

Module description

for the degree programme

Master of Science Computational
and Applied Mathematics

(Version of examination regulation: 20192)

for the winter term 2024/2025

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1	Module name 65860	Modeling and analysis in continuum mechanics I	10 ECTS
2	Courses / lectures	Übung: Tutorial to Modeling and Analysis in Continuum Mechanics 1 (1 SWS)	2 ECTS
		Vorlesung: Modeling and Analysis in Continuum Mechanics 1 (4 SWS)	8 ECTS
3	Lecturers	Dr. Marco Bresciani	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Theory of elasticity (geometrical non-linear modelling, objectivity and isotropy of energy functionals, linearised elasticity, polyconvexity, existence according to J. Ball) • Non-equilibrium thermodynamics and modelling in hydrodynamics (basic concepts in thermodynamics, balance equations, constitutive relations) • Parabolic function spaces and the Aubin-Lions lemma • Weak solution theory for incompressible Navier-Stokes equations 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • derive mathematical models for fluid mechanics and elasticity theory, • evaluate the predictive power of models using physical modelling assumptions and the qualitative characteristics of solutions, • apply analytical techniques to rigorously prove qualitative properties of solutions. 	
7	Prerequisites	Basic knowledge in functional analysis and modelling is recommended.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	Pflichtmodul Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • P.G. Ciarlet: Mathematical elasticity, North-Holland, • S.R. De Groot & P. Mazur: Non-equilibrium thermodynamics, Dover, • C. Eck, H. Garcke & P. Knabner: Mathematical Modeling, Springer, • L.C. Evans: Partial differential equations, AMS, 	

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|--|---|
| | <ul style="list-style-type: none">• I. Liu: Continuum mechanics, Springer,• R. Temam: The Navier-Stokes equations, AMS Chelsea Publishing. |
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1	Module name 65865	Modeling and analysis in continuum mechanics II	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<p>Some (at least two) of the following topics:</p> <ul style="list-style-type: none"> • 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	<p>Students can:</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	Pflichtmodul Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • 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 44460	Architekturen von Superrechnern Architectures of supercomputers	5 ECTS
2	Courses / lectures	Übung: Exercises Architectures of Supercomputers / Übungen Architekturen von Superrechnern (2 SWS) Vorlesung: ArchSup (2 SWS)	2,5 ECTS 2,5 ECTS
3	Lecturers	Farhad Ebrahimiadzandaryani Prof. Dr.-Ing. Dietmar Fey	

4	Module coordinator	
5	Contents	<ul style="list-style-type: none"> • Principles of computer and processor architectures • Modern processor architectures • Homogeneous and heterogeneous multi/many-core processors • Parallel computer architectures • Classification and principles of coupling parallel computers • High speed networks in supercomputers • Examples of supercomputers • Programming of supercomputers
6	Learning objectives and skills	<p>Fachkompetenz Wissen Lernende können die Funktionsweise moderner in Superrechnern eingesetzter Prozessoren wiedergeben. Sie erkennen die besonderen Probleme im Zusammenhang mit dem Energieverbrauch und der Programmierung von Superrechnern.</p> <p>Verstehen Lernende können die Unterschiede bei der Kopplung paralleler Prozesse darstellen. Sie können Parallelrechner hinsichtlich ihrer Speicheranbindung und den grundlegenden Verarbeitungsprinzipien klassifizieren.</p> <p>Anwenden Lernenden sind in der Lage ein eigenes technisches oder mathematisches Problem zur Lösung auf einem Supercomputer umzusetzen und auszuführen. Anhand der in der Vorlesung gezeigten Beispiele sind sie in der Lage, Herausforderungen beim Auffinden von Flaschenhälsen zu verallgemeinern und für ihr konkretes Problem anzuwenden.</p> <p>Analysieren Lernende sind in der Lage, ihre Problemstellungen, z.B. naturwissenschaftliche oder technische Simulationsexperimente, hinsichtlich der Rechen- und Speicheranforderungen für einen Supercomputer geeignet für die Architektur zu charakterisieren.</p> <p>Evaluieren (Beurteilen) Lernende können mithilfe der aufgezeigten Methodiken zur Leistungsmessung von Parallelrechnern unterschiedliche Rechnerarchitekturen bewerten und für ihre Problemstellung die passende Architektur auswählen.</p>
7	Prerequisites	None

8	Integration in curriculum	no Integration in curriculum available!
9	Module compatibility	Pflichtmodul Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Written (30 minutes)
11	Grading procedure	Written (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 120 h Independent study: 30 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	

1	Module name 65875	Programming techniques for supercomputers in CAM	10 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Gerhard Wellein	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	Pflichtmodul Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 120 h Independent study: 180 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	

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Bibliography

- 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

1	Module name 65870	Modeling, simulation and optimization (Practical Course) Modeling, simulation and optimization	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Carsten Gräser	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	Pflichtmodul Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Seminar paper and presentation Seminar paper and presentation	
11	Grading procedure	Seminar paper and presentation (50%) Seminar paper and presentation (50%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 42 h Independent study: 108 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Project-dependent. Will be published on StudOn at the beginning of the semester.	

1	Module name 1999	Master's thesis (M.Sc. Computational and Applied Mathematics 20192) Master's thesis	25 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	The masters 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	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 4	
9	Module compatibility	Pflichtmodul Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Written (6 Monate) Oral (15 min)	
11	Grading procedure	Written (90%) Oral (10%)	
12	Module frequency	Every semester	
13	Resit examinations	The exams of this moduls can only be resit once.	
14	Workload in clock hours	Contact hours: 15 h Independent study: 735 h	
15	Module duration	1 semester	
16	Teaching and examination language	english	
17	Bibliography	Individual, depending on topic of Masters Thesis.	

1	Module name 1500	Elective modules (as selected from FAU-modules)	15 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	
5	Contents	no content description available!
6	Learning objectives and skills	no learning objectives and skills description available!
7	Prerequisites	None
8	Integration in curriculum	no Integration in curriculum available!
9	Module compatibility	Pflichtmodul Master of Science Computational and Applied Mathematics 20192
10	Method of examination	
11	Grading procedure	
12	Module frequency	no Module frequency information available!
13	Workload in clock hours	Contact hours: ?? h (keine Angaben zum Arbeitsaufwand in Präsenzzeit hinterlegt) Independent study: ?? h (keine Angaben zum Arbeitsaufwand im Eigenstudium hinterlegt)
14	Module duration	?? semester (no information for Module duration available)
15	Teaching and examination language	german or english
16	Bibliography	

Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi)

1	Module name 65885	Master's seminar MApA Master`s seminar MApA	5 ECTS
2	Courses / lectures	Masterseminar: Masterseminar (2 SWS)	5 ECTS
		Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS)	5 ECTS
		Masterseminar: Numerical methods for phase-field equations	5 ECTS
3	Lecturers	Prof. Dr. Timm Oertel Prof. Dr. Günther Grün Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Günther Grün
5	Contents	A topic from MApA that relates to the compulsory elective modules offered.
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • 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. <p>For the MApA specialisation:</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Written Presentation (90 minutes) (schriftliche Ausarbeitung 5-10 Seiten)
11	Grading procedure	Written (25%) Presentation (75%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h
14	Module duration	1 semester

15	Teaching and examination language	english
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	Module name 65890	Master's seminar NASi	5 ECTS
2	Courses / lectures	Masterseminar: Masterseminar (2 SWS)	5 ECTS
		Masterseminar: Master seminar "Numerical solutions for eigenvalue problems"	5 ECTS
		Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS)	5 ECTS
		Masterseminar: Numerical methods for phase-field equations	5 ECTS
3	Lecturers	Prof. Dr. Timm Oertel Prof. Dr. Daniel Tenbrinck Prof. Dr. Günther Grün Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Eberhard Bänsch
5	Contents	A topic from NASi that relates to the compulsory elective modules offered.
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> 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. <p>For the NASi specification:</p> <ul style="list-style-type: none"> 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 in curriculum	semester: 3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	<p>Presentation (90 minutes)</p> <p>Written (schriftliche Ausarbeitung 5-10 Seiten)</p>
11	Grading procedure	<p>Presentation (75%)</p> <p>Written (25%)</p>
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 30 h

		Independent study: 120 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	Module name 65909	Subspace correction methods	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Carsten Gräser	
5	Contents	1) Subspace correction as an abstract framework to construct and analyse efficient iterative methods 2) Analysis of additive and multiplicative subspace correction 3) Multigrid and domain decomposition as subspace correction methods 4) Nonlinear subspace correction methods	
6	Learning objectives and skills	Students are <ul style="list-style-type: none"> familiar with the abstract subspace correction framework can select problem adapted methods can analyse specific methods within the framework 	
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 in curriculum	semester: 2	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral (15 minutes) oral exam (15 min)	
11	Grading procedure	Oral (100%) 100% based on oral exam	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> H. Yserentant: Old and New Convergence Proofs for Multigrid Methods, Acta Numer. 1993 J.-C. Xu: Iterative Methods by Space Decomposition and Subspace Correction, SIAM Rev., 1992 Further literature and publications are announced during the lecture 	

1	Module name 65789	Selected Topics in Mathematics of Learning Selected topics in mathematics of learning	5 ECTS
2	Courses / lectures	Vorlesung: Selected Topics in Mathematics of Learning (2 SWS) Übung: Übung Selected Topics in Mathematics of Learning (2 SWS)	3 ECTS 2 ECTS
3	Lecturers	Dr. Marius Yamakou	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann
5	Contents	Advanced methods of mathematical data science, with a focus on teaching mathematical principles of learning processes.
6	Learning objectives and skills	Students gain fundamental theoretical knowledge of learning algorithms in Data Science and will be able to apply the methodologies in a Data Science context.
7	Prerequisites	Basic knowledge in numerical methods and optimization are recommended.
8	Integration in curriculum	semester: 1;3
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Written examination (60 minutes)
11	Grading procedure	Written examination (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 60 h Independent study: 90 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	S. Wright, B. Recht: Optimization for Data Analysis (2022).

1	Module name 65068	Wave Phenomena Wave phenomena	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<p>1) Motivations and applications.</p> <p>2) Linear transport equation: method of characteristics; Fourier analysis and numerical approximations.</p> <p>3) The wave equation: D'Alembert's representation formula; regularity of the solutions; finite speed of propagation of perturbations; Huygens' principle; geometric optics; wave models with sources or sinks; Kirchhoff's representation in \mathbb{R}^3; Poisson's representation in \mathbb{R}^2; the case of general odd and even space dimensions; energy methods: domain of dependence inequality and energy conservation; representation of solutions by using partial Fourier transform; subordination waves-heat; the reflection method and waves on the half-line; separation of variables.</p> <p>4) Klein-Gordon equation: energy estimates; representation of solutions by using Fourier multipliers; von Wahl's transformation.</p> <p>5) Damped wave equation: energy estimates; representation of solutions by using Fourier multipliers; decay behavior and decay rate.</p> <p>6) Damped plate equation: estimates for the energy; estimates for the solution itself and its derivatives;</p> <p>7) Semilinear wave equation: global existence for small data and global existence for large data.</p> <p>8) Diffusion phenomena: parabolic structure of solutions to damped waves and damped plates; diffusion phenomena in thermo-elasticity; traveling waves and reaction-diffusion models.</p> <p>9) Scalar conservation laws: occurrence of shocks and rarefaction waves.</p> <p>10) Linear and nonlinear dispersive waves: Solitary waves for the Korteweg-de Vries equation; plane-wave solutions for the Airy equation and Schrödinger; Fourier analysis.</p> <p>11) Maxwell equations: constitutive equations; special cases; boundary conditions; expansion into wave functions.</p>	
6	Learning objectives and skills	<p>Students are able to:</p> <ul style="list-style-type: none"> • identify significant mechanisms and to apply suitable analytical and numerical methods for their analysis • work interdisciplinary and in problem-oriented way; • use language and techniques related to partial differential equations; • 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 in curriculum	semester: 2
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral (20 minutes)
11	Grading procedure	Oral (100%)
12	Module frequency	Only in summer semester
13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • Ebert, M. R. & Reissig, M. Methods for Partial Differential Equations. Birkhäuser, 2018. • Evans, L. C. Partial Differential Equations. AMS, 2010. • Kirsch, A. and Hettlich, F. The Mathematical Theory of Maxwell's Equations. Lecture Notes, 2013: • https://www.math.kit.edu/ianmip/lehre/maxwellequ2012w/media/main.pdf • Myint-U, T. & Debnath, L. Linear partial differential equations for scientists and engineers. Birkhäuser, 2007. • Reissig, M. Theory of hyperbolic equations. Lecture Notes, 2007: • https://tu-freiberg.de/sites/default/files/media/institut-fuer-angewandte-analysis-9030/reissig/pdehanoi1.pdf • Vichnevetsky, R. & Bowles, J. B. Fourier Analysis of Numerical Approximations of Hyperbolic Equations. SIAM, 1982 <p>Lecture notes will be distributed via StudOn.</p>

1	Module name 65887	Modul Conservation Laws Module: Conservation laws	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Dr. Lukas Pflug	
5	Contents	<ul style="list-style-type: none"> • (Non-)local conservation laws in applications • Linear scalar transport equations and conservation laws • Linear multi-D transport equations and conservation laws • Method of characteristics • Fixed-point methods in Banach spaces • Existence and uniqueness of nonlocal conservation laws • Maximum principles • Regularity and stability of solutions • Local conservation laws, Entropy solutions; • The singular limit problem – approximation of local Entropy solutions by nonlocal conservation laws • Numerical methods 	
6	Learning objectives and skills	Students learn the basic theory on nonlocal conservation laws, apply approximation results, learn fixed-point approaches in Banach spaces and understand the applicability of conservation laws in the applied sciences.	
7	Prerequisites	Some basic knowledge in PDE is of advantage, Sobolev spaces.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral Dauer der mündlichen Prüfung: 15 Min.	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	german or english	
16	Bibliography	<ul style="list-style-type: none"> • Bressan, Alberto. Hyperbolic systems of conservation laws: the one-dimensional Cauchy problem. Vol. 20. Oxford University Press on Demand, 2000. 	

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| | <ul style="list-style-type: none">• Keimer, Alexander, and Lukas Pflug. "Existence, uniqueness and regularity results on nonlocal balance laws." <i>Journal of Differential Equations</i> 263.7 (2017): 4023-4069.• Coclite, Giuseppe Maria, et al. "A general result on the approximation of local conservation laws by nonlocal conservation laws: The singular limit problem for exponential kernels." <i>Annales de l'Institut Henri Poincaré C</i> (2022).• Blandin, Sebastien, and Paola Goatin. "Well-posedness of a conservation law with non-local flux arising in traffic flow modeling." <i>Numerische Mathematik</i> 132.2 (2016): 217-241.• Aggarwal, Aekta, Rinaldo M. Colombo, and Paola Goatin. "Nonlocal systems of conservation laws in several space dimensions." <i>SIAM Journal on Numerical Analysis</i> 53.2 (2015): 963-983. |
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1	Module name 65888	Navier Stokes Equations Navier stokes equations	10 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Emil Wiedemann	
5	Contents	<p>The incompressible Navier-Stokes equations (NSE) are a nonlinear system of partial differential equations fundamental for the modelling of fluid flow. They are extensively used in meteorology and oceanography, but also pose great mathematical challenges. Famously, global regularity of the three-dimensional NSE forms one of the seven Millennium Problems. This course serves as an introduction to the mathematical theory of these equations and includes the following topics:</p> <ul style="list-style-type: none"> • existence of weak solutions of Leray-Hopf type; • local-in-time existence of strong solutions; • the Prodi-Serrin criteria for regularity and energy balance; • partial regularity theory; • the singular limit of vanishing viscosity. <p>The course can be a good preparation for a subsequent master's thesis in the topic.</p>	
6	Learning objectives and skills	Students know and understand the basic theory of the Navier-Stokes equations and have mastered important methods for systems of non-linear partial differential equations. They have a basic understanding of mathematical fluid dynamics.	
7	Prerequisites	Lineare Algebra, Analysis. Empfohlen: erste Kurse in partiellen Differentialgleichungen und Funktionalanalysis.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (20 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 90 h Independent study: 210 h	
14	Module duration	1 semester	
15	Teaching and examination language	german or english	

16	Bibliography	<ul style="list-style-type: none">• J. C. Robinson, J. L. Rodrigo, W. Sadowski: The Three-Dimensional Navier-Stokes Equations. Cambridge University Press, 2016.• P. Constantin, C. Foias: Navier-Stokes Equations. University of Chicago Press, 1988.• W. Ożański: The Partial Regularity Theory of Caffarelli, Kohn, and Nirenberg and its Sharpness. Birkhäuser, 2019.• E. Wiedemann: Navier-Stokes Equations: Lecture Notes. Universität Ulm, 2018/19.
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1	Module name 65083	Efficient discretization of two-phase flow	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Dr. Stefan Metzger	
5	Contents	Based on recent scientific publications, different discretization approaches for two-phase flow are discussed.	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • 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, • learn to compare different discretization methods regarding their specific advantages and disadvantages. 	
7	Prerequisites	Recommended: Numerics of Partial Differential Equations I	
8	Integration in curriculum	no Integration in curriculum available!	
9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Seminar achievement Vortrag (60 Min) + schriftliche Ausarbeitung (5-15 Seiten)	
11	Grading procedure	Seminar achievement (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.	

1	Module name 65089	Scalar conservation laws	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ol style="list-style-type: none"> 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; Kruzhkov'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: Oleinik'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	<p>Students are able to:</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	

9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral (ca. 15 min)
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<p>Chapters 1-10:</p> <ul style="list-style-type: none"> • Bressan, A. Hyperbolic Systems of Conservation Laws: The One-dimensional Cauchy Problem. Oxford University Press, 2000. • Coclite, G. M. Scalar Conservation Laws. Lecture Notes, 2022. • Dafermos, C. M. Hyperbolic Conservation Laws in Continuum Physics. 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: https://metaphor.ethz.ch/x/2019/hs/401-4671-00L/literature/mishra_hyperbolic_pdes.pdf • Salsa, S. Partial differential equations in action. From modelling to theory. Springer, 2016. • Salsa, S. & Verzini, G. Partial differential equations in action. Complements and exercises. Springer, 2015. <p>Chapter 11:</p> <ul style="list-style-type: none"> • 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 Anal., Theory Methods Appl., Ser. A, Theory Methods* 50, No. 4, 455-469 (2002).

Chapter 12:

- Andreianov, B. P., Coclite, G. M. & Donadello, C. Well-posedness for vanishing viscosity solutions of scalar conservation laws on a network. *Discrete Contin. Dyn. Syst.* 37, No. 11, 5913-5942 (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. *Z. Angew. Math. Phys.* 73, No. 6, Paper No. 241, 10 p. (2022).
- 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. *Annales de l'Institut Henri Poincaré C, Analyse Non Linéaire* (2022).
- Keimer, A. & Pflug, L. Existence, uniqueness and regularity results on nonlocal balance laws. *J. Differ. Equations* 263, No. 7, 4023-4069 (2017).

Lecture notes will be distributed via StudOn.

