FRIEDRICH-ALEXANDER
UNIVERSITÄT
ERLANGEN-NÜRNBERG
NATURWISSENSCHAFTLICHE
FAKULTÄT

List of modules for the Master's degree programme Computational and Applied Mathematics for the summer semester 2022

Not all of the listed modules are offered annually. On the other hand, additional modules may be offered.

Department of Mathematics
Friedrich-Alexander-Universität Erlangen-Nürnberg

Last updated: April 14th 2022
Reference: Examination regulations dated Feb 27, 2017

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Dean of Studies (General questions about the programme)

Prof. Dr. Friedrich Knop

Department of Mathematics, Friedrich-Alexander-Universität Erlangen-Nürnberg Cauerstr.11, 91058 Erlangen, Room 01.321 Phone: +49 9131 8567021 E-mail: knop@math.fau.de

Examination Committee for Bachelor's and Master's degree courses in Mathematics (Examination matters for the programme)

Prof. Dr. Eberhard Bänsch

Department of Mathematics, Friedrich-Alexander-Universität Erlangen-Nürnberg

Cauerstrasse 11, 91058 Erlangen, Room 04.323

Phone: +49 9131 8567202, E-mail: baensch@am.uni-erlangen.de

Degree programme manager

Prof. Dr. Günther Grün

Department of Mathematics, Friedrich-Alexander-Universität Erlangen-Nürnberg

Cauerstrasse 11, 91058 Erlangen, Room 04.343

Phone: +49 9131 8567220 E-mail:gruen@math.fau.de

Degree programme administration (Procedures and organisation)

Prof. Dr. Serge Kräutle

Department of Mathematics, Friedrich-Alexander-Universität Erlangen-Nürnberg

Cauerstrasse 11, 91058 Erlangen, Room 04.337

Phone: +49 9131 85 67213 E-mail:kraeutle@math.fau.de

Subject advisor

Prof. Dr. Serge Kräutle

Department of Mathematics, Friedrich-Alexander-Universität Erlangen-Nürnberg

Cauerstrasse 11, 91058 Erlangen, Room 04.337

Phone: +49 9131 85 67213 E-mail:kraeutle@math.fau.de

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Student Service Centre

Christine Gräßel, M. A.

Department of Mathematics, Friedrich-Alexander-Universität Erlangen-Nürnberg

Cauerstrasse 11, 91058 Erlangen, Room 01.385

Phone: +49 9131 8567024, E-mail:ssc@math.fau.de

Last updated: April 14th, 2022

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1	**Module name**	**Module 2: ModAna2: Modeling and Analysis in Continuum Mechanics II**	**ECTS 5**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Exercises: 0.5 semester hrs/week	MApA
3	**Lectures**	Nicola De Nitti nicola.de.nitti@fau.de	
4	**Module coordinator**	Prof. Dr. G. Grün gruen@math.fau.de	
5	**Content**	At least two of the following three topics: • Monotone operators and applications in continuum mechanics, e.g. shear-thinning liquids, • Mathematical concepts of model reduction: homogenization, gamma convergence, asymptotic analysis, • Reaction diffusion models from biology and social sciences; • Models in fluid dynamics (compressible and incompressible Navier-Stokes equations); • Wave phenomena and other hyperbolic equations in continuum mechanics	
6	**Learning objectives and skills**	Students can: • derive mathematical models for several important applications in continuum mechanics. • apply analytical techniques to rigorously prove qualitative properties of solutions.	
7	**Prerequisites**	Recommended: Modeling and Analysis in Continuum Mechanics I	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	Mandatory module for MSc in Computational and Applied Mathematics Mandatory elective module for MSc in Mathematics in the fields of "Modeling, Simulation and Optimization" and "Analysis and Stochastics"	
10	**Method of examination**	oral examination (20 minutes)	
11	**Grading Procedure**	100% based on Oral examination	
12	**Module frequency**	Summer semester (annually)	
13	**Workload**	Contact hours: 35 hrs Independent study: 115 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	

16	**Recommended reading**	• A. Braides: Gamma-convergence for beginners, Oxford University Press, • D. Cioranescu & P. Donato: An introduction to homogenization, Oxford University Press, • L.C. Evans. (2010). Partial differential equations. AMS. • T.A. Roberts (1994). A one-dimensional introduction to continuum mechanics. World Scientific. • R.E. Showalter: Monotone operators in Banach space and nonlinear partial differential equations, AMS • T. Temam and A. Miranville (2005). Mathematical modeling in continuum mechanics. Cambridge University Press. • Handouts and lecture notes distributed via StudOn.

1	**Module name**	**Module 3:** **MoSi: Modeling, Simulation, Optimization (Practical Course)**	**ECTS 5**
2	**Courses/lectures**	Seminar: 3 semester hrs/week	MApA/NASi/Opti
3	**Lectures**	Dr. Daniël Veldman daniel.veldman@math.fau.de	
4	**Module coordinator**	Prof. Dr. Martin Burger martin.burger@fau.de	
5	**Content**	• Modelling, analysis, simulation and/or optimization of problems in engineering or the natural sciences • Numerical algorithms for partial differential equation models (finite differences, finite elements, etc) • Continuous optimization and optimal control	
6	**Learning objectives and skills**	Students • work on problems in engineering or the natural sciences by constructing a suitable mathematical model, • are able to simulate, analyze, and/or optimize the constructed mathematical model using numerical methods, • are able to implement processes using their own or specified software and critically evaluate the results, • are able to set out their approaches and results in a comprehensible and convincing manner, making use of appropriate presentation techniques, • are able to develop and set out in writing the theories and problem solutions they have developed.	
7	**Prerequisites**	Recommended: Modeling and Analysis in Continuum Mechanics I	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	Compulsory module for MSc in Computational Applied Mathematics Mandatory elective module for MSc in Mathematics in the field of "Modeling, Simulation and Optimization"	
10	**Method of examination**	Weekly hand in assignments. Final project.	
11	**Grading Procedure**	Hand in assignments 20% Final project 80%	
12	**Module frequency**	Summer semester (annually)	
13	**Workload**	Contact hours: 42 hrs Independent study: 108 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	
16	**Recommended reading**	Project-dependent. Will be published on StudOn at the beginning of the semester.	

