List of modules for the Master’s degree programme Computational and Applied Mathematics

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

Department Mathematik
Naturwissenschaftliche Fakultät
Friedrich-Alexander-Universität Erlangen-Nürnberg

Last updated: Aug 3, 2026
Reference: Examination regulations dated Aug 11, 2022 and
Examination regulations dated March 05, 2026

Table of Contents

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Curricular Overview

<table>
<tr><td rowspan="2">elective modules (EM) 15 ECTS</td><td>Master phase (MP) 30 ECTS</td><td rowspan="2">mandatory elective modules (MEM) 40 ECTS</td></tr>
<tr><td>Mandatory Modules (MM) 35 ECTS</td></tr>
</table>

Not all listed mandatory elective modules below will be offered in every semester.
On the other hand, additional modules might be offered.

The minimum number of ECTS points is 120.
At least 65 ECTS must belong to the chosen specialization (MapA-NASi, MapA-Opti, or NASI-Opti) .

Master's degree programme Computational and Applied Mathematics

Study plan

Code	Title	Course	SWS				total ECTS	Workload-averaged in ECTS				spezification exam /ungraded task	Factor Grade
			V	Ü	P	S		1. Sem.	2. Sem.	3. Sem.	4. Sem.		
Mandatory Modules													
MApA	**Module 1: Modeling and Analysis in Continuum Mechanics I (65860)**	Modeling and Analysis in Continuum Mechanics I	4				**10**	8				oral exam 20 min. 100%	1
		Tutorials to Part I		1				2					
	Module 2: Modeling and Analysis in Continuum Mechanics II (65865)	Modeling and Analysis in Continuum Mechanics II	2				**5**		4			oral exam 20 min. 100%	1
		Tutorials to Part II		1/2					1				
MApA/ NASi/ Opti	**Module 3: Modeling, Simulation and Optimization (65870)**	Practical Course: Modeling, Simulation and Optimization				3	**5**		5			talk (50%), and coursework 10–15 pages (50%)	1
HPC	**Module 4: Programming Techniques for Supercomputers in CAM (65875)**	Programming Techniques for Supercomputers	4				**10**		5			see examination regulations INF	1
		Tutorials to Programming Techniques for Supercomputers		2					5				
	Module 5: Architectures of Supercomputers (44460)	Architectures of Supercomputers	2				**5**			2,5		see examination regulations INF	1
		Tutorials to Architectures of Supercomputers		2						2,5			
			12	**5,5**	**0**	**3**	**35**	**10**	**20**	**5**	**0**		

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Code	Title	Course	SWS				total ECTS	Workload-averaged in ECTS				spezification exam /ungraded task	Factor Grade
			V	Ü	P	S		1. Sem.	2. Sem.	3. Sem.	4. Sem.		
Master phase													
MapA/ NASi/ Opti	**Module 6a:** Master's seminar MApA	Master's seminar MApA*				2	**5**			5		talk 70-80 min with written report 5–10 pages	1
	Module 6b: Master's seminar NASi	Master's seminar NASi*				2	**5**			5		talk 70-80 min with written report 5–10 pages	1
	Module 6c: Master's seminar Opti	Master's seminar Opti*				2	**5**			5		talk 70-80 min with written report 5–10 pages	1
	Module 7: Masterthesis (1999)	Master colloquium					**25**				2,5	oral exam 15 min. (10%) Thesis (90%)	1
		Master thesis									22,5		
			0	**0**	**0**	**2**	**30**	**0**	**0**	**5**	**25**		
mandatory elective modules													
NASi	**Module 8: Numerics of Partial Differential Equations I (65993)**	Numerics of Partial Differential Equations I	4				**10**	7				written exam 90 min. (100%) with exercises (0%)	1
		Tutorials to Numerics of Partial Differential Equations I		2				3					
NASi	**Module 9: Advanced Discretization Techniques (65900)**	Advanced Discretization Techniques	4				**10**	8		(8)		oral exam 20 min. 100%	1
		Tutorials to Advanced Discretization Techniques		1				2		(2)			
NASi	**Module 10: Advanced Solution Techniques (65901)**	Advanced Solution Techniques	2				**5**		4			oral exam 15 min. 100%	1
		Tutorials to Advanced Solution Techniques		1/2					1				
MApA	**Module 11: Transport and Reaction in Porous Media: Modelling (65902)**	Transport and Reaction in Porous Media: Modelling	2				**5**		4			oral exam 15 min. 100%	1
		Tutorials to Transport and Reaction in Porous Media: Modelling		1/2					1				
NASi	**Module 12: Transport and Reaction in Porous Media: Simulation (65903)**	Transport and Reaction in Porous Media: Simulation	2				**5**			4		oral exam 15 min. 100%	1
		Tutorials to Transport and Reaction in Porous Media: Simulation		1/2						1			
NASi	**Module 13: Numerics of Incompressible Flows I (65904, 65853)**	Numerics of Incompressible Flows Part I	2				**5 or 10**		4			oral exam 15 min. 100%	1
		Tutorials to Numerics of Incompressible Flows Part I		1/2					1				
NASi	**Module 14: Numerics of Incompressible Flows II (65905, 65854)**	Numerics of Incompressible Flows Part II	2				**5 or 10**			4		oral exam 15 min. 100%	1
		Tutorials to Numerics of Incompressible Flows Part II		1/2						1			

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Code	Title	Course	SWS V	SWS Ü	SWS P	SWS S	total ECTS	Workload-averaged in ECTS 1. Sem.	2. Sem.	3. Sem.	4. Sem.	spezification exam /ungraded task	Factor Grade
MApA	**Module 15:** **Inverse Problems (65928)** (formerly also: 65994)	Inverse Problems	2				5	(4)		(4)		oral exam 15 min. 100%	1
		Tutorials to Inverse Problems		1/2				(1)		(1)			
NASi	**Module 16:** **Mathematics of Learning (formerly: Mathematical Data Science 1) (65785)**	Mathematics of Learning	2				5	(4)		(4)		Written exam 60 min. 100%	1
		Tutorials to Mathematics of Learning		1/2				(1)		(1)			
MApA	**Module 17:** **Mathematical Models of Kinetic Theory (65996)** (expired, no longer offered)	Mathematical Models of Kinetic Theory	2				5			4		Oral exam 15 min. 100%	1
		Tutorials to Mathematical Models of Kinetic Theory		1/2						1			
MApA	**Module 18:** **Mathematics of Multiscale Models (65906)**	Mathematics of Multiscale Models	2				5		(4)	(4)		oral exam 15 min. 100%	1
		Tutorials to Mathematics of Multiscale Models		1/2					(1)	(1)			
MApA	**Module 19:** **Theory of Stochastic Evolution Equations (65907)**	Theory of Stochastic Evolution Equations	2				5		4			oral exam 15 min. 100%	1
		Tutorials to Theory of Stochastic Evolution Equations		1/2					1				
NASi	**Module 20:** **Numerics of Stochastic Evolution Equations (65907)**	Numerics of Stochastic Evolution Equations	2				5			4		oral exam 15 min. 100%	1
		Tutorials to Numerics of Stochastic Evolution Equations		1/2						1			
NASi	**Module 21:** **Practical Course on Finite Element Methods for Phase-Separation Equations (65095)** (formerly also: 65863)	Seminar Practical Course on Finite Element Methods for Phase-Separation Equations				3	5	(5)		(5)		oral exam 30 min. 100%	1
MApA	**Module 22:** **Regularity Theory of Elliptic PDEs**	Regularity Theory of Elliptic PDEs	3				5	(4)		(4)		oral exam 20 min. 100%	1
		Tutorials to Regularity Theory of Elliptic PDEs				1		(1)		(1)			
MApA	**Module 23:** **Mathematical Modeling in the Life Sciences (65911)**	Mathematical Modelling in the Life Sciences	2				5			4		oral exam 15 min. 100%	1
		Tutorials to Mathematical Modelling in the Life Sciences		1/2						1			
Opti	**Module 24:** **Mathematical Image Processing (48241)** (replaces the expired module Partial Differential Equations based image processing (65912))	Mathematical image processing	2				5		4			oral exam 20 min. 100% or written exam 60 min 100% depending on the course size	1
		Tutorials to Mathematical image processing		1/2					1				
MApA	**Module 25:** **Analysis of Free-Boundary Problems in Continuum Mechanics (65997)**	Analysis of free-boundary problems in continuum mechanics	2				5			4		oral exam 15 min. 100%	1
		Tutorials to Analysis of free-boundary problems in continuum mechanics		1/2						1			

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Code	Title	Course	SWS				total ECTS	Workload-averaged in ECTS				spezification exam /ungraded task	Factor Grade
			V	Ü	P	S		1. Sem.	2. Sem.	3. Sem.	4. Sem.		
mandatory elective modules													
MApA/ NASi	**Module 26: Partial Differential Equations in Finance (65914)**	PDEs in Finance	2				**5**			4		oral exam 15 min. 100%	1
		Tutorials to PDEs in Finance		1/2						1			
Opti	**Module 27: Introduction to Material- and Shape Optimization (65915)**	Introduction to Material- and Shape Optimization	4				**10**		8			oral exam 20 min. 100%	1
		Tutorials to Material- and Shape Optimization		1					2				
Opti	**Module 28: Advanced Algorithms for Nonlinear Optimization (65916)**	Advanced Algorithms for Nonlinear Optimization	2				**5**	4				oral exam 15 min. 100%	1
		Tutorials to Advanced Algorithms for Nonlinear Optimization		1/2				1					
Opti	**Module 29: Discrete Optimization I (65917)**	Discrete Optimization I	2				**5**	(4)		(4)		written exam 60 min. 100%	1
		Tutorials to Discrete Optimization I		1				(1)		(1)			
Opti	**Module 30: Robust Optimization II (65918)**	Robust Optimization II	2				**5**		4			oral exam 15 min. 100%	1
		Tutorials to Robust Optimization II		1					1				
Opti	**Module 31: Numerical Aspects of Linear and Integer Programming (65919)**	Numerical Aspects of Linear and Integer Programming	2				**5**		4			oral exam 15 min. 100%	1
		Tutorials to Numerical Aspects of Linear and Integer Programming		1/2					1				
Opti	**Module 32: Advanced Nonlinear Optimization (65920)**	Advanced Nonlinear Optimization	4				**10**	(8)		(8)		oral exam 20 min. 100%	1
		Tutorials to Advanced Nonlinear Optimization		1				(2)		(2)			
Opti	**Module 33: Optimization with Partial Differential Equations (65921)**	Optimization with Partial Differential Equations	2				**5**	(4)		(4)		oral exam 15 min. 100%	1
		Tutorials to Optimization with Partial Differential Equations		1/2				(1)		(1)			
Opti	**Module 34: Discrete Optimization II (65933 with 5 ECTS, 65922 with 10 ECTS)**	Discrete Optimization II	2 or 4				**5**		4 or 8			oral exam 20 min. 100%	1
		Tutorials to Discrete Optimization II		1 or 2					1 or 2				
Opti	**Module 35: Optimization in Industry and Economy (65923)**	Optimization in Industry and Economy	2				**5 or 10**	(4)		(4)		oral exam 15 min. 100%	1
		Tutorials to Optimization in Industry and Economy		1				(1)		(1)			
Opti	**Module 36: Project Seminar Optimization (65924)**	Practical Course: Optimization				2	**5**		(5)	(5)		Talk/presentation 45 min. (50%), final report 10-15 pages (50%)	1
Opti	**Module 37: Conic Optimization and Applications**	Conic Optimization and Applications	2				**5**	(2)		(2)		oral exam 15 min. 100%	1
		Tutorials to Conic Optimization and Applications		1				(1)		(1)			

