic and specific methods of the said scientific disciplines,<br>• aquestion a specific technical phenomena, models, theories from the viewpoint of another, aforementioned specialist discipline,<br>• to handle simple and advanced questions in aforementioned scientific disciplines in a sucsessful manner,<br>• justify their decisions on forms of organization and application in practical questions in contexts that go beyond the technical relationship to the subject. |

| | |
|---|---|
| **Personal Competence** | |
| *Social Competence* | **Personal Competences (Social Skills)**<br><br>Students will be able<br><br>• to learn to collaborate in different manner,<br>• to present and analyze problems in the abovementioned fields in a partner or group situation in a manner appropriate to the addressees,<br>• to express themselves competently, in a culturally appropriate and gender-sensitive manner in the language of the country (as far as this study-focus would be chosen),<br>• to explain nontechnical items to auditorium with technical background knowledge. |
| *Autonomy* | **Personal Competences (Self-reliance)**<br><br>Students are able in selected areas<br><br>• to reflect on their own profession and professionalism in the context of real-life fields of application<br>• to organize themselves and their own learning processes<br>• to reflect and decide questions in front of a broad education background<br>• to communicate a nontechnical item in a competent way in writen form or verbaly<br>• to organize themselves as an entrepreneurial subject country (as far as this study-focus would be chosen) |
| **Workload in Hours** | Depends on choice of courses |
| **Credit points** | 6 |

| **Courses** |
|---|
| **Information regarding lectures and courses can be found in the corresponding module handbook published separately.** |

## Module M1421: Research Project

| Courses | | | |
|---|---|---|---|
| **Title** | **Typ** | **Hrs/wk** | **CP** |
| Research Project IIW (L2042) | Projection Course | 8 | 12 |

| | |
|---|---|
| **Module Responsible** | Prof. Görschwin Fey |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | Basic knowledge and techniques in the chosen field of specialization. |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | Students are able to acquire advanced knowledge in a specific field of Computer Science or a closely related subject. |
| *Skills* | Students are able to work self-dependent in a field of Computer Science or a closely related field. |
| **Personal Competence** | |
| *Social Competence* | |
| *Autonomy* | |
| **Workload in Hours** | Independent Study Time 248, Study Time in Lecture 112 |
| **Credit points** | 12 |
| **Course achievement** | None |
| **Examination** | Study work |
| **Examination duration and scale** | Presentation of a current research topic (25-30 min and 5 min discussion). |
| **Assignment for the Following Curricula** | Computer Science in Engineering: Core Qualification: Compulsory |

### Course L2042: Research Project IIW

| | |
|---|---|
| **Typ** | Projection Course |
| **Hrs/wk** | 8 |
| **CP** | 12 |
| **Workload in Hours** | Independent Study Time 248, Study Time in Lecture 112 |
| **Lecturer** | Prof. Volker Turau (sgwe) |
| **Language** | DE/EN |
| **Cycle** | WiSe/SoSe |
| **Content** | Current research topics of the chosen specialization. |
| **Literature** | Aktuelle Literatur zu Forschungsthemen aus der gewählten Vertiefungsrichtung.<br>/<br>Current literature on research topics of the chosen specialization. |

# Specialization I. Computer Science

## Module M0942: Software Security

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Software Security (L1103) | Lecture | 2 | 3 |
| Software Security (L1104) | Recitation Section (small) | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Riccardo Scandariato |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | Familiarity with C/C++, web programming |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | Students can<br>• name the main causes for security vulnerabilities in software<br>• explain current methods for identifying and avoiding security vulnerabilities<br>• explain the fundamental concepts of code-based access control |
| *Skills* | Students are capable of<br>• performing a software vulnerability analysis<br>• developing secure code |
| **Personal Competence** | |
| *Social Competence* | None |
| *Autonomy* | Students are capable of acquiring knowledge independently from professional publications, technical standards, and other sources, and are capable of applying newly acquired knowledge to new problems. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Written exam |
| **Examination duration and scale** | 120 minutes |
| **Assignment for the Following Curricula** | Computer Science: Specialisation I. Computer and Software Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory<br>Information and Communication Systems: Specialisation Secure and Dependable IT Systems: Elective Compulsory |

| Course L1103: Software Security | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Riccardo Scandariato |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | • Reliabilty and Software Security<br>• Attacks exploiting character and integer representations<br>• Buffer overruns<br>• Vulnerabilities in memory managemet: double free attacks<br>• Race conditions<br>• SQL injection<br>• Cross-site scripting and cross-site request forgery<br>• Testing for security; taint analysis<br>• Type safe languages<br>• Development proceses for secure software<br>• Code-based access control |
| **Literature** | M. Howard, D. LeBlanc: Writing Secure Code, 2nd edition, Microsoft Press (2002)<br><br>G. Hoglund, G. McGraw: Exploiting Software, Addison-Wesley (2004)<br><br>L. Gong, G. Ellison, M. Dageforde: Inside Java 2 Platform Security, 2nd edition, Addison-Wesley (2003)<br><br>B. LaMacchia, S. Lange, M. Lyons, R. Martin, K. T. Price: .NET Framework Security, Addison-Wesley Professional (2002)<br><br>D. Gollmann: Computer Security, 3rd edition (2011) |

| Course L1104: Software Security | |
|---|---|
| **Typ** | Recitation Section (small) |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Riccardo Scandariato |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M0753: Software Verification

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Software Verification (L0629) | Lecture | 2 | 3 |
| Software Verification (L0630) | Recitation Section (small) | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Sibylle Schupp |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | • Automata theory and formal languages<br>• Computational logic<br>• Object-oriented programming, algorithms, and data structures<br>• Functional programming or procedural programming<br>• Concurrency |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | Students apply the major verification techniques in model checking and deductive verification. They explain in formal terms syntax and semantics of the underlying logics, and assess the expressivity of different logics as well as their limitations. They classify formal properties of software systems. They find flaws in formal arguments, arising from modeling artifacts or underspecification. |
| *Skills* | Students formulate provable properties of a software system in a formal language. They develop logic-based models that properly abstract from the software under verification and, where necessary, adapt model or property. They construct proofs and property checks by hand or using tools for model checking or deductive verification, and reflect on the scope of the results. Presented with a verification problem in natural language, they select the appropriate verification technique and justify their choice. |
| **Personal Competence** | |
| *Social Competence* | Students discuss relevant topics in class. They defend their solutions orally. They communicate in English. |
| *Autonomy* | Using accompanying on-line material for self study, students can assess their level of knowledge continuously and adjust it appropriately. Working on exercise problems, they receive additional feedback. Within limits, they can set their own learning goals. Upon successful completion, students can identify and precisely formulate new problems in academic or applied research in the field of software verification. Within this field, they can conduct independent studies to acquire the necessary competencies and compile their findings in academic reports. They can devise plans to arrive at new solutions or assess existing ones. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | **Compulsory** Yes; **Bonus** 15 %; **Form** Excercises; **Description** |
| **Examination** | Written exam |
| **Examination duration and scale** | 90 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation I. Computer and Software Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory<br>Information and Communication Systems: Specialisation Secure and Dependable IT Systems: Compulsory<br>Information and Communication Systems: Specialisation Communication Systems, Focus Software: Elective Compulsory<br>International Management and Engineering: Specialisation II. Information Technology: Elective Compulsory |

### Course L0629: Software Verification

| | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Sibylle Schupp |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | • ◦ Model checking (bounded model checking, CTL, LTL)<br>◦ Real-time model checking (TCTL, timed automata)<br>◦ Deductive verification (Hoare logic)<br>◦ Tool support<br>◦ Recent developments of verification techniques and applications |
| **Literature** | • C. Baier and J-P. Katoen, Principles of Model Checking, MIT Press 2007.<br>• M. Huth and M. Bryan, Logic in Computer Science. Modelling and Reasoning about Systems, 2nd Edition, 2004.<br>• Selected Research Papers |

| Course L0630: Software Verification | |
|---|---|
| **Typ** | Recitation Section (small) |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Sibylle Schupp |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M1694: Security of Cyber-Physical Systems

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Security of Cyber-Physical Systems (L2691) | Lecture | 2 | 3 |
| Security of Cyber-Physical Systems (L2692) | Recitation Section (small) | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Sibylle Fröschle |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | IT security, programming skills, statistics |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | The students know and can explain<br>- the threats posed by cyber attacks to cyber-physical systems (CPS)<br>- concrete attacks at a technical level, e.g. on bus systems<br>- security solutions specific to CPS with their capabilities and limitations<br>- examples of security architectures for CPS and the requirements they guarantee<br>- standard security engineering processes for CPS |
| *Skills* | The students are able to<br>- identify security threats and assess the risks for a given CPS<br>- apply attack toolkits to analyse a networked control system, and detect attacks beyond those taught in class<br>- identify and apply security solutions suitable to the requirements<br>- follow security engineering processes to develop a security architecture for a given CPS<br>- recognize challenges and limitations, e.g. posed by novel types of attack |
| **Personal Competence** | |
| *Social Competence* | The students are able to<br>- expertly discuss security risks and incidents of CPS and their mitigation in a solution-oriented fashion with experts and non-experts<br>- foster a security culture with respect to CPS and the corresponding critical infrastructures |
| *Autonomy* | The students are able to<br>- follow up and critically assess current developments in the security of CPS including relevant security incidents<br>- master a new topic within the area by self-study and self-initiated interaction with experts and peers. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | **Compulsory**: No; **Bonus**: 10 %; **Form**: Excercises; **Description**: Die Übungsaufgaben finden semesterbegleitend statt. |
| **Examination** | Written exam |
| **Examination duration and scale** | 120 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation I. Computer and Software Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory<br>Information and Communication Systems: Specialisation Secure and Dependable IT Systems, Focus Software and Signal Processing: Elective Compulsory |

| Course L2691: Security of Cyber-Physical Systems | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Sibylle Fröschle |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | Embedded systems in energy, production, and transportation are currently undergoing a technological transition to highly networked automated cyber-physical systems (CPS). Such systems are potentially vulnerable to cyber attacks, and these can have physical impact. In this course we investigate security threats, solutions and architectures that are specific to CPS. The topics are as follows:<br><br>Fundamentals and motivating examples<br><br>Networked and embedded control systems<br><br>Bus system level attacks<br><br>Intruder detection systems (IDS), in particular physics-based IDS<br><br>System security architectures, including cryptographic solutions<br><br>Adversarial machine learning attacks in the physical world<br><br>Aspects of Location and Localization<br><br>Wireless networks and infrastructures for critical applications<br><br>Communication security architectures and remaining threats<br><br>Intruder detection systems (IDS), in particular data-centric IDS<br><br>Resilience against multi-instance attacks<br><br>Security Engineering of CPS: Process and Norms |
| **Literature** | Recent scientific papers and reports in the public domain. |

| Course L2692: Security of Cyber-Physical Systems | |
|---|---|
| **Typ** | Recitation Section (small) |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Sibylle Fröschle |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M1427: Algorithmic Game Theory