1	**Module name** **65875**	**Module 4:** **PTfS-CAM: Programming Techniques for Supercomputers in CAM**	**ECTS 10**
2	**Courses/lectures**	a) Lectures: 4 semester hrs/week b) Practical: 2 semester hrs/week	
3	**Lecturers**	Prof. Dr. Gerhard Wellein Gerhard.Wellein@rrze.uni-erlangen.de	
4	**Module coordinator**	Prof. Dr. Gerhard Wellein Gerhard.Wellein@rrze.uni-erlangen.de	
5	**Content**	Introduction to the architecture of modern supercomputers Single core architecture and optimisation strategies Memory hierarchy and data access optimization Concepts of parallel computers and parallel computing Efficient “shared memory” parallelisation (OpenMP) Parallelisation approaches for multi-core processors including GPUs Efficient “distributed memory” parallelisation (MPI) Roofline performance model Serial and parallel performance modelling Complete parallel implementation of a modern iterative Poisson solver	
6	**Learning objectives and skills**	Students • acquire a comprehensive overview of programming modern supercomputers efficiently for numerical simulations, • learn modern optimisation and parallelisation strategies, guided by structured performance modelling, • acquire an insight into innovative programming techniques and alternative supercomputer architectures, • are able to implement numerical methods to solve partial differential equations (PDEs) with finite difference (FD) discretization with high hardware efficiency on parallel computers.	
7	**Prerequisites**	Recommended: Experience in C/C++ or Fortran programming; basic knowledge of MPI and OpenMP programming	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	Compulsory module for MSc Computational and Applied Mathematics	
10	**Method of examination**	oral exam (30 minutes)	
11	**Grading Procedure**	100% based on oral exam	
12	**Module frequency**	Summer semester (annually)	
13	**Workload**	Contact hours: 120 hrs Independent study: 180 hrs Total: 300 hrs, corresponding to 10 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	

16	**Recommended reading**	• G. Hager & G. Wellein: Introduction to High Performance Computing for Scientists and Engineers. CRC Computational Science Series, 2010. ISBN 978-1439811924 • J. Hennessy & D. Patterson: Computer Architecture. A Quantitative Approach. Morgan Kaufmann Publishers, Elsevier, 2003. ISBN 1-55860-724-2

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1	**Module name**	**Module 6a: MaSe: Master's seminar MApA**	**ECTS 5**
2	**Courses/lectures**	"Mathematical Modeling and Data Analysis"	
3	**Lecturers**	Prof. Dr. Burger martin.burger@fau.de	
4	**Module coordinator**	Prof. Dr. Günther Grün gruen@math.fau.de	
5	**Content**	A topic from MApA that relates to the compulsory elective modules offered.	
6	**Learning objectives and skills**	Students can use original literature to familiarise themselves with a current research topic, can structure the content acquired both verbally and in writing and make their own contributions to its presentation and/or substance, learn scientific content on the basis of academic lectures and actively discuss it at a plenary session. For the MApA specialisation: make use of analytical techniques to rigorously prove the qualitative characteristics of solutions to mathematical models in applied sciences.	
7	**Prerequisites**	All compulsory modules for the MSc in Computational and Applied Mathematics recommended	
8	**Integration into curriculum**	3rd semester	
9	**Module compatibility**	Compulsory module for MSc in Computational and Applied Mathematics Compulsory module for MSc in Mathematics Compulsory module for MSc in Mathematics and Economics	
10	**Method of examination**	talk/presentation (90 minutes) and handout (5-10 pages)	
11	**Grading Procedure**	talk/presentation 75% handout 25%	
12	**Module frequency**	Winter semester (annually)	
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	
16	**Recommended reading**	Depending on topic. Will be published on StudOn at the beginning of the semester.	

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1	**Module name**	**Module 6b:** **MaSe: Master's seminar NASi**	**ECTS 5**
2	**Courses/lectures**	"Mathematical Modeling and Data Analysis"	
3	**Lecturers**	Prof. Dr. Burger martin.burger@fau.de	
4	**Module coordinator**	Prof. Dr. Eberhard Bänsch baensch@math.fau.de	
5	**Content**	A topic from NASi that relates to the compulsory elective modules offered.	
6	**Learning objectives and skills**	Students can structure the content acquired both verbally and in writing and make their own contributions to its presentation and/or substance, learn scientific content on the basis of academic lectures and actively discuss it at a plenary session. For the NASi specification: can solve exemplary computational problems with given or self-developed software in order to illustrate or verify numerical methods under consideration.	
7	**Prerequisites**	All compulsory modules for the MSc in Computational and Applied Mathematics recommended	
8	**Integration into curriculum**	3rd semester	
9	**Module compatibility**	Compulsory module for MSc in Computational and Applied Mathematics Compulsory module for MSc in Mathematics Compulsory module for Msc in Mathematics and Economics	
10	**Method of examination**	talk/presentation (90 minutes) and handout (5-10 pages)	
11	**Grading Procedure**	talk/presentation 75% handout 25%	
12	**Module frequency**	Winter semester (annually)	
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	
16	**Recommended reading**	Depending on topic. Will be published on StudOn at the beginning of the semester.	