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Code	Title	Course	SWS				total ECTS	Workload-averaged in ECTS				spezification exam /ungraded task	Factor Grade
			V	Ü	P	S		1. Sem.	2. Sem.	3. Sem.	4. Sem.		
mandatory elective modules													
Opti	**Module 38: Lecture Series Partial Differential Equations, Control and Numerics (65700)**	Lecture Series Partial Differential Equations, Control and Numerics	2				**5**		4			written exam 90 min. 100%	1
		Tutorials to Lecture Series Partial Differential Equations, Control and Numerics applications		1					1				
NASi	**Module 39: Numerics of Partial Differential Equations II (65999)**	Numerics of Partial Differential Equations II	2						4			oral exam 15 min. 100%	1
		Tutorials to Numerics of Partial Differential Equations II		1					1				
MApA/ NASi	**Module 40: Efficient Discretization of two-phase Flow (65083)**	Efficient Discretization of two-phase Flow				2	**5**	(5)		(5)		Talk/presentation 60-80min (100%) with handout (0%)	1
NASi	**Module 42: Selected Topic of Mathematics of Learning (formerly: Mathematics of Learning) (65789)**	Selected Topics of Mathematics of Learning	2				**5**	(4)		(4)		Written exam 60 min. 100%	1
		Tutorial to Selected Topics of Mathematics of Learning		1				(1)		(1)			
Opti	**Module 43: Control, Machine Learning and Numerics (65093)**	Control, Machine Learning and Numerics	2				**10**		5			Project work with presentation (50%) and report (50%)	1
		Practicall to Control, Machine Learning and Numerics				3			5				
Opti	**Module 44: Discrete Optimization III (65910)**	Discrete Optimization III	2				**5**			4		Oral exam 15 min. 100%	1
		Tutorials to Discrete Optimization III		1						1			
Opti	**Module 45: Computational Complexity (65092)** (expired, no longer offered in future)	Computational Complexity	2				**5**		4			Oral exam 30 min. 100%	1
		Tutorials to Computational Complexity		1					1				
NASi	**Module 46: Numerical Methods for Nonsmooth Problems**	Numerical Methods for Nonsmooth Problems	4				**10**		8			Written exam 90 min (100%) with exercises (0%)	1
		Tutorials to Numerical Methods for Nonsmooth Problems		2					2				
MApA/ Opti	**Module 47: Wave Phenomena (65068)**	Wave Phenomena	2				**5**		4			Oral exam 20 min. 100%	1
		Tutorials to Wave Phenomena		1/2					1				
NASi	**Module 48: Subspace Correction Methods (65909)**	Subspace Correction Methods	2				**5**			4		Oral exam 15 min. 100%	1
		Tutorials to Subspace Correction Methods		1/2						1			
MApA	**Module 49: Navier Stokes Equations (65888)**	Navier Stokes Equations	4				**10**	(8)	(8)			oral exam 20 min. 100%	1
		Tutorials to Navier-Stokes equations		2				(2)	(2)				
Opti	**Module 50: Polynomial Optimization and Application (65877)**	Polynomial Optimization and Application	2				**5**	(4)		(4)		Oral exam 30 min 100%	1
		Tutorials to Polynomial Optimization and Application		1				(1)		(1)			
MApA	**Module 51: Stochastic Analysis (65970)**	Stochastic Analysis	2				**5**	(4)		(4)		Oral exam 100%	1
			16	**4**	**0**	**0**	**40**	**10**	**10**	**20**	**0**		

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Code	Title	Course	SWS				total ECTS	Workload-averaged in ECTS				spezification exam /ungraded task	Factor Grade
			V	Ü	P	S		1. Sem.	2. Sem.	3. Sem.	4. Sem.		
mandatory elective modules													
MApA	**Module 52:** **Seminar Applied Analysis (65787)**	Seminar Applied Analysis				2	**5**		(5)	(5)		Oral presentation 90 min (80%) and presentation document (20%)	1
MApA	**Module 53:** **Seminar Applied Topics of Applied Analysis (65096)**	Seminar Selected Topics of Applied Analysis				2	**5**		(5)	(5)		Oral presentation 90 min (80%) and presentation document (20%)	1
Opti/ NASi	**Module 54:** **Numerics of Optimal Control (65954)**	Numerics of Optimal Control	2				**5**		4			Oral exam 20 min 100%	1
		Tutorials to Numerics of Optimal Control		2					1				
MApA	**Module 55:** **Semigroups of Linear Operators (65273)**	Semigroups of Linear Operators	4				**10**	(8)	(8)	(8)	(8)	Oral exam 20 min 100%	1
		Stutorials to emigroups of Linear Operators		2				(2)	(2)	(2)	(2)		
Opti	**Module 56:** **Mathematical Foundations of Control and Machine Learning (65894)** (replaces the expired module Introduction to Control and Machine Learning (65067))	Mathematical Foundations of Control and Machine Learning	2				**5**	(4)	(4)			Oral exam 20 min 100%	1
		Tutorials to Mathematical Foundations of Control and Machine Learning		0.5				(1)	(1)				
MApA	**Module 57:** **A primer on functional-analytic methods for PDEs**	A primer on functional-analytic methods for PDEs	2				**5**		5			Oral exam 15 min 100%	1
MApA	**Module 58:** **Modul Conservation Laws (65887)**	Modul Conservation Laws	2				**5**	4				Oral exam 15 min 100%	1
Opti	**Module 59:** **Mathematical Foundations of Control and Machine Learning (65894)**	Lecture Math. Foundations of Control and Machine Learning	2				**5**	4				Oral exam 20 min 100%	1
		Tutorials to Math. Foundations of Control and Machine Learning		1/2				1					
NASi	**Module 60:** **Neural Network Theory (65838)**	Lecture Neural Network Theory	4				**5**				4	Oral exam 20 min 100% or Written exam (60 min)	1
		Tutorial to Neural Network Theory		1							1		
			16	**4**	**0**	**0**	**40**	**10**	**10**	**20**	**0**		

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Code	Title	Course	SWS				total ECTS	Workload-averaged in ECTS				spezification exam /ungraded task	Factor Grade
			V	Ü	P	S		1. Sem.	2. Sem.	3. Sem.	4. Sem.		
elective modules* **													
EM	**elective modules**		0-2	0-2	0-2	0-2	**5**	5				according to the chosen module	1
EM	**elective modules**		0-2	0-2	0-2	0-2	**5**	5				according to the chosen module	1
EM	**elective modules**		0-2	0-2	0-2	0-2	**5**				5	according to the chosen module	1
			0-6	**0-6**	**0-6**	**0-6**	**15**	**10**	**0**	**0**	**5**		
								30	30	30	30		
			Total SWS: 42-48*				120	Total ECTS: 120					

HPC High Performance Computing
MApA Modeling and Applied Analysis
NASi Numerical Analysis and Simulation
Opti Optimization

* Master seminar MApA, Master seminar NASi or Master seminar Opti has to be chosen
** as selected from FAU-modules

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1	**Module name** **65860**	**Module 1:** **ModAna1: Modeling and Analysis in Continuum Mechanics I**	**10 ECTS credits**
2	**Courses/lectures**	a) Lectures: 4 semester hrs/week b) Practical: 1 semester hr/week	**MApA**
3	**Lecturers**	**Profs. Drs. G. Grün, E. Zuazua, S. Metzger**	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	• Theory of elasticity (geometrical nonlinear modelling, objectivity and isotropy of energy functionals, linearized 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**	Students • 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**	Recommended: basic knowledge of linear algebra and calculus; basic knowledge of functional analysis.
8	**Integration into curriculum**	1st semester
9	**Module compatibility**	• Mandatory module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the fields of study “Modelling, Simulation and Optimization”, “Analysis and Stochastics”
10	**Method of examination**	oral exam (20 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Contact hours: 75 hrs Independent study: 225 hrs Total: 300 hrs, corresponding to 10 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• Ciarlet, P.G.: Mathematical elasticity, North-Holland • De Groot S.R. & Mazur P.: Non-equilibrium thermodynamics, Dover • Eck, C., Garcke, H. & Knabner, P.: Mathematical modelling, Springer • Evans, L. C. *Partial Differential Equations*. AMS, 2010 • Liu, I.: Continuum mechanics, Springer • Temam, R.: The Navier-Stokes equations, AMS Chelsea Publishing • Lecture notes will be distributed via StudOn.