1	Module name 65095	Practical course on finite element methods for phase-separation equations Practical course on finite element methods for phase separation equations	5 ECTS
2	Courses / lectures	Vorlesung: Practical Course on Finite Element Methods for Phase-Separation Equations (3 SWS)	5 ECTS
3	Lecturers	Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Finite element discretization for Cahn-Hilliard equations, • Storage concepts for sparse matrices, • Adaptive mesh refinement. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 1	
9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (ca. 30 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • 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 	

1	Module name 65785	Mathematics of Learning Mathematics of learning	5 ECTS
2	Courses / lectures	Vorlesung: Mathematics of Learning (2 SWS) Übung: Übung zu Mathematics of Learning (2 SWS)	3 ECTS 2 ECTS
3	Lecturers	Florian Rösel Prof. Dr. Frauke Liers-Bergmann	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<ul style="list-style-type: none"> 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	<p>Students</p> <ul style="list-style-type: none"> 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 in curriculum	semester: 1;3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Written examination (60 minutes)	
11	Grading procedure	Written examination (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 60 h Independent study: 90 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> Goodfellow, Bengio, Courville, Deep Learning, MIT Press, 2015 Hastie, Tibshirani, Friedman, The Elements of Statistical Learning, 2008 	

1	Module name 65900	Advanced discretization techniques	10 ECTS
2	Courses / lectures	Vorlesung: Advanced Discretization Techniques (4 SWS) Übung: Exercises for Advanced Discretization Techniques (1 SWS)	10 ECTS -
3	Lecturers	Prof. Dr. Carsten Gräser	

4	Module coordinator	Prof. Dr. Eberhard Bänsch
5	Contents	<ul style="list-style-type: none"> conforming and non-conforming finite element methods saddle point problems in Hilbert spaces mixed finite element methods for saddle point problems, in particular for Darcy and Stokes Streamline-Upwind Petrov-Galerkin (SUPG) and discontinuous Galerkin (dG) finite element methods (FEM) for convection dominated problems Finite Volume (FV) methods and their relation to FEM a posteriori error control and adaptive methods
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> have a discriminating understanding, both theoretically and computationally of FE as well as FV methods for the numerical solution of partial differential equations (pde) (in particular of saddle point problems), are capable of developing problem dependent FE or FV methods and judge on their properties regarding stability and effectiveness, are familiar with a broad spectrum of pde problems and their computational solutions, are capable of designing algorithms for adaptive mesh control.
7	Prerequisites	Recommended: Introduction to numerical methods for pdes, functional analysis
8	Integration in curriculum	semester: 1
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h

14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • A. Ern, J.-L. Guermond: Theory and Practice of Finite Elements • A. Quarteroni & A. Valli: Numerical Approximation of Partial Differential Equations • P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Differential Equations, Springer • D. A. Di Pietro & A. Ern: Mathematical aspects of discontinuous Galerkin methods. Springer 2012

1	Module name 65901	Advanced solution techniques	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral oral exam (15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	

16	Bibliography	<ul style="list-style-type: none">• 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 65902	Transport and reaction in porous media: Modelling	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	apl. Prof. Dr. Serge Kräutle	
5	Contents	<ul style="list-style-type: none"> Modeling of fluid flow through a porous medium: Groundwater models, saturated and unsaturated porous medium (Richards equation) Advection, diffusion, dispersion of dissolved substances, (nonlinear) reaction-models (i.a. law of mass action, kinetic / reversible reactions in local equilibrium), the stoichiometric matrix Models of partial (PDEs), ordinary (ODEs) differential equations, and local algebraic 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 and uniqueness of stationary solutions in the stoichiometric space (i.a. introduction to the Feinberg network theory) 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	

16 **Bibliography**

- 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 <https://cbe.osu.edu/chemical-reaction-network-theory>

1	Module name 65903	Transport and reaction in porous media: Simulation	5 ECTS
2	Courses / lectures	Vorlesung: Transport and reaction in porous media: Simulation	-
3	Lecturers	apl. Prof. Dr. Serge Kräutle	

4	Module coordinator	apl. Prof. Dr. Serge Kräutle	
5	Contents	<ul style="list-style-type: none"> • Degenerate parabolic differential equations as multiphase flow models: formulation, model derivation through asymptotic expansion, nonlinear solution methods, discretization methods • Sorption reactions and mineral precipitation-dissolution reactions, formulations as complementarity problems • Models for transport and reactions in porous media, consisting of coupled PDEs and ODEs, if necessary coupled to algebraic equations (AEs) and inequalities for the description of local equilibria (differential-algebraic system) • Different formulations of the system • Different numerical strategies: operator splitting, direct substitutional approach, change of variables and combination/elimination of equations (xi-eta-method), as a basis for different software packages for numerical simulations, connection to optimisation (minimization of Gibbs free energy under constraints) • Treatment of numerical difficulties (nonsmooth equations, treatment of complementarity conditions, guarantee of nonnegativity of numerical solutions of the nonlinear problems, range of convergence of Newton's method, scaling problems, advection dominated problems) 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • use methods for the numerical solving of a class of problems whose complexity goes significantly beyond standard problems (Poisson and heat equation): coupled nonlinear partial and ordinary differential equations (PDEs, ODEs) and algebraic equations (AEs), • put strategies for the treatment of possible difficulties during the numerical solving into practice. 	
7	Prerequisites	<ul style="list-style-type: none"> • Recommended: Basic knowledge in differential equations, • Also useful: Transport and Reaction in Porous Media: Modeling 	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p>	

		Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Partial Differential Equations, Springer • Journal articles will be named in the lecture • Handbooks of Software Packages https://en.www.math.fau.de/angewandte-mathematik-1/forschung/software-2

1	Module name 65904	Numerics of incompressible flows I	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • V. Girault, P.-A. Raviart: Finite element methods for the Navier-Stokes equations. Theory and algorithms. Springer 1986 	

- H. Elman, D. Silvester, A. Wathen: 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

1	Module name 65905	Numerics of incompressible flows II	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • Variational formulation of the instationary Stokes and Navier-Stokes (NVS) equations • Existence and uniqueness of solutions to the instationary Stokes and NVS equations • Time discretisation methods • Fully discrete equations and error estimates • Solution techniques • Operator splitting, projection methods • More general boundary conditions • Coupling of NVS with temperature equation • Computational experiments with academic or commercial codes 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • discretize the instationary NVS equations in time and space, • explain and analyse discretisation schemes and operator splitting techniques, • choose appropriate algorithms for given flow problems and solve them with academic or commercial software. 	
7	Prerequisites	Recommended: Advanced discretization techniques, Numerics of incompressible flows I	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	

16	Bibliography	<ul style="list-style-type: none">• V. Girault & 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. Glowinski: Finite Element Methods for Incompressible Viscous Flow, in : Handbook of Numerical Analysis vol. IX• R. Temam: Navier-Stokes equations. Theory and numerical analysis. North Holland
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1	Module name 65906	Mathematics of multiscale models	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	PD Dr. Nicolas Neuß
5	Contents	<ul style="list-style-type: none"> • Function spaces of periodic functions and asymptotic expansions • Two-scale convergence and unfolding method • Application to differential equation models in continuum mechanics • Multi-scale finite element methods • Numerical upscaling methods
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • have profound expertise about the basic methods in multi-scale analysis and homogenisation, • are able to derive rigorously homogenised (effective) models and analyse the quality of the approximation.
7	Prerequisites	Recommended: Knowledge in modeling as well as analysis and numerics of partial differential equations
8	Integration in curriculum	semester: 3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • D. Cioranescu & P. Donato: An Introduction to Homogenization • U. Hornung (ed.): Homogenization and Porous Media • Y. Efendiev & T. Hou: Multiscale Finite Element Methods

1	Module name 65907	Theory of stochastic evolution equations	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Infinitely dimensional Wiener processes, • Stochastic integral in Hilbert spaces, • Ito-processes and stochastic differential equations, • Optionally: existence results for stochastic partial differential equations or further results on stochastic ODE (Fokker-Planck equations, . . .) 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • characterize Gaussian measures on Hilbert spaces. They explain representation formulas for Q-Wiener processes as well as the derivation of the stochastic integral, • successfully apply concepts to solve stochastic differential equations explicitly and prove existence of solutions to stochastic evolution equations. 	
7	Prerequisites	Basic knowledge in probability theory or functional analysis is recommended.	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • G. Da Prato & J. Zabczyk: Stochastic equations in infinite dimensions, Cambridge University Press • I. Karatzas & S.E. Shreve: Brownian motion and stochastic calculus, Springer • B. Oksendal: Stochastic differential equations, Springer 	

- C. Prévôt & M. Röckner: A concise course on stochastic partial differential equations, Springerchastic Evolution Equations

1	Module name 65908	Numerics of stochastic evolution equations	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Strong and weak approximations, explicit and implicit schemes for stochastic differential equations (SDEs), • Consistency, stability, convergence, • Monte Carlo methods, variance-reduction schemes. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • have critical understanding of capabilities of numerical schemes for stochastic differential equations, • are capable to use own or commercial software for SDEs and to judge results critically. 	
7	Prerequisites	Basic knowledge in probability theory and in numerics is recommended.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • P.E. Kloeden & E. Platen: Numerical solution of stochastic differential equations • B. Lapeyre, E. Pardoux & R. Sentis: Introduction to Monte? Carlo methods for transport and diffusion equations 	

1	Module name 65911	Mathematical modeling in the life sciences	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	apl. Prof. Dr. Maria Neuß	
5	Contents	<ul style="list-style-type: none"> • Biochemical reaction networks, enzyme kinetics • Models for interacting populations (Predator-prey, competition, symbiosis) • Diffusion, reactions, and transport in biological cell tissues and vessels • Structured population models 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • have profound knowledge in the area of mathematical modeling of processes in the life sciences • are able to identify significant mechanisms and to apply suitable analytical and numerical methods for their analysis • are able to work interdisciplinary and problem-oriented. 	
7	Prerequisites	Recommended: Modeling and Analysis in Continuum Mechanics I	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • J. D. Murray: Mathematical Biology I: An Introduction, Mathematical Biology II: Spatial Models and Biomedical Applications • G. de Vries, T. Hillen, et al.: A course in Mathematical Biology • J. Prüss: Mathematische Modelle in der Biologie: Deterministische homogene Systeme 	

1	Module name 65914	Partial differential equations in finance	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> models on pricing for financial derivatives, in particular for European and American-type options, selected deterministic equations of financial mathematics, practical knowledge Ito-calculus and stochastic differential equations, analysis and numerics for Black-Scholes equations, variational inequalities and American-type options. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> explain mathematical models for financial markets and derivatives pricing, apply Ito calculus, derive deterministic models based on pde or variational inequalities and discretize them numerically. 	
7	Prerequisites	Basis knowledge in differential equations, probability theory or functional analysis is recommended.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (ca. 15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> M. Capinski & T. Zastawniak: Mathematics for finance, Springer, N. Hilber, O. Reichmann, C. Schwab & C. Winter: Computational methods for quantitative finance, Springer, 	

- B. Oksendal: Stochastic differential equations, Springer.

1	Module name 65954	Numerik der Optimalen Steuerungen Numerics of optimal control	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Hannes Meinlschmidt	
5	Contents	<p>The following topics are covered: Discretization methods for differential equations, aspects of nonlinear optimization methods, direct discretization methods (fully and reduced discretized), indirect methods based on discretization of necessary optimality conditions as well as methods for efficient sensitivity calculations with internal numerical differentiation and adjoint equations.</p> <p>The material is presented in lecture form. Further acquisition of the essential concepts and techniques takes place through self-study of accompanying literature and the completion of exercises, supported by meetings within the tutorials.</p> <p>By default, the lecture will be given in English (in German only if all participants agree).</p>	
6	Learning objectives and skills	Students explain and use numerical methods for optimal control problems with ordinary differential equations and differential algebraic equations. They apply basic concepts of solution methodology using direct and indirect discretization methods for application problems, for example in technology or economics.	
7	Prerequisites	Recommended: Basic knowledge in numerics, in theory of ordinary differential equations, and in optimization.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral Dauer der mündlichen Prüfung: 15 Min.	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	

13	Workload in clock hours	Contact hours: 60 h Independent study: 90 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	M. Gerdtts, Optimal Control of ODEs and DAEs, De Gruyter, 2012.

1	Module name 65993	Numerics of Partial Differential Equations Numerics of partial differential equations	10 ECTS
2	Courses / lectures	Vorlesung: Numerics of Partial Differential Equations I (4 SWS) Übung: NuPDGU (2 SWS) Übung: Exercises for Numerics of Partial Differential Equations I (2 SWS)	10 ECTS - -
3	Lecturers	Prof. Dr. Günther Grün	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • Classical approach for the Poisson problem (outline) • Variational theory of linear elliptic boundary value problems • Possible discretization methods (FD, FEM, FV, spectral methods) • Conforming FEM for linear elliptic boundary value problems (2nd order) (types of elements, affine-equivalent triangulations, interpolation estimates, error estimates, Aubin-Nitsche) • Aspects of implementation • Iterative methods for large sparse linear systems of equations (condition number of finite element matrices, linear stationary methods (recall), cg method (recall), preconditioning, Krylov subspace methods) • Outlook to nonlinear problems 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • apply algorithmic approaches for models with partial differential equations and explain and evaluate them, • are capable to judge on a numerical methods 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 problems and methods with a focus on conforming finite element methods for linear elliptic problems, • collect and evaluate relevant information and realize relationships. 	
7	Prerequisites	Recommended: basic knowledge in numerics, discretization, and optimization	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p>	

		Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Written examination (90 minutes)
11	Grading procedure	Written examination (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 90 h Independent study: 210 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • A. Ern & J.-L. Guermond: Theory and practice of finite elements. Springer 2004 • W. Hackbusch: Elliptic Differential Equations. Theory and Numerical Treatment. Springer, 2nd edition 2017, (also available in German) • D. Braess: Finite Elements. Cambridge University Press 2010 • A. Quarteroni & A. Valli: Numerical approximation of partial differential equations. Springer 1994 • P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Differential Equations, Springer 2003 • lecture notes

1	Module name 65997	Analysis of free-boundary problems in continuum mechanics	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Derivation of time-dependent free boundary problems in continuum mechanics, • Basic results on existence and qualitative behaviour, • Optimal estimates on the propagation of free boundaries, • Other approaches, e.g. relaxation by phase-field models. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • formulate free-boundary problems in hydrodynamics and in porousmedia flow • explain analytical concepts for existence and nonnegativity results for degenerate parabolic equations as well as techniques for optimal estimates on spreading rates • validate different modeling approaches in a critical way. 	
7	Prerequisites	Recommended: Basic knowledge of analysis of partial differential equations, corresponding to the syllabus of Modeling and Applied Analysis in Continuum Mechanics or that one of other pde-lectures.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (ca. 15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • L.C. Evans: Partial Differential Equations, AMS, • Original journal articles. 	

1	Module name 65999	Numerics of Partial Differential Equations II Numerics of partial differential equations II	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> 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	<p>Students</p> <ul style="list-style-type: none"> apply algorithmic approaches for models with partial differential equations and explain and evaluate them, are capable to judge on a numerical methods 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Written examination (90 minutes)	
11	Grading procedure	Written examination (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	

14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none">• 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.

1	Module name 65787	Seminar Applied Analysis Seminar: Applied analysis	5 ECTS
2	Courses / lectures	Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS)	5 ECTS
3	Lecturers	Prof. Dr. Günther Grün	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	Topics from Applied Analysis to deepen the theoretical contents of the lecture ModAna1	
6	Learning objectives and skills	<div style="border: 1px solid black; padding: 5px;"> <p>Students</p> <ul style="list-style-type: none"> • are able to familiarize themselves with advanced topics using journal articles or graduate textbooks, • can present the acquired content orally in a structured manner, with, if necessary, own additions in content, • actively participate at discussions about mathematical topics raised by the presentations in the seminar. </div>	
7	Prerequisites	Module ModAna1 is recommended	
8	Integration in curriculum	semester: 2	
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Mandatory elective module in M.Sc. Computational and Applied Mathematics	
10	Method of examination	Seminar achievement Oral presentation (90min) and presentation document (4-8 pages)	
11	Grading procedure	Seminar achievement (100%) Oral presentation (80%), presentation document (20%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Determined by the topic chosen	

1	Module name 65879	Differentialgeometrie Differential geometry	10 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	apl. Prof. Dr. Jens Habermann	
5	Contents	<p>Eine Auswahl aus den folgenden Themen:</p> <ul style="list-style-type: none"> • Mannigfaltigkeiten (Tangentialvektoren, Vektorfelder, Flüsse) • Vektorbündel (Tensorbündel und (Semi-)Riemannsche Strukturen) • Differentialformen (Orientierung, Integration) • Affine Zusammenhänge (Paralleltransport, Krümmung) • Geodäten (Distanz, Jacobi Vektorfelder) • Einführung in der geometrischen Analysis • Symplektische und Poisson-Strukturen • Liegruppen und glatte Wirkungen 	
6	Learning objectives and skills	<p>Die Studierenden</p> <ul style="list-style-type: none"> • nennen und erklären die grundlegende Theorie der Mannigfaltigkeiten und ihrer Struktur, • erkennen und verwenden zusätzliche geometrische Strukturen auf Mannigfaltigkeiten wie zum Beispiel affine Zusammenhänge, Riemannsche Metriken oder symplektische Formen. 	
7	Prerequisites	Grundkenntnisse in Topologie, Analysis, Lineare Algebra und Gewöhnliche Differentialgleichungen	
8	Integration in curriculum	no Integration in curriculum available!	
9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Written examination (90 minutes)	
11	Grading procedure	Written examination (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 90 h Independent study: 210 h	
14	Module duration	1 semester	
15	Teaching and examination language		
16	Bibliography	<ul style="list-style-type: none"> • S. Lang: "Differential and Riemannian manifolds" • J.M. Lee: "Introduction to Riemannian Manifolds" • R.L. Bishop and R.J. Crittenden, "Geometry of manifolds" 	

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| | <ul style="list-style-type: none">• F. Warner: "Foundations of Differentiable Manifolds and Lie Groups"• M. Do Carmo: "Riemannian Geometry" |
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1	Module name 65878	Numerische Behandlung Elliptischer PDEs Numerical methods of elliptic PDEs	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	PD Dr. Cornelia Schneider	
5	Contents	<ul style="list-style-type: none"> • Elliptische Differentialgleichungen • Schwache Lösungen • Variationsformulierung • Galerkin Verfahren • Finite Elemente 	
6	Learning objectives and skills	<p>Die Studierenden sollen</p> <ul style="list-style-type: none"> • die Grenzen der Standardverfahren erkennen, wenn die Problemstellung besondere Anforderungen mit sich bringt, • lernen, problemadäquate Lösungen zu finden, • beispielhaft nachvollziehen, wie konkrete praktische Entwicklungen die Fragestellungen der angewandten Mathematik beeinflussen, • mathematische Arbeitsweisen einüben (Entwickeln von mathematischer Intuition und deren formaler Begründung, Schulung des Abstraktionsvermögens, Beweisführung), • in den Übungen ihre mündliche Kommunikationsfähigkeit durch Einüben der freien Rede vor einem Publikum und bei der Diskussion verbessern. 	
7	Prerequisites	Empfohlen: Basis- und Aufbau module Numerik	
8	Integration in curriculum	no Integration in curriculum available!	
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral (20 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 60 h Independent study: 90 h	
14	Module duration	1 semester	
15	Teaching and examination language	german	
16	Bibliography	<ul style="list-style-type: none"> • Hackbusch, W., Theorie und Numerik elliptischer Differentialgleichungen, Teubner 1986 • Brenner, S.C., Scott, L.R, The mathematical theory of finite element methods, Springer, 1994 	

1	Module name 65864	Hyperbolic Conservation Laws and Application	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Emil Wiedemann	
5	Contents	Hyperbolic conservation laws are essential for the description of non-dissipative phenomena such as the flow of inviscid gases or shallow water waves. The mathematical theory is confronted with the lack of regularity, as initially smooth solutions may develop discontinuities (interpreted as shock waves) in finite time. We study scalar conservation laws, for which there is a classical well-posedness theory of entropy solutions due to Kruzhkov. Later, we investigate hyperbolic systems with a special focus on the Riemann problem, which requires a detailed understanding of the geometry of shock and rarefaction curves. Particular emphasis will be on the discussion of models of gas flow and thermodynamics, such as the compressible Euler equations.	
6	Learning objectives and skills	Students know and understand the basic theory of scalar conservation laws and hyperbolic systems. They relate mathematical theory to the modelling of physical phenomena and are familiar with various concepts of entropy. They learn important analytical techniques such as compensated compactness.	
7	Prerequisites	Recommended: Linear Algebra, Analysis, and a beginners' course on partial differential equations.	
8	Integration in curriculum	semester: 1;2;3	
9	Module compatibility	Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral (30 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Will be announced in the lecture.	