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1	**Module name**	**Module 6c:** **MaSe: Master's seminar Opti**	**ECTS 5**
2	**Courses/lectures**		
3	**Lecturers**		
4	**Module coordinator**	Prof. Dr. Michael Stingl michael.stingl@fau.de	
5	**Content**	A topic from Opti that relates to the compulsory elective modules offered.	
6	**Learning objectives and skills**	Students can use original literature to familiarise themselves with a current research topic, can structure the content acquired both verbally and in writing and make their own contributions to its presentation and/or substance, learn scientific content on the basis of academic lectures and actively discuss it at a plenary session. For the Opti specialisation: model theoretical and applied tasks as optimization problems and/or develop optimization algorithms for their solution and/or put these into practice.	
7	**Prerequisites**	All compulsory modules for the MSc in Computational and Applied Mathematics recommended	
8	**Integration into curriculum**	3rd semester	
9	**Module compatibility**	Compulsory module for MSc in Computational and Applied Mathematics Compulsory module for MSc in Mathematics Compulsory module for MSc in Mathematics and Economics	
10	**Method of examination**	talk/presentation (90 minutes) and handout (5-10 pages)	
11	**Grading Procedure**	talk/presentation 75% handout 25%	
12	**Module frequency**	Winter semester (annually)	
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	
16	**Recommended reading**	Depending on topic. Will be published on StudOn at the beginning of the semester.	

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1	**Module name**	**Module 7:** **Master's Thesis**	**ECTS 25**
2	**Courses/lectures**	Oral examination Master's Thesis	
3	**Lectures**	The lecturers for the degree programme in Computational and Applied Mathematics	MaPA/NASI/Opti
4	**Module coordinator**	Prof. Dr. Günther Grün gruen@math.fau.de	
5	**Content**	The master's thesis is in the field of Modelling and Analysis, or Numerical Analysis and Simulation, or Optimization, and deals with a current research topic.	
6	**Learning objectives and skills**	Students are capable of independently follow up a scientific question in the fields of "Modelling and Analysis", "Numerical Analysis and Simulation" or "Optimization" over an extended, specified period, develop original ideas and concepts for solving scientific problems in these fields, apply and improve mathematical methods rather independently - also in unfamiliar and interdisciplinary contexts, present and explain mathematical or interdisciplinary contents clearly in a manner appropriate for the target audience, both in writing and orally, improve their ability to plan and structure by implementing a thematic project.	
7	**Prerequisites**	Successful participation in all mandatory modules (35 ECTS) and at least 20 ECTS from mandatory elective modules	
8	**Integration into curriculum**	4th semester	
9	**Module compatibility**	Master's degree programme in Computational and Applied Mathematics	
10	**Method of examination**	Master's thesis (scope according to examination regulations) Oral exam (15 minutes)	
11	**Grading Procedure**	90% Master's thesis 10% Oral exam	
12	**Module frequency**	Summer semester (annually)	
13	**Workload**	Contact hours: 15 hrs Independent study: 735 hrs Total: 750 hrs, corresponding to 25 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	
16	**Recommended reading**	Individual, depending on topic of Master's Thesis.	

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1	**Module name**	**Module 10: AdSolTech: Advanced Solution Techniques**	**ECTS 5**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	NASi
3	**Lectures**	Dr. Stefan Metzger stefan.metzger@fau.de	
4	**Module coordinator**	Prof. Dr. Eberhard Bänsch baensch@math.fau.de	
5	**Content**	• Krylov subspace methods for large non-symmetric systems of equations • Multilevel methods, especially multigrid (MG) methods, nested and non-nested grid hierarchies • Parallel numerics, especially domain decomposition methods • Inexact Newton/Newton-Krylov methods for discretized nonlinear partial differential equations • Preconditioning and operator-splitting methods	
6	**Learning objectives and skills**	Students • are able to design application-specific own MG algorithms with the theory of multigrid methods and decide for which problems the MG algorithm is suitable to solve large linear systems of equations, • are able to solve sparse nonlinear/non-symmetric systems of equations with modern methods (also with parallel computers), • are able to develop under critical assessment complete and efficient methods for application-orientated problems.	
7	**Prerequisites**	Recommended: Advanced Discretization Techniques	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	Mandatory elective module for MSc in Computational and Applied Mathematics in the field of “Modeling, Simulation and Optimization”	
10	**Method of examination**	Oral exam (20 minutes)	
11	**Grading Procedure**	100% Oral exam	
12	**Module frequency**	Summer semester (annually)	
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	

16	**Recommended reading**	• Quarteroni & A. Valli: Numerical Approximation of Partial Differential Equations • P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Differential Equations • Further literature and scientific publications are announced during the lectures

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1	**Module name**	**Module 11:** **RTpMMod: Transport and Reaction in Porous Media: Modeling**	**ECTS 5**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0,5 semester hrs/week	MApA
3	**Lectures**	Prof. Dr. Serge Kräutle kraeutle@math.fau.de	
4	**Module coordinator**	Prof. Dr. Serge Kräutle kraeutle@math.fau.de	
5	**Content**	• Modeling of fluid flow through a porous medium: Groundwater models (Richards' equation), multiphase flow • Advection, diffusion, dispersion of dissolved substances, (nonlinear) reaction-models (i.a. law of mass action, adsorption, kinetic / in local equilibrium, reactions with minerals) • Models of partial (PDEs), ordinary (ODEs) differential equations, and local conditions • Nonnegativity, boundedness, global existence of solutions, necessary model assumptions in the case of a pure ODE model as well as for a PDE model • Existence of stationary solutions (i.a. introduction to the Feinberg network theory)	
6	**Learning objectives and skills**	Students • are able to model flow and reaction processes in porous media on macro- and micro-scale using partial differential equations, • possess the techniques and the analytical foundations to assess the global existence of solutions.	
7	**Prerequisites**	Recommended: Basic knowledge in differential equations	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	Mandatory elective module: • MSc. Computational and Applied Mathematics • MSc Mathematics with field of "Modelling, Simulation, and Optimization" Non-physical elective module: • MSc Physics	
10	**Method of examination**	Oral exam (20 minutes)	
11	**Grading Procedure**	100% Oral exam	
12	**Module frequency**	Summer semester (annually)	
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	

16	**Recommended reading**	• S. Kräutle: lecture notes https://www.math.fau.de/kraeutle/vorlesungsskripte/ • C. Eck, H. Garcke, P. Knabner: Mathematical Modeling, Springer • J.D. Logan: Transport Modeling in Hydrogeochemical Systems, Springer • M. Feinberg: lecture notes • crnt.osu.edu/LecturesOnReactionNetworks