1	**Module name** **65865**	**Module 2:** **ModAna2: Modeling and Analysis in Continuum Mechanics II**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**MApA**
3	**Lecturers**	**Profs. Drs. G. Grün, E. Zuazua, S. Metzger**	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	At least two of the following topics: • Monotone operators and applications in continuum mechanics, e.g. shear-thinning liquids, • Mathematical concepts of model reduction: homogenization, gamma convergence, asymptotic analysis, • Reaction diffusion models from biology and social sciences; • Models in fluid dynamics (compressible and incompressible Navier-Stokes equations); • Wave phenomena and other hyperbolic equations in continuum mechanics
6	**Learning objectives and skills**	Students can: • derive mathematical models for several important applications in continuum mechanics. • apply analytical techniques to rigorously prove qualitative properties of solutions.
7	**Prerequisites**	Recommended: Modeling and Analysis in Continuum Mechanics I
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Analysis and Stochastics” • Mandatory elective module for MSc in Mathematics and Economics in the field of study “Analysis and Stochastics”
10	**Method of examination**	oral exam (20 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer semester (annually)
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• A. Braides: Gamma-convergence for beginners, Oxford University Press, • D. Cioranescu & P. Donato: An introduction to homogenization, Oxford University Press • L.C. Evans: Partial differential equations, AMS, 2010 • T.A. Roberts: A one-dimensional introduction to continuum mechanics, World Scientific, 1994 • R.E. Showalter: Monotone operators in Banach space and nonlinear partial differential equations, AMS • T. Temam & A. Miranville: Mathematical modeling in continuum mechanics, Cambridge University Press • Depending on the lecturer, handouts and lecture notes may be offered via StudOn

1	**Module name** **65870**	**Module 3:** **MoSi: Practical Course: Modeling, Simulation, Optimization**	**5 ECTS credits**
2	**Courses/lectures**	Seminar: 3 semester hrs/week	**MapA/NASi/Opti**
3	**Lecturers**	**Profs. Drs. G. Grün, E. Zuazua, C. Gräser, F. Frank**	

4	**Module coordinator**	**Prof. Dr. C. Gräser**
5	**Content**	• Modelling, analysis, simulation and/or optimization of problems in engineering or the natural sciences • Numerical algorithms for partial differential equation models (finite differences, finite elements, etc) • Continuous optimization and optimal control
6	**Learning objectives and skills**	Students • work on problems in engineering or the natural sciences by constructing a suitable mathematical model, • are able to simulate, analyze, and/or optimize the constructed mathematical model using numerical methods, • are able to implement processes using their own or specified software and critically evaluate the results, • are able to set out their approaches and results in a comprehensible and convincing manner, making use of appropriate presentation techniques, • are able to develop and set out in writing the theories and problem solutions they have developed.
7	**Prerequisites**	Completion of the module Modeling and Analysis in Continuum Mechanics I
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory module for MSc in Computational Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	Talk and written project report
11	**Grading procedure**	talk 50% report 50%
12	**Module frequency**	Summer semester (annually)
13	**Workload**	Contact hours: 45 hrs Independent study: 105 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	Project-dependent. Will be published on StudOn at the beginning of the semester.

1	**Module name** **65875**	**Module 4:** **PTfS-CAM: Programming Techniques for Supercomputers in CAM**	**10 ECTS credits**
2	**Courses/lectures**	a) Lectures: 4 semester hrs/week b) Practical: 2 semester hrs/week	**HPC**
3	**Lecturers**	**Prof. Dr. G. Wellein**	

4	**Module coordinator**	**Prof. Dr. Gerhard Wellein**
5	**Content**	• Introduction to the architecture of modern supercomputers • Single core architecture and optimisation strategies • Memory hierarchy and data access optimization • Concepts of parallel computers and parallel computing • Efficient “shared memory” parallelisation (OpenMP) • Parallelisation approaches for multi-core processors including GPUs • Efficient “distributed memory” parallelisation (MPI) • Roofline performance model • Serial and parallel performance modelling • Complete parallel implementation of a modern iterative Poisson solver
6	**Learning objectives and skills**	Students • acquire a comprehensive overview of programming modern supercomputers efficiently for numerical simulations, • learn modern optimisation and parallelisation strategies, guided by structured performance modelling, • acquire an insight into innovative programming techniques and alternative supercomputer architectures, • are able to implement numerical methods to solve partial differential equations (PDEs) with finite difference (FD) discretization with high hardware efficiency on parallel computers.
7	**Prerequisites**	Recommended: Experience in C/C++ or Fortran programming; basic knowledge of MPI and OpenMP programming
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	Mandatory module for MSc Computational and Applied Mathematics
10	**Method of examination**	See examination regulations INF
11	**Grading procedure**	See examination regulations INF
12	**Module frequency**	Summer semester (annually)
13	**Workload**	Contact hours: 120 hrs Independent study: 180 hrs Total: 300 hrs, corresponding to 10 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• G. Hager & G. Wellein: Introduction to High Performance Computing for Scientists and Engineers. CRC Computational Science Series, 2010. ISBN 978-1439811924 • J. Hennessy & D. Patterson: Computer Architecture. A Quantitative Approach. Morgan Kaufmann Publishers, Elsevier, 2003. ISBN 1-55860-724-2

1	**Module name** **44460**	**Module 5:** **ArchSup: Architectures of Supercomputers**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 2 semester hrs/week	**HPC**
3	**Lecturers**	**Prof. Dr. D. Fey, Drs. A.Schäfer, J. Hofmann**	

4	**Module coordinator**	**Prof. Dr. Dietmar Fey**
5	**Content**	• 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**	Students • can explain the functionality of modern processors used in supercomputers, • recognise the special problems associated with energy consumption and programming in supercomputers, • can explain the different ways of interconnecting parallel processes, • can classify parallel computers with regard to their storage connection and basic processing principles, • are able to make use of and run a supercomputer to solve their own technical or mathematical problem. Based on the examples demonstrated during the lecture, they are able to generalise challenges associated with the discovery of bottlenecks and use them to solve their specific problem, • are able to characterise their problems (e.g. scientific or technical simulation experiments) with regard to the computing and memory requirements for a supercomputer in a way that is appropriate for the architecture, • can make use of the performance-measuring methods for parallel computers to evaluate various computer architectures and select the appropriate architecture for their problem.
7	**Prerequisites**	None
8	**Integration into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory module for MSc Computation and Applied Mathematics • Mandatory module for Computational Engineering degree programmes (Computer-Assisted Engineering) (Master of Science) and Information Technology (Master of Science)
10	**Method of examination**	See examination regulations INF
11	**Grading procedure**	See examination regulations INF
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Contact hours: 60 hrs Independent study: 90 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• Quinn: Parallel Programming in C with MPI and OpenMP, McGraw-Hill • Hennessy/Patterson: Computer Architecture - A Quantitative Approach, Morgen&Kaufmann

1	**Module name** **65885**	**Module 6a:** **MaSe: Master's seminar MApA**	**5 ECTS credits**
2	**Courses/lectures**	Seminar: 2 semester hrs/week	**MApA**
3	**Lecturers**	**Profs. Drs. G. Grün, Nachfolge Burger, E. Zuazua**	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	A topic from MApA that relates to the compulsory elective modules offered.
6	**Learning objectives and skills**	Students • can use original literature to familiarise themselves with a current research topic, • can structure the content acquired both verbally and in writing and make their own contributions to its presentation and/or substance, • learn scientific content on the basis of academic lectures and actively discuss it at a plenary session. For the MApA specialisation: • make use of analytical techniques to rigorously prove the qualitative characteristics of solutions to mathematical models in applied sciences.
7	**Prerequisites**	All compulsory modules for the MSc in Computational and Applied Mathematics recommended
8	**Integration into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory module for MSc in Computational and Applied Mathematics • Mandatory module for MSc in Mathematics • Mandatory module for MSc in Mathematics and Economics
10	**Method of examination**	talk/presentation (70-80 minutes) with handout (5-10 pages)
11	**Grading procedure**	75 %talk/presentation, 25% handout
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	**Module name** **65890**	**Module 6b:** **MaSe: Master's seminar NASi**	**5 ECTS credits**
2	**Courses/lectures**	Seminar: 2 semester hrs/week	**NASi**
3	**Lecturers**	**Profs. Drs. E. Bänsch, G. Grün, Nachfolge Burger, E. Zuazua**	

4	**Module coordinator**	**Prof. Dr. E. Bänsch**
5	**Content**	A topic from NASi that relates to the compulsory elective modules offered.
6	**Learning objectives and skills**	Students • can structure the content acquired both verbally and in writing and make their own contributions to its presentation and/or substance, • learn scientific content on the basis of academic lectures and actively discuss it at a plenary session. For the NASi specification: • can solve exemplary computational problems with given or self-developed software in order to illustrate or verify numerical methods under consideration.
7	**Prerequisites**	All compulsory modules for the MSc in Computational and Applied Mathematics recommended
8	**Integration into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory module for MSc in Computational and Applied Mathematics • Mandatory module for MSc in Mathematics • Mandatory module for Msc in Mathematics and Economics
10	**Method of examination**	talk/presentation (70-80 minutes) with handout (5-10 pages)
11	**Grading procedure**	75% talk/presentation, 25% handout
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	**Module name** **65895**	**Module 6c:** **MaSe: Master's seminar Opti**	**5 ECTS credits**
2	**Courses/lectures**	Seminar: 2 semester hrs/week	**Opti**
3	**Lecturers**	**Profs. Drs. F. Liers, A. Martin, M. Stingl, E. Zuazua**	

4	**Module coordinator**	**Prof. Dr. M. Stingl**
5	**Content**	A topic from Opti that relates to the compulsory elective modules offered.
6	**Learning objectives and skills**	Students • can use original literature to familiarise themselves with a current research topic, • can structure the content acquired both verbally and in writing and make their own contributions to its presentation and/or substance, • learn scientific content on the basis of academic lectures and actively discuss it at a plenary session. For the Opti specialisation: • model theoretical and applied tasks as optimization problems and/or develop optimization algorithms for their solution and/or put these into practice.
7	**Prerequisites**	All compulsory modules for the MSc in Computational and Applied Mathematics recommended
8	**Integration into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory module for MSc in Computational and Applied Mathematics • Mandatory module for MSc in Mathematics • Mandatory module for MSc in Mathematics and Economics
10	**Method of examination**	talk/presentation (70-80 minutes) with handout (5-10 pages)
11	**Grading procedure**	75% talk/presentation, 25% handout
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	**Module name** **1999**	**Module 7:** **Master's Thesis**	**25 ECTS credits**
2	**Courses/lectures**	Oral examination Master's Thesis	**MapA/NASi/Opti**
3	**Lecturers**	**The lecturers for the degree programme in Computational and Applied Mathematics**	

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

1	**Module name** **65993**	**Module 8:** **NumPDE I: Numerics of Partial Differential Equations I**	**10 ECTS credits**
2	**Courses/lectures**	a) Lecture: 4 semester hrs/week b) Practical: 2 semester hr/week	**NASi**
3	**Lecturers**	**Profs. Drs. E. Bänsch, G. Grün, C. Gräser**	

4	**Module coordinator**	**Prof. Dr. E. Bänsch**
5	**Content**	• Classical theory of linear elliptic boundary value problems (outline) • Finite difference method (FDM) for Poisson's equation in two dimensions (including stability via inverse monotonicity) • Finite element method (FEM) for Poisson's equation in two dimensions (stability and convergence, example: linear finite elements, implementation) • Variational theory of linear elliptic boundary value problems (outline) • FEM for linear elliptic boundary value problems (2^{nd} order) (types of elements, affin-equivalent triangulations, order of convergence, maximum principle) • 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
6	**Learning objectives and skills**	Students • apply algorithmic approaches for models with partial differential equations and explain and evaluate them, • are capable to judge on a numerical method's properties regarding stability and efficiency, • implement (with own or given software) numerical methods and critically evaluate the results, • explain and apply a broad spectrum of 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 into curriculum**	1st semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for BSc Mathematics (in the field Applied Mathematics) • Mandatory elective Module for BSc Technomathematik (in the field Numerical Mathematics, Modelling and Optimization) • Mathematical mandatory elective module for BSc Mathematics and Economics • Non-Physics elective module for MSc Physics
10	**Method of examination**	written exam (90 minutes) with exercises
11	**Grading procedure**	100% based on written exam
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Contact hours: 90 hrs Independent study: 210 hrs Total: 300 hrs, corresponding to 10 ECTS credits