1	Module name 48241	Mathematical Image Processing	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers. This module is offered in every second summer term. The next course will be held in the summer semester 2024.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Daniel Tenbrinck	
5	Contents	<p>This module covers mathematical image processing techniques based on Fourier domain filters, variational methods, and partial differential equations.</p> <p>In particular, the following content will be introduced to the students:</p> <ul style="list-style-type: none"> • contrast enhancement • filtering in Fourier and image domain • Bayesian image denoising • image deblurring / deconvolution • pixel-based clustering • region-based segmentation • image inpainting • nonlocal image processing using graphs 	
6	Learning objectives and skills	<p>Students following this course will</p> <ul style="list-style-type: none"> • learn how image data can be modeled and analyzed mathematically • develop a deeper understanding of mathematical basics and methods for image processing • implement own algorithms for mathematical image processing • discover connections to related mathematical fields, e.g., inverse problems and convex analysis 	
7	Prerequisites	<p>Knowledge in calculus and linear algebra is recommended to understand the mathematical foundations of image processing.</p> <p>Knowledge in functional analysis, numerical mathematics, or inverse problems is helpful to understand advanced concepts in mathematical image processing.</p>	
8	Integration in curriculum	semester: 2;1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	

10	Method of examination	Written or oral Oral examination (20 min.) or written examination (60 min.) depending on size of course.
11	Grading procedure	Written or oral (100%) Oral exam (100%) or written exam (100%) depending on size of course.
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • G. Aubert & P. Kornprobst: Mathematical problems in Image Processing, Springer • K. Bredies & D. Lorenz, Mathematical Image Processing, Springer • S. Osher & R. Fedkiw, Level Set Methods and Dynamic Implicit Surfaces, Springer • A. Elmoataz , O.Lezoray, S. Bogleux: Nonlocal Discrete Regularization on Weighted Graphs: a framework for Image and Manifold Processing, IEEE Transactions On Image Processing, 17 (7), pp: 1047-1060, 2008

1	Module name 65096	Seminar Selected Topics of Applied Analysis Seminar: Selected topics of applied analysis	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	Topics from Applied Analysis to deepen the theoretical contents of the lecture <i>ModAna1</i>	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • are able to familiarize themselves with advanced topics using journal articles or graduate textbooks, • can present the acquired content orally in a structured manner, with, if necessary, own additions in content, • actively participate at discussions about mathematical topics raised by the presentations in the seminar. 	
7	Prerequisites	<p>Linear algebra and calculus are required.</p> <p>Basic knowledge in probability theory is recommended.</p>	
8	Integration in curriculum	no Integration in curriculum available!	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Mandatory elective module in M.Sc. Computational and Applied Mathematics</p> <p>Summer or winter term after participation at <i>ModAna1</i></p>	
10	Method of examination	<p>Presentation</p> <p>Oral (90 minutes)</p> <p>Oral presentation (90min) and presentation document (4-8 pages)</p>	
11	Grading procedure	<p>Presentation (20%)</p> <p>Oral (80%)</p> <p>Oral presentation (80%)</p> <p>presentation document (20%)</p>	
12	Module frequency	Irregular	

13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	Determined by the topic chosen

Specialisation: Modeling and applied analysis (MApA) and optimization (Opti)

1	Module name 65885	Master's seminar MApA Master`s seminar MApA	5 ECTS
2	Courses / lectures	Masterseminar: Masterseminar (2 SWS)	5 ECTS
		Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS)	5 ECTS
		Masterseminar: Numerical methods for phase-field equations	5 ECTS
3	Lecturers	Prof. Dr. Timm Oertel Prof. Dr. Günther Grün Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Günther Grün
5	Contents	A topic from MApA that relates to the compulsory elective modules offered.
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • 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. <p>For the MApA specialisation:</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Written Presentation (90 minutes) (schriftliche Ausarbeitung 5-10 Seiten)
11	Grading procedure	Written (25%) Presentation (75%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h
14	Module duration	1 semester

15	Teaching and examination language	english
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	Module name 65895	Master seminar Opti	5 ECTS
2	Courses / lectures	Masterseminar: Masterseminar (2 SWS) Masterseminar: Master seminar "Numerical solutions for eigenvalue problems" Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS) Masterseminar: Material and Topology Optimization (2 SWS) Masterseminar: Numerical methods for phase-field equations	5 ECTS 5 ECTS 5 ECTS 5 ECTS 5 ECTS
3	Lecturers	Prof. Dr. Timm Oertel Prof. Dr. Daniel Tenbrinck Prof. Dr. Günther Grün Prof. Dr. Michael Stingl Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Michael Stingl
5	Contents	A topic from Opti that relates to the compulsory elective modules offered.
6	Learning objectives and skills	Students <ul style="list-style-type: none"> • 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: <ul style="list-style-type: none"> • 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 in curriculum	semester: 3
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Presentation (90 minutes) Written (schriftliche Ausarbeitung 5-10 Seiten)

11	Grading procedure	Presentation (75%) Written (25%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	Module name 65910	Discrete optimization III	5 ECTS
2	Courses / lectures	Vorlesung: Diskrete Optimierung III (2 SWS) Übung: Tutorial zu Diskrete Optimierung III (1 SWS)	5 ECTS -
3	Lecturers	Prof. Dr. Timm Oertel	

4	Module coordinator	Prof. Dr. Timm Oertel	
5	Contents	<p>In this lecture we will discuss selected topics in discrete and mixed-integer optimization. Possible topics include lattice methods, integer programming in fixed dimension, recent research on (mixed) integer linear and/or (mixed) integer nonlinear programming and so on. The specific topics may vary and will be announced in due time.</p> <p>FORMERLY: 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.</p>	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • use basic terms of discrete optimization • model real-world discrete optimization problems, determine their complexity and solve them with appropriate mathematical methods. 	
7	Prerequisites	<p>Recommended: Knowledge in linear and combinatorial optimization, discrete optimization I and II</p>	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (15 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	<p>Contact hours: 45 h Independent study: 105 h</p>	
14	Module duration	1 semester	

15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • 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

1	Module name 65068	Wave Phenomena Wave phenomena	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<p>1) Motivations and applications.</p> <p>2) Linear transport equation: method of characteristics; Fourier analysis and numerical approximations.</p> <p>3) The wave equation: D'Alembert's representation formula; regularity of the solutions; finite speed of propagation of perturbations; Huygens' principle; geometric optics; wave models with sources or sinks; Kirchhoff's representation in \mathbb{R}^3; Poisson's representation in \mathbb{R}^2; the case of general odd and even space dimensions; energy methods: domain of dependence inequality and energy conservation; representation of solutions by using partial Fourier transform; subordination waves-heat; the reflection method and waves on the half-line; separation of variables.</p> <p>4) Klein-Gordon equation: energy estimates; representation of solutions by using Fourier multipliers; von Wahl's transformation.</p> <p>5) Damped wave equation: energy estimates; representation of solutions by using Fourier multipliers; decay behavior and decay rate.</p> <p>6) Damped plate equation: estimates for the energy; estimates for the solution itself and its derivatives;</p> <p>7) Semilinear wave equation: global existence for small data and global existence for large data.</p> <p>8) Diffusion phenomena: parabolic structure of solutions to damped waves and damped plates; diffusion phenomena in thermo-elasticity; traveling waves and reaction-diffusion models.</p> <p>9) Scalar conservation laws: occurrence of shocks and rarefaction waves.</p> <p>10) Linear and nonlinear dispersive waves: Solitary waves for the Korteweg-de Vries equation; plane-wave solutions for the Airy equation and Schrödinger; Fourier analysis.</p> <p>11) Maxwell equations: constitutive equations; special cases; boundary conditions; expansion into wave functions.</p>	
6	Learning objectives and skills	<p>Students are able to:</p> <ul style="list-style-type: none"> • identify significant mechanisms and to apply suitable analytical and numerical methods for their analysis • work interdisciplinary and in problem-oriented way; • use language and techniques related to partial differential equations; • 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 in curriculum	semester: 2
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral (20 minutes)
11	Grading procedure	Oral (100%)
12	Module frequency	Only in summer semester
13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • Ebert, M. R. & Reissig, M. Methods for Partial Differential Equations. Birkhäuser, 2018. • Evans, L. C. Partial Differential Equations. AMS, 2010. • Kirsch, A. and Hettlich, F. The Mathematical Theory of Maxwell's Equations. Lecture Notes, 2013: • https://www.math.kit.edu/ianmip/lehre/maxwellequ2012w/media/main.pdf • Myint-U, T. & Debnath, L. Linear partial differential equations for scientists and engineers. Birkhäuser, 2007. • Reissig, M. Theory of hyperbolic equations. Lecture Notes, 2007: • https://tu-freiberg.de/sites/default/files/media/institut-fuer-angewandte-analysis-9030/reissig/pdehanoi1.pdf • Vichnevetsky, R. & Bowles, J. B. Fourier Analysis of Numerical Approximations of Hyperbolic Equations. SIAM, 1982 <p>Lecture notes will be distributed via StudOn.</p>

1	Module name 65928	Inverse Problems	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Daniel Tenbrinck
5	Contents	<ul style="list-style-type: none"> • Examples of inverse and ill posed problems in engineering and medical imaging • Linear regularization methods in Hilbert spaces and singular value decomposition • Variational methods for regularization and image reconstruction problems • Tomographic reconstruction and Radon transforms
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • develop understanding for special aspects of inverse problems and ill posedness, • apply regularization methods to inverse problems and develop a basic understanding of their properties, • derive and solve inverse problems arising from technical and biomedical applications.
7	Prerequisites	None
8	Integration in curriculum	semester: 1;3
9	Module compatibility	Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral (ca. 15 min)
11	Grading procedure	Oral (100%)
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 38 h Independent study: 112 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • H. Engl, M. Hanke, A. Neubauer: Regularization Methods for Inverse Problems, Kluwer 1996 • M. Benning, M. Burger: Modern Regularization Methods for Inverse Problems, Acta Numerica 2018

1	Module name 65887	Modul Conservation Laws Module: Conservation laws	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Dr. Lukas Pflug	
5	Contents	<ul style="list-style-type: none"> • (Non-)local conservation laws in applications • Linear scalar transport equations and conservation laws • Linear multi-D transport equations and conservation laws • Method of characteristics • Fixed-point methods in Banach spaces • Existence and uniqueness of nonlocal conservation laws • Maximum principles • Regularity and stability of solutions • Local conservation laws, Entropy solutions; • The singular limit problem – approximation of local Entropy solutions by nonlocal conservation laws • Numerical methods 	
6	Learning objectives and skills	Students learn the basic theory on nonlocal conservation laws, apply approximation results, learn fixed-point approaches in Banach spaces and understand the applicability of conservation laws in the applied sciences.	
7	Prerequisites	Some basic knowledge in PDE is of advantage, Sobolev spaces.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral Dauer der mündlichen Prüfung: 15 Min.	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	german or english	
16	Bibliography	<ul style="list-style-type: none"> • Bressan, Alberto. Hyperbolic systems of conservation laws: the one-dimensional Cauchy problem. Vol. 20. Oxford University Press on Demand, 2000. 	

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| | <ul style="list-style-type: none">• Keimer, Alexander, and Lukas Pflug. "Existence, uniqueness and regularity results on nonlocal balance laws." <i>Journal of Differential Equations</i> 263.7 (2017): 4023-4069.• Coclite, Giuseppe Maria, et al. "A general result on the approximation of local conservation laws by nonlocal conservation laws: The singular limit problem for exponential kernels." <i>Annales de l'Institut Henri Poincaré C</i> (2022).• Blandin, Sebastien, and Paola Goatin. "Well-posedness of a conservation law with non-local flux arising in traffic flow modeling." <i>Numerische Mathematik</i> 132.2 (2016): 217-241.• Aggarwal, Aekta, Rinaldo M. Colombo, and Paola Goatin. "Nonlocal systems of conservation laws in several space dimensions." <i>SIAM Journal on Numerical Analysis</i> 53.2 (2015): 963-983. |
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1	Module name 65888	Navier Stokes Equations Navier stokes equations	10 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Emil Wiedemann	
5	Contents	<p>The incompressible Navier-Stokes equations (NSE) are a nonlinear system of partial differential equations fundamental for the modelling of fluid flow. They are extensively used in meteorology and oceanography, but also pose great mathematical challenges. Famously, global regularity of the three-dimensional NSE forms one of the seven Millennium Problems. This course serves as an introduction to the mathematical theory of these equations and includes the following topics:</p> <ul style="list-style-type: none"> • existence of weak solutions of Leray-Hopf type; • local-in-time existence of strong solutions; • the Prodi-Serrin criteria for regularity and energy balance; • partial regularity theory; • the singular limit of vanishing viscosity. <p>The course can be a good preparation for a subsequent master's thesis in the topic.</p>	
6	Learning objectives and skills	Students know and understand the basic theory of the Navier-Stokes equations and have mastered important methods for systems of non-linear partial differential equations. They have a basic understanding of mathematical fluid dynamics.	
7	Prerequisites	Lineare Algebra, Analysis. Empfohlen: erste Kurse in partiellen Differentialgleichungen und Funktionalanalysis.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (20 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 90 h Independent study: 210 h	
14	Module duration	1 semester	
15	Teaching and examination language	german or english	

16	Bibliography	<ul style="list-style-type: none">• J. C. Robinson, J. L. Rodrigo, W. Sadowski: The Three-Dimensional Navier-Stokes Equations. Cambridge University Press, 2016.• P. Constantin, C. Foias: Navier-Stokes Equations. University of Chicago Press, 1988.• W. Ożański: The Partial Regularity Theory of Caffarelli, Kohn, and Nirenberg and its Sharpness. Birkhäuser, 2019.• E. Wiedemann: Navier-Stokes Equations: Lecture Notes. Universität Ulm, 2018/19.
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1	Module name 65083	Efficient discretization of two-phase flow	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Dr. Stefan Metzger	
5	Contents	Based on recent scientific publications, different discretization approaches for two-phase flow are discussed.	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • 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, • learn to compare different discretization methods regarding their specific advantages and disadvantages. 	
7	Prerequisites	Recommended: Numerics of Partial Differential Equations I	
8	Integration in curriculum	no Integration in curriculum available!	
9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Seminar achievement Vortrag (60 Min) + schriftliche Ausarbeitung (5-15 Seiten)	
11	Grading procedure	Seminar achievement (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.	

1	Module name 65089	Scalar conservation laws	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ol style="list-style-type: none"> 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; Kruzhkov'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: Oleinik'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	<p>Students are able to:</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	

9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral (ca. 15 min)
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<p>Chapters 1-10:</p> <ul style="list-style-type: none"> • Bressan, A. Hyperbolic Systems of Conservation Laws: The One-dimensional Cauchy Problem. Oxford University Press, 2000. • Coclite, G. M. Scalar Conservation Laws. Lecture Notes, 2022. • Dafermos, C. M. Hyperbolic Conservation Laws in Continuum Physics. 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: https://metaphor.ethz.ch/x/2019/hs/401-4671-00L/literature/mishra_hyperbolic_pdes.pdf • Salsa, S. Partial differential equations in action. From modelling to theory. Springer, 2016. • Salsa, S. & Verzini, G. Partial differential equations in action. Complements and exercises. Springer, 2015. <p>Chapter 11:</p> <ul style="list-style-type: none"> • 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 Anal., Theory Methods Appl., Ser. A, Theory Methods* 50, No. 4, 455-469 (2002).

Chapter 12:

- Andreianov, B. P., Coclite, G. M. & Donadello, C. Well-posedness for vanishing viscosity solutions of scalar conservation laws on a network. *Discrete Contin. Dyn. Syst.* 37, No. 11, 5913-5942 (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. *Z. Angew. Math. Phys.* 73, No. 6, Paper No. 241, 10 p. (2022).
- 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. *Annales de l'Institut Henri Poincaré C, Analyse Non Linéaire* (2022).
- Keimer, A. & Pflug, L. Existence, uniqueness and regularity results on nonlocal balance laws. *J. Differ. Equations* 263, No. 7, 4023-4069 (2017).

Lecture notes will be distributed via StudOn.

1	Module name 65093	Control, machine learning and numerics	10 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ul style="list-style-type: none"> 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	<p>Students are able to</p> <ul style="list-style-type: none"> 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Variable	
11	Grading procedure	Variable (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	
14	Module duration	1 semester	

15	Teaching and examination language	english
16	Bibliography	<ol style="list-style-type: none"> 1) L. Bottou, F. E. Curtis, and J. Nocedal, Optimization methods for large-scale machine learning. <i>SIAM Review</i>, 60 (2) (2018) , 223-311. 2) J. M. Coron, Control and Nonlinearity, <i>Mathematical Surveys and Monographs</i>, 143, AMS, 2009. 3) I. Goodfellow, Y. Bengio, & A. Courville, <i>Deep Learning</i>. MIT press, 2016. 4) R. Glowinski, J. L. Lions, and J. He, Exact and Approximate Controllability for Distributed Parameter Systems: A Numerical Approach, <i>Encyclopedia Math. Appl.</i>, Cambridge University Press, Cambridge, UK, 2008. 5) C. F. Higham, and D. J. Higham, Deep learning: An introduction for applied mathematicians. <i>SIAM Review</i>, 61 (4) (2019), 860-891. 6) J. Nocedal, and S. Wright, <i>Numerical Optimization</i>. Springer Science & Business Media, 2006. 7) D. Ruiz-Balet, and E. Zuazua, Neural ODE control for classification, approximation and transport. <i>arXiv preprint arXiv:2104.05278</i>, (2021). 8) E. Zuazua, Propagation, observation, and control of waves approximated by finite difference methods, <i>SIAM Review</i>, 47 (2) (2005), 197-243. 9) E. Zuazua, Controllability and observability of partial differential equations: some results and open problems, in <i>Handbook of Differential Equations: Evolutionary Equations</i>. Vol. 3. North-Holland, 2006. 527-621.

1	Module name 65700	Lecture Series Partial Differential Equations, Control and Numerics (PdeConNum) Lecture series: Partial differential equations, control and numerics (PdeConNum)	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ul style="list-style-type: none"> • Examples of PDE models arising in industrial applications, Biology and Social Sciences • Long time asymptotics • Control of trajectories • Numerics for long time dynamics and control • Some applications in the control of population dynamics 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • develop understanding for special aspects of dynamical systems control, • apply numerical methods to control problems and develop a basic understanding of their properties, • derive and solve inverse problems arising from applications. 	
7	Prerequisites	Recommended: basic knowledge in functional analysis	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (15 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • J. M. Coron, Control and nonlinearity, Mathematical Surveys and Monographs, 143, AMS, 2009 • E. Zuazua. Propagation, observation, and control of waves approximated by finite difference methods. SIAM Review, 47 (2) (2005), 197-243 	

1	Module name 65862	Conic Optimization and Applications Conic optimisation and applications	5 ECTS
2	Courses / lectures	Vorlesung: Conic Optimization and Applications (2 SWS) Übung: Übung Conic Optimization and Applications (2 SWS)	5 ECTS -
3	Lecturers	Prof. Dr. Giovanni Fantuzzi	

4	Module coordinator	Prof. Dr. Jan Rolfes
5	Contents	<p>In modern Convex Optimization the theory of semidefinite optimization plays a central role. Semidefinite optimization is a generalization of linear optimization, where one wants to optimize linear functions over positive semidefinite matrices restricted by linear constraints. A wide class of convex optimization problems can be modeled using semidefinite optimization. On the one hand, there are algorithms to solve semidefinite optimization problems, which are efficient in theory and practice. On the other hand, semidefinite optimization is a tool of particular usefulness and elegance.</p> <p>Overview of topics:</p> <ul style="list-style-type: none"> • Topological properties of cones • Foundations of conic optimization, theorems of the alternative, duality • Applications in Eigenvalue optimization and robust optimization • Approximations of combinatorial optimization problems such as MAXCUT, packing problems, coloring problems, Shannon capacity • Symmetry reduction of optimization
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • gain insight of the fundamental concepts in conic optimization • apply algorithmic techniques to problems in the fields of combinatorics, geometry and algebra • extend their expertise in geometry, in particular about the interplay between the fields of geometry and optimization
7	Prerequisites	Recommended: at least one of the modules Linear and combinatorial optimization, robust optimization, discrete optimization
8	Integration in curriculum	semester: 1;3
9	Module compatibility	Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral Dauer der mündlichen Prüfung: 15 Min.
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester

13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • M. Laurent, F. Vallentin: lecture notes • http://www.mi.uni-koeln.de/opt/wp-content/uploads/2015/10/laurent_vallentin_sdo_2012_05.pdf • Further literature and scientific publications are announced during the lectures

1	Module name 65902	Transport and reaction in porous media: Modelling	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	apl. Prof. Dr. Serge Kräutle	
5	Contents	<ul style="list-style-type: none"> Modeling of fluid flow through a porous medium: Groundwater models, saturated and unsaturated porous medium (Richards equation) Advection, diffusion, dispersion of dissolved substances, (nonlinear) reaction-models (i.a. law of mass action, kinetic / reversible reactions in local equilibrium), the stoichiometric matrix Models of partial (PDEs), ordinary (ODEs) differential equations, and local algebraic 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 and uniqueness of stationary solutions in the stoichiometric space (i.a. introduction to the Feinberg network theory) 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	

16 **Bibliography**

- 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 <https://cbe.osu.edu/chemical-reaction-network-theory>

1	Module name 65906	Mathematics of multiscale models	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	PD Dr. Nicolas Neuß
5	Contents	<ul style="list-style-type: none"> • Function spaces of periodic functions and asymptotic expansions • Two-scale convergence and unfolding method • Application to differential equation models in continuum mechanics • Multi-scale finite element methods • Numerical upscaling methods
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • have profound expertise about the basic methods in multi-scale analysis and homogenisation, • are able to derive rigorously homogenised (effective) models and analyse the quality of the approximation.
7	Prerequisites	Recommended: Knowledge in modeling as well as analysis and numerics of partial differential equations
8	Integration in curriculum	semester: 3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MAPa) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • D. Cioranescu & P. Donato: An Introduction to Homogenization • U. Hornung (ed.): Homogenization and Porous Media • Y. Efendiev & T. Hou: Multiscale Finite Element Methods

1	Module name 65907	Theory of stochastic evolution equations	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Infinitely dimensional Wiener processes, • Stochastic integral in Hilbert spaces, • Ito-processes and stochastic differential equations, • Optionally: existence results for stochastic partial differential equations or further results on stochastic ODE (Fokker-Planck equations, . . .) 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • characterize Gaussian measures on Hilbert spaces. They explain representation formulas for Q-Wiener processes as well as the derivation of the stochastic integral, • successfully apply concepts to solve stochastic differential equations explicitly and prove existence of solutions to stochastic evolution equations. 	
7	Prerequisites	Basic knowledge in probability theory or functional analysis is recommended.	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • G. Da Prato & J. Zabczyk: Stochastic equations in infinite dimensions, Cambridge University Press • I. Karatzas & S.E. Shreve: Brownian motion and stochastic calculus, Springer • B. Oksendal: Stochastic differential equations, Springer 	

- C. Prévôt & M. Röckner: A concise course on stochastic partial differential equations, Springerchastic Evolution Equations

1	Module name 65911	Mathematical modeling in the life sciences	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	apl. Prof. Dr. Maria Neuß	
5	Contents	<ul style="list-style-type: none"> • Biochemical reaction networks, enzyme kinetics • Models for interacting populations (Predator-prey, competition, symbiosis) • Diffusion, reactions, and transport in biological cell tissues and vessels • Structured population models 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • have profound knowledge in the area of mathematical modeling of processes in the life sciences • are able to identify significant mechanisms and to apply suitable analytical and numerical methods for their analysis • are able to work interdisciplinary and problem-oriented. 	
7	Prerequisites	Recommended: Modeling and Analysis in Continuum Mechanics I	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • J. D. Murray: Mathematical Biology I: An Introduction, Mathematical Biology II: Spatial Models and Biomedical Applications • G. de Vries, T. Hillen, et al.: A course in Mathematical Biology • J. Prüss: Mathematische Modelle in der Biologie: Deterministische homogene Systeme 	

1	Module name 65914	Partial differential equations in finance	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> models on pricing for financial derivatives, in particular for European and American-type options, selected deterministic equations of financial mathematics, practical knowledge Ito-calculus and stochastic differential equations, analysis and numerics for Black-Scholes equations, variational inequalities and American-type options. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> explain mathematical models for financial markets and derivatives pricing, apply Ito calculus, derive deterministic models based on pde or variational inequalities and discretize them numerically. 	
7	Prerequisites	Basis knowledge in differential equations, probability theory or functional analysis is recommended.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (ca. 15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> M. Capinski & T. Zastawniak: Mathematics for finance, Springer, N. Hilber, O. Reichmann, C. Schwab & C. Winter: Computational methods for quantitative finance, Springer, 	

- B. Oksendal: Stochastic differential equations, Springer.