1	**Module name**	**Module 13:** **NuIF1: Numerics of Incompressible Flows I**	**ECTS 5**
2	**Courses/lectures**	a) Lecture: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	NASi
3	**Lectures**	Prof. Dr. Eberhard Bänsch baensch@math.fau.de	
4	**Module coordinator**	Prof. Dr. Eberhard Bänsch baensch@math.fau.de	
5	**Content**	• Mathematical modelling of (incompressible) flows • Variational formulation, existence and (non-)uniqueness of solutions to the stationary Navier-Stokes (NVS) equations • Stable finite element (FE) discretization of the stationary (Navier-) Stokes equations • Error estimates • Solution techniques for the saddle point problem	
6	**Learning objectives and skills**	Students • explain and apply the mathematical theory for the stationary, incompressible Navier-Stokes equations, • analyse FE discretization for the stationary Stokes equations and apply them to practical problems, • explain the meaning of the inf-sup condition, • choose the appropriate function spaces, stabilisation techniques and solution techniques and apply them to concrete problem settings.	
7	**Prerequisites**	Recommended: Advanced discretization techniques	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	Mandatory elective module for MSc in Computational and Applied Mathematics in the field of “Modeling, Simulation and Optimization”	
10	**Method of examination**	oral exam (20 minutes)	
11	**Grading Procedure**	100% based on oral examination	
12	**Module frequency**	summer semester (annually)	
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	one semester	
15	**Teaching and examination language**	English	

16	**Recommended reading**	• V. Girault1 & P.-A. Raviart: Finite element methods for the Navier-Stokes equations. Theory and algorithms. Springer 1986 • H. Elman, D. Silvester & A. Rathen: Finite elements and fast iterative solvers: with applications in incompressible fluid dynamics. Oxford University Press 2014 • R. Temam: Navier-Stokes equations. Theory and numerical analysis. North Holland

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1	**Module name**	**Module 16: MoL: Mathematics of Learning**	**ECTS 5**
2	**Courses/lectures**	a) Lecture: 2 semester hrs/week b) Practical: 2 semester hrs/week	
3	**Lecturers**	Prof. Dr. Frauke Liers frauke.liers@math.uni-erlangen.de	
4	**Module coordinator**	Prof. Dr. M. Burger martin.burger@fau.de	
5	**Content**	- Machine learning: empirical risk minimization, kernel methods and variational models - Mathematical aspects of deep learning - Ranking problems - Mathematical models of network interaction	
6	**Learning objectives and skills**	Students - develop understanding of modern big data and state of the art methods to analyze them, - apply state of the art algorithms to large data sets, - derive models for network / graph structured data.	
7	**Prerequisites**	Prerequisites: Basic knowledge in numerical methods and optimization is recommended.	
8	**Integration into curriculum**	1st semester or 3rd semester	
9	**Module compatibility**	Mandatory module for: - M. Sc. Data Sciences Mandatory elective module for: - M. Sc. Computational and Applied Mathematics Elective module for: - M. Sc. Mathematics - M. Sc. Mathematics and Economics	
10	**Method of examination**	Oral exam (15 minutes)	
11	**Grading Procedure**	100% based on oral exam	
12	**Module frequency**	Module frequency Wintersemester (annualy)	
13	**Workload**	Contact hours: 60 hrs Independent study: 90 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	One Semester	
15	**Teaching and examination language**	English	
16	**Recommended reading**	Courville, Goodfellow, Bengio, Deep Learning, MIT Press, 2015 Hastie, Tibshirani, Friedman, The Elements of Statistical Learning, 2008	

1	**Module name**	**Module 21:** **PcFem: Practical Course on Finite Element Methods for Phase-Separation Equations**	**ECTS 5**
2	**Courses/lectures**	Seminar: 3 semester hrs/week	
3	**Lecturers**	Dr. Stefan Metzger metzger@math.fau.de	NASi
4	**Module coordinator**	Prof. Dr. Günther Grün gruen@math.fau.de	
5	**Content**	• Finite element discretization for Cahn-Hilliard equations, • Storage concepts for sparse matrices, • Adaptive mesh refinement.	
6	**Learning objectives and skills**	Students • implement a finite element solver for phase-separation equations, • are able to compare and implement different storage concepts for sparse matrices, • are able to implement finite element solvers based on adaptive meshes, • are able to derive and implement efficient discretizations for phase-separation equations, • are able to validate their implementation.	
7	**Prerequisites**	Recommended: Numerics of Partial Differential Equations I	
8	**Integration into curriculum**	1st or 3rd semester	
9	**Module compatibility**	• Mandatory elective module for BSc in Mathematics • Mandatory elective module for BSC in Technomathematics • Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”	
10	**Method of examination**	Oral exam (30 minutes)	
11	**Grading Procedure**	100% Oral exam	
12	**Module frequency**	Winter semester (not annually)	
13	**Workload**	Contact hours: 45 hrs Independent study: 105 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	one semester	

15	**Teaching and examination language**	English
16	**Recommended reading**	• P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Differential Equations, Springer 2003 • D. Braess: Finite Elements. Cambridge University Press 2010 • B. Stroustrup: The C++ programming language, Addison-Wesley 2014