14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Differential Equations, Springer 2003 • S. Larssen & V. Thomee: Partial Differential Equations with Numerical Methods. Springer 2005 • D. Braess: Finite Elements. Cambridge University Press 2010 • lecture notes

1	**Module name** **65900**	**Module 9:** **AdDiscTech: Advanced Discretization Techniques**	**10 ECTS credits**
2	**Courses/lectures**	a) Lecture: 4 semester hrs/week b) Practical: 1 semester hr/week	**NASi**
3	**Lecturers**	**Profs. Drs. E. Bänsch, G. Grün, N.N.**	

4	**Module coordinator**	**Prof. Dr. E. Bänsch**
5	**Content**	• 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**	Students • 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 into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	oral exam (20 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Contact hours: 75 hrs Independent study: 225 hrs Total: 300 hrs, corresponding to 10 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English

16	**Recommended reading**	• 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 Piettro & A. Ern: Mathematical aspects of discontinuous Galerkin methods. Springer 2012

1	**Module name** **65901**	**Module 10:** **AdSolTech: Advanced Solution Techniques**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**NASi**
3	**Lecturers**	**Profs. Drs. E. Bänsch, C. Gräser**	

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

1	**Module name** **65902**	**Module 11:** **RTpMMod: Transport and Reaction in Porous Media: Modeling**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0,5 semester hrs/week	**MapA**
3	**Lecturers**	**Prof. Dr. S. Kräutle, Drs. N. Ray, A. Prechtel**	

4	**Module coordinator**	**Prof. Dr. S. Kräutle**
5	**Content**	• Modelling of fluid flow through a porous medium: Groundwater models (Richards' equation), multiphase flow • Advection, diffusion, dispersion of dissolved substances, (nonlinear) reaction-models (i.a. law of mass action, adsorption, kinetic / in local equilibrium, reactions with minerals) • Models of partial (PDEs), ordinary (ODEs) differential equations, and local conditions • Nonnegativity, boundedness, global existence of solutions, necessary model assumptions in the case of a pure ODE model as well as for a PDE model • Existence of stationary solutions (i.a. introduction to the Feinberg network theory)
6	**Learning objectives and skills**	Students • are able to model flow and reaction processes in porous media on macro- and micro-scale using partial differential equations, • possess the techniques and the analytical foundations to assess the global existence of solutions.
7	**Prerequisites**	Recommended: Basic knowledge in differential equations
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of "Modeling, Simulation, and Optimisation" • Master Physics, non-physical elective module
10	**Method of examination**	Oral exam (15 minutes)
11	**Grading procedure**	100% Oral exam
12	**Module frequency**	Summer semester (annually)
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	- S. Kräutle: lecture notes math.fau.de/kraeutle/vorlesungsskripte/ - C. Eck, H. Garcke, P. Knabner: Mathematical Modeling, Springer - J.D. Logan: Transport Modeling in Hydrogeochemical Systems, Springer - M. Feinberg: lecture notes crnt.osu.edu/LecturesOnReactionNetworks

1	**Module name** **65903**	**Module 12:** **RTpMSim: Transport and Reaction in Porous Media: Simulation**	**5 ECTS creadits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**NASi**
3	**Lecturers**	**Prof. Dr. S. Kräutle, Drs. N. Ray, A. Prechtel**	

4	**Module coordinator**	**Prof. Dr. S. Kräutle**
5	**Content**	• Degenerate parabolic differential equations as multiphase flow models: formulation, nonlinear solution methods, discretization methods • 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 (operator splitting, change of variables, combination of the equations, elimination of AEs), as a basis for different software packages for numerical simulations, connection to optimisation (Gibbs energy) • Treatment of numerical difficulties (Guarantee of nonnegativity of numerical solutions of the (nonlinear) problems, scaling problems, convection dominated problems
6	**Learning objectives and skills**	Students • 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**	• Recommended: Basic knowledge in differential equations, • Useful also: Transport and Reaction in Porous Media: Modeling
8	**Integration into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of "Modeling, Simulation, and Optimisation" • Master Physics, non-physical elective module
10	**Method of examination**	Oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (not annually)
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	- P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Partial Differential Equations, Springer - Handbooks of Software Packages, https://en.www.math.fau.de/angewandte-mathematik-1/forschung/software-2

1	**Module name 65904 for the 5-ECTS vers. 65853 for the 10-ECTS-vers.**	**Module 13: NuIF1: Numerics of Incompressible Flows I**	**5 or 10 ECTS credits**
2	**Courses/lectures**	a) Lecture: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**NASi**
3	**Lecturers**	**Prof. Dr. E. Bänsch, Prof. Dr. G. Grün**	

4	**Module coordinator**	**Prof. Dr. E. Bänsch**
5	**Content**	• Mathematical modelling of (incompressible) flows • Variational formulation, existence and (non-)uniqueness of solutions to the stationary Navier-Stokes (NVS) equations • Stable finite element (FE) discretization of the stationary (Navier-) Stokes equations • Error estimates • Solution techniques for the saddle point problem
6	**Learning objectives and skills**	Students • explain and apply the mathematical theory for the stationary, incompress-ible 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 solu-tion techniques and apply them to concrete problem settings.
7	**Prerequisites**	Recommended: Advanced discretization techniques
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathem. • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral examination
12	**Module frequency**	Summer semester (annually)
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• V. 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 Univ. Press 2014 • R. Temam: Navier-Stokes equations. Theory and numerical analysis. North Holland

1	**Module name** **65905 vor the 5-ECTS vers.** **65854 for the 10-ECTS-vers.**	**Module 14:** **NuIF2: Numerics of Incompressible Flows II**	**5 or 10 ECTS credits**
2	**Courses/lectures**	a) Lecture: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**NASi**
3	**Lecturers**	**Prof. Dr. E. Bänsch, Prof. Dr. G. Grün**	

4	**Module coordinator**	**Prof. Dr. E. Bänsch**
5	**Content**	• 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**	Students • 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 into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Annually (usually in winter semester)
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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

1	**Module name 65928** (formerly also 65994)	**Module 15: InvP: Inverse Problems**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**MApA**
3	**Lecturers**	**Prof. Dr. D. Tenbrinck**	

4	**Module coordinator**	**Prof. Dr. D. Tenbrinck**
5	**Content**	• 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**	Students • 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**	Recommended: basic knowledge in functional analysis
8	**Integration into curriculum**	1^{st} or 3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Compulsory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	Oral exam (15 minutes)
11	**Grading procedure**	100% Oral exam
12	**Module frequency**	Winter semester (not annually) To check whether the course is offered in the current semester, see Campo campo.fau.de or module handbook of current semester
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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 65785**	**Module 16: MoL: Mathematics of Learning (formerly: MaDS: Mathematical Data Science 1)**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 1/2 semester hrs/week	**NASi**
3	**Lecturers**	**Profs. Drs. F. Liers, D. Tenbrinck**	

4	**Module coordinator**	**Prof. Dr. F. Liers**
5	**Content**	• Machine learning: empirical risk minimization, kernel methods, and variational models • Mathematical aspects of deep learning • Ranking problems • Mathematical models of graph structured data
6	**Learning objectives and skills**	Students • develop understanding of modern big data and state of the art methods to analyze them, • apply state of the art algorithms to large data sets, • derive models for network / graph structured data.
7	**Prerequisites**	Recommended: basic knowledge in numerical methods and optimization
8	**Integration into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory module for MSc in Data Science • Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	written exam (60min)
11	**Grading procedure**	100% written exam
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• I. Goodfellow, Y. Bengio, A. Courville: Deep Learning, MIT Press, 2015 • T. Hastie, R. Tibshirani, J. Friedman: The Elements of Statistical Learning, Springer, 2008

1	**Module name** **65996**	**Module 17:** **MaKiT: Mathematical Models of Kinetic Theory** (expired, no longer offered in future)	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**MApA**
3	**Lecturers**	**Formerly: Prof. Dr. M. Burger**	

4	**Module coordinator**	formerly: **Prof. Dr. M. Burger**
5	**Content**	• Microscopic stochastic interaction models and simulation • Mean-field and Boltzmann-Grad limit • Analysis of kinetic equations, linear and nonlinear Boltzmann equation • Hydrodynamic limits • Fokker-Planck and nonlinear diffusion equations
6	**Learning objectives and skills**	Students • develop understanding of modeling macroscopic phenomena emerging from local random interactions, • understand the advantages and limitations of different continuum descriptions, • derive and analyze models at different scales.
7	**Prerequisites**	Recommended: basic knowledge in modeling and partial differential equations
8	**Integration into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	Oral exam (15 minutes)
11	**Grading procedure**	100% Oral exam
12	**Module frequency**	Winter semester (not annually) To check whether the course is offered in the current semester, see Campo campo.fau.de or module handbook of current semester
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• L. Pareschi, G. Toscani: Interacting Multiagent Systems: Kinetik Equations and Monte Carlo Methods, Oxford University Press 2013 • C. Cercignani, R. Illner, M. Pulvirenti: The Mathematical Theory of Dilute Gases. Applied Mathematical Sciences, 106, Springer, 1994

1	**Module name 65906**	**Module 18: MaMM: Mathematics of Multiscale Models**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**MApA**
3	**Lecturers**	**Prof. Dr. M. Neuss-Radu, Dr. N. Neuß**	

4	**Module coordinator**	**Dr. N. Neuß**
5	**Content**	• 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**	Students • 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 into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	Oral exam (15 minutes)
11	**Grading procedure**	100% Oral exam
12	**Module frequency**	At least once every two years To check whether the course is offered in the current semester, see Campo campo.fau.de or module handbook of current semester
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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**	**Module 19:** **ThSDE: Theory of Stochastic Evolution Equations**	**5 ECTS credits**
2	**Courses/lectures**	Lecture: 2 semester hrs/week Practical: 0.5 semester hrs/week	**MApA**
3	**Lecturers**	**Prof. Dr. G. Grün, N.N.**	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	• 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**	Students • 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 into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of “Analysis and Stochastics” • Mandatory elective module for MSc in Mathematics and Economics in the field of “Stochastics and Risk Management”
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer semester (not annually) To check whether the course is currently offered, see Campo campo.fau.de or module handbook of current semester
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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, Springer