1	Module name 65915	Introduction to material- and shape optimization	10 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Michael Stingl	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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	<p>Recommended:</p> <ul style="list-style-type: none"> • Knowledge in nonlinear optimization, • Basic knowledge in numerics of partial differential equations 	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • J. Haslinger & R. Mäkinen: Introduction to shape optimization, SIAM, 	

- M. P. Bendsoe & O. Sigmund: Topology Optimization: Theory, Methods and Applications, Springer.

1	Module name 65916	Advanced algorithms for nonlinear optimization	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Michael Stingl	
5	Contents	Several of the following topics: <ul style="list-style-type: none"> • Trust region methods • Iterative methods in the presence of noisy data • Interior point methods for nonlinear problems • Modified barrier and augmented Lagrangian methods • Local and global convergence analysis 	
6	Learning objectives and skills	Students <ul style="list-style-type: none"> • use methods of nonlinear constrained optimization in finite dimensional spaces, • analyse convergence behaviour of these methods and derive robust and efficient realisations, • apply these abilities to technical and economic applications. 	
7	Prerequisites	Basic knowledge in nonlinear optimization is recommended.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • C.T. Kelley: Iterative Methods for Optimization, SIAM, • J. Nocedal & S. Wright: Numerical Optimization, Springer. 	

1	Module name 65917	Discrete optimization I	5 ECTS
2	Courses / lectures	Vorlesung: Discrete Optimization I (2 SWS) Übung: Tutorial zu Discrete Optimization I (1 SWS)	5 ECTS -
3	Lecturers	Kevin-Martin Aigner Florian Rösel	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann
5	Contents	Theoretical and practical fundamentals of solving difficult mixed-integer linear optimization problems (MIPs) constitute the main focus of this lecture. At first, the concept of NP-completeness and a selection of common NP-complete problems will be presented. As for polyhedral theory, fundamentals concerning the structure of faces of convex polyhedra will be covered. Building upon these fundamentals, cutting plane algorithms as well as branch-and-cut algorithms for solving MIPs will be taught. Finally, some typical problems of discrete optimization, e.g., the knapsack problem, the traveling salesman problem or the set packing problem will be discussed.
6	Learning objectives and skills	Students <ul style="list-style-type: none"> • will gain basic theoretical knowledge of solving mixed-integer linear optimization problems (MIPs), • are able to solve MIPs with the help of state-of-the-art optimization software.
7	Prerequisites	Recommended: Linear and Combinatorial Optimization
8	Integration in curriculum	semester: 1
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	

1	Module name 65918	Robust optimization II	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<ul style="list-style-type: none"> 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	<p>Students</p> <ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Recommended: Robust Optimization I 	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> Lecture notes, will be published on StudOn at the beginning of the semester. 	

1	Module name 65919	Numerical aspects of linear and integer programming	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral (ca. 15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • 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 65920	Advanced nonlinear optimization	10 ECTS
2	Courses / lectures	Vorlesung mit Übung: Advanced nonlinear optimization	10 ECTS
3	Lecturers	Prof. Dr. Michael Stingl	

4	Module coordinator	Prof. Dr. Wolfgang Achtziger	
5	Contents	<ul style="list-style-type: none"> advanced optimality conditions and constraint qualifications for constrained optimization problems penalty, barrier and augmented Lagrangian methods: theory and algorithms interior point methods sequential quadratic programming 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> explain and extend their knowledge on theory and algorithms of nonlinear optimization problems, apply solution techniques to different advanced types of optimization problems, derive and solve optimization problems arising from technical and economical applications. 	
7	Prerequisites	Basic knowledge in nonlinear optimization is recommended.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral oral exam (20 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> M.S. Bazaraa, H.D. Sherali & C.M. Shetty: Nonlinear Programming Theory and Algorithms, Wiley, New York, J. Nocedal & S. Wright: Numerical Optimization, Springer. 	

1	Module name 65921	Optimization with partial differential equations	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Michael Stingl	
5	Contents	<p>Several of the following topics:</p> <ul style="list-style-type: none"> • Optimization and control in Banach spaces • Concepts of controllability and stabilization • Optimal control of Partial differential equations • Singular Perturbations and asymptotic analysis • Numerical realizations of optimal controls • Technical, medical and economic applications 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • explain and use theory as well as numerical methods for optimization, control and stabilization in the context of partial differential equations, • apply these abilities to technical and economic applications. 	
7	Prerequisites	Basic knowledge in numerics, partial differential equations, and nonlinear optimization is recommended.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • F. Tröltzsch: Optimal Control of Partial Differential Equations, AMS • G. Leugering & P. Kogut: Optimal Control of PDEs in Reticulated Domains, Birkhäuser 	

1	Module name 65923	Optimization in industry and economy	5 ECTS
2	Courses / lectures	Vorlesung: Optimization in Industry and Economy (Mathematics of Learning) (2 SWS) Übung: Übung zu Optimization in Industry and Economy (Mathematics of Learning) (1 SWS)	5 ECTS -
3	Lecturers	Prof. Dr. Frauke Liers-Bergmann	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<p>This course focuses on modeling and solving real-world optimization problems occurring in industry and economics. Advantages and disadvantages of different modeling techniques will be outlined. In order to achieve efficient solution approaches, different reformulations and their numerical results will be discussed. Students will learn how to present optimization results properly as well as how to interpret and evaluate these results for practical applications. The latter may include but is not limited to the optimization of transport networks (gas, water, energy), air traffic management and mathematical modeling/optimization of market mechanisms in the energy sector.</p>	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • model complex real-world optimization problems with respect to efficient • solvability, • classify the models and use appropriate solution strategies, • evaluate the achieved computational results. 	
7	Prerequisites	Recommended: Modul LKOpt: Linear and combinatorial optimization	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	

14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none">• Lecture notes (will be published on StudOn at the beginning of the semester)• Up-to-date research literature (will be published on StudOn at the beginning of the semester)

1	Module name 65924	Project seminar optimization	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	A specific application is to be used to implement the knowledge of mathematical optimisation models and methods acquired during the degree programme thus far. The content is taken from a current problem, often in close collaboration with an industrial partner. Examples might be the water supply for a city, the design of an energy-efficient facade for an office building or railway construction site management.	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> organise themselves into teams to carry out a large project in which they independently model a real problem, develop and implement solutions and apply their results in practical situations, strengthen their communication skills by presenting and discussing the results of the project work, discuss information, ideas, problems and solutions at an academic level with each other and with the lecturers. 	
7	Prerequisites	Recommended: knowledge in combinatorial optimisation	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Seminar paper Presentation	
11	Grading procedure	Seminar paper (50%) Presentation (50%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Project-dependent. Will be published on StudOn at the beginning of the semester.	

1	Module name 65933	Discrete optimization II	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Timm Oertel	
5	Contents	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 <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • 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

1	Module name 65954	Numerik der Optimalen Steuerungen Numerics of optimal control	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Hannes Meinlschmidt	
5	Contents	<p>The following topics are covered: Discretization methods for differential equations, aspects of nonlinear optimization methods, direct discretization methods (fully and reduced discretized), indirect methods based on discretization of necessary optimality conditions as well as methods for efficient sensitivity calculations with internal numerical differentiation and adjoint equations.</p> <p>The material is presented in lecture form. Further acquisition of the essential concepts and techniques takes place through self-study of accompanying literature and the completion of exercises, supported by meetings within the tutorials.</p> <p>By default, the lecture will be given in English (in German only if all participants agree).</p>	
6	Learning objectives and skills	Students explain and use numerical methods for optimal control problems with ordinary differential equations and differential algebraic equations. They apply basic concepts of solution methodology using direct and indirect discretization methods for application problems, for example in technology or economics.	
7	Prerequisites	Recommended: Basic knowledge in numerics, in theory of ordinary differential equations, and in optimization.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral Dauer der mündlichen Prüfung: 15 Min.	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	

13	Workload in clock hours	Contact hours: 60 h Independent study: 90 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	M. Gerdtts, Optimal Control of ODEs and DAEs, De Gruyter, 2012.

1	Module name 65959	Theorie der Optimalsteuerungen Optimal control theory	10 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Hannes Meinlschmidt	
5	Contents	<p>Grundlagen zu folgenden Themen:</p> <ul style="list-style-type: none"> • Diskrete und kontinuierliche Dynamische Systeme in allgemeinen Räumen • Eingabe- und Ausgabeoperatoren, Beobachter und Aktuatoren • Lösungstheorie und qualitative Theorie • Steuerbarkeit und Stabilisierbarkeit • Restriktionen für Steuerungen und Zuständen • Open-Loop- und Closed-Loop-Steuerungen • Pontriagin'sches Maximum-Prinzip • Dynamische Programmierung • Numerische Realisierung optimaler Steuerungen <p>Die Präsentation des Stoffes erfolgt in Vorlesungsform. Die weitere Aneignung der wesentlichen Begriffe und Techniken erfolgt durch Selbststudium begleitender Literatur, unterstützt durch Zusammenkünfte innerhalb der Übungen.</p>	
6	Learning objectives and skills	<p>Die Studierenden</p> <ul style="list-style-type: none"> • erklären und verwenden eine vertiefte Theorie und vertiefte numerische Methoden im Umgang mit der Steuerung, Stabilisierung und Optimalsteuerung im Kontext der gewöhnlichen Differentialgleichungen. Diese Fähigkeiten sind sowohl in naturwissenschaftlichen, medizinischen, wirtschaftswissenschaftlichen als auch und insbesondere in Ingenieurwissenschaften von Bedeutung. 	
7	Prerequisites	<p>empfohlen:</p> <ul style="list-style-type: none"> • Grundkenntnisse der Numerik, der gewöhnlichen und partiellen Differentialgleichungen, der Optimierung 	
8	Integration in curriculum	semester: 2;1;3	
9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral mündliche Prüfung (20 Min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	

14	Module duration	1 semester
15	Teaching and examination language	german
16	Bibliography	<ul style="list-style-type: none">• E. Sontag, Mathematical Control Theory, Springer-Verlag 2000• F. Tröltzsch, Steuerungstheorie Partieller Differentialgleichungen, Vieweg Verlag, 2003

1	Module name 65997	Analysis of free-boundary problems in continuum mechanics	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Derivation of time-dependent free boundary problems in continuum mechanics, • Basic results on existence and qualitative behaviour, • Optimal estimates on the propagation of free boundaries, • Other approaches, e.g. relaxation by phase-field models. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • formulate free-boundary problems in hydrodynamics and in porousmedia flow • explain analytical concepts for existence and nonnegativity results for degenerate parabolic equations as well as techniques for optimal estimates on spreading rates • validate different modeling approaches in a critical way. 	
7	Prerequisites	Recommended: Basic knowledge of analysis of partial differential equations, corresponding to the syllabus of Modeling and Applied Analysis in Continuum Mechanics or that one of other pde-lectures.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (ca. 15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • L.C. Evans: Partial Differential Equations, AMS, • Original journal articles. 	

1	Module name 65787	Seminar Applied Analysis Seminar: Applied analysis	5 ECTS
2	Courses / lectures	Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS)	5 ECTS
3	Lecturers	Prof. Dr. Günther Grün	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	Topics from Applied Analysis to deepen the theoretical contents of the lecture ModAna1	
6	Learning objectives and skills	<div style="border: 1px solid black; padding: 5px;"> <p>Students</p> <ul style="list-style-type: none"> • are able to familiarize themselves with advanced topics using journal articles or graduate textbooks, • can present the acquired content orally in a structured manner, with, if necessary, own additions in content, • actively participate at discussions about mathematical topics raised by the presentations in the seminar. </div>	
7	Prerequisites	Module ModAna1 is recommended	
8	Integration in curriculum	semester: 2	
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Mandatory elective module in M.Sc. Computational and Applied Mathematics	
10	Method of examination	Seminar achievement Oral presentation (90min) and presentation document (4-8 pages)	
11	Grading procedure	Seminar achievement (100%) Oral presentation (80%), presentation document (20%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Determined by the topic chosen	

1	Module name 65879	Differentialgeometrie Differential geometry	10 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	apl. Prof. Dr. Jens Habermann	
5	Contents	<p>Eine Auswahl aus den folgenden Themen:</p> <ul style="list-style-type: none"> • Mannigfaltigkeiten (Tangentialvektoren, Vektorfelder, Flüsse) • Vektorbündel (Tensorbündel und (Semi-)Riemannsche Strukturen) • Differentialformen (Orientierung, Integration) • Affine Zusammenhänge (Paralleltransport, Krümmung) • Geodäten (Distanz, Jacobi Vektorfelder) • Einführung in der geometrischen Analysis • Symplektische und Poisson-Strukturen • Liegruppen und glatte Wirkungen 	
6	Learning objectives and skills	<p>Die Studierenden</p> <ul style="list-style-type: none"> • nennen und erklären die grundlegende Theorie der Mannigfaltigkeiten und ihrer Struktur, • erkennen und verwenden zusätzliche geometrische Strukturen auf Mannigfaltigkeiten wie zum Beispiel affine Zusammenhänge, Riemannsche Metriken oder symplektische Formen. 	
7	Prerequisites	Grundkenntnisse in Topologie, Analysis, Lineare Algebra und Gewöhnliche Differentialgleichungen	
8	Integration in curriculum	no Integration in curriculum available!	
9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Written examination (90 minutes)	
11	Grading procedure	Written examination (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 90 h Independent study: 210 h	
14	Module duration	1 semester	
15	Teaching and examination language		
16	Bibliography	<ul style="list-style-type: none"> • S. Lang: "Differential and Riemannian manifolds" • J.M. Lee: "Introduction to Riemannian Manifolds" • R.L. Bishop and R.J. Crittenden, "Geometry of manifolds" 	

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|--|--|
| | <ul style="list-style-type: none">• F. Warner: "Foundations of Differentiable Manifolds and Lie Groups"• M. Do Carmo: "Riemannian Geometry" |
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1	Module name 65864	Hyperbolic Conservation Laws and Application	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Emil Wiedemann	
5	Contents	<p>Hyperbolic conservation laws are essential for the description of non-dissipative phenomena such as the flow of inviscid gases or shallow water waves. The mathematical theory is confronted with the lack of regularity, as initially smooth solutions may develop discontinuities (interpreted as shock waves) in finite time. We study scalar conservation laws, for which there is a classical well-posedness theory of entropy solutions due to Kruzhkov. Later, we investigate hyperbolic systems with a special focus on the Riemann problem, which requires a detailed understanding of the geometry of shock and rarefaction curves. Particular emphasis will be on the discussion of models of gas flow and thermodynamics, such as the compressible Euler equations.</p>	
6	Learning objectives and skills	<p>Students know and understand the basic theory of scalar conservation laws and hyperbolic systems. They relate mathematical theory to the modelling of physical phenomena and are familiar with various concepts of entropy. They learn important analytical techniques such as compensated compactness.</p>	
7	Prerequisites	<p>Recommended: Linear Algebra, Analysis, and a beginners' course on partial differential equations.</p>	
8	Integration in curriculum	semester: 1;2;3	
9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (30 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Will be announced in the lecture.	

1	Module name 65877	Polynomial Optimization and Application	5 ECTS
2	Courses / lectures	Übung: Exercise Polynomial optimization and applications (1 SWS) Vorlesung: Polynomial optimization and applications (2 SWS)	- 5 ECTS
3	Lecturers	Prof. Dr. Giovanni Fantuzzi	

4	Module coordinator	Prof. Dr. Giovanni Fantuzzi
5	Contents	<p>Polynomial optimization problems (POPs) form a broad class of optimization problems that find applications to control theory, dynamical systems, optimal transport, power flow networks, fluid mechanics, and many other fields. This course will introduce students to a modern approach to solving POPs through semidefinite programming techniques. More specifically, the course will cover:</p> <ul style="list-style-type: none"> • The basics of semidefinite programs • The theory of sum-of-squares (SOS) polynomials • Moment-SOS hierarchies for polynomial optimization problems • Applications (e.g. to dynamical system analysis) <p>Students will also have the opportunity to put the theory into practice with “hands-on” practical assignments.</p>
6	Learning objectives and skills	<p>By the end of the course, students should be able to:</p> <ul style="list-style-type: none"> • Explain what polynomial optimization problems (POPs) are • Give examples of applications where POPs arise • Formulate semidefinite programming relaxations of POPs • Apply moment-SOS hierarchies to a range of problems • Solve POPs in practice using existing software
7	Prerequisites	Previous experience with optimization (especially convex and/or conic optimization) and with differential equations is desirable.
8	Integration in curriculum	semester: 1;3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral (30 minutes)
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h
14	Module duration	1 semester

15	Teaching and examination language	
16	Bibliography	Lecture notes will be provided as the course progresses. A reading list will also be provided at the start of the course.

1	Module name 48241	Mathematical Image Processing	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers. This module is offered in every second summer term. The next course will be held in the summer semester 2024.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Daniel Tenbrinck	
5	Contents	<p>This module covers mathematical image processing techniques based on Fourier domain filters, variational methods, and partial differential equations.</p> <p>In particular, the following content will be introduced to the students:</p> <ul style="list-style-type: none"> • contrast enhancement • filtering in Fourier and image domain • Bayesian image denoising • image deblurring / deconvolution • pixel-based clustering • region-based segmentation • image inpainting • nonlocal image processing using graphs 	
6	Learning objectives and skills	<p>Students following this course will</p> <ul style="list-style-type: none"> • learn how image data can be modeled and analyzed mathematically • develop a deeper understanding of mathematical basics and methods for image processing • implement own algorithms for mathematical image processing • discover connections to related mathematical fields, e.g., inverse problems and convex analysis 	
7	Prerequisites	<p>Knowledge in calculus and linear algebra is recommended to understand the mathematical foundations of image processing. Knowledge in functional analysis, numerical mathematics, or inverse problems is helpful to understand advanced concepts in mathematical image processing.</p>	
8	Integration in curriculum	semester: 2;1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	

10	Method of examination	Written or oral Oral examination (20 min.) or written examination (60 min.) depending on size of course.
11	Grading procedure	Written or oral (100%) Oral exam (100%) or written exam (100%) depending on size of course.
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • G. Aubert & P. Kornprobst: Mathematical problems in Image Processing, Springer • K. Bredies & D. Lorenz, Mathematical Image Processing, Springer • S. Osher & R. Fedkiw, Level Set Methods and Dynamic Implicit Surfaces, Springer • A. Elmoataz , O.Lezoray, S. Bogleux: Nonlocal Discrete Regularization on Weighted Graphs: a framework for Image and Manifold Processing, IEEE Transactions On Image Processing, 17 (7), pp: 1047-1060, 2008

1	Module name 65970	Stochastische Analysis Stochastic analysis	5 ECTS
2	Courses / lectures	Vorlesung: Stochastische Analysis (2 SWS) Übung: Übung zur Stochastischen Analysis (2 SWS)	5 ECTS -
3	Lecturers	Prof. Dr. Torben Krüger	

4	Module coordinator	Prof. Dr. Torben Krüger	
5	Contents	<ul style="list-style-type: none"> • Itokalkulus • Diffusionsprozesse • Stochastische Differentialgleichungen • Die Präsentation des Stoffes erfolgt in Vorlesungsform. 	
6	Learning objectives and skills	<p>Die Studierenden erwerben die Fähigkeit komplexere Strukturen der Stochastik selbständig zu erfassen und auf exemplarische Problemstellungen anzuwenden. Diese bilden eine Basis für eine Spezialisierung in Stochastik undentsprechenden wirtschaftsmathematischen Themen.</p>	
7	Prerequisites	empfohlen: Kenntnisse der Wahrscheinlichkeitstheorie sind zum Verständnis hilfreich	
8	Integration in curriculum	semester: 1	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral Dauer der mündlichen Prüfung: 15 Min.	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	german	
16	Bibliography	Die vorbereitende Literatur wird für jede Lehrveranstaltung jedes Semester neu festgelegt.	