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Algorithmic game theory (L2060) | Lecture | 2 | 4 |
| Algorithmic game theory (L2061) | Recitation Section (large) | 2 | 2 |

| | |
|---|---|
| **Module Responsible** | Prof. Matthias Mnich |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | • Mathematics I<br>• Mathematics II<br>• Algorithms and Data Structures |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | • Students can name the basic concepts in algorithmic game theory and mechanism design. They are able to explain them using appropriate examples.<br>• Students can discuss logical connections between these concepts. They are capable of illustrating these connections with the help of examples.<br>• They know game and mechanism design strategies and can reproduce them. |
| *Skills* | • Students can model strategic interaction systems of agents with the help of the concepts studied in this course. Moreover, they are capable of analyzing their efficiency and equilibria, by applying established methods.<br>• Students are able to discover and verify further logical connections between the concepts studied in the course.<br>• For a given problem, the students can develop and execute a suitable approach, and are able to critically evaluate the results. |
| **Personal Competence** | |
| *Social Competence* | • Students are able to work together in teams. They are capable to use mathematics as a common language.<br>• In doing so, they can communicate new concepts according to the needs of their cooperating partners. Moreover, they can design examples to check and deepen the understanding of their peers. |
| *Autonomy* | • Students are capable of checking their understanding of complex concepts on their own. They can specify open questions precisely and know where to get help in solving them.<br>• Students have developed sufficient persistence to be able to work for longer periods in a goal-oriented manner on hard problems. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Written exam |
| **Examination duration and scale** | 90 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation I. Computer and Software Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory |

| Course L2060: Algorithmic game theory | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 4 |
| **Workload in Hours** | Independent Study Time 92, Study Time in Lecture 28 |
| **Lecturer** | Prof. Matthias Mnich |
| **Language** | DE/EN |
| **Cycle** | SoSe |
| **Content** | Algorithmic game theory is a topic at the intersection of economics and computation. It deals with analyzing the behavior and interactions of strategic agents, who often try to maximize their incentives. The environment in which those agents interact is referred to as a game. We wish to understand if the agents can reach an "equilibrium", or steady state of the game, in which agents have no incentive to deviate from their chosen strategies. The algorithmic part is to design efficient methods to find equilibria in games, and to make recommendations to the agents so that they can quickly reach a state of personal satisfaction.<br><br>We will also study mechanism design. In mechanism design, we wish to design markets and auctions and give strategic options to agents, so that they have an incentive to act rationally. We also wish to design the markets and auctions so that they are efficient, in the sense that all goods are cleared and agents do not overpay for the goods which they acquire.<br><br>Topics:<br>• basic equilibrium concepts (Nash equilibria, correlated equilibria, ...)<br>• strategic actions (best-response dynamics, no-regret dynamics, ...)<br>• auction design (revenue-maximizing auctions, Vickrey auctions)<br>• stable matching theory (preference aggregations, kidney exchanges, ...)<br>• price of anarchy and selfish routing (Braess' paradox, congestion games, ...) |
| **Literature** | • T. Roughgarden: Twenty Lectures on Algorithmic Game Theory, Cambridge University Press, 2016.<br>• N. Nisan, T. Roughgarden, E. Tardos, V. Vazirani. Algorithmic Game Theory. Cambridge University Press, 2007. |

| Course L2061: Algorithmic game theory | |
|---|---|
| **Typ** | Recitation Section (large) |
| **Hrs/wk** | 2 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 32, Study Time in Lecture 28 |
| **Lecturer** | Prof. Matthias Mnich |
| **Language** | DE/EN |
| **Cycle** | SoSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M1400: Design of Dependable Systems

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Designing Dependable Systems (L2000) | Lecture | 2 | 3 |
| Designing Dependable Systems (L2001) | Recitation Section (small) | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Görschwin Fey |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | Basic knowledge about data structures and algorithms |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | In the following "dependable" summarizes the concepts Reliability, Availability, Maintainability, Safety and Security.<br><br>Knowledge about approaches for designing dependable systems, e.g.,<br>• Structural solutions like modular redundancy<br>• Algorithmic solutions like handling byzantine faults or checkpointing<br><br>Knowledge about methods for the analysis of dependable systems |
| *Skills* | Ability to implement dependable systems using the above approaches.<br><br>Ability to analyzs the dependability of systems using the above methods for analysis. |
| **Personal Competence** | |
| *Social Competence* | Students<br>• discuss relevant topics in class and<br>• present their solutions orally. |
| *Autonomy* | Using accompanying material students independently learn in-depth relations between concepts explained in the lecture and additional solution strategies. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | **Compulsory** Yes; **Bonus** None; **Form** Subject theoretical and practical work; **Description** Die Lösung einer Aufgabe ist Zulassungsvoraussetzung für die Prüfung. Die Aufgabe wird in Vorlesung und Übung definiert. |
| **Examination** | Oral exam |
| **Examination duration and scale** | 30 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation I. Computer and Software Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory<br>Information and Communication Systems: Specialisation Secure and Dependable IT Systems: Elective Compulsory<br>Mechatronics: Specialisation System Design: Elective Compulsory<br>Microelectronics and Microsystems: Specialisation Embedded Systems: Elective Compulsory |

| Course L2000: Designing Dependable Systems | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Görschwin Fey |
| **Language** | DE/EN |
| **Cycle** | SoSe |
| **Content** | Description<br><br>The term dependability comprises various aspects of a system. These are typically:<br><br>• Reliability<br>• Availability<br>• Maintainability<br>• Safety<br>• Security<br><br>This makes dependability a core aspect that has to be considered early in system design, no matter whether software, embedded systems or full scale cyber-physical systems are considered.<br>Contents<br><br>The module introduces the basic concepts for the design and the analysis of dependable systems. Design examples for getting practical hands-on-experience in dependable design techniques. The module focuses towards embedded systems. The following topics are covered:<br><br>• Modelling<br>• Fault Tolerance<br>• Design Concepts<br>• Analysis Techniques |
| **Literature** | |

| Course L2001: Designing Dependable Systems | |
|---|---|
| **Typ** | Recitation Section (small) |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Görschwin Fey |
| **Language** | DE/EN |
| **Cycle** | SoSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M1774: Advanced Internet Computing

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Advanced Internet Computing (L2916) | Lecture | 2 | 3 |
| Advanced Internet Computing (L2917) | Project-/problem-based Learning | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Stefan Schulte |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | Good programming skills are necessary. Previous knowledge in the field of distributed systems is helpful. |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | After successful completion of the course, students are able to:<br>• Describe basic concepts of Cloud Computing, the Internet of Things (IoT), and blockchain technologies<br>• Discuss and assess critical aspects of Cloud Computing, the IoT, and blockchain technologies<br>• Select and apply cloud and IoT technologies for particular application areas<br>• Design and develop practical solutions for the integration of smart objects in IoT, Cloud, and blockchain software<br>• Implement IoT services |
| *Skills* | The students acquire the ability to model Internet-based distributed systems and to work with these systems. This comprises especially the ability to select and utilize fitting technologies for different application areas. Furthermore, students are able to critically assess the chosen technologies. |
| **Personal Competence** | |
| *Social Competence* | Students can work on complex problems both independently and in teams. They can exchange ideas with each other and use their individual strengths to solve the problem. |
| *Autonomy* | Students are able to independently investigate a complex problem and assess which competencies are required to solve it. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | **Compulsory**: Yes; **Bonus**: 20 %; **Form**: Subject theoretical and practical work; **Description**: Gruppenarbeit mit aktuellen Technologien aus dem Bereich Internet of Things |
| **Examination** | Written exam |
| **Examination duration and scale** | 90 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation I. Computer and Software Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory<br>Information and Communication Systems: Specialisation Communication Systems, Focus Software: Elective Compulsory<br>Information and Communication Systems: Specialisation Secure and Dependable IT Systems, Focus Networks: Elective Compulsory |

### Course L2916: Advanced Internet Computing

| | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Stefan Schulte |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | This lecture discusses modern Internet-based distributed systems in three blocks: (i) Cloud computing, (ii) the Internet of Things, and (iii) blockchain technologies. The following topics will be covered in the single lectures:<br>• Cloud Computing<br>• Elastic Computing<br>• Technologies for identification for the IoT: RFID & EPC<br>• Communication in the IoT: Standards and protocols<br>• Security and trust in the IoT: Concerns and solution approaches<br>• Edge and Fog Computing<br>• Application areas: Smart factories, smart cities, smart healthcare<br>• Blockchain technologies<br>• Consensus |
| **Literature** | Will be discussed in the lecture |

| Course L2917: Advanced Internet Computing | |
|---|---|
| **Typ** | Project-/problem-based Learning |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Stefan Schulte |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | This project-/problemoriented part of the module augments the theoretical content of the lecture by a concrete technical problem, which needs to be solved by the students in group work during the semester. Possible topics are (blockchain-based) sensor data integration, Big Data processing, Cloud-based redundant data storages, and Cloud-based Onion Routing. |
| **Literature** | Will be discussed in the lecture. |

## Module M1810: Autonomous Cyber-Physical Systems

| Courses | | | |
|---|---|---|---|
| **Title** | **Typ** | **Hrs/wk** | **CP** |
| Autonomous Cyber-Physical Systems (L3000) | Lecture | 2 | 3 |
| Autonomous Cyber-Physical Systems (L3001) | Recitation Section (small) | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Bernd-Christian Renner |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | • Very Good knowledge and practical experience in programming in the C language (Module: Procedural Programming)<br>• Basic knowledge in software engineering<br>• Basic knowledge in wired and wireless communication protocols<br>• Principal understanding of simple electronic circuits |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | |
| *Skills* | |
| **Personal Competence** | |
| *Social Competence* | |
| *Autonomy* | |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | **Compulsory** No · **Bonus** 10 % · **Form** Attestation · **Description** |
| **Examination** | Written exam |
| **Examination duration and scale** | 90 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation I. Computer and Software Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory |

### Course L3000: Autonomous Cyber-Physical Systems

| | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Bernd-Christian Renner |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | |
| **Literature** | |

### Course L3001: Autonomous Cyber-Physical Systems

| | |
|---|---|
| **Typ** | Recitation Section (small) |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Bernd-Christian Renner |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M1812: Constraint Satisfaction Problems

| **Courses** | | | |
|---|---|---|---|
| **Title** | **Typ** | **Hrs/wk** | **CP** |
| Constraint Satisfaction Problems (L3002) | Lecture | 2 | 3 |
| Constraint Satisfaction Problems (L3003) | Recitation Section (large) | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Antoine Mottet |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | The students should have followed the courses Complexity Theory, Discrete Algebraic Structures, Linear Algebra. |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | • Students can describe basic concepts from the theory of constraint satisfaction such as primitive positive formulas, interpretations, polymorphisms, clones<br>• Students can discuss the connections between these concepts<br>• Students know proofs strategies and can reproduce them |
| *Skills* | • Students can use CSPs to model problems from complexity theory and decide their complexity using methods from the course. |
| **Personal Competence** | |
| *Social Competence* | |
| *Autonomy* | |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Oral exam |
| **Examination duration and scale** | 30 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation I. Computer and Software Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory<br>Technomathematics: Specialisation II. Informatics: Elective Compulsory |