1	**Module name** **65908**	**Module 20:** **NuSDE: Numerics of Stochastic Evolution Equations**	**5 ECTS credits**
2	**Courses/lectures**	Lectures: 2 semester hrs/week Practical: 0.5 semester hrs/week	**NASi**
3	**Lecturers**	**Prof. Dr. G. Grün, N.N.**	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	• 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**	Students • 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 into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of "Analysis and Stochastics" • Mandatory elective module for MSc in Mathematics and Economics in the field of "Stochastics and Risk Management"
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (not annually) To check whether the course is currently offered, see Campo campo.fau.de or module handbook of current semester
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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** **65095** **(formerly also: 65863)**	**Module 21:** **PcFem: Practical Course on Finite Element Methods for Phase-Separation Equations**	**5 ECTS credits**
2	**Courses/lectures**	Seminar: 3 semester hrs/week	**NASi**
3	**Lecturers**	**Prof. Dr. S. Metzger**	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	• Finite element discretization for Cahn-Hilliard equations, • Storage concepts for sparse matrices, • Adaptive mesh refinement.
6	**Learning objectives and skills**	Students • implement a finite element solver for phase-separation equations, • are able to compare and implement different storage concepts for sparse matrices, • are able to implement finite element solvers based on adaptive meshes, • are able to derive and implement efficient discretizations for phase-separation equations, • are able to validate their implementation.
7	**Prerequisites**	Recommended: Numerics of Partial Differential Equations I
8	**Integration into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory elective module for BSc in Mathematics • Mandatory elective module for BSC in Technomathematics • Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	Oral exam (30 minutes)
11	**Grading procedure**	100% Oral exam
12	**Module frequency**	Winter semester (not annually)
13	**Workload**	Contact hours: 45 hrs Independent study: 105 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• P. Knabner & L. Angermann: Numerical Methods for Elliptic and Parabolic Differential Equations, Springer 2003 • D. Braess: Finite Elements. Cambridge University Press 2010 • B. Stroustrup: The C++ programming language, Addison-Wesley 2014

1	**Module name**	**Module 22:** **RegPDE: Regularity theory of elliptic PDEs**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 3 semester hrs/week b) Practical: 1 semester hrs/week	**MApA**
3	**Lecturers**	**Dr. C. Schneider**	

4	**Module coordinator**	**Dr. C. Schneider**
5	**Content**	• Elliptic partial differential equations • Variational formulation • Function spaces • Regularity of solutions in Sobolev and Besov spaces
6	**Learning objectives and skills**	Students • see the relevance of regularity theory for practical problems, in particular, for the numerical treatment of PDEs; they get acquainted with the basic methods for proving regularity estimates • learn how methods from functional analysis, numerics and approximation theory interact • practice their mathematical skills (develop mathematical intuition and its formal justification, improve their ability to think about abstract problems, learn new methods of proof)
7	**Prerequisites**	Recommended: Analysis-modules of Bachelor programme, module NumPDE
8	**Integration into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Analysis and stochastics”
10	**Method of examination**	Oral exam (20 minutes)
11	**Grading procedure**	100% Oral exam
12	**Module frequency**	Winter semester (not annually) To check whether the course is offered, see Campo campo.fau.de or module handbook of current semester
13	**Workload**	Contact hours: 60 hrs Independent study: 90 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• R. A. Adams, J. J. F. Fournier, Sobolev spaces, Pure and Applied mathematics 140, Elsevier, Academic Press (2003) • W. Hackbusch, Elliptic differential equations, Springer Series in Computational Mathematics, vol 18 (1992). • P. Grisvard, Elliptic problems in non smooth domains, Pitman, Boston (1985). • V. Kozlov, V. Maz’ya, J. Rossmann, Elliptic boundary value problems in domains with point singularities, AMS (1997).

1	**Module name** **65911**	**Module 23:** **MaMoLS: Mathematical Modeling in the Life Sciences**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0,5 semester hrs/week	**MApA**
3	**Lecturers**	**Prof. Dr. Neuss-Radu**	

4	**Module coordinator**	**Prof. Dr. Neuss-Radu**
5	**Content**	• 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**	Students • 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 into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modelling, Analysis and Optimization”
10	**Method of examination**	Oral exam (15 minutes)
11	**Grading procedure**	100% Oral exam
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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** **48241** (formerly 65912)	**Module 24:** **IPro: Mathematical Image Processing** (formerly: Partial Differential Equations Based Image Processing)	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hr/week	**Opti**
3	**Lecturers**	**Prof. Dr. D. Tenbrinck**	

4	**Module coordinator**	**Prof. Dr. D. Tenbrinck**
5	**Content**	This module covers mathematical image processing techniques based on Fourier domain filters, variational methods, and partial differential equations. In particular, the following content will be introduced to the students: • contrast enhancement • filtering in Fourier and image domain • Bayesian image denoising • image deblurring / deconvolution • pixel-based clustering • region-based segmentation • image impainting • nonlocal image processing using graphs
6	**Learning objectives and skills**	Students • explain mathematical and algorithmic methods for image processing, • apply above image processing methods in computerised practical exercises, • apply analytical techniques to evaluate the qualitative characteristics of the above methods.
7	**Prerequisites**	Knowledge in calculus and linear algebra is recommended. Knowledge in functional analysis, numerical mathematics, or inverse problems is helpful to understand advanced concepts in mathematical image processing.
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics • Mandatory elective module for MSc Mathematics in the fields of study "Modeling, Simulation and Optimization" • Mandatory elective module for MSc Integrated Life Science • Mandatory elective module for MSc Data Science in the field of study Mathematical Theory
10	**Method of examination**	oral exam (20 minutes) or written exam (60 min) depending on the number of participants
11	**Grading procedure**	100% based on the exam
12	**Module frequency**	Every second summer semester. To check whether the course is offered, see module handbook of current semester
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• G. Aubert & P. Kornprobst: Mathematical problems in image processing, Springer • 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. Bougleux: 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** **65997**	**Module 25:** **AnFBP: Analysis of free-boundary problems in continuum mechanics**	**ECTS 5 credits**
2	**Courses/lectures**	Lecture: 2 semester hrs/week Practical: 0.5 semester hrs/week	**MApA**
3	**Lectures**	**Prof. Dr. G. Grün**	
4	**Module coordinator**	**Prof. Dr. G. Grün**	
5	**Content**	• 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**	Students • formulate free-boundary problems in hydrodynamics and in porous-media 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 into curriculum**	3rd semester	
9	**Module compatibility**	• Mandatory elective module MSc Computational and Applied Mathematics, • Mandatory elective module MSc Mathematics in the field of study "Analysis and Stochastics"	
10	**Method of examination**	oral exam (15 minutes)	
11	**Grading Procedure**	100% based on oral exam	
12	**Module frequency**	Winter semester (not annually) To check whether the course is offered, see Campo campo.fau.de or module handbook of current semester	
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	
16	**Recommended reading**	L.C. Evans: Partial Differential Equations, AMS, Original journal articles.	

1	**Module name** **65914**	**Module 26:** **PDFin: Partial Differential Equations in Finance**	**5 ECTS credits**
2	**Courses/lectures**	Lecture: 2 semester hrs/week Practical: 0.5 semester hrs/week	**MApA/NASi**
3	**Lecturers**	**Profs. Drs. E. Bänsch, G. Grün**	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	• 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**	Students • 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 into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory elective module MSc Computational and Applied Mathematics, • Mandatory elective module MSc Mathematics in the field of study “Modelling, Analysis and Optimization” • Compulsory elective module MSc Mathematics and Economics in the field of study “Stochastics and Risk Management”
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (not annually) To check whether the course is offered, see module handbook of current semester
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• M. Capiński & 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**	**Module 27:** **MSOpt: Introduction to Material and Shape Optimization**	**10 ECTS credits**
2	**Courses/lectures**	a) Lectures: 4 semester hrs/week b) Practical: 1 semester hr/week	**Opti**
3	**Lecturers**	**Profs. Drs. M. Stingl**	

4	**Module coordinator**	**Prof. Dr. M. Stingl**
5	**Content**	• shape-, material- and topology optimization models • linear elasticity and contact problems • existence of solutions of shape, material and topology optimization problems • approximation of shape, material and topology optimization problems by convergent schemes
6	**Learning objectives and skills**	Students • derive mathematical models for shape-, material and topology optimization problems, • apply regularization techniques to guarantee to existence of solutions, • approximate design problems by finite dimensional discretizations, • derive algebraic forms and solve these by nonlinear programming techniques.
7	**Prerequisites**	Recommended: Knowledge in nonlinear optimization, Basic knowledge in numerics of partial differential equations
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc Mathematics in the field of study "Modelling, Analysis and Computation" • Mandatory elective module for MSc Mathematics and Economics in the field of study “Optimization and Process Management”
10	**Method of examination**	oral exam (20 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer semester (annually)
13	**Workload**	Contact hours: 75 hrs Independent study: 225 hrs Total: 300 hrs, corresponding to 10 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• J. Haslinger & R. Mäkinen: Introduction to shape optimization, SIAM, • M. P. Bendsoe & O. Sigmund: Topology Optimization: Theory, Methods and Applications, Springer.

1	**Module name** **65916**	**Module 28:** **AlgNLOpt: Advanced Algorithms for Nonlinear Optimization**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**Opti**
3	**Lecturers**	**Profs. Drs. M. Stingl, H. Meinlschmidt**	
4	**Module coordinator**	**Prof. Dr. M. Stingl**	
5	**Content**	Several of the following topics: • 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 • 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 into curriculum**	1st semester	
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for the MSc in Mathematics and Economics in the field of study “Optimization and process management”	
10	**Method of examination**	oral exam (15 minutes)	
11	**Grading procedure**	100% based on oral exam	
12	**Module frequency**	Winter semester (not annually) To check whether the course is offered, see Campo campo.fau.de or module handbook of current sememster	
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits	
14	**Module duration**	One semester	
15	**Teaching and examination language**	English	
16	**Recommended reading**	• C.T. Kelley: Iterative Methods for Optimization, SIAM, • J. Nocedal & S. Wright: Numerical Optimization, Springer.	