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1	**Module name** **65912**	**Module 24:** **IPro: Partial Differential Equations Based Image Processing**	**ECTS 5**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hr/week	
3	**Lecturers**	Prof. Dr. Martin Burger martin.burger@fau.de	
4	**Module coordinator**	Dr. Michael Fried fried@math.fau.de	
5	**Content**	basics of image processing variational methods in image processing including total variation deblurring using different partial differential equations basics of image reconstruction	
6	**Learning objectives and skills**	Students explain mathematical and algorithmic methods for image processing, apply above image processing methods in computerised practical exercises, • apply analytical techniques to evaluate the qualitative characteristics of the above methods.	
7	**Prerequisites**	Basic knowledge in functional analysis and numerical methods for pdes is recommended.	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	Mandatory elective module for MSc Computational and Applied Mathematics Mandatory elective module for MSc Mathematics • Compulsory elective module MSc Integrated Life Science	
10	**Method of examination**	oral exam (20 minutes)	
11	**Grading Procedure**	100% based on oral exam	
12	**Module frequency**	if requested: every second summer semester To check whether the course is offered, see UnivIS univis.fau.de or module handbook of current semester	
13	**Workload**	contact hours: 37.5 hrs independent study: 112.5 hrs total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	one semester	
15	**Teaching and examination language**	English	
16	**Recommended reading**	• G. Aubert & P. Kornprobst: Mathematical problems in image processing, Springer • Bredies & Lorenz, Mathematical Image Processing, Springer • Burger & Osher, Level Set and PDE based reconstruction methods, Springer	

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1	**Module name**	**Module 27: MSOpt: Introduction to Material and Shape Optimization**	**ECTS 10**
2	**Courses/lectures**	a) Lectures: 4 semester hrs/week b) Practical: 1 semester hr/week	Opti
3	**Lecturers**	Prof. Dr. Michael Stingl michael.stingl@fau.de	
4	**Module coordinator**	Prof. Dr. Michael Stingl michael.stingl@fau.de	
5	**Content**	• shape-, material- and topology optimization models • linear elasticity and contact problems • existence of solutions of shape, material and topology optimization problems • approximation of shape, material and topology optimization problems by convergent schemes	
6	**Learning objectives and skills**	Students • derive mathematical models for shape-, material and topology optimization problems, • apply regularization techniques to guarantee to existence of solutions, • approximate design problems by finite dimensional discretizations, • derive algebraic forms and solve these by nonlinear programming techniques.	
7	**Prerequisites**	Recommended: • Knowledge in nonlinear optimization, • Basic knowledge in numerics of partial differential equations	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics • Mandatory elective module for MSc Mathematics in the fields of “Modeling, Simulation and Optimization” • Mandatory elective module for MSc Mathematics and Economics in the fields of study “Optimization and Process Management”	
10	**Method of examination**	oral exam (20 minutes)	
11	**Grading Procedure**	100% based on oral exam	
12	**Module frequency**	Summer semester (annually)	
13	**Workload**	Contact hours: 75 hrs Independent study: 225 hrs Total: 300 hrs, corresponding to 10 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	

16	**Recommended reading**	• J. Haslinger & R. Mäkinen: Introduction to shape optimization, SIAM, • M. P. Bendsoe & O. Sigmund: Topology Optimization: Theory, Methods and Applications, Springer.

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1	**Module name**	**Module 30:** **RobOpt II: Robust Optimization II**	**ECTS 5**
2	**Courses/lectures**	a) Lectures: 2 weekly lecture hours b) Practical: 1 weekly lecture hour	Opti
3	**Lecturers**	Prof. Dr. Timm Oertel timm.oertel@fau.de	
4	**Module coordinator**	Prof. Dr. Frauke Liers frauke.liers@math.uni-erlangen.de	
5	**Content**	• In practice, provided data for mathematical optimization problems is often not fully known. Robust optimization aims at finding the best solution which is feasible for input data varying within certain tolerances. The lecture covers advanced methods of robust optimization in theory and modeling. In particular, robust network flows, robust integer optimization and robust approximation are included. Further, state-of-the-art concepts, e.g., "light robustness" or "adjustable robustness" will be discussed by means of real-world applications.	
6	**Learning objectives and skills**	Students • will be able to identify complex optimization problems under uncertainties as well as suitably model and analyze the corresponding robust optimization problem with the help of advanced techniques of robust optimization, • learn the handling of appropriate solving techniques and how to analyze the corresponding results.	
7	**Prerequisites**	• Recommended: Robust Optimization I	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics, • Mandatory elective module for MSc Mathematics in the field of study “Modelling, Simulation and Optimization” • Mandatory elective module for the MSc in Mathematics and Economics in the field of study “Optimization and process management”	
10	**Method of examination**	oral exam (15 minutes)	
11	**Grading Procedure**	100% based on oral exam	
12	**Module frequency**	Summer semester (not annually) To check whether the course is offered in the current semester, see UnivIS univis.fau.de or module handbook of current semester	
13	**Workload**	Total: 150 h • Attendance: 45 h • Self-study: 105 h	
14	**Module duration**	1 semester	
15	**Teaching and examination language**	English	

16	**Recommended reading**	• Lecture notes, will be published on StudOn at the beginning of the semester.

1	**Module name**	**Module 31:** **NALIP: Numerical Aspects of Linear and Integer Programming**	**ECTS 5**
2	**Courses/lectures**	a) Lectures: 2 weekly lecture hours b) Practical: 0.5 weekly lecture hour	Opti
3	**Lecturers**	Dr. Andreas Bärmann andreas.baermann@math.uni-erlangen.de	
4	**Module coordinator**	Prof. Dr. Alexander Martin alexander.martin@fau.de	
5	**Content**	• Revised Simplex (with bounds) • Simplex Phase I • Dual Simplex • LP Presolve/Postsolve • Scaling • MIP Solution Techniques	
6	**Learning objectives and skills**	Students are able to explain and use methods and numerical approaches for solving linear and mixed-integer programs in practice.	
7	**Prerequisites**	Knowledge in linear algebra and combinatorial optimization is recommended.	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics • Mandatory elective module for MSc Mathematics in the field of “Modeling, Simulation and Optimization” • Mandatory elective module for MSc Mathematics and Economics in the fields of “Optimization and Process Management”	
10	**Method of examination**	oral exam (15 minutes)	
11	**Grading Procedure**	100% based on oral exam	
12	**Module frequency**	Summer semester (not annually) To check whether the course is offered, see UnivIS univis.fau.de or module handbook of current semester	
13	**Workload**	Attendance: 45 h Self-study: 105 h	
14	**Module duration**	1 semester	
15	**Teaching and examination language**	English	
16	**Recommended reading**	• V. Chvátal: Linear Programming, W. H. Freeman and Company, New York, 1983 • L.A. Wolsey: Integer Programming, John Wiley and Sons, Inc., 1998	