### Course L3002: Constraint Satisfaction Problems

| | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Antoine Mottet |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | This course gives an introduction to the topic of constraint satisfaction problems and their complexity. It will cover the basics of the theory such as the universal-algebraic approach to constraint satisfaction and several classical algorithms such as local consistency checking and the Bulatov-Dalmau algorithm. We will finally discuss the recent research directions in the field. |
| **Literature** | |

### Course L3003: Constraint Satisfaction Problems

| | |
|---|---|
| **Typ** | Recitation Section (large) |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Antoine Mottet |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M0836: Communication Networks

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Selected Topics of Communication Networks (L0899) | Project-/problem-based Learning | 2 | 2 |
| Communication Networks (L0897) | Lecture | 2 | 2 |
| Communication Networks Excercise (L0898) | Project-/problem-based Learning | 1 | 2 |

| | |
|---|---|
| **Module Responsible** | Prof. Andreas Timm-Giel |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | • Fundamental stochastics<br>• Basic understanding of computer networks and/or communication technologies is beneficial |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | Students are able to describe the principles and structures of communication networks in detail. They can explain the formal description methods of communication networks and their protocols. They are able to explain how current and complex communication networks work and describe the current research in these examples. |
| *Skills* | Students are able to evaluate the performance of communication networks using the learned methods. They are able to work out problems themselves and apply the learned methods. They can apply what they have learned autonomously on further and new communication networks. |
| **Personal Competence** | |
| *Social Competence* | Students are able to define tasks themselves in small teams and solve these problems together using the learned methods. They can present the obtained results. They are able to discuss and critically analyse the solutions. |
| *Autonomy* | Students are able to obtain the necessary expert knowledge for understanding the functionality and performance capabilities of new communication networks independently. |
| **Workload in Hours** | Independent Study Time 110, Study Time in Lecture 70 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Presentation |
| **Examination duration and scale** | 1.5 hours colloquium with three students, therefore about 30 min per student. Topics of the colloquium are the posters from the previous poster session and the topics of the module. |
| **Assignment for the Following Curricula** | Electrical Engineering: Specialisation Information and Communication Systems: Elective Compulsory<br>Electrical Engineering: Specialisation Control and Power Systems Engineering: Elective Compulsory<br>Aircraft Systems Engineering: Core Qualification: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory<br>Information and Communication Systems: Specialisation Communication Systems: Elective Compulsory<br>Information and Communication Systems: Specialisation Secure and Dependable IT Systems, Focus Networks: Elective Compulsory<br>International Management and Engineering: Specialisation II. Information Technology: Elective Compulsory<br>Mechatronics: Technical Complementary Course: Elective Compulsory<br>Microelectronics and Microsystems: Specialisation Communication and Signal Processing: Elective Compulsory<br>Theoretical Mechanical Engineering: Specialisation Robotics and Computer Science: Elective Compulsory |

### Course L0899: Selected Topics of Communication Networks

| | |
|---|---|
| **Typ** | Project-/problem-based Learning |
| **Hrs/wk** | 2 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 32, Study Time in Lecture 28 |
| **Lecturer** | Prof. Andreas Timm-Giel |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | Example networks selected by the students will be researched on in a PBL course by the students in groups and will be presented in a poster session at the end of the term. |
| **Literature** | • see lecture |

| Course L0897: Communication Networks | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 32, Study Time in Lecture 28 |
| **Lecturer** | Prof. Andreas Timm-Giel, Dr.-Ing. Koojana Kuladinithi |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | |
| **Literature** | • Skript des Instituts für Kommunikationsnetze<br>• Tannenbaum, Computernetzwerke, Pearson-Studium<br><br>Further literature is announced at the beginning of the lecture. |

| Course L0898: Communication Networks Excercise | |
|---|---|
| **Typ** | Project-/problem-based Learning |
| **Hrs/wk** | 1 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 46, Study Time in Lecture 14 |
| **Lecturer** | Prof. Andreas Timm-Giel |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | Part of the content of the lecture Communication Networks are reflected in computing tasks in groups, others are motivated and addressed in the form of a PBL exercise. |
| **Literature** | • announced during lecture |

## Module M1249: Medical Imaging

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Medical Imaging (L1694) | Lecture | 2 | 3 |
| Medical Imaging (L1695) | Recitation Section (small) | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Tobias Knopp |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | Basic knowledge in linear algebra, numerics, and signal processing |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | After successful completion of the module, students are able to describe reconstruction methods for different tomographic imaging modalities such as computed tomography and magnetic resonance imaging. They know the necessary basics from the fields of signal processing and inverse problems and are familiar with both analytical and iterative image reconstruction methods. The students have a deepened knowledge of the imaging operators of computed tomography and magnetic resonance imaging. |
| *Skills* | The students are able to implement reconstruction methods and test them using tomographic measurement data. They can visualize the reconstructed images and evaluate the quality of their data and results. In addition, students can estimate the temporal complexity of imaging algorithms. |
| **Personal Competence** | |
| *Social Competence* | Students can work on complex problems both independently and in teams. They can exchange ideas with each other and use their individual strengths to solve the problem. |
| *Autonomy* | Students are able to independently investigate a complex problem and assess which competencies are required to solve it. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Written exam |
| **Examination duration and scale** | 90 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation II: Intelligence Engineering: Elective Compulsory<br>Electrical Engineering: Specialisation Medical Technology: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory<br>Interdisciplinary Mathematics: Specialisation Computational Methods in Biomedical Imaging: Compulsory<br>Microelectronics and Microsystems: Specialisation Communication and Signal Processing: Elective Compulsory<br>Theoretical Mechanical Engineering: Specialisation Bio- and Medical Technology: Elective Compulsory |

### Course L1694: Medical Imaging

| | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Tobias Knopp |
| **Language** | DE/EN |
| **Cycle** | WiSe |
| **Content** | • Overview about different imaging methods<br>• Signal processing<br>• Inverse problems<br>• Computed tomography<br>• Magnetic resonance imaging<br>• Compressed Sensing<br>• Magnetic particle imaging |
| **Literature** | **Bildgebende Verfahren in der Medizin**; O. Dössel; Springer, Berlin, 2000<br>**Bildgebende Systeme für die medizinische Diagnostik**; H. Morneburg (Hrsg.); Publicis MCD, München, 1995<br>**Introduction to the Mathematics of Medical Imaging**; C. L.Epstein; Siam, Philadelphia, 2008<br>**Medical Image Processing, Reconstruction and Restoration**; J. Jan; Taylor and Francis, Boca Raton, 2006<br>**Principles of Magnetic Resonance Imaging**; Z.-P. Liang and P. C. Lauterbur; IEEE Press, New York, 1999 |

| Course L1695: Medical Imaging | |
|---|---|
| **Typ** | Recitation Section (small) |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Tobias Knopp |
| **Language** | DE/EN |
| **Cycle** | WiSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M1780: Massively Parallel Systems: Architecture and Programming

| Courses | | | |
|---|---|---|---|
| **Title** | **Typ** | **Hrs/wk** | **CP** |
| Massively Parallel Systems: Architecture and Programming (L2936) | Lecture | 2 | 3 |
| Massively Parallel Systems: Architecture and Programming (L2937) | Project-/problem-based Learning | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Sohan Lal |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | An introductory module on computer Engineering or computer architecture, good programming skills in C/C++. |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | The course starts with parallel computers classification, multithreading, and covers the architecture of centralized and distributed shared-memory parallel systems, multiprocessor cache coherence, snooping / directory-based cache coherence protocols, implementation, and limitations. Next, students study interconnection networks and routing in parallel systems. To ensure the correctness of shared-memory multithreaded programs, independent of the speed of execution of their individual threads, the important topics of memory consistency and synchronization will be covered in detail. As a case study, the architecture of a few accelerators such as GPUs will also be discussed in detail. Besides understanding the architecture and organization of parallel systems, programming them is also very challenging. The course will also cover how to program massively parallel systems using API/libraries such as CUDA/OpenCL/MPI/OpenMP. |
| *Skills* | After completing this course, students will be able to understand the architecture and organization of parallel systems. They will be able to evaluate different design choices and make decisions while designing a parallel system. In addition, they will be able to program parallel systems (ranging from an embedded system to a supercomputer) using CUDA/OpenCL/MPI/OpenMP. |
| **Personal Competence** | |
| *Social Competence* | The course will encourage students to work in small groups to solve complex problems, thus, inculcating the importance of teamwork. |
| *Autonomy* | Today, parallel computers are present everywhere. Students will be able to not only program parallel computers independently, but also understand their underlying organization and architecture. This will further help to understand the performance issues of parallel applications and provide insights to improve them. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | **Compulsory** Yes; **Bonus** 20 %; **Form** Subject theoretical and practical work; **Description** |
| **Examination** | Oral exam |
| **Examination duration and scale** | 25 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation I. Computer and Software Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation I. Computer Science: Elective Compulsory |

### Course L2936: Massively Parallel Systems: Architecture and Programming

| | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Sohan Lal |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | Brief outline:<br>• Parallel computers and their classification<br>• Centralized and distributed shared-memory architectures: snooping vs directory-based cache coherence protocols, implementation, and limitations<br>• Chip multiprocessors: software-based, block (coarse-grain), interleaved (fine-grain), simultaneous multithreading<br>• Synchronization: high-level primitives and implementation, memory consistency models: sequential and weaker memory consistency models<br>• Interconnection networks: topologies (direct and indirect networks) and routing techniques<br>• Graphics Processing Units (GPUs) architecture and programming using CUDA/OpenCL<br>• Parallel programming with message passing interface (MPI), OpenMP |
| **Literature** | • Michel Dubois, Murali Annavaram, and Per Stenström, Parallel Computer Organization and Design (Book)<br>• David A Patterson and John L. Hennessy, Computer Architecture: A Quantitative Approach, Elsevier (Book)<br>• David B. Kirk, Wen-mei W. Hwu, Programming Massivley Parallel Processors, Elsevier (Book) |

| Course L2937: Massively Parallel Systems: Architecture and Programming | |
|---|---|
| **Typ** | Project-/problem-based Learning |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Sohan Lal |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | There will be 3-4 assignments for project-based learning consisting of the following:<br>• Implement and compare different cache coherence protocols using a simulator or a high-level, event-driven simulation interface such as SystemC<br>• Programming massively parallel systems to solve computationally intensive problems such as password cracking using CUDA/OpenCL/MPI/OpenMP |
| **Literature** | The following literature will be useful for project-based learning. The further required resources will be discussed during the course.<br>• David B. Kirk, Wen-mei W. Hwu, Programming Massivley Parallel Processors, Elsevier (Book)<br>• MPI Forum, https://www.mpi-forum.org/<br>• SystemC, https://www.accellera.org/community/systemc |