1	**Module name** **65917**	**Module 29:** **DiscOpt I: Discrete Optimization I**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 weekly lecture hours b) Practical: 1 weekly lecture hour	**Opti**
3	**Lecturers**	**Profs. Drs. F. Liers, Drs. A. Bärmann, K.-M. Aigner**	

4	**Module coordinator**	**Prof. Dr. F. Liers**
5	**Content**	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 • 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 into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics, • Mandatory elective module for MSc in Mathematics in the field of study “Modelling, Simulation and Optimization” • Mandatory elective module for the MSc in Mathematics and Economics in the field of study “Optimization and process management”
10	**Method of examination**	written exam (60 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (not annually) To check whether the course is offered, see module handbook of current semester
13	**Workload**	Attendance: 45 h Self-study: 105 h Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	one semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• Lecture notes • Conforti, Cornuéjols & Zambelli: Integer Programming, Springer 2014 • B. Grünbaum: Convex Polytopes, Springer, 2003 • B. Korte & J. Vygen: Combinatorial Optimization, Springer 2005 • G. L. Nemhauser & L.A. Wolsey: Integer and Combinatorial Optimization, Wiley 1994 • A. Schrijver: Theory of Linear and Integer Programming, Wiley 1986 • L.A. Wolsey: Integer Programming, Wiley 1998 • G. Ziegler: Lectures on Polytopes, Springer, 1995

1	**Module name** **65918**	**Module 30:** **RobOpt II: Robust Optimization II**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 weekly lecture hours b) Practical: 1 weekly lecture hour	**Opti**
3	**Lecturers**	**Profs. Drs. M. Hartisch, F. Liers**	

4	**Module coordinator**	**Prof. Dr. F. Liers**
5	**Content**	In practice, provided data for mathematical optimization problems is often not fully known. Robust optimization aims at finding the best solution which is feasible for input data varying within certain tolerances. The lecture covers advanced methods of robust optimization in theory and modeling. In particular, robust network flows, robust integer optimization and robust approximation are included. Further, state-of-the-art concepts, e.g., "light robustness" or "adjustable robustness" will be discussed by means of real-world applications.
6	**Learning objectives and skills**	Students • will be able to identify complex optimization problems under uncertainties as well as suitably model and analyze the corresponding robust optimization problem with the help of advanced techniques of robust optimization, • learn the handling of appropriate solving techniques and how to analyze the corresponding results.
7	**Prerequisites**	Recommended: Robust Optimization I
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics, • Mandatory elective module for MSc Mathematics in the field of study “Modelling, Simulation and Optimization” • Mandatory elective module for the MSc in Mathematics and Economics in the field of study “Optimization and process management”
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer semester (not annually) To check whether the course is offered in the current semester, see module handbook of current semester
13	**Workload**	Attendance: 45 h Self-study: 105 h
14	**Module duration**	1 semester
15	**Teaching and examination language**	English
16	**Recommended reading**	Lecture notes, will be published on StudOn at the beginning of the semester.

1	**Module name** **65919**	**Module 31:** **NALIP: Numerical Aspects of Linear and Integer Programming**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 weekly lecture hours b) Practical: 0.5 weekly lecture hour	**Opti**
3	**Lecturers**	**Prof. Dr. F. Liers**	

4	**Module coordinator**	**Prof. Dr. F. Liers**
5	**Content**	• Revised Simplex (with bounds) • Simplex Phase I • Dual Simplex • LP Presolve/Postsolve • Scaling • MIP Solution Techniques
6	**Learning objectives and skills**	Students are able to explain and use methods and numerical approaches for solving linear and mixed-integer programs in practice.
7	**Prerequisites**	Knowledge in linear algebra and combinatorial optimization is recommended.
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics, • Mandatory elective module for MSc Mathematics in the field of study “Modelling, Simulation and Optimization” • Mandatory elective Module for MSc Mathematics and Economics in the field of study “Optimization and Process Management”
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer semester (not annually) To check whether the course is offered, see Campo or module handbook of current semester
13	**Workload**	Attendance: 37.5 h Self-study: 112.5 h
14	**Module duration**	1 semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• V. Chvátal: Linear Programming, W. H. Freeman and Company, New York, 1983 • L.A. Wolsey: Integer Programming, John Wiley and Sons, Inc., 1998

1	**Module name** **65920**	**Module 32:** **AdvNLOpt: Advanced Nonlinear Optimization**	**10 ECTS credits**
2	**Courses/lectures**	a) Lectures: 4 semester hrs/week b) Practical: 1 semester hr/week	**Opti**
3	**Lecturers**	**Profs. Drs. W. Achtziger, M. Stingl**	

4	**Module coordinator**	**Prof. Dr. W. Achtziger**
5	**Content**	• 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**	Students • 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 into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modelling, Simulation and Optimization” • Mandatory elective module for MSc in Mathematics and Economics in the field of study “Optimization and Process Management”
10	**Method of examination**	oral exam (20 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (not annually) To check whether the course is offered, see Campo campo.fau.de or module handbook of current semester
13	**Workload**	Contact hours: 75 hrs Independent study: 225 hrs Total: 300 hrs, corresponding to 10 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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	**Module 33:** **OptPDE: Optimization with Partial Differential Equations**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**Opti**
3	**Lecturers**	**Profs. Drs. M. Stingl, H. Meinlschmidt**	

4	**Module coordinator**	**Prof. Dr. M. Stingl**
5	**Content**	Several of the following topics: • 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**	Students • 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 into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modelling, Simulation and Optimization” • Mandatory elective module for MSc in Mathematics and Economics in the field of study “Optimization and Process Management”
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (not annually) To check whether the course is offered, see Campo campo.fau.de or module handbook of current semester
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	- F. Tröltzsch: Optimal Control of Partial Differential Equations, AMS, - G. Leugering & P. Kogut: Optimal Control of PDEs in Reticulated Domains, Birkhäuser.

1	**Module name** **65933**	**Module 34-a:** **DiscOpt II: Discrete Optimization II**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 weekly lecture hours b) Practical: 1 weekly lecture hour	**Opti**
3	**Lecturers**	**Profs. Drs. F. Liers, T. Oertel**	

4	**Module coordinator**	**Prof. Dr. T. Oertel**
5	**Content**	In this lecture we cover theoretical aspects and solution strategies for difficult integer and mixed-integer optimization problems. First, we point out the equivalence between separation and optimization. Second, fundamental results of integral polyhedra, lattices and lattice polyhedra as well as its importance to discrete optimization are discussed. Furthermore, we introduce solution strategies for large-scale optimization problems, e.g., decomposition methods or approximation algorithms and heuristics based on linear programming. In addition, we discuss applications arising in engineering, finance, energy management or public transport.
6	**Learning objectives and skills**	Students • use basic terms of discrete optimization, • model real-world discrete optimization problems, determine their complexity and solve them with appropriate mathematical methods.
7	**Prerequisites**	Recommended: Knowledge in linear and combinatorial optimization, discrete optimization I
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics
10	**Method of examination**	oral exam (20 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer semester (annually 34-a or 34-b)
13	**Workload**	Attendance: 45 h Self-study: 105 h
14	**Module duration**	1 semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• Lecture notes • D. Bertsimas & R. Weismantel: Optimization over Integers, Dynamic Ideas, 2005 • Conforti, Cornuéjols & Zambelli: Integer Programming, Springer 2014 • G. L. Nemhauser & L.A. Wolsey: Integer and Combinatorial Optimization, Wiley 1994 • A. Schrijver: Combinatorial optimization Vol. A - C, Springer 2003 • A. Schrijver: Theory of Linear and Integer Programming, Wiley, 1986 • L.A. Wolsey: Integer Programming, Wiley

1	**Module name** **65922**	**Module 34-b:** **DiscOpt II: Discrete Optimization II**	**510ECTS credits**
2	**Courses/lectures**	a) Lectures: 4 weekly lecture hours b) Practical: 2 weekly lecture hour	**Opti**
3	**Lecturers**	**Profs. Drs. F. Liers, T. Oertel**	

4	**Module coordinator**	**Prof. Dr. T. Oertel**
5	**Content**	In this lecture, we cover theoretical aspects of discrete optimization. Taking a geometric approach, a focus will be on lattice theory, studying the interplay of lattices and convex bodies. Topics will include: Reduced bases, like the LLL-reduced basis,Minkowski's Thteorem on successive minima, The closest lattice vector problem, Lenstra's algorithm for linear integer optimization in fixed dimension, Barvinok's Algorithm for counting integer points in polytopes.
6	**Learning objectives and skills**	Students • use basic terms of discrete optimization, • model real-world discrete optimization problems, determine their complexity and solve them with appropriate mathematical methods.
7	**Prerequisites**	Recommended: Knowledge in linear and combinatorial optimization, discrete optimization I
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics, • Mandatory elective module for MSc Mathematics in the field of study "Modelling, Simulation and Optimization" • Mandatory elective module for MSc Mathematics and Economics in the field "Optimization and Process Management" • MSc Data Science, field of study "Mathem. Theorie/Grundlagen" • MSc Informatik • MSc Artificial Intelligence
10	**Method of examination**	oral exam (20 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer semester (annually 34-a or 34-b)
13	**Workload**	Attendance: 90 h Self-study: 210 h
14	**Module duration**	1 semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• Lecture notes • Conforti, Cornuéjols & Zambelli: Integer Programming, Springer 2014 • Grötschel, Lovász , Schrijver, Geometric Algorithms and Combinatorial Optimization, Springer, 1993 • A. Schrijver: Theory of Linear and Integer Programming, Wiley, 1986 • An extended reading list will be provided at the start of the course

1	**Module name** **65923**	**Module 35:** **OptIE: Optimization in Industry and Economy**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 weekly lecture hours b) Practical: 1 weekly lecture hour	**Opti**
3	**Lecturers**	**Profs. Drs. M.C. Düker, F. Liers**	

4	**Module coordinator**	**Prof. Dr. F. Liers**
5	**Content**	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.
6	**Learning objectives and skills**	Students • 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: Knowledge in linear and combinatorial optimization
8	**Integration into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics, • Mandatory elective module for MSc Mathematics in the field of study "Modelling, Simulation and Optimization" • Mandatory elective module for MSc Mathematics and Economics in the field "Optimization and Process Management"
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Attendance: 45 h Self-study: 105 h Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	1 semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• Lecture notes (will be published on StudOn at the beginning of the semester) • Up-to-date research literature (will be published on StudOn at the beginning of the semester)

1	**Module name** **65924**	**Module 36:** **ProjO: Project Seminar Optimization**	**5 ECTS credits**
2	**Courses/lectures**	Seminar: 2 semester hrs/week	**Opti**
3	**Lecturers**	**Prof. Dr. F. Liers**	

4	**Module coordinator**	**Prof. Dr. F. Liers**
5	**Content**	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**	Students • 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 into curriculum**	2nd or 3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied Mathematics, • Mandatory elective module for MSc Mathematics in the field of study “Modelling, Simulation and Optimization” • Mandatory elective module for MSc Mathematics and Economics in the field “Optimization and Process Management”
10	**Method of examination**	Talk/presentation (45 minutes) with final report (10-15 pages)
11	**Grading procedure**	Talk/presentation (50%) final report (50%)
12	**Module frequency**	Summer or winter semester (annually) To check whether the course is offered in the current semester, see Campo campo.fau.de or module handbook of current semester
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	Project-dependent. Will be published on StudOn at the beginning of the semester.