1	**Module name**	**Module 34:** **DiscOpt II: Discrete Optimization II**	**ECTS 5**
2	**Courses/lectures**	a) Lectures: 2 weekly lecture hours b) Practical: 1 weekly lecture hour	
3	**Lecturers**	Prof. Dr. Alexander Martin alexander.martin@fau.de	
4	**Module coordinator**	Prof. Dr. Alexander Martin alexander.martin@fau.de	
5	**Content**	In this lecture, we cover theoretical aspects and solution strategies for difficult integer and mixed-integer optimization problems. First, we show the equivalence between separation and optimization. Then, we present solution strategies for large-scale optimization problems, e.g., decomposition methods and approximation algorithms. Finally, we deal with conditions for the existence of integer polyhedra. We also discuss applications for example from the fields of engineering, finance, energy or public transport.	
6	**Learning objectives and skills**	Students • use basic terms of discrete optimization • model real-world discrete optimization problems, determine their complexity and solve them with appropriate mathematical methods.	
7	**Prerequisites**	Recommended: Knowledge in linear and combinatorial optimization, discrete optimization I	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	Mandatory elective module for MSc Computational and Applied Mathematics, Elective module for MSc Mathematics, Elective module for MSc Mathematics and Economics, Elective module for MSc in Data Science, Core/research module MSc Mathematics within “Modeling, simulation, optimization”, MSc Mathematics and Economics within “Optimization and process management”	
10	**Method of examination**	oral exam (15 minutes)	
11	**Grading Procedure**	100% based on oral exam	
12	**Module frequency**	Summer semester (annually)	
13	**Workload**	Attendance: 45 h Self-study: 105 h	
14	**Module duration**	1 semester	
15	**Teaching and examination language**	English	

16	**Recommended reading**	Lecture notes Bertsimas, Weismantel: Optimization over Integers, Dynamic Ideas, 2005 Conforti, Cornuéjols, Zambelli: Integer Programming, Springer 2014 Nemhauser, Wolsey: Integer and Combinatorial Optimization, Wiley 1994 Schrijver: Combinatorial optimization Vol. A - C, Springer 2003 Schrijver: Theory of Linear and Integer Programming, Wiley, 1986 Wolsey: Integer Programming, Wiley, 2021

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1	**Module name**	**Module 39: NumPDE II: Numerics of Partial Differential Equations II**	**ECTS 5**
2	**Courses/lectures**	a) Lecture: 2 semester hrs/week b) Practical: 1 semester hr/week	NASi
3	**Lecturers**	Prof. Dr. Eberhard Bänsch baensch@math.fau.de	
4	**Module coordinator**	Prof. Dr. Günther Grün gruen@math.fau.de	
5	**Content**	• Classical and weak theory for linear parabolic initial-boundary-value problems (IBVPs) (outline), • finite-element method (FEM) for 2nd-order linear parabolic IVBPs (semi-discretisation in space, time discretisation by one-step methods, stability, comparison principles, order of convergence), • FEM for semi-linear elliptic and parabolic equations (fixed-point- and Newton-methods, secondary iterations), • higher-order time discretisation, extrapolation, time-step control.	
6	**Learning objectives and skills**	Students • apply algorithmic approaches for models with partial differential equations and explain and evaluate them, • are capable to judge on a numerical method’s properties regarding stability and efficiency, • implement (with own or given software) numerical methods and critically evaluate the results, • explain and apply a broad spectrum of methods with a focus on conforming finite element methods for parabolic problems, extending these approaches also to nonlinear problems, • collect and evaluate relevant information and realize relationships.	
7	**Prerequisites**	Recommended: basic knowledge in numerics and numerics of pde	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for BSc Mathematics • Mandatory module for BSc Technomathematik • Non-Physics elective module for MSc Physics	
10	**Method of examination**	written exam (90 minutes) with exercises	
11	**Grading Procedure**	100% based on written exam	
12	**Module frequency**	Summer semester (annually)	
13	**Workload**	Contact hours: 45 hrs Independent study: 105 hrs Total: 150 hrs, corresponding to 5 ECTS credits	

14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• P. Knabner, L. Angermann, Numerical Methods for Elliptic and Parabolic Partial Differential Equations, Springer, New York, 2003. • S. Larsson, V. Thomée, Partial Differential Equations with Numerical Methods, Springer, Berlin, 2005.

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1	**Module name**	**Module 43:** **CML: Control, Machine Learning and Numerics**	**ECTS 10**
2	**Courses/lectures**	a) Lecture: 2 semester hrs/week b) Practical: 3 semester hrs/week	
3	**Lectures**	Prof. Dr. Enrique Zuazua enrique.zuazua@fau.de Dr. Yongcun Song yongcun.song@fau.de	**Opti**
4	**Module coordinator**	Prof. Dr. Enrique Zuazua enrique.zuazua@fau.de	
5	**Content**	• several topics related to the control of Ordinary Differential Equations (ODE) and Partial Differential Equations (PDE), including controllability, observability, and some of the most fundamental work that has been done in the subject in recent years. • an introduction to Machine Learning, focusing mainly on the use of control techniques for the analysis of Deep Neural Networks as a tool to address, for instance, the problem of Supervised Learning. • some classical computational techniques related to the control of ODE and PDE, and machine learning.	
6	**Learning objectives and skills**	Students are able to • understand some basic theory on control and machine learning. • learn about recent advances on control and machine learning. • implement some computational techniques using their own or specified software and critically evaluate the results, • set out their approaches and results in a comprehensible and convincing manner, making use of appropriate presentation techniques.	
7	**Prerequisites**	Basic knowledge of calculus, linear algebra, ODE and PDE. Familiarity with scientific computing is helpful.	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	Mandatory elective module for MSc Data Science (Simulation and Numerics) Mandatory elective module for MSc in Computational and Applied Mathematics (Opti)	
10	**Method of examination**	Project work with presentation and report	
11	**Grading Procedure**	50 % presentation and 50 % report	
12	**Module frequency**	Summer semester (annually)	
13	**Workload**	Contact hours: 75 hrs Independent study: 105 hrs Total: 180 hrs, corresponding to 10 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	