# Specialization II. Engineering Science

## Module M0676: Digital Communications

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Digital Communications (L0444) | Lecture | 2 | 3 |
| Digital Communications (L0445) | Recitation Section (large) | 2 | 2 |
| Laboratory Digital Communications (L0646) | Practical Course | 1 | 1 |

| | |
|---|---|
| **Module Responsible** | Prof. Gerhard Bauch |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | • Mathematics 1-3<br>• Signals and Systems<br>• Fundamentals of Communications and Random Processes |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | The students are able to understand, compare and design modern digital information transmission schemes. They are familiar with the properties of linear and non-linear digital modulation methods. They can describe distortions caused by transmission channels and design and evaluate detectors including channel estimation and equalization. They know the principles of single carrier transmission and multi-carrier transmission as well as the fundamentals of basic multiple access schemes.<br><br>The students are familiar with the contents of lecture and tutorials. They can explain and apply them to new problems. |
| *Skills* | The students are able to design and analyse a digital information transmission scheme including multiple access. They are able to choose a digital modulation scheme taking into account transmission rate, required bandwidth, error probability, and further signal properties. They can design an appropriate detector including channel estimation and equalization taking into account performance and complexity properties of suboptimum solutions. They are able to set parameters of a single carrier or multi carrier transmission scheme and trade the properties of both approaches against each other. |
| **Personal Competence** | |
| *Social Competence* | The students can jointly solve specific problems. |
| *Autonomy* | The students are able to acquire relevant information from appropriate literature sources. They can control their level of knowledge during the lecture period by solving tutorial problems, software tools, clicker system. |
| **Workload in Hours** | Independent Study Time 110, Study Time in Lecture 70 |
| **Credit points** | 6 |
| **Course achievement** | **Compulsory** Yes / **Bonus** None / **Form** Written elaboration / **Description** |
| **Examination** | Written exam |
| **Examination duration and scale** | 90 min |
| **Assignment for the Following Curricula** | Electrical Engineering: Core Qualification: Compulsory<br>Computer Science in Engineering: Specialisation II. Engineering Science: Elective Compulsory<br>Information and Communication Systems: Specialisation Communication Systems: Compulsory<br>Information and Communication Systems: Specialisation Secure and Dependable IT Systems, Focus Networks: Elective Compulsory<br>International Management and Engineering: Specialisation II. Information Technology: Elective Compulsory<br>International Management and Engineering: Specialisation II. Electrical Engineering: Elective Compulsory<br>Microelectronics and Microsystems: Core Qualification: Elective Compulsory |

### Course L0444: Digital Communications

| | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Gerhard Bauch |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | • Repetition: Baseband Transmission<br>  ◦ Pulse shaping: Non-return to zero (NRZ) rectangular pulses, raised-cosine pulses, square-root raised-cosine pulses<br>  ◦ Power spectral density (psd) of baseband signals<br>  ◦ Intersymbol interference (ISI)<br>  ◦ First and second Nyquist criterion<br>  ◦ AWGN channel<br>  ◦ Matched filter<br>  ◦ Matched-filter receiver and correlation receiver<br>  ◦ Noise whitening matched filter<br>  ◦ Discrete-time AWGN channel model |

- Representation of bandpass signals and systems in the equivalent baseband
  - Quadrature amplitude modulation (QAM)
  - Equivalent baseband signal and system
  - Analytical signal
  - Equivalent baseband random process, equivalent baseband white Gaussian noise process
  - Equivalent baseband AWGN channel
  - Equivalent baseband channel model with frequency-offset and phase noise
  - Equivalent baseband Rayleigh fading and Rice fading channel models
  - Equivalent baseband frequency-selective channel model
  - Discrete memoryless channels (DMC)
- Bandpass transmission via carrier modulation
  - Amplitude modulation, frequency modulation, phase modulation
  - Linear digital modulation methods
    - On-off keying, M-ary amplitude shift keying (M-ASK), M-ary phase shift keying (M-PSK), M-ary quadrature amplitude modulation (M-QAM), offset-QPSK
    - Signal space representation of transmit signal constellations and signals
    - Energy of linear digital modulated signals, average energy per symbol
    - Power spectral density of linear digital modulated signals
    - Bandwidth efficiency
    - Correlation coefficient of elementary signals
    - Error probabilities of linear digital modulation methods
      - Error functions
      - Gray mapping and natural mapping
      - Bit error probabilities, symbol error probabilities, pairwise symbol error probabilities
      - Euclidean distance and Hamming distance
      - Exact and approximate computation of error probabilities
      - Performance comparison of modulation schemes in terms of per bit SNR vs. per symbol SNR
    - Hierarchical modulation, multilevel modulation
    - Effects of carrier phase offset and carrier frequency offset
    - Differential modulation
      - M-ary differential phase shift keying (M-PSK)
      - Coherent and non-coherent detection of DPSK
      - p/M-differential phase shift keying (p/M-DPSK)
      - Differential amplitude and phase shift keying (DAPSK)
  - Non-linear digital modulation methods
    - Frequency shift keying (FSK)
    - Modulation index
    - Minimum shift keying (MSK)
      - Offset-QPSK representation of MSK
      - MSK with differential precoding and rotation
      - Bit error probabilities of MSK
      - Gaussian minimum shift keying (GMSK)
      - Power spectral density of MSK and GMSK
    - Continuous phase modulation (CPM)
      - General description of CPM signals
      - Frequency pulses and phase pulses
    - Coherent and non-coherent detection of FSK
  - Performance comparison of linear and non-linear digital modulation methods
- Frequency-selective channels, ISI channels
  - Intersymbol interference and frequency-selectivity
  - RMS delay spread
  - Narrowband and broadband channels
  - Equivalent baseband transmission model for frequency-selective channels
  - Receive filter design
- Equalization
  - Symbol-spaced and fractionally-spaced equalizers
  - Inverse system
  - Non-recursive linear equalizers
    - Linear zero-forcing (ZF) equalizer
    - Linear minimum mean squared error (MMSE) equalizer
  - Non-linear equalization:
    - Decision feedback equalizer (DFE)
    - Tomlinson-Harashima precoding
  - Maximum a posteriori probability (MAP) and maximum likelihood equalizer, Viterbi algorithm
- Single-carrier vs. multi-carrier transmission
- Multi-carrier transmission
  - General multicarrier transmission
  - Orthogonal frequency division multiplex (OFDM)
    - OFDM implementation using the Fast Fourier Transform (FFT)
    - Cyclic guard interval

|  |  |
|---|---|
|  | - Power spectral density of OFDM<br>- Peak-to-average power ratio (PAPR)<br>• Multiple access<br>  ◦ Principles of time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), non-orthogonal multiple access (NOMA), hybrid multiple access<br>• Spread spectrum communications<br>  ◦ Direct sequence spread spectrum communications<br>  ◦ Frequency hopping<br>  ◦ Protection against eavesdropping<br>  ◦ Protection against narrowband jammers<br>  ◦ Short vs. long spreading codes<br>  ◦ Direct sequence spread spectrum communications in frequency-selective channels<br>    - Rake receiver<br>  ◦ Code division multiple access (CDMA)<br>    - Design criteria of spreading sequences, autocorrelation function and crosscorrelation function of spreading sequences<br>    - Intersymbol interference (ISI) and multiple access interference (MAI)<br>    - Pseudo noise (PN) sequences, maximum length sequences (m-sequences), Gold codes, Walsh-Hadamard codes, orthogonal variable spreading factor (OVSF) codes<br>    - Multicode transmission<br>    - CDMA in uplink and downlink of a wireless communications system<br>    - Single-user detection vs. multi-user detection |
| **Literature** | K. Kammeyer: Nachrichtenübertragung, Teubner<br><br>P.A. Höher: Grundlagen der digitalen Informationsübertragung, Teubner.<br><br>J.G. Proakis, M. Salehi: Digital Communications. McGraw-Hill.<br><br>S. Haykin: Communication Systems. Wiley<br><br>R.G. Gallager: Principles of Digital Communication. Cambridge<br><br>A. Goldsmith: Wireless Communication. Cambridge.<br><br>D. Tse, P. Viswanath: Fundamentals of Wireless Communication. Cambridge. |

| **Course L0445: Digital Communications** |  |
|---|---|
| **Typ** | Recitation Section (large) |
| **Hrs/wk** | 2 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 32, Study Time in Lecture 28 |
| **Lecturer** | Prof. Gerhard Bauch |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

| Course L0646: Laboratory Digital Communications | |
|---|---|
| **Typ** | Practical Course |
| **Hrs/wk** | 1 |
| **CP** | 1 |
| **Workload in Hours** | Independent Study Time 16, Study Time in Lecture 14 |
| **Lecturer** | Prof. Gerhard Bauch |
| **Language** | DE/EN |
| **Cycle** | WiSe |
| **Content** | - DSL transmission<br><br>- Random processes<br><br>- Digital data transmission |
| **Literature** | K. Kammeyer: Nachrichtenübertragung, Teubner<br><br>P.A. Höher: Grundlagen der digitalen Informationsübertragung, Teubner.<br><br>J.G. Proakis, M. Salehi: Digital Communications. McGraw-Hill.<br><br>S. Haykin: Communication Systems. Wiley<br><br>R.G. Gallager: Principles of Digital Communication. Cambridge<br><br>A. Goldsmith: Wireless Communication. Cambridge.<br><br>D. Tse, P. Viswanath: Fundamentals of Wireless Communication. Cambridge. |

## Module M1250: Electrical Power Systems II: Operation and Information Systems of Electrical Power Grids

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Electrical Power Systems II: Operation and Information Systems of Electrical Power Grids (L1696) | Lecture | 3 | 4 |
| Electrical Power Systems II: Operation and Information Systems of Electrical Power Grids (L1697) | Recitation Section (large) | 2 | 2 |

| | |
|---|---|
| **Module Responsible** | Prof. Christian Becker |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | Fundamentals of Electrical Engineering,<br><br>Electrical Power Systems I,<br><br>Mathematics I, II, III |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | Students are able to explain in detail and critically evaluate technologies and information systems for operational management of conventional and modern electric power systems as well as methods and algorithms for steady-state network calculation, failure calculation, power system operation and optimization. They are additonally able to apply these methods to real electric power systems. |
| *Skills* | With completion of this module the students are able to apply the acquired skills for planning and analysis of real electric power systems and to critically evaluate the results. |
| **Personal Competence** | |
| *Social Competence* | The students can participate in specialized and interdisciplinary discussions, advance ideas and represent their own work results in front of others. |
| *Autonomy* | Students can independently tap knowledge of the emphasis of the lectures and apply it within further research activities. |
| **Workload in Hours** | Independent Study Time 110, Study Time in Lecture 70 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Oral exam |
| **Examination duration and scale** | 45 min |
| **Assignment for the Following Curricula** | Electrical Engineering: Core Qualification: Compulsory<br>Energy Systems: Specialisation Energy Systems: Elective Compulsory<br>Computer Science in Engineering: Specialisation II. Engineering Science: Elective Compulsory |

| Course L1696: Electrical Power Systems II: Operation and Information Systems of Electrical Power Grids | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 3 |
| **CP** | 4 |
| **Workload in Hours** | Independent Study Time 78, Study Time in Lecture 42 |
| **Lecturer** | Prof. Christian Becker |
| **Language** | DE |
| **Cycle** | WiSe |
| **Content** | • steaedy-state modelling of electric power systems<br>∘ conventional components<br>∘ Flexible AC Transmission Systems (FACTS) and HVDC<br>∘ grid modelling<br>• grid operation<br>∘ electric power supply processes<br>∘ grid and power system management<br>∘ grid provision<br>• grid control systems<br>∘ information and communication systems for power system management<br>∘ IT architectures of bay-, substation and network control level<br>∘ IT integration (energy market / supply shortfall management / asset management)<br>∘ future trends of process control technology<br>∘ smart grids<br>• functions and steady-state computations for power system operation and plannung<br>∘ load-flow calculations<br>∘ sensitivity analysis and power flow control<br>∘ power system optimization<br>∘ short-circuit calculation<br>∘ asymmetric failure calculation<br>▪ symmetric components<br>▪ calculation of asymmetric failures<br>∘ state estimation |
| **Literature** | E. Handschin: Elektrische Energieübertragungssysteme, Hüthig Verlag<br><br>B. R. Oswald: Berechnung von Drehstromnetzen, Springer-Vieweg Verlag<br><br>V. Crastan: Elektrische Energieversorgung Bd. 1 & 3, Springer Verlag<br><br>E.-G. Tietze: Netzleittechnik Bd. 1 & 2, VDE-Verlag |

| Course L1697: Electrical Power Systems II: Operation and Information Systems of Electrical Power Grids | |
|---|---|
| **Typ** | Recitation Section (large) |
| **Hrs/wk** | 2 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 32, Study Time in Lecture 28 |
| **Lecturer** | Prof. Christian Becker |
| **Language** | DE |
| **Cycle** | WiSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M0673: Information Theory and Coding