1	Module name 65096	Seminar Selected Topics of Applied Analysis Seminar: Selected topics of applied analysis	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	Topics from Applied Analysis to deepen the theoretical contents of the lecture <i>ModAna1</i>	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • are able to familiarize themselves with advanced topics using journal articles or graduate textbooks, • can present the acquired content orally in a structured manner, with, if necessary, own additions in content, • actively participate at discussions about mathematical topics raised by the presentations in the seminar. 	
7	Prerequisites	<p>Linear algebra and calculus are required.</p> <p>Basic knowledge in probability theory is recommended.</p>	
8	Integration in curriculum	no Integration in curriculum available!	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Mandatory elective module in M.Sc. Computational and Applied Mathematics</p> <p>Summer or winter term after participation at <i>ModAna1</i></p>	
10	Method of examination	<p>Presentation</p> <p>Oral (90 minutes)</p> <p>Oral presentation (90min) and presentation document (4-8 pages)</p>	
11	Grading procedure	<p>Presentation (20%)</p> <p>Oral (80%)</p> <p>Oral presentation (80%)</p> <p>presentation document (20%)</p>	
12	Module frequency	Irregular	

13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	Determined by the topic chosen

1	Module name 65067	Introduction to control and machine learning	5 ECTS
2	Courses / lectures	Vorlesung mit Übung: Introduction to Control and Machine Learning (2 SWS)	5 ECTS
3	Lecturers	Prof. Dr. Enrique Zuazua Iriondo Ziqi Wang	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ul style="list-style-type: none"> 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. 	
6	Learning objectives and skills	Students are able to <ul style="list-style-type: none"> understand some basic theory on control and machine learning. learn about recent advances on control and machine learning. set out their approaches and results in a comprehensible and convincing manner, making use of appropriate presentation techniques. 	
7	Prerequisites	Recommended: basic knowledge of calculus, linear algebra, ODE and PDE.	
8	Integration in curriculum	semester: 2	
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 <ul style="list-style-type: none"> Mandatory elective module for MSc in Data Science in the field of study "Simulation and Numerics" Mandatory elective module for MSc in Computational and Applied Mathematics in the specialization "OPTI" 	
10	Method of examination	Oral (15 minutes) oral exam (20 minutes)	
11	Grading procedure	Oral (100%) 100% based on oral exam	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 62,5	
14	Module duration	1 semester	

15	Teaching and examination language	english
16	Bibliography	<p>[1] L. Bottou, F. E. Curtis, and J. Nocedal, Optimization methods for large-scale machine learning. SIAM Review, 60 (2) (2018) , 223-311.</p> <p>[2] J. M. Coron, Control and Nonlinearity, Mathematical Surveys and Monographs, 143, AMS, 2009.</p> <p>[3] I. Goodfellow, Y. Bengio, & A. Courville, Deep Learning. MIT press, 2016.</p> <p>[4] C. F. Higham, and D. J. Higham, Deep learning: An introduction for applied mathematicians. SIAM Review, 61 (4) (2019), 860-891.</p> <p>[5] J. Nocedal, and S. Wright, Numerical Optimization. Springer Science & Business Media, 2006.</p> <p>[6] D. Ruiz-Balet, and E. Zuazua, Neural ODE control for classification, approximation and transport. arXiv preprint arXiv:2104.05278, (2021).</p> <p>[7] E. Zuazua, Propagation, observation, and control of waves approximated by finite difference methods, SIAM Review, 47 (2) (2005), 197-243.</p> <p>[8] 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.</p>

Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti)

1	Module name 65890	Master's seminar NASi	5 ECTS
2	Courses / lectures	Masterseminar: Masterseminar (2 SWS)	5 ECTS
		Masterseminar: Master seminar "Numerical solutions for eigenvalue problems"	5 ECTS
		Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS)	5 ECTS
		Masterseminar: Numerical methods for phase-field equations	5 ECTS
3	Lecturers	Prof. Dr. Timm Oertel Prof. Dr. Daniel Tenbrinck Prof. Dr. Günther Grün Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Eberhard Bänsch
5	Contents	A topic from NASi that relates to the compulsory elective modules offered.
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • 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. <p>For the NASi specification:</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	<p>Presentation (90 minutes)</p> <p>Written (schriftliche Ausarbeitung 5-10 Seiten)</p>
11	Grading procedure	<p>Presentation (75%)</p> <p>Written (25%)</p>
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 30 h

		Independent study: 120 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	Module name 65895	Master seminar Opti	5 ECTS
2	Courses / lectures	Masterseminar: Masterseminar (2 SWS) Masterseminar: Master seminar "Numerical solutions for eigenvalue problems" Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS) Masterseminar: Material and Topology Optimization (2 SWS) Masterseminar: Numerical methods for phase-field equations	5 ECTS 5 ECTS 5 ECTS 5 ECTS 5 ECTS
3	Lecturers	Prof. Dr. Timm Oertel Prof. Dr. Daniel Tenbrinck Prof. Dr. Günther Grün Prof. Dr. Michael Stingl Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Michael Stingl
5	Contents	A topic from Opti that relates to the compulsory elective modules offered.
6	Learning objectives and skills	Students <ul style="list-style-type: none"> • 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: <ul style="list-style-type: none"> • 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 in curriculum	semester: 3
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Presentation (90 minutes) Written (schriftliche Ausarbeitung 5-10 Seiten)

11	Grading procedure	Presentation (75%) Written (25%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	Module name 65910	Discrete optimization III	5 ECTS
2	Courses / lectures	Vorlesung: Diskrete Optimierung III (2 SWS) Übung: Tutorial zu Diskrete Optimierung III (1 SWS)	5 ECTS -
3	Lecturers	Prof. Dr. Timm Oertel	

4	Module coordinator	Prof. Dr. Timm Oertel	
5	Contents	<p>In this lecture we will discuss selected topics in discrete and mixed-integer optimization. Possible topics include lattice methods, integer programming in fixed dimension, recent research on (mixed) integer linear and/or (mixed) integer nonlinear programming and so on. The specific topics may vary and will be announced in due time.</p> <p>FORMERLY: 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.</p>	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • use basic terms of discrete optimization • model real-world discrete optimization problems, determine their complexity and solve them with appropriate mathematical methods. 	
7	Prerequisites	<p>Recommended: Knowledge in linear and combinatorial optimization, discrete optimization I and II</p>	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (15 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	<p>Contact hours: 45 h Independent study: 105 h</p>	
14	Module duration	1 semester	

15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • 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

1	Module name 65909	Subspace correction methods	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Carsten Gräser	
5	Contents	1) Subspace correction as an abstract framework to construct and analyse efficient iterative methods 2) Analysis of additive and multiplicative subspace correction 3) Multigrid and domain decomposition as subspace correction methods 4) Nonlinear subspace correction methods	
6	Learning objectives and skills	Students are <ul style="list-style-type: none"> familiar with the abstract subspace correction framework can select problem adapted methods can analyse specific methods within the framework 	
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 in curriculum	semester: 2	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral (15 minutes) oral exam (15 min)	
11	Grading procedure	Oral (100%) 100% based on oral exam	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> H. Yserentant: Old and New Convergence Proofs for Multigrid Methods, Acta Numer. 1993 J.-C. Xu: Iterative Methods by Space Decomposition and Subspace Correction, SIAM Rev., 1992 Further literature and publications are announced during the lecture 	

1	Module name 65068	Wave Phenomena Wave phenomena	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<p>1) Motivations and applications.</p> <p>2) Linear transport equation: method of characteristics; Fourier analysis and numerical approximations.</p> <p>3) The wave equation: D'Alembert's representation formula; regularity of the solutions; finite speed of propagation of perturbations; Huygens' principle; geometric optics; wave models with sources or sinks; Kirchhoff's representation in \mathbb{R}^3; Poisson's representation in \mathbb{R}^2; the case of general odd and even space dimensions; energy methods: domain of dependence inequality and energy conservation; representation of solutions by using partial Fourier transform; subordination waves-heat; the reflection method and waves on the half-line; separation of variables.</p> <p>4) Klein-Gordon equation: energy estimates; representation of solutions by using Fourier multipliers; von Wahl's transformation.</p> <p>5) Damped wave equation: energy estimates; representation of solutions by using Fourier multipliers; decay behavior and decay rate.</p> <p>6) Damped plate equation: estimates for the energy; estimates for the solution itself and its derivatives;</p> <p>7) Semilinear wave equation: global existence for small data and global existence for large data.</p> <p>8) Diffusion phenomena: parabolic structure of solutions to damped waves and damped plates; diffusion phenomena in thermo-elasticity; traveling waves and reaction-diffusion models.</p> <p>9) Scalar conservation laws: occurrence of shocks and rarefaction waves.</p> <p>10) Linear and nonlinear dispersive waves: Solitary waves for the Korteweg-de Vries equation; plane-wave solutions for the Airy equation and Schrödinger; Fourier analysis.</p> <p>11) Maxwell equations: constitutive equations; special cases; boundary conditions; expansion into wave functions.</p>	
6	Learning objectives and skills	<p>Students are able to:</p> <ul style="list-style-type: none"> • identify significant mechanisms and to apply suitable analytical and numerical methods for their analysis • work interdisciplinary and in problem-oriented way; • use language and techniques related to partial differential equations; • 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 in curriculum	semester: 2
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral (20 minutes)
11	Grading procedure	Oral (100%)
12	Module frequency	Only in summer semester
13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • Ebert, M. R. & Reissig, M. Methods for Partial Differential Equations. Birkhäuser, 2018. • Evans, L. C. Partial Differential Equations. AMS, 2010. • Kirsch, A. and Hettlich, F. The Mathematical Theory of Maxwell's Equations. Lecture Notes, 2013: • https://www.math.kit.edu/ianmip/lehre/maxwellequ2012w/media/main.pdf • Myint-U, T. & Debnath, L. Linear partial differential equations for scientists and engineers. Birkhäuser, 2007. • Reissig, M. Theory of hyperbolic equations. Lecture Notes, 2007: • https://tu-freiberg.de/sites/default/files/media/institut-fuer-angewandte-analysis-9030/reissig/pdehanoi1.pdf • Vichnevetsky, R. & Bowles, J. B. Fourier Analysis of Numerical Approximations of Hyperbolic Equations. SIAM, 1982 <p>Lecture notes will be distributed via StudOn.</p>

1	Module name 65089	Scalar conservation laws	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ol style="list-style-type: none"> 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; Kruzhkov'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: Oleinik'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	<p>Students are able to:</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	

9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral (ca. 15 min)
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<p>Chapters 1-10:</p> <ul style="list-style-type: none"> • Bressan, A. Hyperbolic Systems of Conservation Laws: The One-dimensional Cauchy Problem. Oxford University Press, 2000. • Coclite, G. M. Scalar Conservation Laws. Lecture Notes, 2022. • Dafermos, C. M. Hyperbolic Conservation Laws in Continuum Physics. 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: https://metaphor.ethz.ch/x/2019/hs/401-4671-00L/literature/mishra_hyperbolic_pdes.pdf • Salsa, S. Partial differential equations in action. From modelling to theory. Springer, 2016. • Salsa, S. & Verzini, G. Partial differential equations in action. Complements and exercises. Springer, 2015. <p>Chapter 11:</p> <ul style="list-style-type: none"> • 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 Anal., Theory Methods Appl., Ser. A, Theory Methods* 50, No. 4, 455-469 (2002).

Chapter 12:

- Andreianov, B. P., Coclite, G. M. & Donadello, C. Well-posedness for vanishing viscosity solutions of scalar conservation laws on a network. *Discrete Contin. Dyn. Syst.* 37, No. 11, 5913-5942 (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. *Z. Angew. Math. Phys.* 73, No. 6, Paper No. 241, 10 p. (2022).
- 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. *Annales de l'Institut Henri Poincaré C, Analyse Non Linéaire* (2022).
- Keimer, A. & Pflug, L. Existence, uniqueness and regularity results on nonlocal balance laws. *J. Differ. Equations* 263, No. 7, 4023-4069 (2017).

Lecture notes will be distributed via StudOn.

1	Module name 65083	Efficient discretization of two-phase flow	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Dr. Stefan Metzger	
5	Contents	Based on recent scientific publications, different discretization approaches for two-phase flow are discussed.	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • 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, • learn to compare different discretization methods regarding their specific advantages and disadvantages. 	
7	Prerequisites	Recommended: Numerics of Partial Differential Equations I	
8	Integration in curriculum	no Integration in curriculum available!	
9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Seminar achievement Vortrag (60 Min) + schriftliche Ausarbeitung (5-15 Seiten)	
11	Grading procedure	Seminar achievement (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.	

1	Module name 65093	Control, machine learning and numerics	10 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ul style="list-style-type: none"> 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	<p>Students are able to</p> <ul style="list-style-type: none"> 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Variable	
11	Grading procedure	Variable (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	
14	Module duration	1 semester	

15	Teaching and examination language	english
16	Bibliography	<ol style="list-style-type: none"> 1) L. Bottou, F. E. Curtis, and J. Nocedal, Optimization methods for large-scale machine learning. <i>SIAM Review</i>, 60 (2) (2018) , 223-311. 2) J. M. Coron, Control and Nonlinearity, <i>Mathematical Surveys and Monographs</i>, 143, AMS, 2009. 3) I. Goodfellow, Y. Bengio, & A. Courville, <i>Deep Learning</i>. MIT press, 2016. 4) R. Glowinski, J. L. Lions, and J. He, Exact and Approximate Controllability for Distributed Parameter Systems: A Numerical Approach, <i>Encyclopedia Math. Appl.</i>, Cambridge University Press, Cambridge, UK, 2008. 5) C. F. Higham, and D. J. Higham, Deep learning: An introduction for applied mathematicians. <i>SIAM Review</i>, 61 (4) (2019), 860-891. 6) J. Nocedal, and S. Wright, <i>Numerical Optimization</i>. Springer Science & Business Media, 2006. 7) D. Ruiz-Balet, and E. Zuazua, Neural ODE control for classification, approximation and transport. <i>arXiv preprint arXiv:2104.05278</i>, (2021). 8) E. Zuazua, Propagation, observation, and control of waves approximated by finite difference methods, <i>SIAM Review</i>, 47 (2) (2005), 197-243. 9) E. Zuazua, Controllability and observability of partial differential equations: some results and open problems, in <i>Handbook of Differential Equations: Evolutionary Equations</i>. Vol. 3. North-Holland, 2006. 527-621.

1	Module name 65095	Practical course on finite element methods for phase-separation equations Practical course on finite element methods for phase separation equations	5 ECTS
2	Courses / lectures	Vorlesung: Practical Course on Finite Element Methods for Phase-Separation Equations (3 SWS)	5 ECTS
3	Lecturers	Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Finite element discretization for Cahn-Hilliard equations, • Storage concepts for sparse matrices, • Adaptive mesh refinement. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 1	
9	Module compatibility	Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral (ca. 30 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • 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 	

1	Module name 65700	Lecture Series Partial Differential Equations, Control and Numerics (PdeConNum) Lecture series: Partial differential equations, control and numerics (PdeConNum)	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ul style="list-style-type: none"> • Examples of PDE models arising in industrial applications, Biology and Social Sciences • Long time asymptotics • Control of trajectories • Numerics for long time dynamics and control • Some applications in the control of population dynamics 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • develop understanding for special aspects of dynamical systems control, • apply numerical methods to control problems and develop a basic understanding of their properties, • derive and solve inverse problems arising from applications. 	
7	Prerequisites	Recommended: basic knowledge in functional analysis	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (15 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • J. M. Coron, Control and nonlinearity, Mathematical Surveys and Monographs, 143, AMS, 2009 • E. Zuazua. Propagation, observation, and control of waves approximated by finite difference methods. SIAM Review, 47 (2) (2005), 197-243 	

1	Module name 65785	Mathematics of Learning Mathematics of learning	5 ECTS
2	Courses / lectures	Vorlesung: Mathematics of Learning (2 SWS) Übung: Übung zu Mathematics of Learning (2 SWS)	3 ECTS 2 ECTS
3	Lecturers	Florian Rösel Prof. Dr. Frauke Liers-Bergmann	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<ul style="list-style-type: none"> 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	<p>Students</p> <ul style="list-style-type: none"> 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 in curriculum	semester: 1;3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Written examination (60 minutes)	
11	Grading procedure	Written examination (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 60 h Independent study: 90 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> Goodfellow, Bengio, Courville, Deep Learning, MIT Press, 2015 Hastie, Tibshirani, Friedman, The Elements of Statistical Learning, 2008 	

1	Module name 65862	Conic Optimization and Applications Conic optimisation and applications	5 ECTS
2	Courses / lectures	Vorlesung: Conic Optimization and Applications (2 SWS) Übung: Übung Conic Optimization and Applications (2 SWS)	5 ECTS -
3	Lecturers	Prof. Dr. Giovanni Fantuzzi	

4	Module coordinator	Prof. Dr. Jan Rolfes
5	Contents	<p>In modern Convex Optimization the theory of semidefinite optimization plays a central role. Semidefinite optimization is a generalization of linear optimization, where one wants to optimize linear functions over positive semidefinite matrices restricted by linear constraints. A wide class of convex optimization problems can be modeled using semidefinite optimization. On the one hand, there are algorithms to solve semidefinite optimization problems, which are efficient in theory and practice. On the other hand, semidefinite optimization is a tool of particular usefulness and elegance.</p> <p>Overview of topics:</p> <ul style="list-style-type: none"> • Topological properties of cones • Foundations of conic optimization, theorems of the alternative, duality • Applications in Eigenvalue optimization and robust optimization • Approximations of combinatorial optimization problems such as MAXCUT, packing problems, coloring problems, Shannon capacity • Symmetry reduction of optimization
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • gain insight of the fundamental concepts in conic optimization • apply algorithmic techniques to problems in the fields of combinatorics, geometry and algebra • extend their expertise in geometry, in particular about the interplay between the fields of geometry and optimization
7	Prerequisites	Recommended: at least one of the modules Linear and combinatorial optimization, robust optimization, discrete optimization
8	Integration in curriculum	semester: 1;3
9	Module compatibility	Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral Dauer der mündlichen Prüfung: 15 Min.
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester

13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • M. Laurent, F. Vallentin: lecture notes • http://www.mi.uni-koeln.de/opt/wp-content/uploads/2015/10/laurent_vallentin_sdo_2012_05.pdf • Further literature and scientific publications are announced during the lectures

1	Module name 65900	Advanced discretization techniques	10 ECTS
2	Courses / lectures	Vorlesung: Advanced Discretization Techniques (4 SWS) Übung: Exercises for Advanced Discretization Techniques (1 SWS)	10 ECTS -
3	Lecturers	Prof. Dr. Carsten Gräser	

4	Module coordinator	Prof. Dr. Eberhard Bänsch
5	Contents	<ul style="list-style-type: none"> conforming and non-conforming finite element methods saddle point problems in Hilbert spaces mixed finite element methods for saddle point problems, in particular for Darcy and Stokes Streamline-Upwind Petrov-Galerkin (SUPG) and discontinuous Galerkin (dG) finite element methods (FEM) for convection dominated problems Finite Volume (FV) methods and their relation to FEM a posteriori error control and adaptive methods
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> have a discriminating understanding, both theoretically and computationally of FE as well as FV methods for the numerical solution of partial differential equations (pde) (in particular of saddle point problems), are capable of developing problem dependent FE or FV methods and judge on their properties regarding stability and effectiveness, are familiar with a broad spectrum of pde problems and their computational solutions, are capable of designing algorithms for adaptive mesh control.
7	Prerequisites	Recommended: Introduction to numerical methods for pdes, functional analysis
8	Integration in curriculum	semester: 1
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h

14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • A. Ern, J.-L. Guermond: Theory and Practice of Finite Elements • A. Quarteroni & A. Valli: Numerical Approximation of Partial Differential Equations • P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Differential Equations, Springer • D. A. Di Pietro & A. Ern: Mathematical aspects of discontinuous Galerkin methods. Springer 2012

1	Module name 65901	Advanced solution techniques	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral oral exam (15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	

16	Bibliography	<ul style="list-style-type: none">• 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 65903	Transport and reaction in porous media: Simulation	5 ECTS
2	Courses / lectures	Vorlesung: Transport and reaction in porous media: Simulation	-
3	Lecturers	apl. Prof. Dr. Serge Kräutle	

4	Module coordinator	apl. Prof. Dr. Serge Kräutle	
5	Contents	<ul style="list-style-type: none"> • Degenerate parabolic differential equations as multiphase flow models: formulation, model derivation through asymptotic expansion, nonlinear solution methods, discretization methods • Sorption reactions and mineral precipitation-dissolution reactions, formulations as complementarity problems • Models for transport and reactions in porous media, consisting of coupled PDEs and ODEs, if necessary coupled to algebraic equations (AEs) and inequalities for the description of local equilibria (differential-algebraic system) • Different formulations of the system • Different numerical strategies: operator splitting, direct substitutional approach, change of variables and combination/elimination of equations (xi-eta-method), as a basis for different software packages for numerical simulations, connection to optimisation (minimization of Gibbs free energy under constraints) • Treatment of numerical difficulties (nonsmooth equations, treatment of complementarity conditions, guarantee of nonnegativity of numerical solutions of the nonlinear problems, range of convergence of Newton's method, scaling problems, advection dominated problems) 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • use methods for the numerical solving of a class of problems whose complexity goes significantly beyond standard problems (Poisson and heat equation): coupled nonlinear partial and ordinary differential equations (PDEs, ODEs) and algebraic equations (AEs), • put strategies for the treatment of possible difficulties during the numerical solving into practice. 	
7	Prerequisites	<ul style="list-style-type: none"> • Recommended: Basic knowledge in differential equations, • Also useful: Transport and Reaction in Porous Media: Modeling 	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p>	

		Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Partial Differential Equations, Springer • Journal articles will be named in the lecture • Handbooks of Software Packages https://en.www.math.fau.de/angewandte-mathematik-1/forschung/software-2

1	Module name 65904	Numerics of incompressible flows I	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • V. Girault, P.-A. Raviart: Finite element methods for the Navier-Stokes equations. Theory and algorithms. Springer 1986 	

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| | <ul style="list-style-type: none">• H. Elman, D. Silvester, A. Wathen: 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 65905	Numerics of incompressible flows II	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • Variational formulation of the instationary Stokes and Navier-Stokes (NVS) equations • Existence and uniqueness of solutions to the instationary Stokes and NVS equations • Time discretisation methods • Fully discrete equations and error estimates • Solution techniques • Operator splitting, projection methods • More general boundary conditions • Coupling of NVS with temperature equation • Computational experiments with academic or commercial codes 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • discretize the instationary NVS equations in time and space, • explain and analyse discretisation schemes and operator splitting techniques, • choose appropriate algorithms for given flow problems and solve them with academic or commercial software. 	
7	Prerequisites	Recommended: Advanced discretization techniques, Numerics of incompressible flows I	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	

16	Bibliography	<ul style="list-style-type: none">• V. Girault & 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. Glowinski: Finite Element Methods for Incompressible Viscous Flow, in : Handbook of Numerical Analysis vol. IX• R. Temam: Navier-Stokes equations. Theory and numerical analysis. North Holland
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1	Module name 65908	Numerics of stochastic evolution equations	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Strong and weak approximations, explicit and implicit schemes for stochastic differential equations (SDEs), • Consistency, stability, convergence, • Monte Carlo methods, variance-reduction schemes. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • have critical understanding of capabilities of numerical schemes for stochastic differential equations, • are capable to use own or commercial software for SDEs and to judge results critically. 	
7	Prerequisites	Basic knowledge in probability theory and in numerics is recommended.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • P.E. Kloeden & E. Platen: Numerical solution of stochastic differential equations • B. Lapeyre, E. Pardoux & R. Sentis: Introduction to Monte? Carlo methods for transport and diffusion equations 	

1	Module name 65914	Partial differential equations in finance	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> models on pricing for financial derivatives, in particular for European and American-type options, selected deterministic equations of financial mathematics, practical knowledge Ito-calculus and stochastic differential equations, analysis and numerics for Black-Scholes equations, variational inequalities and American-type options. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> explain mathematical models for financial markets and derivatives pricing, apply Ito calculus, derive deterministic models based on pde or variational inequalities and discretize them numerically. 	
7	Prerequisites	Basis knowledge in differential equations, probability theory or functional analysis is recommended.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (ca. 15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> M. Capinski & T. Zastawniak: Mathematics for finance, Springer, N. Hilber, O. Reichmann, C. Schwab & C. Winter: Computational methods for quantitative finance, Springer, 	

- B. Oksendal: Stochastic differential equations, Springer.