1	**Module name** **65862**	**Module 37:** **COA: Conic Optimization and Applications** (expired, no longer offered in future)	**5 ECTS credits**
2	**Courses/lectures**	a) Lecture: 2 semester hrs/week b) Practical: 1 semester hr/weekwave phenomena	**Opti**
3	**Lecturers**	formerly: **Dr. J. Rolfes**	
4	**Module coordinator**	Formerly: **Dr. J. Rolfes**	
5	**Content**	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. Overview of topics: • 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 MAX-CUT, packing problems, coloring problems, Shannon capacity • Symmetry reduction of optimization	
6	**Learning objectives and skills**	Students • 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 into curriculum**	1st or 3rd semester	
9	**Module compatibility**	• Mandatory elective module for MSc Computational and Applied – • Mathematics • Mandatory elective module for MSc Mathematics in the field of “Modeling, Simulation and Optimization” • Mandatory elective module for MSc Mathematics and Economics in the fields of “Optimization and Process Management”	
10	**Method of examination**	oral exam (15 minutes)	
11	**Grading Procedure**	100% based on oral exam	
12	**Module frequency**	Winter semester (not annually) To check whether the course is offered in the current semester, see Campo campo.fau.de or module handbook of current semester	

13	**Workload**	Contact hours: 45 hrs Independent study: 105 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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 65700**	**Module 38: PdeConNum: Lecture Series Partial Differential Equations, Control and Numerics**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**Opti**
3	**Lecturers**	**Prof. Dr. E. Zuazua**	

4	**Module coordinator**	**Prof. Dr. E. Zuazua**
5	**Content**	• 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**	Students • 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 into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	Oral exam (15 minutes)
11	**Grading procedure**	100% Oral exam
12	**Module frequency**	Summer semester (annually)
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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 65999	Module 39: NumPDE II: Numerics of Partial Differential Equations II	5 ECTS credits
2	Courses/lectures	a) Lecture: 2 semester hrs/week b) Practical: 1 semester hr/week	NASi
3	Lecturers	Profs. Drs. E. Bänsch, G. Grün	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	• Classical and weak theory for linear parabolic initial-boundary-value problems (IBVPs) (outline), • finite-element method (FEM) for 2nd-order linear parabolic IVBPs (semi-discretisation in space, time discretisation by one-step methods, stability, comparison principles, order of convergence), • FEM for semi-linear elliptic and parabolic equations (fixed-point- and Newton-methods, secondary iterations), • higher-order time discretisation, extrapolation, time-step control.
6	**Learning objectives and skills**	Students • apply algorithmic approaches for models with partial differential equations and explain and evaluate them, • are capable to judge on a numerical method's properties regarding stability and efficiency, • implement (with own or given software) numerical methods and critically evaluate the results, • explain and apply a broad spectrum of methods with a focus on conforming finite element methods for parabolic problems, extending these approaches also to nonlinear problems, • collect and evaluate relevant information and realize relationships.
7	**Prerequisites**	Recommended: basic knowledge in numerics and numerics of pde
8	**Integration into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for BSc Mathematics • Mandatory module for BSc Technomathematik • Non-Physics elective module for MSc Physics
10	**Method of examination**	written exam (90 minutes) with exercises
11	**Grading procedure**	100% based on written exam
12	**Module frequency**	Summer semester (annually)
13	**Workload**	Contact hours: 45 hrs Independent study: 105 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• P. Knabner, L. Angermann, Numerical Methods for Elliptic and Parabolic Partial

		Differential Equations, Springer, New York, 2003. • S. Larsson, V. Thomée, Partial Differential Equations with Numerical Methods, Springer, Berlin, 2005.

1	**Module name** **65083**	**Module 40:** **DiscTPFlow: Efficient Discretization of two-phase Flow**	**5 ECTS credits**
2	**Courses/lectures**	Seminar: 2 semester hrs/week	**MApA, NASi**
3	**Lecturers**	**Prof. Dr. St. Metzger**	

4	**Module coordinator**	**Prof. Dr. St Metzger**
5	**Content**	• Based on recent scientific publications, different discretization approaches for two-phase flow are discussed.
6	**Learning objectives and skills**	Students • can use original literature to familiarise themselves with a current research topic, • can structure the content acquired both verbally and in writing and make their own contributions to its presentation and/or substance, • learn scientific content on the basis of academic lectures and actively discuss it at a plenary session, • learn to compare different discretization methods regarding their specific advantages and disadvantages.
7	**Prerequisites**	Recommended: Numerics of Partial Differential Equations I
8	**Integration into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory elective module for BSc in Mathematics in the field "Applied Mathematics" • Mandatory elective module for BSc in Technomathematics • Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study "Modeling, Simulation and Optimization"
10	**Method of examination**	Talk/presentation (60-80 minutes) with handout (5-10 pages)
11	**Grading procedure**	100% talk/presentation with handout
12	**Module frequency**	Winter semester (not annually)
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	Depending on topic. Will be published on StudOn at the beginning of the semester.

1	**Module name 65789**	**Module 42: SMoL: Selected Topics of Mathematics of Learning (formerly: Mathematics of Learning)**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 2 semester hrs/week	**NASi**
3	**Lecturers**	**Profs. Dr. F. Liers, M.-C. Düker, Dr. M. Yamakou**	

4	**Module coordinator**	**Prof. Dr. F. Liers**
5	**Content**	Advanced methods of mathematical data sciences, 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**	Recommended: basic knowledge in numerical methods and optimization
8	**Integration into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory module for MSc in Data Science • Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics in the field of study “Modeling, Simulation and Optimization”
10	**Method of examination**	Written exam (60 minutes)
11	**Grading procedure**	100% written exam
12	**Module frequency**	Winter semester (annually, starting in WS22/23)
13	**Workload**	Contact hours: 60 hrs Independent study: 90 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• S. Wright & B. Recht: Optimization for data analysis, 2022

1	**Module name** **65093**	**Module 43:** **CML: Control, Machine Learning and Numerics**	**10 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 3 semester hrs/week	**Opti**
3	**Lecturers**	**Prof. Dr. E. Zuazua, Dr. Y. Song**	

4	**Module coordinator**	**Prof. Dr. E. Zuazua**
5	**Content**	• several topics related to the control of Ordinary Differential Equations (ODE) and Partial Differential Equations (PDE), including controllability, observability, and some of the most fundamental work that has been done in the subject in recent years. • an introduction to Machine Learning, focusing mainly on the use of control techniques for the analysis of Deep Neural Networks as a tool to address, for instance, the problem of Supervised Learning. • some classical computational techniques related to the control of ODE and PDE, and machine learning.
6	**Learning objectives and skills**	Students are able to • understand some basic theory on control and machine learning. • learn about recent advances on control and machine learning. • implement some computational techniques using their own or specified software and critically evaluate the results, • set out their approaches and results in a comprehensible and convincing manner, making use of appropriate presentation techniques.
7	**Prerequisites**	Recommended: Basic knowledge of calculus, linear algebra, ODE and PDE. Familiarity with scientific computing is helpful.
8	**Integration into curriculum**	2^{nd} semester
9	**Module compatibility**	• Mandatory module for MSc in Data Science (Simulation and Numerics) • Mandatory elective module for MSc in Computational and Applied Mathematics
10	**Method of examination**	Project work with presentation and report
11	**Grading procedure**	50% presentation and 50% report
12	**Module frequency**	Summer semester (annually)
13	**Workload**	Contact hours: 75 hrs Independent study: 225 hrs Total: 300 hrs, corresponding to 10 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• L. Bottou, F. E. Curtis, and J. Nocedal, Optimization methods for large-scale machine learning. SIAM Review, 60 (2) (2018) , 223-311. • J. M. Coron, Control and Nonlinearity, Mathematical Surveys and Monographs, 143, AMS, 2009. • I. Goodfellow, Y. Bengio, & A. Courville, Deep Learning. MIT press, 2016. • R. Glowinski, J. L. Lions, and J. He, Exact and Approximate Controllability for Distributed Parameter Systems: A Numerical Approach, Encyclopedia Math. Appl., Cambridge University Press, Cambridge, UK, 2008. • C. F. Higham, and D. J. Higham, Deep learning: An introduction for applied mathematicians. SIAM Review, 61 (4) (2019), 860-891. • J. Nocedal, and S. Wright, Numerical Optimization. Springer Science & Business Media, 2006. • D. Ruiz-Balet, and E. Zuazua, Neural ODE control for classification, approximation and transport. arXiv preprint arXiv:2104.05278, (2021).

		• E. Zuazua, Propagation, observation, and control of waves approximated by finite difference methods, SIAM Review, 47 (2) (2005), 197-243. • 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.

1	**Module name** **65910**	**Module 44:** **DiscOpt III: Discrete Optimization**	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 1 semester hrs/week	**Opti**
3	**Lecturers**	**Profs. Drs. T. Oertel, F. Liers**	

4	**Module coordinator**	**Prof. Dr. T. Oertel**
5	**Content**	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.
6	**Learning objectives and skills**	Students • use basic terms of discrete optimization • model real-world discrete optimization problems, determine their complexity and solve them with appropriate mathematical methods.
7	**Prerequisites**	Recommended: Knowledge in linear and combinatorial optimization, discrete optimization I, discrete optimization II
8	**Integration into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory module for MSc in Data Science (Simulation and Numerics) • Mandatory elective module for MSc in Computational and Applied Mathematics • Elective module for Msc Mathematics • Elective module for Msc Mathematics and Economics • Elective module for Msc Data Sciences • Core/research module for Msc Mathematics within the spezialisation „Modelling, simulation and optimization“ • Core/research module for Msc Mathematics and Economics within the spezialisation „Optimization and process management“
10	**Method of examination**	Oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (annually)
13	**Workload**	Contact hours: 45 hrs Independent study: 105 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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** **65092**	**Module 45:** **CC: Computational Complexity** (expired, no longer offered in future)	**5 ECTS credits**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Tutorial: 1 semester hrs/week	**Opti**
3	**Lecturers**	formerly: **Prof. Dr. Y. Giannakopoulos**	