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Information Theory and Coding (L0436) | Lecture | 3 | 4 |
| Information Theory and Coding (L0438) | Recitation Section (large) | 2 | 2 |

| | |
|---|---|
| **Module Responsible** | Prof. Gerhard Bauch |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | • Mathematics 1-3<br>• Probability theory and random processes<br>• Basic knowledge of communications engineering (e.g. from lecture "Fundamentals of Communications and Random Processes") |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | The students know the basic definitions for quantification of information in the sense of information theory. They know Shannon's source coding theorem and channel coding theorem and are able to determine theoretical limits of data compression and error-free data transmission over noisy channels. They understand the principles of source coding as well as error-detecting and error-correcting channel coding. They are familiar with the principles of decoding, in particular with modern methods of iterative decoding. They know fundamental coding schemes, their properties and decoding algorithms.<br><br>The students are familiar with the contents of lecture and tutorials. They can explain and apply them to new problems. |
| *Skills* | The students are able to determine the limits of data compression as well as of data transmission through noisy channels and based on those limits to design basic parameters of a transmission scheme. They can estimate the parameters of an error-detecting or error-correcting channel coding scheme for achieving certain performance targets. They are able to compare the properties of basic channel coding and decoding schemes regarding error correction capabilities, decoding delay, decoding complexity and to decide for a suitable method. They are capable of implementing basic coding and decoding schemes in software. |
| **Personal Competence** | |
| *Social Competence* | The students can jointly solve specific problems. |
| *Autonomy* | The students are able to acquire relevant information from appropriate literature sources. They can control their level of knowledge during the lecture period by solving tutorial problems, software tools, clicker system. |
| **Workload in Hours** | Independent Study Time 110, Study Time in Lecture 70 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Written exam |
| **Examination duration and scale** | 90 min |
| **Assignment for the Following Curricula** | Electrical Engineering: Specialisation Information and Communication Systems: Elective Compulsory<br>Computer Science in Engineering: Specialisation II. Engineering Science: Elective Compulsory<br>Information and Communication Systems: Core Qualification: Compulsory<br>International Management and Engineering: Specialisation II. Electrical Engineering: Elective Compulsory<br>Mechatronics: Technical Complementary Course: Elective Compulsory |

### Course L0436: Information Theory and Coding

| | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 3 |
| **CP** | 4 |
| **Workload in Hours** | Independent Study Time 78, Study Time in Lecture 42 |
| **Lecturer** | Prof. Gerhard Bauch |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | • Introduction to information theory and coding<br>• Definitions of information: Self information, entropy<br>• Binary entropy function<br>• Source coding theorem<br>• Entropy of continuous random variables: Differential entropy, differential entropy of uniformly and Gaussian distributed random variables<br>• Source coding<br>  ◦ Principles of lossless source coding<br>  ◦ Optimal source codes<br>  ◦ Prefix codes, prefix-free codes, instantaneous codes<br>  ◦ Morse code<br>  ◦ Huffman code<br>  ◦ Shannon code |

  - Bounds on the average codeword length
  - Relative entropy, Kullback-Leibler distance, Kullback-Leibler divergence
  - Cross entropy
  - Lempel-Ziv algorithm
  - Lempel-Ziv-Welch (LZW) algorithm
  - Text compression and image compression using variants of the Lempel-Ziv algorithm
- Channel models
  - AWGN channel
  - Binary-input AWGN channel
  - Binary symmetric channel (BSC)
  - Relationship between AWGN channel and BSC
  - Binary error and erasure channel (BEEC)
  - Binary erasure channel (BEC)
  - Discrete memoryless channels (DMC)
- Definitions of information for multiple random variables
  - Mutual information and channel capacity
  - Entropy, conditional entropy
  - Chain rules for entropy and mutual information
- Channel coding theorem
- Channel capacity of fundamental channels: BSC, BEC, AWGN channel, binary-input AWGN channel etc.
- Power-limited vs. bandlimited transmission
- Capacity of parallel AWGN channels
  - Waterfilling
  - Examples: Multiple input multiple output (MIMO) channels, complex equivalent baseband channels, orthogonal frequency division multiplex (OFDM)
- Source-channel coding theorem, separation theorem
- Multiuser information theory
  - Multiple access channel (MAC)
  - Broadcast channel
  - Principles of multiple access, time division multiple access (TDMA), frequency division multiple access (FDMA), non-orthogonal multiple access (NOMA), hybrid multiple access
  - Achievable rate regions of TDMA and FDMA with power constraint, energy constraint, power spectral density constraint, respectively
  - Achievable rate region of the two-user and K-user multiple access channels
  - Achievable rate region of the two-user and K user broadcast channels
  - Multiuser diversity
- Channel coding
  - Principles and types of channel coding
  - Code rate, data rate, Hamming distance, minimum Hamming distance, Hamming weight, minimum Hamming weight
  - Error detecting and error correcting codes
  - Simple block codes: Repetition codes, single parity check codes, Hamming code, etc.
  - Syndrome decoding
  - Representations of binary data
  - Non-binary symbol alphabets and non-binary codes
  - Code and encoder, systematic and non-systematic encoders
  - Properties of Hamming distance and Hamming weight
  - Decoding spheres
  - Perfect codes
  - Linear codes
  - Decoding principles
    - Syndrome decoding
    - Maximum a posteriori probability (MAP) decoding and maximum likelihood (ML) decoding
    - Hard decision and soft decision decoding
    - Log-likelihood ratios (LLRs), boxplus operation
    - MAP and ML decoding using log-likelihood ratios
    - Soft-in soft-out decoders
  - Error rate performance comparison of codes in terms of SNR per info bit vs. SNR per code bit
  - Linear block codes
    - Generator matrix and parity check matrix, properties of generator matrix and parity check matrix
    - Dual codes
  - Low density parity check (LDPC) codes
    - Sparse parity check matrix
    - Tanner graphs, cycles and girth
    - Degree distributions
    - Code rate and degree distribution
    - Regular and irregular LDPC codes
    - Message passing decoding
      - Message passing decoding in binary erasure channels (BEC)
      - Systematic encoding using erasure message passing decoding
      - Message passing decoding in binary symmetric channels (BSC)

|  |  |
|---|---|
|  | ▪ Extrinsic information<br>▪ Bit-flipping decoding<br>▪ Effects of short cycles in the Tanner graph<br>▪ Alternative bit-flipping decoding<br>▪ Soft decision message passing decoding: Sum product decoding<br>▪ Bit error rate performance of LDPC codes<br>▪ Repeat accumulate codes and variants of repeat accumulate codes<br>▪ Message passing decoding and turbo decoding of repeat accumulate codes<br>◦ Convolutional codes<br>▪ Encoding using shift registers<br>▪ Trellis representation<br>▪ Hard decision and soft decision Viterbi decoding<br>▪ Bit error rate performance of convolutional codes<br>▪ Asymptotic coding gain<br>▪ Viterbi decoding complexity<br>▪ Free distance and optimum convolutional codes<br>▪ Generator polynomial description and octal description<br>▪ Catastrophic convolutional codes<br>▪ Non-systematic and recursive systematic convolutional (RSC) encoders<br>▪ Rate compatible punctured convolutional (RCPC) codes<br>▪ Hybrid automatic repeat request (HARQ) with incremental redundancy<br>▪ Unequal error protection with punctured convolutional codes<br>▪ Error patterns of convolutional codes<br>◦ Concatenated codes<br>▪ Serial concatenated codes<br>▪ Parallel concatenated codes, Turbo codes<br>▪ Iterative decoding, turbo decoding<br>▪ Bit error rate performance of turbo codes<br>▪ Interleaver design for turbo codes<br>◦ Coded modulation<br>▪ Principle of coded modulation<br>▪ Achievable rates with PSK/QAM modulation<br>▪ Trellis coded modulation (TCM)<br>▪ Set partitioning<br>▪ Ungerböck codes<br>▪ Multilevel coding<br>▪ Bit-interleaved coded modulation |
| **Literature** | Bossert, M.: Kanalcodierung. Oldenbourg.<br><br>Friedrichs, B.: Kanalcodierung. Springer.<br><br>Lin, S., Costello, D.: Error Control Coding. Prentice Hall.<br><br>Roth, R.: Introduction to Coding Theory.<br><br>Johnson, S.: Iterative Error Correction. Cambridge.<br><br>Richardson, T., Urbanke, R.: Modern Coding Theory. Cambridge University Press.<br><br>Gallager, R. G.: Information theory and reliable communication. Whiley-VCH<br><br>Cover, T., Thomas, J.: Elements of information theory. Wiley. |

| **Course L0438: Information Theory and Coding** |  |
|---|---|
| **Typ** | Recitation Section (large) |
| **Hrs/wk** | 2 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 32, Study Time in Lecture 28 |
| **Lecturer** | Prof. Gerhard Bauch |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M1666: Intelligent Systems Lab