16	**Recommended reading**	[1] L. Bottou, F. E. Curtis, and J. Nocedal, Optimization methods for large-scale machine learning. SIAM Review, 60 (2) (2018) , 223-311. [2] J. M. Coron, Control and Nonlinearity, Mathematical Surveys and Monographs, 143, AMS, 2009. [3] I. Goodfellow, Y. Bengio, & A. Courville, Deep Learning. MIT press, 2016. [4] R. Glowinski, J. L. Lions, and J. He, Exact and Approximate Controllability for Distributed Parameter Systems: A Numerical Approach, Encyclopedia Math. Appl., Cambridge University Press, Cambridge, UK, 2008. [5] C. F. Higham, and D. J. Higham, Deep learning: An introduction for applied mathematicians. SIAM Review, 61 (4) (2019), 860-891. [6] J. Nocedal, and S. Wright, Numerical Optimization. Springer Science & Business Media, 2006. [7] D. Ruiz-Balet, and E. Zuazua, Neural ODE control for classification, approximation and transport. arXiv preprint arXiv:2104.05278, (2021). [8] E. Zuazua, Propagation, observation, and control of waves approximated by finite difference methods, SIAM Review, 47 (2) (2005), 197-243. [9] E. Zuazua, Controllability and observability of partial differential equations: some results and open problems, in Handbook of Differential Equations: Evolutionary Equations. Vol. 3. North-Holland, 2006. 527-621.

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NATURWISSENSCHAFTLICHE FAKULTÄT

1	**Module name**	**Module 45: CC: Computational Complexity**	**ECTS 5**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 1 semester hrs/week	
3	**Lecturers**	Prof. Dr. Yiannis Giannakopoulos yiannis.giannakopoulos@fau.de	Opti
4	**Module coordinator**	Prof. Dr. Yiannis Giannakopoulos yiannis.giannakopoulos@fau.de	
5	**Content**	Potential topics include: • P, NP, and NP-completeness • Complexity classes and reductions • Boolean circuits • The polynomial-time hierarchy • Space complexity • Randomized computation • Counting complexity • Introduction to the PCP theorem and hardness of approximation • Average-case complexity	
6	**Learning objectives and skills**	Upon successful completion of the module, students: • Have a rigorous understand of the concept of computation and its formal limitations • Have knowledge of the fundamental complexity classes (including P, NP and PSPACE) • Understand the notion of completeness and are able to design and understand reductions between these classes • Are exposed to various formal computation models, including Boolean circuits and randomness	
7	**Prerequisites**	Undergraduate-level course in algorithms and/or discrete optimization Basic knowledge of analysis, linear algebra and probability	
8	**Integration into curriculum**	From 1st semester	
9	**Module compatibility**	• M. Sc. Data Science (Databased optimization) • M. Sc. Mathematics (Modeling, Simulation and Optimization) • M. Sc. Mathematics and Economics: (Optimisation and process management) • M. Sc. in Computational and Applied Mathematics Also offered as a Mathematics minor ("Nebenfach Mathematik") for: • B. Sc. (Computer Science) • M. Sc. (Artificial Intelligence)	
10	**Method of examination**	Oral exam (30 minutes)	
11	**Grading Procedure**	Oral exam (100%)	

12	**Module frequency**	Annually (summer semester)
13	**Workload**	Attendance: 45 h Self-study: 105 h
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• Oded Goldreich. “Computational Complexity: A Conceptual Perspective”. Cambridge University Press, 2008. • Sanjeev Arora and Boaz Barak. “Computational Complexity: A Modern Approach”. Cambridge University Press, 2009 • Christos H. Papadimitriou. “Computational Complexity”. Addison-Wesley, 1994.

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1	**Module name**	**Module 46: NMNP: Numerical Methods for Nonsmooth Problems**	**ECTS 10**
2	**Courses/lectures**	a) Lectures: 4 semester hrs/week b) Practical: 2 semester hrs/week	
3	**Lecturers**	Prof. Dr. Carsten Gräser graeser@math.fau.de	MApA
4	**Module coordinator**	Prof. Dr. Carsten Gräser graeser@math.fau.de	
5	**Content**	1. Examples of nonsmooth problems involving partial differential equations (PDEs) (e.g. contact of elastic bodies, friction, phase transition, shallow ice glacier models, brittle fracture,...) 2. Elements of convex analysis (constrained and nonsmooth minimization problems, variational inequalities) 3. Discretization of nonsmooth problems (e.g. finite elements, DG) 4. Efficient algebraic solvers (active set, relaxation, nonsmooth multigrid methods)	
6	**Learning objectives and skills**	Students are • familiar with different formulations of nonsmooth problems (minimization, variational inequality, subdifferential inclusion) • familiar with basic existence and well-posedness results • capable of discretizing nonsmooth problems using variational methods and solving the discrete problems efficiently • aware of the intrisic difficulties for analysis and numerics arising from nonsmoothness	
7	**Prerequisites**	Recommended: Introduction to numerical methods for PDEs Recommended: Basic knowledge of functional analysis (but the necessary terminology and results are briefly provided during the lecture)	
8	**Integration into curriculum**	1st semester	
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics	
10	**Method of examination**	written exam (90 minutes) with exercises	
11	**Grading Procedure**	100% based on written exam	
12	**Module frequency**	Summer semester	
13	**Workload**	Contact hours: 90 hrs Independent study: 210 hrs Total: 300 hrs, corresponding to 10 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	