1	Module name 65915	Introduction to material- and shape optimization	10 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Michael Stingl	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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	<p>Recommended:</p> <ul style="list-style-type: none"> • Knowledge in nonlinear optimization, • Basic knowledge in numerics of partial differential equations 	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • J. Haslinger & R. Mäkinen: Introduction to shape optimization, SIAM, 	

- M. P. Bendsoe & O. Sigmund: Topology Optimization: Theory, Methods and Applications, Springer.

1	Module name 65916	Advanced algorithms for nonlinear optimization	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Michael Stingl	
5	Contents	Several of the following topics: <ul style="list-style-type: none"> • Trust region methods • Iterative methods in the presence of noisy data • Interior point methods for nonlinear problems • Modified barrier and augmented Lagrangian methods • Local and global convergence analysis 	
6	Learning objectives and skills	Students <ul style="list-style-type: none"> • use methods of nonlinear constrained optimization in finite dimensional spaces, • analyse convergence behaviour of these methods and derive robust and efficient realisations, • apply these abilities to technical and economic applications. 	
7	Prerequisites	Basic knowledge in nonlinear optimization is recommended.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • C.T. Kelley: Iterative Methods for Optimization, SIAM, • J. Nocedal & S. Wright: Numerical Optimization, Springer. 	

1	Module name 65917	Discrete optimization I	5 ECTS
2	Courses / lectures	Vorlesung: Discrete Optimization I (2 SWS) Übung: Tutorial zu Discrete Optimization I (1 SWS)	5 ECTS -
3	Lecturers	Kevin-Martin Aigner Florian Rösel	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann
5	Contents	Theoretical and practical fundamentals of solving difficult mixed-integer linear optimization problems (MIPs) constitute the main focus of this lecture. At first, the concept of NP-completeness and a selection of common NP-complete problems will be presented. As for polyhedral theory, fundamentals concerning the structure of faces of convex polyhedra will be covered. Building upon these fundamentals, cutting plane algorithms as well as branch-and-cut algorithms for solving MIPs will be taught. Finally, some typical problems of discrete optimization, e.g., the knapsack problem, the traveling salesman problem or the set packing problem will be discussed.
6	Learning objectives and skills	Students <ul style="list-style-type: none"> • will gain basic theoretical knowledge of solving mixed-integer linear optimization problems (MIPs), • are able to solve MIPs with the help of state-of-the-art optimization software.
7	Prerequisites	Recommended: Linear and Combinatorial Optimization
8	Integration in curriculum	semester: 1
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	

1	Module name 65918	Robust optimization II	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<ul style="list-style-type: none"> 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	<p>Students</p> <ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Recommended: Robust Optimization I 	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> Lecture notes, will be published on StudOn at the beginning of the semester. 	

1	Module name 65919	Numerical aspects of linear and integer programming	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral (ca. 15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • 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 65920	Advanced nonlinear optimization	10 ECTS
2	Courses / lectures	Vorlesung mit Übung: Advanced nonlinear optimization	10 ECTS
3	Lecturers	Prof. Dr. Michael Stingl	

4	Module coordinator	Prof. Dr. Wolfgang Achtziger	
5	Contents	<ul style="list-style-type: none"> advanced optimality conditions and constraint qualifications for constrained optimization problems penalty, barrier and augmented Lagrangian methods: theory and algorithms interior point methods sequential quadratic programming 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> explain and extend their knowledge on theory and algorithms of nonlinear optimization problems, apply solution techniques to different advanced types of optimization problems, derive and solve optimization problems arising from technical and economical applications. 	
7	Prerequisites	Basic knowledge in nonlinear optimization is recommended.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral oral exam (20 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> M.S. Bazaraa, H.D. Sherali & C.M. Shetty: Nonlinear Programming Theory and Algorithms, Wiley, New York, J. Nocedal & S. Wright: Numerical Optimization, Springer. 	

1	Module name 65921	Optimization with partial differential equations	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Michael Stingl	
5	Contents	<p>Several of the following topics:</p> <ul style="list-style-type: none"> • Optimization and control in Banach spaces • Concepts of controllability and stabilization • Optimal control of Partial differential equations • Singular Perturbations and asymptotic analysis • Numerical realizations of optimal controls • Technical, medical and economic applications 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • explain and use theory as well as numerical methods for optimization, control and stabilization in the context of partial differential equations, • apply these abilities to technical and economic applications. 	
7	Prerequisites	Basic knowledge in numerics, partial differential equations, and nonlinear optimization is recommended.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • F. Tröltzsch: Optimal Control of Partial Differential Equations, AMS • G. Leugering & P. Kogut: Optimal Control of PDEs in Reticulated Domains, Birkhäuser 	

1	Module name 65923	Optimization in industry and economy	5 ECTS
2	Courses / lectures	Vorlesung: Optimization in Industry and Economy (Mathematics of Learning) (2 SWS) Übung: Übung zu Optimization in Industry and Economy (Mathematics of Learning) (1 SWS)	5 ECTS -
3	Lecturers	Prof. Dr. Frauke Liers-Bergmann	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<p>This course focuses on modeling and solving real-world optimization problems occurring in industry and economics. Advantages and disadvantages of different modeling techniques will be outlined. In order to achieve efficient solution approaches, different reformulations and their numerical results will be discussed. Students will learn how to present optimization results properly as well as how to interpret and evaluate these results for practical applications. The latter may include but is not limited to the optimization of transport networks (gas, water, energy), air traffic management and mathematical modeling/optimization of market mechanisms in the energy sector.</p>	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • model complex real-world optimization problems with respect to efficient • solvability, • classify the models and use appropriate solution strategies, • evaluate the achieved computational results. 	
7	Prerequisites	Recommended: Modul LKOpt: Linear and combinatorial optimization	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	

14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none">• Lecture notes (will be published on StudOn at the beginning of the semester)• Up-to-date research literature (will be published on StudOn at the beginning of the semester)

1	Module name 65924	Project seminar optimization	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	A specific application is to be used to implement the knowledge of mathematical optimisation models and methods acquired during the degree programme thus far. The content is taken from a current problem, often in close collaboration with an industrial partner. Examples might be the water supply for a city, the design of an energy-efficient facade for an office building or railway construction site management.	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> organise themselves into teams to carry out a large project in which they independently model a real problem, develop and implement solutions and apply their results in practical situations, strengthen their communication skills by presenting and discussing the results of the project work, discuss information, ideas, problems and solutions at an academic level with each other and with the lecturers. 	
7	Prerequisites	Recommended: knowledge in combinatorial optimisation	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Seminar paper Presentation	
11	Grading procedure	Seminar paper (50%) Presentation (50%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Project-dependent. Will be published on StudOn at the beginning of the semester.	

1	Module name 65933	Discrete optimization II	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Timm Oertel	
5	Contents	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 <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • 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

1	Module name 65954	Numerik der Optimalen Steuerungen Numerics of optimal control	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Hannes Meinlschmidt	
5	Contents	<p>The following topics are covered: Discretization methods for differential equations, aspects of nonlinear optimization methods, direct discretization methods (fully and reduced discretized), indirect methods based on discretization of necessary optimality conditions as well as methods for efficient sensitivity calculations with internal numerical differentiation and adjoint equations.</p> <p>The material is presented in lecture form. Further acquisition of the essential concepts and techniques takes place through self-study of accompanying literature and the completion of exercises, supported by meetings within the tutorials.</p> <p>By default, the lecture will be given in English (in German only if all participants agree).</p>	
6	Learning objectives and skills	Students explain and use numerical methods for optimal control problems with ordinary differential equations and differential algebraic equations. They apply basic concepts of solution methodology using direct and indirect discretization methods for application problems, for example in technology or economics.	
7	Prerequisites	Recommended: Basic knowledge in numerics, in theory of ordinary differential equations, and in optimization.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral Dauer der mündlichen Prüfung: 15 Min.	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	

13	Workload in clock hours	Contact hours: 60 h Independent study: 90 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	M. Gerdt, Optimal Control of ODEs and DAEs, De Gruyter, 2012.

1	Module name 65959	Theorie der Optimalsteuerungen Optimal control theory	10 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Hannes Meinlschmidt	
5	Contents	<p>Grundlagen zu folgenden Themen:</p> <ul style="list-style-type: none"> • Diskrete und kontinuierliche Dynamische Systeme in allgemeinen Räumen • Eingabe- und Ausgabeoperatoren, Beobachter und Aktuatoren • Lösungstheorie und qualitative Theorie • Steuerbarkeit und Stabilisierbarkeit • Restriktionen für Steuerungen und Zuständen • Open-Loop- und Closed-Loop-Steuerungen • Pontriagin'sches Maximum-Prinzip • Dynamische Programmierung • Numerische Realisierung optimaler Steuerungen <p>Die Präsentation des Stoffes erfolgt in Vorlesungsform. Die weitere Aneignung der wesentlichen Begriffe und Techniken erfolgt durch Selbststudium begleitender Literatur, unterstützt durch Zusammenkünfte innerhalb der Übungen.</p>	
6	Learning objectives and skills	<p>Die Studierenden</p> <ul style="list-style-type: none"> • erklären und verwenden eine vertiefte Theorie und vertiefte numerische Methoden im Umgang mit der Steuerung, Stabilisierung und Optimalsteuerung im Kontext der gewöhnlichen Differentialgleichungen. Diese Fähigkeiten sind sowohl in naturwissenschaftlichen, medizinischen, wirtschaftswissenschaftlichen als auch und insbesondere in Ingenieurwissenschaften von Bedeutung. 	
7	Prerequisites	<p>empfohlen:</p> <ul style="list-style-type: none"> • Grundkenntnisse der Numerik, der gewöhnlichen und partiellen Differentialgleichungen, der Optimierung 	
8	Integration in curriculum	semester: 2;1;3	
9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral mündliche Prüfung (20 Min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	

14	Module duration	1 semester
15	Teaching and examination language	german
16	Bibliography	<ul style="list-style-type: none">• E. Sontag, Mathematical Control Theory, Springer-Verlag 2000• F. Tröltzsch, Steuerungstheorie Partieller Differentialgleichungen, Vieweg Verlag, 2003

1	Module name 65993	Numerics of Partial Differential Equations Numerics of partial differential equations	10 ECTS
2	Courses / lectures	Vorlesung: Numerics of Partial Differential Equations I (4 SWS) Übung: NuPDGU (2 SWS) Übung: Exercises for Numerics of Partial Differential Equations I (2 SWS)	10 ECTS - -
3	Lecturers	Prof. Dr. Günther Grün	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • Classical approach for the Poisson problem (outline) • Variational theory of linear elliptic boundary value problems • Possible discretization methods (FD, FEM, FV, spectral methods) • Conforming FEM for linear elliptic boundary value problems (2nd order) (types of elements, affine-equivalent triangulations, interpolation estimates, error estimates, Aubin-Nitsche) • Aspects of implementation • Iterative methods for large sparse linear systems of equations (condition number of finite element matrices, linear stationary methods (recall), cg method (recall), preconditioning, Krylov subspace methods) • Outlook to nonlinear problems 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • apply algorithmic approaches for models with partial differential equations and explain and evaluate them, • are capable to judge on a numerical methods 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 problems and methods with a focus on conforming finite element methods for linear elliptic problems, • collect and evaluate relevant information and realize relationships. 	
7	Prerequisites	Recommended: basic knowledge in numerics, discretization, and optimization	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p>	

		Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Written examination (90 minutes)
11	Grading procedure	Written examination (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 90 h Independent study: 210 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • A. Ern & J.-L. Guermond: Theory and practice of finite elements. Springer 2004 • W. Hackbusch: Elliptic Differential Equations. Theory and Numerical Treatment. Springer, 2nd edition 2017, (also available in German) • D. Braess: Finite Elements. Cambridge University Press 2010 • A. Quarteroni & A. Valli: Numerical approximation of partial differential equations. Springer 1994 • P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Differential Equations, Springer 2003 • lecture notes

1	Module name 65999	Numerics of Partial Differential Equations II Numerics of partial differential equations II	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • apply algorithmic approaches for models with partial differential equations and explain and evaluate them, • are capable to judge on a numerical methods 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Written examination (90 minutes)	
11	Grading procedure	Written examination (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	

14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none">• 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.

1	Module name 65877	Polynomial Optimization and Application	5 ECTS
2	Courses / lectures	Übung: Exercise Polynomial optimization and applications (1 SWS) Vorlesung: Polynomial optimization and applications (2 SWS)	- 5 ECTS
3	Lecturers	Prof. Dr. Giovanni Fantuzzi	

4	Module coordinator	Prof. Dr. Giovanni Fantuzzi
5	Contents	<p>Polynomial optimization problems (POPs) form a broad class of optimization problems that find applications to control theory, dynamical systems, optimal transport, power flow networks, fluid mechanics, and many other fields. This course will introduce students to a modern approach to solving POPs through semidefinite programming techniques. More specifically, the course will cover:</p> <ul style="list-style-type: none"> • The basics of semidefinite programs • The theory of sum-of-squares (SOS) polynomials • Moment-SOS hierarchies for polynomial optimization problems • Applications (e.g. to dynamical system analysis) <p>Students will also have the opportunity to put the theory into practice with “hands-on” practical assignments.</p>
6	Learning objectives and skills	<p>By the end of the course, students should be able to:</p> <ul style="list-style-type: none"> • Explain what polynomial optimization problems (POPs) are • Give examples of applications where POPs arise • Formulate semidefinite programming relaxations of POPs • Apply moment-SOS hierarchies to a range of problems • Solve POPs in practice using existing software
7	Prerequisites	Previous experience with optimization (especially convex and/or conic optimization) and with differential equations is desirable.
8	Integration in curriculum	semester: 1;3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral (30 minutes)
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h
14	Module duration	1 semester

15	Teaching and examination language	
16	Bibliography	Lecture notes will be provided as the course progresses. A reading list will also be provided at the start of the course.

1	Module name 65789	Selected Topics in Mathematics of Learning Selected topics in mathematics of learning	5 ECTS
2	Courses / lectures	Vorlesung: Selected Topics in Mathematics of Learning (2 SWS) Übung: Übung Selected Topics in Mathematics of Learning (2 SWS)	3 ECTS 2 ECTS
3	Lecturers	Dr. Marius Yamakou	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann
5	Contents	Advanced methods of mathematical data science, with a focus on teaching mathematical principles of learning processes.
6	Learning objectives and skills	Students gain fundamental theoretical knowledge of learning algorithms in Data Science and will be able to apply the methodologies in a Data Science context.
7	Prerequisites	Basic knowledge in numerical methods and optimization are recommended.
8	Integration in curriculum	semester: 1;3
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Written examination (60 minutes)
11	Grading procedure	Written examination (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 60 h Independent study: 90 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	S. Wright, B. Recht: Optimization for Data Analysis (2022).

1	Module name 48241	Mathematical Image Processing	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers. This module is offered in every second summer term. The next course will be held in the summer semester 2024.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Daniel Tenbrinck	
5	Contents	<p>This module covers mathematical image processing techniques based on Fourier domain filters, variational methods, and partial differential equations.</p> <p>In particular, the following content will be introduced to the students:</p> <ul style="list-style-type: none"> • contrast enhancement • filtering in Fourier and image domain • Bayesian image denoising • image deblurring / deconvolution • pixel-based clustering • region-based segmentation • image inpainting • nonlocal image processing using graphs 	
6	Learning objectives and skills	<p>Students following this course will</p> <ul style="list-style-type: none"> • learn how image data can be modeled and analyzed mathematically • develop a deeper understanding of mathematical basics and methods for image processing • implement own algorithms for mathematical image processing • discover connections to related mathematical fields, e.g., inverse problems and convex analysis 	
7	Prerequisites	<p>Knowledge in calculus and linear algebra is recommended to understand the mathematical foundations of image processing. Knowledge in functional analysis, numerical mathematics, or inverse problems is helpful to understand advanced concepts in mathematical image processing.</p>	
8	Integration in curriculum	semester: 2;1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	

10	Method of examination	Written or oral Oral examination (20 min.) or written examination (60 min.) depending on size of course.
11	Grading procedure	Written or oral (100%) Oral exam (100%) or written exam (100%) depending on size of course.
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • G. Aubert & P. Kornprobst: Mathematical problems in Image Processing, Springer • K. Bredies & D. Lorenz, Mathematical Image Processing, Springer • S. Osher & R. Fedkiw, Level Set Methods and Dynamic Implicit Surfaces, Springer • A. Elmoataz , O.Lezoray, S. Bogleux: Nonlocal Discrete Regularization on Weighted Graphs: a framework for Image and Manifold Processing, IEEE Transactions On Image Processing, 17 (7), pp: 1047-1060, 2008

1	Module name 65096	Seminar Selected Topics of Applied Analysis Seminar: Selected topics of applied analysis	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	Topics from Applied Analysis to deepen the theoretical contents of the lecture <i>ModAna1</i>	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • are able to familiarize themselves with advanced topics using journal articles or graduate textbooks, • can present the acquired content orally in a structured manner, with, if necessary, own additions in content, • actively participate at discussions about mathematical topics raised by the presentations in the seminar. 	
7	Prerequisites	<p>Linear algebra and calculus are required.</p> <p>Basic knowledge in probability theory is recommended.</p>	
8	Integration in curriculum	no Integration in curriculum available!	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Mandatory elective module in M.Sc. Computational and Applied Mathematics</p> <p>Summer or winter term after participation at <i>ModAna1</i></p>	
10	Method of examination	<p>Presentation</p> <p>Oral (90 minutes)</p> <p>Oral presentation (90min) and presentation document (4-8 pages)</p>	
11	Grading procedure	<p>Presentation (20%)</p> <p>Oral (80%)</p> <p>Oral presentation (80%)</p> <p>presentation document (20%)</p>	
12	Module frequency	Irregular	

13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	Determined by the topic chosen

1	Module name 65067	Introduction to control and machine learning	5 ECTS
2	Courses / lectures	Vorlesung mit Übung: Introduction to Control and Machine Learning (2 SWS)	5 ECTS
3	Lecturers	Prof. Dr. Enrique Zuazua Iriondo Ziqi Wang	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ul style="list-style-type: none"> 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. 	
6	Learning objectives and skills	<p>Students are able to</p> <ul style="list-style-type: none"> understand some basic theory on control and machine learning. learn about recent advances on control and machine learning. set out their approaches and results in a comprehensible and convincing manner, making use of appropriate presentation techniques. 	
7	Prerequisites	Recommended: basic knowledge of calculus, linear algebra, ODE and PDE.	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <ul style="list-style-type: none"> Mandatory elective module for MSc in Data Science in the field of study "Simulation and Numerics" Mandatory elective module for MSc in Computational and Applied Mathematics in the specialization "OPTI" 	
10	Method of examination	Oral (15 minutes) oral exam (20 minutes)	
11	Grading procedure	Oral (100%) 100% based on oral exam	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 62,5	
14	Module duration	1 semester	