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Intelligent Systems Lab (L2709) | Project-/problem-based Learning | 6 | 6 |

| | |
|---|---|
| **Module Responsible** | Prof. Alexander Schlaefer |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | Very good programming skills<br>Good knowledge in mathematics<br>Prior knowledge in machine learning is very helpful<br>Prior knowledge in image processing / computer vision is helpful<br>Prior knowledge in robotics is very helpful<br>Prior knowledge in microprocessor programming is helpful |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | Students will be able to explain aspects of intelligent systems (e.g. autonomy, sensing the environment, interacting with the environment) and provide links to ai / robotics / machine learning / computer vision. |
| *Skills* | Students can analyze a complex application scenario and use artificial intelligence methods (particularly from robotics, machine learning, computer vision) to implement an intelligent system. Furthermore, students will be able to define criteria to assess the function of the system and evaluate the system. |
| **Personal Competence** | |
| *Social Competence* | The students can define project aims and scope and organize the project as team work. They can present their results in an appropriate manner. |
| *Autonomy* | The students take responsibility for their tasks and coordinate their individual work with other group members. They deliver their work on time. They independently acquire additional knowledge by doing a specific literature research. |
| **Workload in Hours** | Independent Study Time 96, Study Time in Lecture 84 |
| **Credit points** | 6 |
| **Course achievement** | **Compulsory** / **Bonus** / **Form** / **Description**<br>Yes / None / Group discussion |
| **Examination** | Written elaboration |
| **Examination duration and scale** | approx. 8 pages, time frame: over the course of the semester |
| **Assignment for the Following Curricula** | Computer Science in Engineering: Specialisation II. Engineering Science: Elective Compulsory |

### Course L2709: Intelligent Systems Lab

| | |
|---|---|
| **Typ** | Project-/problem-based Learning |
| **Hrs/wk** | 6 |
| **CP** | 6 |
| **Workload in Hours** | Independent Study Time 96, Study Time in Lecture 84 |
| **Lecturer** | Prof. Alexander Schlaefer |
| **Language** | DE/EN |
| **Cycle** | SoSe |
| **Content** | The actual project topic will be defined as part of the project. |
| **Literature** | Wird in der Veranstaltung bekannt gegeben. |

## Module M1785: Machine Learning in Electrical Engineering and Information Technology

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| General Introduction Machine Learning (L3004) | Lecture | 1 | 2 |
| Machine Learning Applications in Electric Power Systems (L3008) | Lecture | 1 | 1 |
| Machine Learning in Electromagnetic Compatibility (EMC) Engineering (L3006) | Lecture | 1 | 1 |
| Machine Learning in High-Frequency Technology and Radar (L3007) | Lecture | 1 | 1 |
| Machine Learning in Wireless Communications (L3005) | Lecture | 1 | 1 |

| | |
|---|---|
| **Module Responsible** | Prof. Gerhard Bauch |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | The module is designed for a diverse audience, i.e. students with different background. It shall be suitable for both students with deeper knowledge in machine learning methods but less knowledge in electrical engineering, e.g. math or computer science students, and students with deeper knowledge in electrical engineering but less knowledge in machine learning methods, e.g. electrical engineering students. Machine learning methods will be explained on a relatively high level indicating mainly principle ideas. The focus is on specific applications in electrical engineering and information technology.<br><br>The chapters of the course will be understandable in different depth depending on the individual background of the student. The individual background of the students will be taken into consideration in the oral exam. |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | |
| *Skills* | |
| **Personal Competence** | |
| *Social Competence* | |
| *Autonomy* | |
| **Workload in Hours** | Independent Study Time 110, Study Time in Lecture 70 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Oral exam |
| **Examination duration and scale** | 30 min |
| **Assignment for the Following Curricula** | Electrical Engineering: Specialisation Information and Communication Systems: Elective Compulsory<br>Electrical Engineering: Specialisation Microwave Engineering, Optics, and Electromagnetic Compatibility: Elective Compulsory<br>Electrical Engineering: Specialisation Control and Power Systems Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation II. Engineering Science: Elective Compulsory<br>Information and Communication Systems: Specialisation Communication Systems, Focus Software: Elective Compulsory |

| Course L3004: General Introduction Machine Learning | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 1 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 46, Study Time in Lecture 14 |
| **Lecturer** | Dr. Maximilian Stark |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | • From Rule-Based Systems to Machine Learning<br>  ◦ Brief overview recent advances in ML in various domain<br>  ◦ Outline and expected learning outcomes<br>  ◦ Basics statistical inference and statistics<br>  ◦ Basics of information theory<br>• The Notions of Learning in Machine Learning<br>  ◦ Unsupervised and supervised machine learning<br>  ◦ Model-based and data-driven machine learning<br>  ◦ Hybrid modelling<br>  ◦ Online/offline/meta/transfer learning<br>  ◦ General loss functions<br>• Introduction to Deep Learning<br>  ◦ Variants of neural networks<br>  ◦ MLP<br>  ◦ Conv. neural networks<br>  ◦ Recurrent neural networks<br>  ◦ Training neural networks<br>  ◦ (Stochastic) Gradient Descent<br>• Regression vs. Classification<br>  ◦ Classification as supervised learning problem<br>  ◦ Hands-On Session<br>• Representation Learning and Generative Models<br>  ◦ AutoEncoders<br>  ◦ Directed Generative Models<br>  ◦ Undirected Generative Models<br>  ◦ Generative Adversarial Neural Networks<br>• Probabilistic Graphical Models<br>  ◦ Bayesian Networks<br>  ◦ Variational inference (variational autoencoder) |
| **Literature** | |

| Course L3008: Machine Learning Applications in Electric Power Systems | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 1 |
| **CP** | 1 |
| **Workload in Hours** | Independent Study Time 16, Study Time in Lecture 14 |
| **Lecturer** | Prof. Christian Becker, Dr. Davood Babazadeh |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | |
| **Literature** | |

| Course L3006: Machine Learning in Electromagnetic Compatibility (EMC) Engineering | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 1 |
| **CP** | 1 |
| **Workload in Hours** | Independent Study Time 16, Study Time in Lecture 14 |
| **Lecturer** | Prof. Christian Schuster, Dr. Cheng Yang |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | Electromagnetic Compatibility (EMC) Engineering deals with design, simulation, measurement, and certification of electronic and electric components and systems in such a way that their operation is safe, reliable, and efficient in any possible application. Safety is hereby understood as safe with respect to parasitic effects of electromagnetic fields on humans as well as on the operation of other components and systems nearby. Examples for components and systems range from the wiring in aircraft and ships to high-speed interconnects in server systems and wirless interfaces for brain implants. In this part of the course we will give an introduction to the physical basics of EMC engineering and then show how methods of Machine Learning (ML) can be applied to expand todays physcis-based approaches in EMC Engineering. |
| **Literature** | |

| Course L3007: Machine Learning in High-Frequency Technology and Radar | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 1 |
| **CP** | 1 |
| **Workload in Hours** | Independent Study Time 16, Study Time in Lecture 14 |
| **Lecturer** | Prof. Alexander Kölpin, Dr. Fabian Lurz |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | |
| **Literature** | |

| Course L3005: Machine Learning in Wireless Communications | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 1 |
| **CP** | 1 |
| **Workload in Hours** | Independent Study Time 16, Study Time in Lecture 14 |
| **Lecturer** | Dr. Maximilian Stark |
| **Language** | EN |
| **Cycle** | SoSe |
| **Content** | • Supervised Learning Application - Channel Coding<br>  ◦ Recap channel coding and block codes<br>  ◦ Block codes as trainable neural networks<br>  ◦ Tanner graph with trainable weights<br>  ◦ Hands-on session<br>• Supervised Learning Application - Modulation Detection<br>  ◦ Recap wireless modulation schemes<br>  ◦ Convolutional neuronal networks for blind detection of modulation schemes<br>  ◦ Hands-on session<br>• Autoencoder Application - Constellation Shaping I<br>  ◦ Recap channel capacity and constellation shaping,<br>  ◦ Capacity achieving machine learning systems<br>  ◦ Information theoretical explanation of the autoencoder training<br>  ◦ Hands-on session<br>• Autoencoder Application - Constellation Shaping II<br>  ◦ Training without a channel model<br>  ◦ Mutual information neural estimator<br>  ◦ Hands-on session<br>• Generative Adversarial Network Application - Channel Modelling<br>  ◦ Recap realistic channels with non-linear hardware impairments<br>  ◦ Training a digital twin of a realistic channel with insufficient training data<br>  ◦ Hands-on session<br>• Recurrent Neural Network Application - Channel prediction<br>  ◦ Recap time-varying channel models<br>  ◦ Recurrent neural networks for temporal prediction<br>  ◦ Hands-on session |
| **Literature** | |

## Module M0677: Digital Signal Processing and Digital Filters

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Digital Signal Processing and Digital Filters (L0446) | Lecture | 3 | 4 |
| Digital Signal Processing and Digital Filters (L0447) | Recitation Section (large) | 2 | 2 |

| | |
|---|---|
| **Module Responsible** | Prof. Gerhard Bauch |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | • Mathematics 1-3<br>• Signals and Systems<br>• Fundamentals of signal and system theory as well as random processes.<br>• Fundamentals of spectral transforms (Fourier series, Fourier transform, Laplace transform) |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | The students know and understand basic algorithms of digital signal processing. They are familiar with the spectral transforms of discrete-time signals and are able to describe and analyse signals and systems in time and image domain. They know basic structures of digital filters and can identify and assess important properties including stability. They are aware of the effects caused by quantization of filter coefficients and signals. They are familiar with the basics of adaptive filters. They can perform traditional and parametric methods of spectrum estimation, also taking a limited observation window into account.<br><br>The students are familiar with the contents of lecture and tutorials. They can explain and apply them to new problems. |
| *Skills* | The students are able to apply methods of digital signal processing to new problems. They can choose and parameterize suitable filter striuctures. In particular, the can design adaptive filters according to the minimum mean squared error (MMSE) criterion and develop an efficient implementation, e.g. based on the LMS or RLS algorithm. Furthermore, the students are able to apply methods of spectrum estimation and to take the effects of a limited observation window into account. |
| **Personal Competence** | |
| *Social Competence* | The students can jointly solve specific problems. |
| *Autonomy* | The students are able to acquire relevant information from appropriate literature sources. They can control their level of knowledge during the lecture period by solving tutorial problems, software tools, clicker system. |
| **Workload in Hours** | Independent Study Time 110, Study Time in Lecture 70 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Written exam |
| **Examination duration and scale** | 90 min |
| **Assignment for the Following Curricula** | Electrical Engineering: Specialisation Control and Power Systems Engineering: Elective Compulsory<br>Computer Science in Engineering: Specialisation II. Engineering Science: Elective Compulsory<br>Information and Communication Systems: Specialisation Communication Systems, Focus Signal Processing: Elective Compulsory<br>Mechanical Engineering and Management: Specialisation Mechatronics: Elective Compulsory<br>Mechatronics: Specialisation Intelligent Systems and Robotics: Elective Compulsory<br>Microelectronics and Microsystems: Specialisation Communication and Signal Processing: Elective Compulsory<br>Theoretical Mechanical Engineering: Specialisation Robotics and Computer Science: Elective Compulsory |

| Course L0446: Digital Signal Processing and Digital Filters | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 3 |
| **CP** | 4 |
| **Workload in Hours** | Independent Study Time 78, Study Time in Lecture 42 |
| **Lecturer** | Prof. Gerhard Bauch |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | • Transforms of discrete-time signals:<br>  ◦ Discrete-time Fourier Transform (DTFT)<br>  ◦ Discrete Fourier-Transform (DFT), Fast Fourier Transform (FFT)<br>  ◦ Z-Transform<br>• Correspondence of continuous-time and discrete-time signals, sampling, sampling theorem<br>• Fast convolution, Overlap-Add-Method, Overlap-Save-Method<br>• Fundamental structures and basic types of digital filters<br>• Characterization of digital filters using pole-zero plots, important properties of digital filters<br>• Quantization effects<br>• Design of linear-phase filters<br>• Fundamentals of stochastic signal processing and adaptive filters<br>  ◦ MMSE criterion<br>  ◦ Wiener Filter<br>  ◦ LMS- and RLS-algorithm<br>• Traditional and parametric methods of spectrum estimation |
| **Literature** | K.-D. Kammeyer, K. Kroschel: Digitale Signalverarbeitung. Vieweg Teubner.<br><br>V. Oppenheim, R. W. Schafer, J. R. Buck: Zeitdiskrete Signalverarbeitung. Pearson StudiumA. V.<br><br>W. Hess: Digitale Filter. Teubner.<br><br>Oppenheim, R. W. Schafer: Digital signal processing. Prentice Hall.<br><br>S. Haykin: Adaptive flter theory.<br><br>L. B. Jackson: Digital filters and signal processing. Kluwer.<br><br>T.W. Parks, C.S. Burrus: Digital filter design. Wiley. |

| Course L0447: Digital Signal Processing and Digital Filters | |
|---|---|
| **Typ** | Recitation Section (large) |
| **Hrs/wk** | 2 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 32, Study Time in Lecture 28 |
| **Lecturer** | Prof. Gerhard Bauch |
| **Language** | EN |
| **Cycle** | WiSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