16	**Recommended reading**	• I. Ekeland & R. Témam: Convex Analysis and Variational Problems, SIAM • R. Glowinski & J.-L. Lions & R. Trémolières: Numerical Analysis of Variational Inequalities, North Holland • Further literature and publications are announced during the lecture

1	**Module name**	**Free Elective Module: Scalar Conservation laws**	**ECTS 5**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Exercises: 0.5 semester hrs/week	
3	**Lecturers**	Nicola De Nitti nicola.de.nitti@fau.de	MApA
4	**Module coordinator**	Prof. Dr. Enrique Zuazua enrique.zuazua@fau.de	
5	**Content**	1. **Introduction:** applications and examples of conservation laws. 2. **Review of functional analysis:** L^p spaces; functions of bounded variation. 3. **The method of characteristics:** semilinear equations with constant coefficients; semilinear equations with variable coefficients; quasilinear equations. 4. **Entropy solutions:** discontinuous solutions of conservation laws; Rankine-Hugoniot condition; entropy and entropy flux; entropy solutions; Liu condition; Kruzkhov's theorem; uniqueness and stability of entropy solutions. 5. **Riemann problem:** solutions of the Riemann problem for convex fluxes; solutions of the Riemann problem for general fluxes. 6. **Front-tracking:** construction of front-tracking approximations; existence of entropy solutions in BV. 7. **Vanishing viscosity:** viscous approximation; BV a priori estimates; existence of entropy solutions in BV. 8. **Compensated compactness and applications to conservation laws:** Young measures; Murat's lemma; div-curl lemma; Tartar's theorem; existence of entropy solutions in $L^1 \cap L^\infty$. 9. **Oleinik's estimate:** Oleink's estimate for conservation laws with convex fluxes; uniqueness via Oleinik's estimate. 10. **Lax-Oleinik's formula:** Legendre's transform; Lax-Oleinik's formula. 11. **Hamilton-Jacobi equations:** motivation; viscosity solutions; well-posedness of viscosity solutions; equivalence between entropy solutions of conservation laws and viscosity solutions of Hamilton-Jacobi equations. 12. **Conservation laws on networks:** motivations; entropy condition at a junction; vanishing viscosity approximation. 13. **Nonlocal conservation laws:** motivations; well-posedness of nonlocal conservation laws; the nonlocal-to-local singular limit problem.	
6	**Learning objectives and skills**	Students are able to: • use language and techniques related to scalar conservation laws – especially regarding entropy solutions, Riemann problems, viscous approximations, and front tracking algorithms; • work out the examples and applications that accompany the theory.	
7	**Prerequisites**	Recommended: knowledge of linear algebra and calculus; basic knowledge of functional analysis.	
8	**Integration into curriculum**	2nd semester	
9	**Module compatibility**	Free elective: • M.Sc. Computational Applied Mathematics • The course is open also to Ph.D. candidates in the Mathematics and Data Science Departments	
10	**Method of examination**	Oral examination (20 minutes)	

11	**Grading Procedure**	100% based on oral examination
12	**Module frequency**	Winter semester
13	**Workload**	Contact hours: 35 hrs Independent study: 115 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English

16	**Recommended reading**	Chapters 1-10: • Bressan, A. *Hyperbolic Systems of Conservation Laws: The One-dimensional Cauchy Problem*. Oxford, 2000. • Coclite, G. M. *Scalar Conservation Laws*. Lecture Notes, 2020. • Dafermos, C. M. *Hyperbolic Conservation Laws in Continuum Physic*s. Springer, 2016. • Evans, L. C. *Partial Differential Equations*. AMS, 2010. • Godlewski, E. & Raviart P.-A. *Numerical Approximation of Hyperbolic Systems of Conservation Laws.* Springer, 2021. • Godlewski, E. & Raviart P.-A. *Hyperbolic Systems of Conservation Laws*. Ellipses, 1990. • Holden, H. & Risebro, N. H. *Front Tracking for Hyperbolic Conservation Laws*. Springer, 2015. • LeVeque, R. J. *Numerical Methods for Conservation Laws.* Birkhäuser, 1992. • Mishra, S., Fjordholm, U. S. & Abgrall, R. *Numerical methods for conservation laws and related equations*. Lecture Notes, 2019. Chapter 11: • Bressan, A. *Viscosity Solutions of Hamilton-Jacobi Equations and Optimal Control Problems*. Lecture Notes, 2011: http://personal.psu.edu/axb62/PSPDF/HJ-lnotes.pdf. • Corrias, L., Falcone, M. and Natalini, R. Numerical Schemes for Conservation Laws via Hamilton-Jacobi Equations. *Mathematics of Computation.* Vol. 64, No. 210 (Apr., 1995), pp. 555-580. • Evans, L. C. *Partial Differential Equations*. AMS, 2010. • Karlsen, K. H. & Risebro, N. H. A note on front tracking and the equivalence between viscosity solutions of Hamilton–Jacobi equations and entropy solutions of scalar conservation laws. *Nonlinear Analysis: Theory, Methods & Applications.* Volume 50, Issue 4, August 2002, Pages 455-469. Chapter 12: • Andreianov, B. P., Coclite, G. M. & Donadello, C. Well-posedness for vanishing viscosity solutions of scalar conservation laws on a network. *Discrete & Continuous Dynamical Systems*, 2017. Chapter 13: • Coclite, G. M., De Nitti, N., Keimer, A. & Pflug, L. On existence and uniqueness of weak solutions to nonlocal conservation laws with BV kernels. *Preprint*, 2020. • Coclite, G. M. Coron, J.-M., De Nitti, N., Keimer, A. & Pflug, L. A general result on the approximation of local conservation laws by nonlocal conservation laws: The singular limit problem for exponential kernels. *Preprint*, 2020 • Keimer, A. & Pflug, L. Existence, uniqueness and regularity results on nonlocal balance laws. *J. Differential Equations*, 263(7):4023–4069, 2017. Lecture notes will be distributed via StudOn.