15	Teaching and examination language	english
16	Bibliography	<p>[1] L. Bottou, F. E. Curtis, and J. Nocedal, Optimization methods for large-scale machine learning. SIAM Review, 60 (2) (2018) , 223-311.</p> <p>[2] J. M. Coron, Control and Nonlinearity, Mathematical Surveys and Monographs, 143, AMS, 2009.</p> <p>[3] I. Goodfellow, Y. Bengio, & A. Courville, Deep Learning. MIT press, 2016.</p> <p>[4] C. F. Higham, and D. J. Higham, Deep learning: An introduction for applied mathematicians. SIAM Review, 61 (4) (2019), 860-891.</p> <p>[5] J. Nocedal, and S. Wright, Numerical Optimization. Springer Science & Business Media, 2006.</p> <p>[6] D. Ruiz-Balet, and E. Zuazua, Neural ODE control for classification, approximation and transport. arXiv preprint arXiv:2104.05278, (2021).</p> <p>[7] E. Zuazua, Propagation, observation, and control of waves approximated by finite difference methods, SIAM Review, 47 (2) (2005), 197-243.</p> <p>[8] 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.</p>

Non-Specialisation modules

1	Module name 65071	Seminar on Evolution Equations Seminar: Evolution equations	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<p>Topics in the complex of evolution equations, depending on the interest and previous knowledge of the attending students; possible topics include, but are not limited to:</p> <ul style="list-style-type: none"> • semigroups of operators (Hille-Yosida theorem, Stone theorem, analytic semigroups,) • variational methods and Galerkin scheme • theory of Bochner function spaces (embeddings, Aubin-Lions-Simon compactness) 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • work on and investigate an advanced topic in the complex of evolution equations, • report on and present their findings about their topic both orally and in written form by using appropriate means for presentation and communication, • understand the relationship and scope of their particular topic related to others considered within the complex of evolution equations, • discuss their and other participants topics and converse with the lecturer about questions and insights on an appropriate level 	
7	Prerequisites	Recommended: Functional Analysis, Differential Equations, basics in Lebesgue integration	
8	Integration in curriculum	semester: 1	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Seminar achievement	
11	Grading procedure	Seminar achievement (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 21 h Independent study: 129 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Will be announced at a first meeting, depending on the topics considered	

1	Module name 65075	A primer on functional-analytic methods for PDEs	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<p>Basics and foundations in the following topics:</p> <ul style="list-style-type: none"> • Banach and Hilbert spaces, • dual spaces and weak topology, • compact operators, their spectral theory, • Sobolev spaces, approximation and trace theorems • variational formulation of PDEs, • Sobolev solutions to linear elliptic PDEs (Lax-Milgram/ Fredholm alternative) 	
6	Learning objectives and skills	<p>Students are able to:</p> <ul style="list-style-type: none"> • name and explain fundamental concepts in functional analysis, • navigate between weak and strong topologies and have an understanding of their relation and respective properties, • work with Sobolev spaces and weak derivatives and give qualitative information about Sobolev functions, • identify, set up and work with variational formulations of linear elliptic PDEs in order to derive existence/uniqueness of solutions in the Sobolev setting 	
7	Prerequisites	Recommended: Basic knowledge in normed vector spaces, Lebesgue integration and Linear Algebra	
8	Integration in curriculum	semester: 1	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral (15 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • H. W. Alt: Linear Functional Analysis, Springer • A. Bressan: Lecture Notes on Functional Analysis: With Applications to Linear Partial Differential Equations, AMS • H. Brezis: Functional Analysis, Sobolev Spaces and Partial Differential Equations, Springer • L. C. Evans: Partial Differential Equations, AMS • W. Hackbusch: Theorie und Numerik elliptischer Differentialgleichungen, Vieweg+Teubner 	

- Lecture notes

1	Module name 65700	Lecture Series Partial Differential Equations, Control and Numerics (PdeConNum) Lecture series: Partial differential equations, control and numerics (PdeConNum)	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ul style="list-style-type: none"> • Examples of PDE models arising in industrial applications, Biology and Social Sciences • Long time asymptotics • Control of trajectories • Numerics for long time dynamics and control • Some applications in the control of population dynamics 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • develop understanding for special aspects of dynamical systems control, • apply numerical methods to control problems and develop a basic understanding of their properties, • derive and solve inverse problems arising from applications. 	
7	Prerequisites	Recommended: basic knowledge in functional analysis	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (15 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • J. M. Coron, Control and nonlinearity, Mathematical Surveys and Monographs, 143, AMS, 2009 • E. Zuazua. Propagation, observation, and control of waves approximated by finite difference methods. SIAM Review, 47 (2) (2005), 197-243 	

1	Module name 65785	Mathematics of Learning Mathematics of learning	5 ECTS
2	Courses / lectures	Vorlesung: Mathematics of Learning (2 SWS) Übung: Übung zu Mathematics of Learning (2 SWS)	3 ECTS 2 ECTS
3	Lecturers	Florian Rösel Prof. Dr. Frauke Liers-Bergmann	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<ul style="list-style-type: none"> 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	<p>Students</p> <ul style="list-style-type: none"> 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 in curriculum	semester: 1;3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Written examination (60 minutes)	
11	Grading procedure	Written examination (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 60 h Independent study: 90 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> Goodfellow, Bengio, Courville, Deep Learning, MIT Press, 2015 Hastie, Tibshirani, Friedman, The Elements of Statistical Learning, 2008 	

1	Module name 65885	Master's seminar MApA Master`s seminar MApA	5 ECTS
2	Courses / lectures	Masterseminar: Masterseminar (2 SWS)	5 ECTS
		Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS)	5 ECTS
		Masterseminar: Numerical methods for phase-field equations	5 ECTS
3	Lecturers	Prof. Dr. Timm Oertel Prof. Dr. Günther Grün Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Günther Grün
5	Contents	A topic from MApA that relates to the compulsory elective modules offered.
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • 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. <p>For the MApA specialisation:</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Written Presentation (90 minutes) (schriftliche Ausarbeitung 5-10 Seiten)
11	Grading procedure	Written (25%) Presentation (75%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h
14	Module duration	1 semester

15	Teaching and examination language	english
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	Module name 65890	Master's seminar NASi	5 ECTS
2	Courses / lectures	Masterseminar: Masterseminar (2 SWS)	5 ECTS
		Masterseminar: Master seminar "Numerical solutions for eigenvalue problems"	5 ECTS
		Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS)	5 ECTS
		Masterseminar: Numerical methods for phase-field equations	5 ECTS
3	Lecturers	Prof. Dr. Timm Oertel Prof. Dr. Daniel Tenbrinck Prof. Dr. Günther Grün Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Eberhard Bänsch
5	Contents	A topic from NASi that relates to the compulsory elective modules offered.
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> 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. <p>For the NASi specification:</p> <ul style="list-style-type: none"> 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 in curriculum	semester: 3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	<p>Presentation (90 minutes)</p> <p>Written (schriftliche Ausarbeitung 5-10 Seiten)</p>
11	Grading procedure	<p>Presentation (75%)</p> <p>Written (25%)</p>
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 30 h

		Independent study: 120 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	Module name 65895	Master seminar Opti	5 ECTS
2	Courses / lectures	Masterseminar: Masterseminar (2 SWS) Masterseminar: Master seminar "Numerical solutions for eigenvalue problems" Hauptseminar / Masterseminar: Masterseminar MApA/ NASi - Seminar Applied Analysis (2 SWS) Masterseminar: Material and Topology Optimization (2 SWS) Masterseminar: Numerical methods for phase-field equations	5 ECTS 5 ECTS 5 ECTS 5 ECTS 5 ECTS
3	Lecturers	Prof. Dr. Timm Oertel Prof. Dr. Daniel Tenbrinck Prof. Dr. Günther Grün Prof. Dr. Michael Stingl Dr. Stefan Metzger	

4	Module coordinator	Prof. Dr. Michael Stingl
5	Contents	A topic from Opti that relates to the compulsory elective modules offered.
6	Learning objectives and skills	Students <ul style="list-style-type: none"> • 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: <ul style="list-style-type: none"> • 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 in curriculum	semester: 3
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Presentation (90 minutes) Written (schriftliche Ausarbeitung 5-10 Seiten)

11	Grading procedure	Presentation (75%) Written (25%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	Module name 65900	Advanced discretization techniques	10 ECTS
2	Courses / lectures	Vorlesung: Advanced Discretization Techniques (4 SWS) Übung: Exercises for Advanced Discretization Techniques (1 SWS)	10 ECTS -
3	Lecturers	Prof. Dr. Carsten Gräser	

4	Module coordinator	Prof. Dr. Eberhard Bänsch
5	Contents	<ul style="list-style-type: none"> conforming and non-conforming finite element methods saddle point problems in Hilbert spaces mixed finite element methods for saddle point problems, in particular for Darcy and Stokes Streamline-Upwind Petrov-Galerkin (SUPG) and discontinuous Galerkin (dG) finite element methods (FEM) for convection dominated problems Finite Volume (FV) methods and their relation to FEM a posteriori error control and adaptive methods
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> have a discriminating understanding, both theoretically and computationally of FE as well as FV methods for the numerical solution of partial differential equations (pde) (in particular of saddle point problems), are capable of developing problem dependent FE or FV methods and judge on their properties regarding stability and effectiveness, are familiar with a broad spectrum of pde problems and their computational solutions, are capable of designing algorithms for adaptive mesh control.
7	Prerequisites	Recommended: Introduction to numerical methods for pdes, functional analysis
8	Integration in curriculum	semester: 1
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h

14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • A. Ern, J.-L. Guermond: Theory and Practice of Finite Elements • A. Quarteroni & A. Valli: Numerical Approximation of Partial Differential Equations • P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Differential Equations, Springer • D. A. Di Pietro & A. Ern: Mathematical aspects of discontinuous Galerkin methods. Springer 2012

1	Module name 65901	Advanced solution techniques	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral oral exam (15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	

16	Bibliography	<ul style="list-style-type: none">• 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 65902	Transport and reaction in porous media: Modelling	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	apl. Prof. Dr. Serge Kräutle	
5	Contents	<ul style="list-style-type: none"> Modeling of fluid flow through a porous medium: Groundwater models, saturated and unsaturated porous medium (Richards equation) Advection, diffusion, dispersion of dissolved substances, (nonlinear) reaction-models (i.a. law of mass action, kinetic / reversible reactions in local equilibrium), the stoichiometric matrix Models of partial (PDEs), ordinary (ODEs) differential equations, and local algebraic 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 and uniqueness of stationary solutions in the stoichiometric space (i.a. introduction to the Feinberg network theory) 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	

16 **Bibliography**

- 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 <https://cbe.osu.edu/chemical-reaction-network-theory>

1	Module name 65903	Transport and reaction in porous media: Simulation	5 ECTS
2	Courses / lectures	Vorlesung: Transport and reaction in porous media: Simulation	-
3	Lecturers	apl. Prof. Dr. Serge Kräutle	

4	Module coordinator	apl. Prof. Dr. Serge Kräutle	
5	Contents	<ul style="list-style-type: none"> • Degenerate parabolic differential equations as multiphase flow models: formulation, model derivation through asymptotic expansion, nonlinear solution methods, discretization methods • Sorption reactions and mineral precipitation-dissolution reactions, formulations as complementarity problems • Models for transport and reactions in porous media, consisting of coupled PDEs and ODEs, if necessary coupled to algebraic equations (AEs) and inequalities for the description of local equilibria (differential-algebraic system) • Different formulations of the system • Different numerical strategies: operator splitting, direct substitutional approach, change of variables and combination/elimination of equations (xi-eta-method), as a basis for different software packages for numerical simulations, connection to optimisation (minimization of Gibbs free energy under constraints) • Treatment of numerical difficulties (nonsmooth equations, treatment of complementarity conditions, guarantee of nonnegativity of numerical solutions of the nonlinear problems, range of convergence of Newton's method, scaling problems, advection dominated problems) 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • use methods for the numerical solving of a class of problems whose complexity goes significantly beyond standard problems (Poisson and heat equation): coupled nonlinear partial and ordinary differential equations (PDEs, ODEs) and algebraic equations (AEs), • put strategies for the treatment of possible difficulties during the numerical solving into practice. 	
7	Prerequisites	<ul style="list-style-type: none"> • Recommended: Basic knowledge in differential equations, • Also useful: Transport and Reaction in Porous Media: Modeling 	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p>	

		Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Partial Differential Equations, Springer • Journal articles will be named in the lecture • Handbooks of Software Packages https://en.www.math.fau.de/angewandte-mathematik-1/forschung/software-2

1	Module name 65904	Numerics of incompressible flows I	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • V. Girault, P.-A. Raviart: Finite element methods for the Navier-Stokes equations. Theory and algorithms. Springer 1986 	

- H. Elman, D. Silvester, A. Wathen: 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

1	Module name 65905	Numerics of incompressible flows II	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • Variational formulation of the instationary Stokes and Navier-Stokes (NVS) equations • Existence and uniqueness of solutions to the instationary Stokes and NVS equations • Time discretisation methods • Fully discrete equations and error estimates • Solution techniques • Operator splitting, projection methods • More general boundary conditions • Coupling of NVS with temperature equation • Computational experiments with academic or commercial codes 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • discretize the instationary NVS equations in time and space, • explain and analyse discretisation schemes and operator splitting techniques, • choose appropriate algorithms for given flow problems and solve them with academic or commercial software. 	
7	Prerequisites	Recommended: Advanced discretization techniques, Numerics of incompressible flows I	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	

16	Bibliography	<ul style="list-style-type: none">• V. Girault & 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. Glowinski: Finite Element Methods for Incompressible Viscous Flow, in : Handbook of Numerical Analysis vol. IX• R. Temam: Navier-Stokes equations. Theory and numerical analysis. North Holland
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1	Module name 65906	Mathematics of multiscale models	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	PD Dr. Nicolas Neuß
5	Contents	<ul style="list-style-type: none"> • Function spaces of periodic functions and asymptotic expansions • Two-scale convergence and unfolding method • Application to differential equation models in continuum mechanics • Multi-scale finite element methods • Numerical upscaling methods
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • have profound expertise about the basic methods in multi-scale analysis and homogenisation, • are able to derive rigorously homogenised (effective) models and analyse the quality of the approximation.
7	Prerequisites	Recommended: Knowledge in modeling as well as analysis and numerics of partial differential equations
8	Integration in curriculum	semester: 3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • D. Cioranescu & P. Donato: An Introduction to Homogenization • U. Hornung (ed.): Homogenization and Porous Media • Y. Efendiev & T. Hou: Multiscale Finite Element Methods

1	Module name 65907	Theory of stochastic evolution equations	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Infinitely dimensional Wiener processes, • Stochastic integral in Hilbert spaces, • Ito-processes and stochastic differential equations, • Optionally: existence results for stochastic partial differential equations or further results on stochastic ODE (Fokker-Planck equations, . . .) 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • characterize Gaussian measures on Hilbert spaces. They explain representation formulas for Q-Wiener processes as well as the derivation of the stochastic integral, • successfully apply concepts to solve stochastic differential equations explicitly and prove existence of solutions to stochastic evolution equations. 	
7	Prerequisites	Basic knowledge in probability theory or functional analysis is recommended.	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • G. Da Prato & J. Zabczyk: Stochastic equations in infinite dimensions, Cambridge University Press • I. Karatzas & S.E. Shreve: Brownian motion and stochastic calculus, Springer • B. Oksendal: Stochastic differential equations, Springer 	

- C. Prévôt & M. Röckner: A concise course on stochastic partial differential equations, Springerchastic Evolution Equations

1	Module name 65908	Numerics of stochastic evolution equations	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Strong and weak approximations, explicit and implicit schemes for stochastic differential equations (SDEs), • Consistency, stability, convergence, • Monte Carlo methods, variance-reduction schemes. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • have critical understanding of capabilities of numerical schemes for stochastic differential equations, • are capable to use own or commercial software for SDEs and to judge results critically. 	
7	Prerequisites	Basic knowledge in probability theory and in numerics is recommended.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • P.E. Kloeden & E. Platen: Numerical solution of stochastic differential equations • B. Lapeyre, E. Pardoux & R. Sentis: Introduction to Monte? Carlo methods for transport and diffusion equations 	

1	Module name 65911	Mathematical modeling in the life sciences	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	apl. Prof. Dr. Maria Neuß	
5	Contents	<ul style="list-style-type: none"> • Biochemical reaction networks, enzyme kinetics • Models for interacting populations (Predator-prey, competition, symbiosis) • Diffusion, reactions, and transport in biological cell tissues and vessels • Structured population models 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • have profound knowledge in the area of mathematical modeling of processes in the life sciences • are able to identify significant mechanisms and to apply suitable analytical and numerical methods for their analysis • are able to work interdisciplinary and problem-oriented. 	
7	Prerequisites	Recommended: Modeling and Analysis in Continuum Mechanics I	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • J. D. Murray: Mathematical Biology I: An Introduction, Mathematical Biology II: Spatial Models and Biomedical Applications • G. de Vries, T. Hillen, et al.: A course in Mathematical Biology • J. Prüss: Mathematische Modelle in der Biologie: Deterministische homogene Systeme 	

1	Module name 65914	Partial differential equations in finance	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> models on pricing for financial derivatives, in particular for European and American-type options, selected deterministic equations of financial mathematics, practical knowledge Ito-calculus and stochastic differential equations, analysis and numerics for Black-Scholes equations, variational inequalities and American-type options. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> explain mathematical models for financial markets and derivatives pricing, apply Ito calculus, derive deterministic models based on pde or variational inequalities and discretize them numerically. 	
7	Prerequisites	Basis knowledge in differential equations, probability theory or functional analysis is recommended.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (ca. 15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> M. Capinski & T. Zastawniak: Mathematics for finance, Springer, N. Hilber, O. Reichmann, C. Schwab & C. Winter: Computational methods for quantitative finance, Springer, 	

- B. Oksendal: Stochastic differential equations, Springer.

1	Module name 65915	Introduction to material- and shape optimization	10 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Michael Stingl	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • 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	<p>Recommended:</p> <ul style="list-style-type: none"> • Knowledge in nonlinear optimization, • Basic knowledge in numerics of partial differential equations 	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • J. Haslinger & R. Mäkinen: Introduction to shape optimization, SIAM, 	

- M. P. Bendsoe & O. Sigmund: Topology Optimization: Theory, Methods and Applications, Springer.

1	Module name 65916	Advanced algorithms for nonlinear optimization	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Michael Stingl	
5	Contents	Several of the following topics: <ul style="list-style-type: none"> • Trust region methods • Iterative methods in the presence of noisy data • Interior point methods for nonlinear problems • Modified barrier and augmented Lagrangian methods • Local and global convergence analysis 	
6	Learning objectives and skills	Students <ul style="list-style-type: none"> • use methods of nonlinear constrained optimization in finite dimensional spaces, • analyse convergence behaviour of these methods and derive robust and efficient realisations, • apply these abilities to technical and economic applications. 	
7	Prerequisites	Basic knowledge in nonlinear optimization is recommended.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • C.T. Kelley: Iterative Methods for Optimization, SIAM, • J. Nocedal & S. Wright: Numerical Optimization, Springer. 	

1	Module name 65917	Discrete optimization I	5 ECTS
2	Courses / lectures	Vorlesung: Discrete Optimization I (2 SWS) Übung: Tutorial zu Discrete Optimization I (1 SWS)	5 ECTS -
3	Lecturers	Kevin-Martin Aigner Florian Rösel	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann
5	Contents	Theoretical and practical fundamentals of solving difficult mixed-integer linear optimization problems (MIPs) constitute the main focus of this lecture. At first, the concept of NP-completeness and a selection of common NP-complete problems will be presented. As for polyhedral theory, fundamentals concerning the structure of faces of convex polyhedra will be covered. Building upon these fundamentals, cutting plane algorithms as well as branch-and-cut algorithms for solving MIPs will be taught. Finally, some typical problems of discrete optimization, e.g., the knapsack problem, the traveling salesman problem or the set packing problem will be discussed.
6	Learning objectives and skills	Students <ul style="list-style-type: none"> • will gain basic theoretical knowledge of solving mixed-integer linear optimization problems (MIPs), • are able to solve MIPs with the help of state-of-the-art optimization software.
7	Prerequisites	Recommended: Linear and Combinatorial Optimization
8	Integration in curriculum	semester: 1
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Oral
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	

1	Module name 65918	Robust optimization II	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<ul style="list-style-type: none"> 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	<p>Students</p> <ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Recommended: Robust Optimization I 	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> Lecture notes, will be published on StudOn at the beginning of the semester. 	