# Specialization III. Mathematics

## Module M1428: Linear and Nonlinear Optimization

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Linear and Nonlinear Optimization (L2062) | Lecture | 4 | 4 |
| Linear and Nonlinear Optimization (L2063) | Recitation Section (large) | 1 | 2 |

| | |
|---|---|
| **Module Responsible** | Prof. Matthias Mnich |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | • Discrete Algebraic Structures<br>• Mathematics I<br>• Graph Theory and Optimization |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | • Students can name the basic concepts in linear and non-linear optimization. They are able to explain them using appropriate examples.<br>• Students can discuss logical connections between these concepts. They are capable of illustrating these connections with the help of examples.<br>• They know proof strategies and can reproduce them. |
| *Skills* | • Students can model problems in linear and non-linear optimization with the help of the concepts studied in this course. Moreover, they are capable of solving them by applying established methods.<br>• Students are able to discover and verify further logical connections between the concepts studied in the course.<br>• For a given problem, the students can develop and execute a suitable approach, and are able to critically evaluate the results. |
| **Personal Competence** | |
| *Social Competence* | • Students are able to work together in teams. They are capable to use mathematics as a common language.<br>• In doing so, they can communicate new concepts according to the needs of their cooperating partners. Moreover, they can design examples to check and deepen the understanding of their peers. |
| *Autonomy* | • Students are capable of checking their understanding of complex concepts on their own. They can specify open questions precisely and know where to get help in solving them.<br>• Students have developed sufficient persistence to be able to work for longer periods in a goal-oriented manner on hard problems. |
| **Workload in Hours** | Independent Study Time 110, Study Time in Lecture 70 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Written exam |
| **Examination duration and scale** | 90 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation III. Mathematics: Elective Compulsory<br>Computer Science in Engineering: Specialisation III. Mathematics: Elective Compulsory |

| **Course L2062: Linear and Nonlinear Optimization** | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 4 |
| **CP** | 4 |
| **Workload in Hours** | Independent Study Time 64, Study Time in Lecture 56 |
| **Lecturer** | Prof. Matthias Mnich |
| **Language** | DE/EN |
| **Cycle** | WiSe |
| **Content** | • Modelling linear programming problems<br>• Graphical method<br>• Algebraic background<br>• Convexity<br>• Polyhedral theory<br>• Simplex method<br>• Degeneracy and convergence<br>• duality<br>• interior-point methods<br>• quadratic optimization<br>• integer linear programming |
| **Literature** | • A. Schrijver: Combinatorial Optimization: Polyhedra and Efficiency. Springer, 2003<br>• B. Korte and T. Vygen: Combinatorial Optimization: Theory and Algorithms. Springer, 2018<br>• T. Cormen, Ch. Leiserson, R. Rivest, C. Stein: Introduction to Algorithms. MIT Press, 2013 |

| **Course L2063: Linear and Nonlinear Optimization** | |
|---|---|
| **Typ** | Recitation Section (large) |
| **Hrs/wk** | 1 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 46, Study Time in Lecture 14 |
| **Lecturer** | Prof. Matthias Mnich |
| **Language** | DE/EN |
| **Cycle** | WiSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M0881: Mathematical Image Processing

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Mathematical Image Processing (L0991) | Lecture | 3 | 4 |
| Mathematical Image Processing (L0992) | Recitation Section (small) | 1 | 2 |

| | |
|---|---|
| **Module Responsible** | Prof. Marko Lindner |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | • Analysis: partial derivatives, gradient, directional derivative<br>• Linear Algebra: eigenvalues, least squares solution of a linear system |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | Students are able to<br>• characterize and compare diffusion equations<br>• explain elementary methods of image processing<br>• explain methods of image segmentation and registration<br>• sketch and interrelate basic concepts of functional analysis |
| *Skills* | Students are able to<br>• implement and apply elementary methods of image processing<br>• explain and apply modern methods of image processing |
| **Personal Competence** | |
| *Social Competence* | Students are able to work together in heterogeneously composed teams (i.e., teams from different study programs and background knowledge) and to explain theoretical foundations. |
| *Autonomy* | • Students are capable of checking their understanding of complex concepts on their own. They can specify open questions precisely and know where to get help in solving them.<br>• Students have developed sufficient persistence to be able to work for longer periods in a goal-oriented manner on hard problems. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Oral exam |
| **Examination duration and scale** | 20 min |
| **Assignment for the Following Curricula** | Bioprocess Engineering: Specialisation A - General Bioprocess Engineering: Elective Compulsory<br>Computer Science: Specialisation III. Mathematics: Elective Compulsory<br>Computer Science in Engineering: Specialisation III. Mathematics: Elective Compulsory<br>Interdisciplinary Mathematics: Specialisation Computational Methods in Biomedical Imaging: Compulsory<br>Mechatronics: Technical Complementary Course: Elective Compulsory<br>Mechatronics: Specialisation System Design: Elective Compulsory<br>Mechatronics: Specialisation Intelligent Systems and Robotics: Elective Compulsory<br>Technomathematics: Specialisation I. Mathematics: Elective Compulsory<br>Theoretical Mechanical Engineering: Specialisation Robotics and Computer Science: Elective Compulsory<br>Process Engineering: Specialisation Process Engineering: Elective Compulsory |

| Course L0991: Mathematical Image Processing | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 3 |
| **CP** | 4 |
| **Workload in Hours** | Independent Study Time 78, Study Time in Lecture 42 |
| **Lecturer** | Prof. Marko Lindner |
| **Language** | DE/EN |
| **Cycle** | WiSe |
| **Content** | • basic methods of image processing<br>• smoothing filters<br>• the diffusion / heat equation<br>• variational formulations in image processing<br>• edge detection<br>• de-convolution<br>• inpainting<br>• image segmentation<br>• image registration |
| **Literature** | Bredies/Lorenz: Mathematische Bildverarbeitung |

| Course L0992: Mathematical Image Processing | |
|---|---|
| **Typ** | Recitation Section (small) |
| **Hrs/wk** | 1 |
| **CP** | 2 |
| **Workload in Hours** | Independent Study Time 46, Study Time in Lecture 14 |
| **Lecturer** | Prof. Marko Lindner |
| **Language** | DE/EN |
| **Cycle** | WiSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M1405: Randomised Algorithms and Random Graphs

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Randomised Algorithms and Random Graphs (L2010) | Lecture | 2 | 3 |
| Randomised Algorithms and Random Graphs (L2011) | Recitation Section (large) | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Anusch Taraz |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | • Students can describe basic concepts in the area of Randomized Algorithms and Random Graphs such as random walks, tail bounds, fingerprinting and algebraic techniques, first and second moment methods, and various random graph models. They are able to explain them using appropriate examples.<br>• Students can discuss logical connections between these concepts. They are capable of illustrating these connections with the help of examples.<br>• They know proof strategies and can apply them. |
| *Skills* | • Students can model problems with the help of the concepts studied in this course. Moreover, they are capable of solving them by applying established methods.<br>• Students are able to explore and verify further logical connections between the concepts studied in the course.<br>• For a given problem, the students can develop and execute a suitable technique, and are able to critically evaluate the results. |
| **Personal Competence** | |
| *Social Competence* | • Students are able to work together in teams. They are capable to establish a common language.<br>• In doing so, they can communicate new concepts according to the needs of their cooperating partners. Moreover, they can design examples to check and deepen the understanding of their peers. |
| *Autonomy* | • Students are capable of checking their understanding of complex concepts on their own. They can specify open questions precisely and know where to get help in solving them.<br>• Students have developed sufficient persistence to be able to work for longer periods in a goal-oriented manner on hard problems. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Oral exam |
| **Examination duration and scale** | 30 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation III. Mathematics: Elective Compulsory<br>Computer Science in Engineering: Specialisation III. Mathematics: Elective Compulsory |

| Course L2010: Randomised Algorithms and Random Graphs | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Anusch Taraz, Prof. Volker Turau |
| **Language** | DE/EN |
| **Cycle** | SoSe |
| **Content** | Randomized Algorithms:<br>• introduction and recalling basic tools from probability<br>• randomized search<br>• random walks<br>• text search with fingerprinting<br>• parallel and distributed algorithms<br>• online algorithms<br><br>Random Graphs:<br>• typical properties<br>• first and second moment method<br>• tail bounds<br>• thresholds and phase transitions<br>• probabilistic method<br>• models for complex networks |
| **Literature** | • Motwani, Raghavan: Randomized Algorithms<br>• Worsch: Randomisierte Algorithmen<br>• Dietzfelbinger: Randomisierte Algorithmen<br>• Bollobas: Random Graphs<br>• Alon, Spencer: The Probabilistic Method<br>• Frieze, Karonski: Random Graphs<br>• van der Hofstad: Random Graphs and Complex Networks |

| Course L2011: Randomised Algorithms and Random Graphs | |
|---|---|
| **Typ** | Recitation Section (large) |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Anusch Taraz, Prof. Volker Turau |
| **Language** | DE/EN |
| **Cycle** | SoSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M0711: Numerical Mathematics II

**Courses**

| Title | Typ | Hrs/wk | CP |
|---|---|---|---|
| Numerical Mathematics II (L0568) | Lecture | 2 | 3 |
| Numerical Mathematics II (L0569) | Recitation Section (small) | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Prof. Sabine Le Borne |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | • Numerical Mathematics I<br>• Python knowledge |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | Students are able to<br>• name advanced numerical methods for interpolation, approximation, integration, eigenvalue problems, eigenvalue problems, nonlinear root finding problems and explain their core ideas,<br>• repeat convergence statements for the numerical methods, sketch convergence proofs,<br>• explain practical aspects of numerical methods concerning runtime and storage needs<br>• explain aspects regarding the practical implementation of numerical methods with respect to computational and storage complexity. |
| *Skills* | Students are able to<br>• implement, apply and compare advanced numerical methods in Python,<br>• justify the convergence behaviour of numerical methods with respect to the problem and solution algorithm and to transfer it to related problems,<br>• for a given problem, develop a suitable solution approach, if necessary through composition of several algorithms, to execute this approach and to critically evaluate the results |
| **Personal Competence** | |
| *Social Competence* | Students are able to<br>• work together in heterogeneously composed teams (i.e., teams from different study programs and background knowledge), explain theoretical foundations and support each other with practical aspects regarding the implementation of algorithms. |
| *Autonomy* | Students are capable<br>• to assess whether the supporting theoretical and practical excercises are better solved individually or in a team,<br>• to assess their individual progess and, if necessary, to ask questions and seek help. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Oral exam |
| **Examination duration and scale** | 25 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation III. Mathematics: Elective Compulsory<br>Computer Science in Engineering: Specialisation III. Mathematics: Elective Compulsory<br>Technomathematics: Specialisation I. Mathematics: Elective Compulsory<br>Theoretical Mechanical Engineering: Core Qualification: Elective Compulsory |

| Course L0568: Numerical Mathematics II | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Sabine Le Borne, Dr. Jens-Peter Zemke |
| **Language** | DE/EN |
| **Cycle** | SoSe |
| **Content** | 1. Error and stability: Notions and estimates<br>2. Rational interpolation and approximation<br>3. Multidimensional interpolation (RBF) and approximation (neural nets)<br>4. Quadrature: Gaussian quadrature, orthogonal polynomials<br>5. Linear systems: Perturbation theory of decompositions, structured matrices<br>6. Eigenvalue problems: LR-, QD-, QR-Algorithmus<br>7. Nonlinear systems of equations: Newton and Quasi-Newton methods, line search (optional)<br>8. Krylov space methods: Arnoldi-, Lanczos methods (optional) |
| **Literature** | • Skript<br>• Stoer/Bulirsch: Numerische Mathematik 1, Springer<br>• Dahmen, Reusken: Numerik für Ingenieure und Naturwissenschaftler, Springer |

| Course L0569: Numerical Mathematics II | |
|---|---|
| **Typ** | Recitation Section (small) |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Prof. Sabine Le Borne, Dr. Jens-Peter Zemke |
| **Language** | DE/EN |
| **Cycle** | SoSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

## Module M1552: Advanced Machine Learning

| Courses | | | |
|---|---|---|---|
| **Title** | **Typ** | **Hrs/wk** | **CP** |
| Advanced Machine Learning (L2322) | Lecture | 2 | 3 |
| Advanced Machine Learning (L2323) | Recitation Section (small) | 2 | 3 |

| | |
|---|---|
| **Module Responsible** | Dr. Jens-Peter Zemke |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | 1. Mathematics I-III<br>2. Numerical Mathematics 1/ Numerics<br>3. Programming skills, preferably in Python |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | Students are able to name, state and classify state-of-the-art neural networks and their corresponding mathematical basics. They can assess the difficulties of different neural networks. |
| *Skills* | Students are able to implement, understand, and, tailored to the field of application, apply neural networks. |
| **Personal Competence** | |
| *Social Competence* | Students can<br>• develop and document joint solutions in small teams;<br>• form groups to further develop the ideas and transfer them to other areas of applicability;<br>• form a team to develop, build, and advance a software library. |
| *Autonomy* | Students are able to<br>• correctly assess the time and effort of self-defined work;<br>• assess whether the supporting theoretical and practical excercises are better solved individually or in a team;<br>• define test problems for testing and expanding the methods;<br>• assess their individual progess and, if necessary, to ask questions and seek help. |
| **Workload in Hours** | Independent Study Time 124, Study Time in Lecture 56 |
| **Credit points** | 6 |
| **Course achievement** | None |
| **Examination** | Oral exam |
| **Examination duration and scale** | 25 min |
| **Assignment for the Following Curricula** | Computer Science: Specialisation III. Mathematics: Elective Compulsory<br>Computer Science in Engineering: Specialisation III. Mathematics: Elective Compulsory<br>Mechatronics: Specialisation Intelligent Systems and Robotics: Elective Compulsory<br>Mechatronics: Technical Complementary Course: Elective Compulsory<br>Technomathematics: Specialisation I. Mathematics: Elective Compulsory<br>Theoretical Mechanical Engineering: Specialisation Robotics and Computer Science: Elective Compulsory |

### Course L2322: Advanced Machine Learning

| | |
|---|---|
| **Typ** | Lecture |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Dr. Jens-Peter Zemke |
| **Language** | DE/EN |
| **Cycle** | WiSe |
| **Content** | 1. Basics: analogy; layout of neural nets, universal approximation, NP-completeness<br>2. Feedforward nets: backpropagation, variants of Stochastic Gradients<br>3. Deep Learning: problems and solution strategies<br>4. Deep Belief Networks: energy based models, Contrastive Divergence<br>5. CNN: idea, layout, FFT and Winograds algorithms, implementation details<br>6. RNN: idea, dynamical systems, training, LSTM<br>7. ResNN: idea, relation to neural ODEs<br>8. Standard libraries: Tensorflow, Keras, PyTorch<br>9. Recent trends |
| **Literature** | 1. Skript<br>2. Online-Werke:<br>◦ http://neuralnetworksanddeeplearning.com/<br>◦ https://www.deeplearningbook.org/ |

| Course L2323: Advanced Machine Learning | |
|---|---|
| **Typ** | Recitation Section (small) |
| **Hrs/wk** | 2 |
| **CP** | 3 |
| **Workload in Hours** | Independent Study Time 62, Study Time in Lecture 28 |
| **Lecturer** | Dr. Jens-Peter Zemke |
| **Language** | DE/EN |
| **Cycle** | WiSe |
| **Content** | See interlocking course |
| **Literature** | See interlocking course |

# Specialization IV. Subject Specific Focus

## Module M1434: Technical Complementary Course I for Computational Science and Engineering

| Courses | | | |
|---|---|---|---|
| **Title** | **Typ** | **Hrs/wk** | **CP** |

| | |
|---|---|
| **Module Responsible** | Prof. Görschwin Fey |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | |
| *Skills* | |
| **Personal Competence** | |
| *Social Competence* | |
| *Autonomy* | |
| **Workload in Hours** | Depends on choice of courses |
| **Credit points** | 12 |
| **Assignment for the Following Curricula** | Computer Science in Engineering: Specialisation IV. Subject Specific Focus: Elective Compulsory |

## Module M1435: Technical Complementary Course II for Computational Science and Engineering

| Courses | | | |
|---|---|---|---|
| **Title** | **Typ** | **Hrs/wk** | **CP** |

| | |
|---|---|
| **Module Responsible** | Prof. Görschwin Fey |
| **Admission Requirements** | None |
| **Recommended Previous Knowledge** | |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | |
| *Skills* | |
| **Personal Competence** | |
| *Social Competence* | |
| *Autonomy* | |
| **Workload in Hours** | Depends on choice of courses |
| **Credit points** | 12 |
| **Assignment for the Following Curricula** | Computer Science in Engineering: Specialisation IV. Subject Specific Focus: Elective Compulsory |

# Thesis

## Module M-002: Master Thesis

| Courses | | | |
|---|---|---|---|
| Title | Typ | Hrs/wk | CP |

| | |
|---|---|
| **Module Responsible** | Professoren der TUHH |
| **Admission Requirements** | • According to General Regulations §21 (1):<br><br>At least 60 credit points have to be achieved in study programme. The examinations board decides on exceptions. |
| **Recommended Previous Knowledge** | |
| **Educational Objectives** | After taking part successfully, students have reached the following learning results |
| **Professional Competence** | |
| *Knowledge* | • The students can use specialized knowledge (facts, theories, and methods) of their subject competently on specialized issues.<br>• The students can explain in depth the relevant approaches and terminologies in one or more areas of their subject, describing current developments and taking up a critical position on them.<br>• The students can place a research task in their subject area in its context and describe and critically assess the state of research. |
| *Skills* | The students are able:<br><br>• To select, apply and, if necessary, develop further methods that are suitable for solving the specialized problem in question.<br>• To apply knowledge they have acquired and methods they have learnt in the course of their studies to complex and/or incompletely defined problems in a solution-oriented way.<br>• To develop new scientific findings in their subject area and subject them to a critical assessment. |
| **Personal Competence** | |
| *Social Competence* | Students can<br><br>• Both in writing and orally outline a scientific issue for an expert audience accurately, understandably and in a structured way.<br>• Deal with issues competently in an expert discussion and answer them in a manner that is appropriate to the addressees while upholding their own assessments and viewpoints convincingly. |
| *Autonomy* | Students are able:<br><br>• To structure a project of their own in work packages and to work them off accordingly.<br>• To work their way in depth into a largely unknown subject and to access the information required for them to do so.<br>• To apply the techniques of scientific work comprehensively in research of their own. |
| **Workload in Hours** | Independent Study Time 900, Study Time in Lecture 0 |
| **Credit points** | 30 |
| **Course achievement** | None |
| **Examination** | Thesis |
| **Examination duration and scale** | According to General Regulations |
| **Assignment for the Following Curricula** | Civil Engineering: Thesis: Compulsory<br>Bioprocess Engineering: Thesis: Compulsory<br>Chemical and Bioprocess Engineering: Thesis: Compulsory<br>Computer Science: Thesis: Compulsory<br>Digital Journalism: Thesis: Compulsory<br>Electrical Engineering: Thesis: Compulsory<br>Energy Systems: Thesis: Compulsory<br>Environmental Engineering: Thesis: Compulsory<br>Aircraft Systems Engineering: Thesis: Compulsory<br>Global Innovation Management: Thesis: Compulsory<br>Computer Science in Engineering: Thesis: Compulsory<br>Information and Communication Systems: Thesis: Compulsory<br>Interdisciplinary Mathematics: Thesis: Compulsory<br>International Production Management: Thesis: Compulsory<br>International Management and Engineering: Thesis: Compulsory<br>Joint European Master in Environmental Studies - Cities and Sustainability: Thesis: Compulsory<br>Logistics, Infrastructure and Mobility: Thesis: Compulsory<br>Materials Science: Thesis: Compulsory |

| | |
|---|---|
| | Mechanical Engineering and Management: Thesis: Compulsory<br>Mechatronics: Thesis: Compulsory<br>Biomedical Engineering: Thesis: Compulsory<br>Microelectronics and Microsystems: Thesis: Compulsory<br>Product Development, Materials and Production: Thesis: Compulsory<br>Renewable Energies: Thesis: Compulsory<br>Naval Architecture and Ocean Engineering: Thesis: Compulsory<br>Ship and Offshore Technology: Thesis: Compulsory<br>Teilstudiengang Lehramt Metalltechnik: Thesis: Compulsory<br>Theoretical Mechanical Engineering: Thesis: Compulsory<br>Process Engineering: Thesis: Compulsory<br>Water and Environmental Engineering: Thesis: Compulsory<br>Certification in Engineering & Advisory in Aviation: Thesis: Compulsory |