1	Module name 65919	Numerical aspects of linear and integer programming	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral (ca. 15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • 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 65920	Advanced nonlinear optimization	10 ECTS
2	Courses / lectures	Vorlesung mit Übung: Advanced nonlinear optimization	10 ECTS
3	Lecturers	Prof. Dr. Michael Stingl	

4	Module coordinator	Prof. Dr. Wolfgang Achtziger	
5	Contents	<ul style="list-style-type: none"> advanced optimality conditions and constraint qualifications for constrained optimization problems penalty, barrier and augmented Lagrangian methods: theory and algorithms interior point methods sequential quadratic programming 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> explain and extend their knowledge on theory and algorithms of nonlinear optimization problems, apply solution techniques to different advanced types of optimization problems, derive and solve optimization problems arising from technical and economical applications. 	
7	Prerequisites	Basic knowledge in nonlinear optimization is recommended.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral oral exam (20 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> M.S. Bazaraa, H.D. Sherali & C.M. Shetty: Nonlinear Programming Theory and Algorithms, Wiley, New York, J. Nocedal & S. Wright: Numerical Optimization, Springer. 	

1	Module name 65921	Optimization with partial differential equations	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Michael Stingl	
5	Contents	<p>Several of the following topics:</p> <ul style="list-style-type: none"> • Optimization and control in Banach spaces • Concepts of controllability and stabilization • Optimal control of Partial differential equations • Singular Perturbations and asymptotic analysis • Numerical realizations of optimal controls • Technical, medical and economic applications 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • explain and use theory as well as numerical methods for optimization, control and stabilization in the context of partial differential equations, • apply these abilities to technical and economic applications. 	
7	Prerequisites	Basic knowledge in numerics, partial differential equations, and nonlinear optimization is recommended.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • F. Tröltzsch: Optimal Control of Partial Differential Equations, AMS • G. Leugering & P. Kogut: Optimal Control of PDEs in Reticulated Domains, Birkhäuser 	

1	Module name 65923	Optimization in industry and economy	5 ECTS
2	Courses / lectures	Vorlesung: Optimization in Industry and Economy (Mathematics of Learning) (2 SWS) Übung: Übung zu Optimization in Industry and Economy (Mathematics of Learning) (1 SWS)	5 ECTS -
3	Lecturers	Prof. Dr. Frauke Liers-Bergmann	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	<p>This course focuses on modeling and solving real-world optimization problems occurring in industry and economics. Advantages and disadvantages of different modeling techniques will be outlined. In order to achieve efficient solution approaches, different reformulations and their numerical results will be discussed. Students will learn how to present optimization results properly as well as how to interpret and evaluate these results for practical applications. The latter may include but is not limited to the optimization of transport networks (gas, water, energy), air traffic management and mathematical modeling/optimization of market mechanisms in the energy sector.</p>	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • model complex real-world optimization problems with respect to efficient • solvability, • classify the models and use appropriate solution strategies, • evaluate the achieved computational results. 	
7	Prerequisites	Recommended: Modul LKOpt: Linear and combinatorial optimization	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	

14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none">• Lecture notes (will be published on StudOn at the beginning of the semester)• Up-to-date research literature (will be published on StudOn at the beginning of the semester)

1	Module name 65924	Project seminar optimization	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann	
5	Contents	A specific application is to be used to implement the knowledge of mathematical optimisation models and methods acquired during the degree programme thus far. The content is taken from a current problem, often in close collaboration with an industrial partner. Examples might be the water supply for a city, the design of an energy-efficient facade for an office building or railway construction site management.	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> organise themselves into teams to carry out a large project in which they independently model a real problem, develop and implement solutions and apply their results in practical situations, strengthen their communication skills by presenting and discussing the results of the project work, discuss information, ideas, problems and solutions at an academic level with each other and with the lecturers. 	
7	Prerequisites	Recommended: knowledge in combinatorial optimisation	
8	Integration in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Seminar paper Presentation	
11	Grading procedure	Seminar paper (50%) Presentation (50%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 30 h Independent study: 120 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	Project-dependent. Will be published on StudOn at the beginning of the semester.	

1	Module name 65933	Discrete optimization II	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Timm Oertel	
5	Contents	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 <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • 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

1	Module name 65993	Numerics of Partial Differential Equations Numerics of partial differential equations	10 ECTS
2	Courses / lectures	Vorlesung: Numerics of Partial Differential Equations I (4 SWS) Übung: NuPDGU (2 SWS) Übung: Exercises for Numerics of Partial Differential Equations I (2 SWS)	10 ECTS - -
3	Lecturers	Prof. Dr. Günther Grün	

4	Module coordinator	Prof. Dr. Eberhard Bänsch	
5	Contents	<ul style="list-style-type: none"> • Classical approach for the Poisson problem (outline) • Variational theory of linear elliptic boundary value problems • Possible discretization methods (FD, FEM, FV, spectral methods) • Conforming FEM for linear elliptic boundary value problems (2nd order) (types of elements, affine-equivalent triangulations, interpolation estimates, error estimates, Aubin-Nitsche) • Aspects of implementation • Iterative methods for large sparse linear systems of equations (condition number of finite element matrices, linear stationary methods (recall), cg method (recall), preconditioning, Krylov subspace methods) • Outlook to nonlinear problems 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • apply algorithmic approaches for models with partial differential equations and explain and evaluate them, • are capable to judge on a numerical methods 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 problems and methods with a focus on conforming finite element methods for linear elliptic problems, • collect and evaluate relevant information and realize relationships. 	
7	Prerequisites	Recommended: basic knowledge in numerics, discretization, and optimization	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p>	

		Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Written examination (90 minutes)
11	Grading procedure	Written examination (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 90 h Independent study: 210 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • A. Ern & J.-L. Guermond: Theory and practice of finite elements. Springer 2004 • W. Hackbusch: Elliptic Differential Equations. Theory and Numerical Treatment. Springer, 2nd edition 2017, (also available in German) • D. Braess: Finite Elements. Cambridge University Press 2010 • A. Quarteroni & A. Valli: Numerical approximation of partial differential equations. Springer 1994 • P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Differential Equations, Springer 2003 • lecture notes

1	Module name 65997	Analysis of free-boundary problems in continuum mechanics	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • Derivation of time-dependent free boundary problems in continuum mechanics, • Basic results on existence and qualitative behaviour, • Optimal estimates on the propagation of free boundaries, • Other approaches, e.g. relaxation by phase-field models. 	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • formulate free-boundary problems in hydrodynamics and in porousmedia flow • explain analytical concepts for existence and nonnegativity results for degenerate parabolic equations as well as techniques for optimal estimates on spreading rates • validate different modeling approaches in a critical way. 	
7	Prerequisites	Recommended: Basic knowledge of analysis of partial differential equations, corresponding to the syllabus of Modeling and Applied Analysis in Continuum Mechanics or that one of other pde-lectures.	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192</p> <p>Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (ca. 15 min)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> • L.C. Evans: Partial Differential Equations, AMS, • Original journal articles. 	

1	Module name 65999	Numerics of Partial Differential Equations II Numerics of partial differential equations II	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students</p> <ul style="list-style-type: none"> • apply algorithmic approaches for models with partial differential equations and explain and evaluate them, • are capable to judge on a numerical methods 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Written examination (90 minutes)	
11	Grading procedure	Written examination (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h	

14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none">• 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.

1	Module name 65877	Polynomial Optimization and Application	5 ECTS
2	Courses / lectures	Übung: Exercise Polynomial optimization and applications (1 SWS) Vorlesung: Polynomial optimization and applications (2 SWS)	- 5 ECTS
3	Lecturers	Prof. Dr. Giovanni Fantuzzi	

4	Module coordinator	Prof. Dr. Giovanni Fantuzzi
5	Contents	<p>Polynomial optimization problems (POPs) form a broad class of optimization problems that find applications to control theory, dynamical systems, optimal transport, power flow networks, fluid mechanics, and many other fields. This course will introduce students to a modern approach to solving POPs through semidefinite programming techniques. More specifically, the course will cover:</p> <ul style="list-style-type: none"> • The basics of semidefinite programs • The theory of sum-of-squares (SOS) polynomials • Moment-SOS hierarchies for polynomial optimization problems • Applications (e.g. to dynamical system analysis) <p>Students will also have the opportunity to put the theory into practice with “hands-on” practical assignments.</p>
6	Learning objectives and skills	<p>By the end of the course, students should be able to:</p> <ul style="list-style-type: none"> • Explain what polynomial optimization problems (POPs) are • Give examples of applications where POPs arise • Formulate semidefinite programming relaxations of POPs • Apply moment-SOS hierarchies to a range of problems • Solve POPs in practice using existing software
7	Prerequisites	Previous experience with optimization (especially convex and/or conic optimization) and with differential equations is desirable.
8	Integration in curriculum	semester: 1;3
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>
10	Method of examination	Oral (30 minutes)
11	Grading procedure	Oral (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 45 h Independent study: 105 h
14	Module duration	1 semester

15	Teaching and examination language	
16	Bibliography	Lecture notes will be provided as the course progresses. A reading list will also be provided at the start of the course.

1	Module name 65789	Selected Topics in Mathematics of Learning Selected topics in mathematics of learning	5 ECTS
2	Courses / lectures	Vorlesung: Selected Topics in Mathematics of Learning (2 SWS) Übung: Übung Selected Topics in Mathematics of Learning (2 SWS)	3 ECTS 2 ECTS
3	Lecturers	Dr. Marius Yamakou	

4	Module coordinator	Prof. Dr. Frauke Liers-Bergmann
5	Contents	Advanced methods of mathematical data science, with a focus on teaching mathematical principles of learning processes.
6	Learning objectives and skills	Students gain fundamental theoretical knowledge of learning algorithms in Data Science and will be able to apply the methodologies in a Data Science context.
7	Prerequisites	Basic knowledge in numerical methods and optimization are recommended.
8	Integration in curriculum	semester: 1;3
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192
10	Method of examination	Written examination (60 minutes)
11	Grading procedure	Written examination (100%)
12	Module frequency	Only in winter semester
13	Workload in clock hours	Contact hours: 60 h Independent study: 90 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	S. Wright, B. Recht: Optimization for Data Analysis (2022).

1	Module name 65093	Control, machine learning and numerics	10 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Enrique Zuazua Iriondo	
5	Contents	<ul style="list-style-type: none"> • 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	<p>Students are able to</p> <ul style="list-style-type: none"> • 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 in curriculum	semester: 2	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Variable	
11	Grading procedure	Variable (100%)	
12	Module frequency	Only in summer semester	
13	Workload in clock hours	Contact hours: 75 h Independent study: 225 h	
14	Module duration	1 semester	

15	Teaching and examination language	english
16	Bibliography	<ol style="list-style-type: none"> 1) L. Bottou, F. E. Curtis, and J. Nocedal, Optimization methods for large-scale machine learning. <i>SIAM Review</i>, 60 (2) (2018) , 223-311. 2) J. M. Coron, Control and Nonlinearity, <i>Mathematical Surveys and Monographs</i>, 143, AMS, 2009. 3) I. Goodfellow, Y. Bengio, & A. Courville, <i>Deep Learning</i>. MIT press, 2016. 4) R. Glowinski, J. L. Lions, and J. He, Exact and Approximate Controllability for Distributed Parameter Systems: A Numerical Approach, <i>Encyclopedia Math. Appl.</i>, Cambridge University Press, Cambridge, UK, 2008. 5) C. F. Higham, and D. J. Higham, Deep learning: An introduction for applied mathematicians. <i>SIAM Review</i>, 61 (4) (2019), 860-891. 6) J. Nocedal, and S. Wright, <i>Numerical Optimization</i>. Springer Science & Business Media, 2006. 7) D. Ruiz-Balet, and E. Zuazua, Neural ODE control for classification, approximation and transport. <i>arXiv preprint arXiv:2104.05278</i>, (2021). 8) E. Zuazua, Propagation, observation, and control of waves approximated by finite difference methods, <i>SIAM Review</i>, 47 (2) (2005), 197-243. 9) E. Zuazua, Controllability and observability of partial differential equations: some results and open problems, in <i>Handbook of Differential Equations: Evolutionary Equations</i>. Vol. 3. North-Holland, 2006. 527-621.

1	Module name 65910	Discrete optimization III	5 ECTS
2	Courses / lectures	Vorlesung: Diskrete Optimierung III (2 SWS) Übung: Tutorial zu Diskrete Optimierung III (1 SWS)	5 ECTS -
3	Lecturers	Prof. Dr. Timm Oertel	

4	Module coordinator	Prof. Dr. Timm Oertel	
5	Contents	<p>In this lecture we will discuss selected topics in discrete and mixed-integer optimization. Possible topics include lattice methods, integer programming in fixed dimension, recent research on (mixed) integer linear and/or (mixed) integer nonlinear programming and so on. The specific topics may vary and will be announced in due time.</p> <p>FORMERLY: 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.</p>	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • use basic terms of discrete optimization • model real-world discrete optimization problems, determine their complexity and solve them with appropriate mathematical methods. 	
7	Prerequisites	<p>Recommended: Knowledge in linear and combinatorial optimization, discrete optimization I and II</p>	
8	Integration in curriculum	semester: 3	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (15 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	<p>Contact hours: 45 h Independent study: 105 h</p>	
14	Module duration	1 semester	

15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • 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

1	Module name 65909	Subspace correction methods	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Carsten Gräser	
5	Contents	1) Subspace correction as an abstract framework to construct and analyse efficient iterative methods 2) Analysis of additive and multiplicative subspace correction 3) Multigrid and domain decomposition as subspace correction methods 4) Nonlinear subspace correction methods	
6	Learning objectives and skills	Students are <ul style="list-style-type: none"> familiar with the abstract subspace correction framework can select problem adapted methods can analyse specific methods within the framework 	
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 in curriculum	semester: 2	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral (15 minutes) oral exam (15 min)	
11	Grading procedure	Oral (100%) 100% based on oral exam	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	english	
16	Bibliography	<ul style="list-style-type: none"> H. Yserentant: Old and New Convergence Proofs for Multigrid Methods, Acta Numer. 1993 J.-C. Xu: Iterative Methods by Space Decomposition and Subspace Correction, SIAM Rev., 1992 Further literature and publications are announced during the lecture 	

1	Module name 65888	Navier Stokes Equations Navier stokes equations	10 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Emil Wiedemann	
5	Contents	<p>The incompressible Navier-Stokes equations (NSE) are a nonlinear system of partial differential equations fundamental for the modelling of fluid flow. They are extensively used in meteorology and oceanography, but also pose great mathematical challenges. Famously, global regularity of the three-dimensional NSE forms one of the seven Millennium Problems. This course serves as an introduction to the mathematical theory of these equations and includes the following topics:</p> <ul style="list-style-type: none"> • existence of weak solutions of Leray-Hopf type; • local-in-time existence of strong solutions; • the Prodi-Serrin criteria for regularity and energy balance; • partial regularity theory; • the singular limit of vanishing viscosity. <p>The course can be a good preparation for a subsequent master's thesis in the topic.</p>	
6	Learning objectives and skills	Students know and understand the basic theory of the Navier-Stokes equations and have mastered important methods for systems of non-linear partial differential equations. They have a basic understanding of mathematical fluid dynamics.	
7	Prerequisites	Lineare Algebra, Analysis. Empfohlen: erste Kurse in partiellen Differentialgleichungen und Funktionalanalysis.	
8	Integration in curriculum	semester: 1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	
10	Method of examination	Oral (20 minutes)	
11	Grading procedure	Oral (100%)	
12	Module frequency	Irregular	
13	Workload in clock hours	Contact hours: 90 h Independent study: 210 h	
14	Module duration	1 semester	
15	Teaching and examination language	german or english	

16	Bibliography	<ul style="list-style-type: none">• J. C. Robinson, J. L. Rodrigo, W. Sadowski: The Three-Dimensional Navier-Stokes Equations. Cambridge University Press, 2016.• P. Constantin, C. Foias: Navier-Stokes Equations. University of Chicago Press, 1988.• W. Ożański: The Partial Regularity Theory of Caffarelli, Kohn, and Nirenberg and its Sharpness. Birkhäuser, 2019.• E. Wiedemann: Navier-Stokes Equations: Lecture Notes. Universität Ulm, 2018/19.
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1	Module name 48241	Mathematical Image Processing	5 ECTS
2	Courses / lectures	No teaching units are offered for the module in the current semester. For further information on teaching units please contact the module managers. This module is offered in every second summer term. The next course will be held in the summer semester 2024.	
3	Lecturers	-	

4	Module coordinator	Prof. Dr. Daniel Tenbrinck	
5	Contents	<p>This module covers mathematical image processing techniques based on Fourier domain filters, variational methods, and partial differential equations.</p> <p>In particular, the following content will be introduced to the students:</p> <ul style="list-style-type: none"> • contrast enhancement • filtering in Fourier and image domain • Bayesian image denoising • image deblurring / deconvolution • pixel-based clustering • region-based segmentation • image inpainting • nonlocal image processing using graphs 	
6	Learning objectives and skills	<p>Students following this course will</p> <ul style="list-style-type: none"> • learn how image data can be modeled and analyzed mathematically • develop a deeper understanding of mathematical basics and methods for image processing • implement own algorithms for mathematical image processing • discover connections to related mathematical fields, e.g., inverse problems and convex analysis 	
7	Prerequisites	<p>Knowledge in calculus and linear algebra is recommended to understand the mathematical foundations of image processing. Knowledge in functional analysis, numerical mathematics, or inverse problems is helpful to understand advanced concepts in mathematical image processing.</p>	
8	Integration in curriculum	semester: 2;1	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p>	

10	Method of examination	Written or oral Oral examination (20 min.) or written examination (60 min.) depending on size of course.
11	Grading procedure	Written or oral (100%) Oral exam (100%) or written exam (100%) depending on size of course.
12	Module frequency	Irregular
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	<ul style="list-style-type: none"> • G. Aubert & P. Kornprobst: Mathematical problems in Image Processing, Springer • K. Bredies & D. Lorenz, Mathematical Image Processing, Springer • S. Osher & R. Fedkiw, Level Set Methods and Dynamic Implicit Surfaces, Springer • A. Elmoataz , O.Lezoray, S. Bogleux: Nonlocal Discrete Regularization on Weighted Graphs: a framework for Image and Manifold Processing, IEEE Transactions On Image Processing, 17 (7), pp: 1047-1060, 2008

1	Module name 65970	Stochastische Analysis Stochastic analysis	5 ECTS
2	Courses / lectures	Vorlesung: Stochastische Analysis (2 SWS) Übung: Übung zur Stochastischen Analysis (2 SWS)	5 ECTS -
3	Lecturers	Prof. Dr. Torben Krüger	

4	Module coordinator	Prof. Dr. Torben Krüger	
5	Contents	<ul style="list-style-type: none"> • Itokalkulus • Diffusionsprozesse • Stochastische Differentialgleichungen • Die Präsentation des Stoffes erfolgt in Vorlesungsform. 	
6	Learning objectives and skills	Die Studierenden erwerben die Fähigkeit komplexere Strukturen der Stochastik selbständig zu erfassen und auf exemplarische Problemstellungen anzuwenden. Diese bilden eine Basis für eine Spezialisierung in Stochastik undentsprechenden wirtschaftsmathematischen Themen.	
7	Prerequisites	empfohlen: Kenntnisse der Wahrscheinlichkeitstheorie sind zum Verständnis hilfreich	
8	Integration in curriculum	semester: 1	
9	Module compatibility	Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MApA) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192	
10	Method of examination	Oral Dauer der mündlichen Prüfung: 15 Min.	
11	Grading procedure	Oral (100%)	
12	Module frequency	Only in winter semester	
13	Workload in clock hours	Contact hours: 37,5 Independent study: 112,5	
14	Module duration	1 semester	
15	Teaching and examination language	german	
16	Bibliography	Die vorbereitende Literatur wird für jede Lehrveranstaltung jedes Semester neu festgelegt.	

1	Module name 65096	Seminar Selected Topics of Applied Analysis Seminar: Selected topics of applied analysis	5 ECTS
2	Courses / lectures	No courses / lectures available for this module!	
3	Lecturers	No lecturers available since there are no courses / lectures for this module!	

4	Module coordinator	Prof. Dr. Günther Grün	
5	Contents	Topics from Applied Analysis to deepen the theoretical contents of the lecture <i>ModAna1</i>	
6	Learning objectives and skills	<p>Students</p> <ul style="list-style-type: none"> • are able to familiarize themselves with advanced topics using journal articles or graduate textbooks, • can present the acquired content orally in a structured manner, with, if necessary, own additions in content, • actively participate at discussions about mathematical topics raised by the presentations in the seminar. 	
7	Prerequisites	<p>Linear algebra and calculus are required.</p> <p>Basic knowledge in probability theory is recommended.</p>	
8	Integration in curriculum	no Integration in curriculum available!	
9	Module compatibility	<p>Non-Specialisation modules Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and numerical analysis and simulation (NASi) Master of Science Computational and Applied Mathematics 20192 Specialisation: Modeling and applied analysis (MAPa) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192 Specialisation: Numerical analysis and simulation (NASi) and optimization (Opti) Master of Science Computational and Applied Mathematics 20192</p> <p>Mandatory elective module in M.Sc. Computational and Applied Mathematics</p> <p>Summer or winter term after participation at <i>ModAna1</i></p>	
10	Method of examination	<p>Presentation</p> <p>Oral (90 minutes)</p> <p>Oral presentation (90min) and presentation document (4-8 pages)</p>	
11	Grading procedure	<p>Presentation (20%)</p> <p>Oral (80%)</p> <p>Oral presentation (80%)</p> <p>presentation document (20%)</p>	
12	Module frequency	Irregular	

13	Workload in clock hours	Contact hours: 35 h Independent study: 115 h
14	Module duration	1 semester
15	Teaching and examination language	english
16	Bibliography	Determined by the topic chosen