4	**Module coordinator**	formerly: **Prof. Dr. Y. Giannakopoulos**
5	**Content**	Potential topics include: • P, NP, and NP-completeness • Complexity classes and reductions • Boolean circuits • The polynomial-time hierarchy • Space complexity • Randomized computation • Counting complexity • Introduction to the PCP theorem and hardness of approximation • Average-case complexity
6	**Learning objectives and skills**	Upon successful completion of the module, students: • Have a rigorous understand of the concept of computation and its formal limitations • Have knowledge of the fundamental complexity classes (including P, NP and PSPACE) • Understand the notion of completeness and are able to design and understand reductions between these classes • Are exposed to various formal computation models, including Boolean circuits and randomness
7	**Prerequisites**	Recommended: • Undergraduate-level course in discrete mathematics (including, e.g., basics of combinatorics, graphs, logic and set theory), • undergraduate-level course in algorithms and/or discrete optimization, • basic knowledge of analysis, linear algebra and probability
8	**Integration into curriculum**	from 1st semester
9	**Module compatibility**	• Mandatory elective module for Msc in Computational and Applied Mathematics • Elective module for Msc Mathematics • Elective module for Msc Mathematics and Economics, fields of study “Optimization and Process Management”, “Modeling, Simulation and Optimization” • Elective module for MSc Data Science (Databased Optimization, Mathematical Theory / Basics of Data Science, Machine learning / artificial intelligence) • Mathematics Minor („Nebenfach Mathematik“) in Bsc / Msc Computer Science („Informatik“) • Mathematics Minor in Msc Artificial Intellicence

10	**Method of examination**	Oral exam (30 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer semester (annually)
13	**Workload**	Contact hours: 45 hrs Independent study: 105 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• O. Goldreich, Computational Complexity: A Conceptual Perspective, Cambridge University Press, 2008 • S. A. and B. Barak, Computational Complexity: A Modern Approach Cambridge University Press, 2009 • Ch. H. Papadimitriou. Computational Complexity. Addison-Wesley, 1994

1	Module name	**Module 46:** **NumNonsmooth: Numerical Methods for Nonsmooth Problems**	**10 ECTS**
2	Courses/lectures	a) Lectures: 4 semester hrs/week b) Practical: 2 semester hrs/week	**NASi**
3	Lecturers	**Prof. Dr. C. Gräser**	

4	**Module coordinator**	**Prof. Dr. C. Gräser**
5	**Content**	• Examples of nonsmooth problems involving partial differential equations (PDEs) (e.g. contact of elastic bodies, friction, phase transition, shallow ice glacier models, brittle fracture,...) • Elements of convex analysis (constrained and nonsmooth minimization problems, variational inequalities) • Discretization of nonsmooth problems (e.g. finite elements, DG) • Efficient algebraic solvers (active set, relaxation, nonsmooth multigrid methods)
6	**Learning objectives and skills**	Students are • familiar with different formulations of nonsmooth problems (minimization, variational inequality, subdifferential inclusion) • familiar with basic existence and well-posedness results • capable of discretizing nonsmooth problems using variational methods and solving the discrete problems efficiently • aware of the intrisic difficulties for analysis and numerics arising from nonsmoothness
7	**Prerequisites**	Recommended: Introduction to numerical methods for PDEs Recommended: Basic knowledge of functional analysis (but the necessary terminology and results are briefly provided during the lecture)
8	**Integration into curriculum**	From 1st semester onwards
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Mandatory elective module for MSc in Mathematics
10	**Method of examination**	written exam (90 minutes) with exercises
11	**Grading procedure**	100% based on written exam
12	**Module frequency**	Summer semester (not annually)
13	**Workload**	Contact hours: 90 hrs Independent study: 210 hrs Total: 300 hrs, corresponding to 10 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• I. Ekeland & R. Témam: Convex Analysis and Variational Problems, SIAM • R. Glowinski & J.-L. Lions & R. Trémolières: Numerical Analysis of Variational Inequalities, North Holland • Further literature and publications are announced during the lecture

1	**Module name** **65068**	**Module 47:** **WavePh: Wave Phenomena**	**5 ECTS**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**MApA/Opti**
3	**Lecturers**	**Prof. Dr. E. Zuazua, N. De Nitti**	

4	**Module coordinator**	**Prof. Dr. E. Zuazua**
5	**Content**	1. **Motivations and applications.** 2. **Linear transport equation:** method of characteristics; Fourier analysis and numerical approximations. 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 R^3; Poisson's representation in 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. 4. **Klein-Gordon equation:** energy estimates; representation of solutions by using Fourier multipliers; von Wahl's transformation. 5. **Damped wave equation:** energy estimates; representation of solutions by using Fourier multipliers; decay behavior and decay rate. 6. **Damped plate equation:** estimates for the energy; estimates for the solution itself and its derivatives; 7. **Semilinear wave equation:** global existence for small data and global existence for large data. 8. **Diffusion phenomena:** parabolic structure of solutions to damped waves and damped plates; diffusion phenomena in thermo-elasticity; traveling waves and reaction-diffusion models. 9. **Scalar conservation laws:** occurrence of shocks and rarefaction waves. 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. 11. **Maxwell equations**: constitutive equations; special cases; boundary conditions; expansion into wave functions.
6	**Learning objectives and skills**	Students are able to: • 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 into curriculum**	2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics
10	**Method of examination**	oral exam (20 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer semester (not annually)
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits

14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• M.R. Ebert, M. Reissig: Methods for Partial Differential Equations, Birkhäuser, 2018. • L.C. Evans, Partial Differential Equations. AMS, 2010. • M. Reissig, Theory of hyperbolic equations. Lecture Notes, 2007: https://tu-freiberg.de/sites/default/files/media/institut-fuer-angewandte-analysis-9030/reissig/pdehanoi1.pdf • T. Myint-U, L. Debnath, Linear partial differential equations for scientists and engineers. Birkhäuser, 2007. • R. Vichnevetsky, J.B. Bowles, Fourier Analysis of Numerical Approximations of Hyperbolic Equations. SIAM, 1982 • Lecture notes will be distributed via StudOn.

1	**Module name** **65909**	**Module 48:** **SupS: Subspace Correction Methods**	**5 ECTS**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Practical: 0.5 semester hrs/week	**NASi**
3	**Lecturers**	**Prof. Dr. C. Gräser**	

4	**Module coordinator**	**Prof. Dr. C. Gräser**
5	**Content**	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 • 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 • Basic knowledge of functional analysis (but the necessary terminology and results are briefly provided during the lecture)
8	**Integration into curriculum**	3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Elective module in MSc in Mathematics in the field MSO • Elective module in MSc in Mathematics and Economics
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (not annually)
13	**Workload**	Contact hours: 37,5 hrs Independent study: 112,5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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**	**Module 49: NaSto: Navier Stokes Equations**	**10 ECTS**
2	**Courses/lectures**	a) Lectures: 4 semester hrs/week b) Practical: 2 semester hrs/week	**MApA**
3	**Lecturers**	**Prof. Dr. E. Wiedemann**	

4	**Module coordinator**	**Prof. Dr. E. Wiedemann**
5	**Content**	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 Millenium Problems. This course serves as an introduction to the mathematical theory of these equations and includes the following topics: • existence of weak solutions of Leray-Hopf type • local-in-time existence of strong solutions • the Prodin-Serrin criteria for regularity and energy balance • partial regularity theory • the singular limit of vanishing viscosity The course can be a good preparation for a subsequent master's thesis in the topic.
6	**Learning objectives and skills**	Students know and understand • the underlying theory of the Navier-Stokes equations • can handle the main methods for systems of nonlinear partial differential equations • gain a basic understanding of mathematical fluid dynamics
7	**Prerequisites**	Recommended: • basic courses in partial differential equations and in functional analysis
8	**Integration into curriculum**	1st semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Elective module in MSc in Mathematics in the field Analysis&Stochastics and in the field MSO
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer or winter semester (not annually)
13	**Workload**	Contact hours: 90 hrs Independent study: 210 hrs Total: 300 hrs, corresponding to 10 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• Robinson, Rodrigo, Sadowski: The three-dimensional Navier-Stokes equations, Cambridge University Press, 1988 • Constantin, Fojas: Navier-Stokes equations, University of Chicago Press, 1988 • Ozanski: The partial regularity theory of Caffarelli, Kohn, and Nirenberg and its sharpness, Birkhäuser, 2019 • Wiedemann: Navier-Stokes equations: Lecture notes, Universität Ulm, 2018/19

1	**Module name 65877**	**Module 50: PolyOpt: Polynomial Optimizsation and Application**	**5 ECTS**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Tutorial: 1 semester hrs/week	**Opti**
3	**Lecturers**	**Prof. Dr. G. Fantuzzi**	

4	**Module coordinator**	**Prof. Dr. G. Fantuzzi**
5	**Content**	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: • 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) Students will also have the opportunity to put the theory into practice with “hands-on” practical assignments.
6	**Learning objectives and skills**	By the end of the course, students should be able to: • 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**	Recommended: • Previous experience with optimization (especially convex and/or conic optimization) and with differential equations is desirable.
8	**Integration into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • Elective module in MSc in Mathematics in the field MSO
10	**Method of examination**	oral exam (30 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester (not annually)
13	**Workload**	Contact hours: 45 hrs Independent study: 105 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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 65970	Module 51: StochAna: Stochastic Analysis (Stochastische Analysis)	5 ECTS
2	Courses/lectures	Lecture: 2 semester hrs/week	MApA
3	Lecturers	Prof. Dr. T. Krüger	

4	**Module coordinator**	**Prof. Dr. T. Krüger**
5	**Content**	• Ito calculus • diffusion processes • stochastic differential equations
6	**Learning objectives and skills**	Students acquire the potential to analyze complex structures in stochastics and to apply these to specific problems. The obtained knowledge forms a basis for further specialization in stochastics and related economathematical topics.
7	**Prerequisites**	Recommended: • some knowledge on probability theory
8	**Integration into curriculum**	1st or 3rd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • BSc Mathematics • MSc Mathematics • MSc Data Science
10	**Method of examination**	oral exam (30 minutes)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Winter semester
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	The literature will be announced individually for every taking place of the lecture.

1	**Module name** **65787**	**Module 52:** **SemMApA: Seminar Applied Analysis**	**5 ECTS**
2	**Courses/lectures**	Seminar: 2 semester hrs/week	**MApA**
3	**Lecturers**	**Prof. Dr. G. Grün**	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	Topics from Applied Analysis to deepen the theoretical contents of the lecture ModAna1.
6	**Learning objectives and skills**	Students • 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**	Recommended: • module ModAna1
8	**Integration into curriculum**	2nd or 3rd semester, after ModAna1
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics
10	**Method of examination**	oral presentation (90 minutes) and presentation document (4-8 pages)
11	**Grading procedure**	80% based on oral presentation, 20% based on presentation document
12	**Module frequency**	Winter semester or summer semester
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	The literature will be determined depending on the chosen topic.

1	**Module name** **65096**	**Module 53:** **SemMApASeTo: Seminar Selected Topics of Applied Analysis**	**5 ECTS**
2	**Courses/lectures**	Seminar: 2 semester hrs/week	**MApA**
3	**Lecturers**	**Prof. Dr. M. Neuss-Radu**	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	Topics from Applied Analysis to deepen the theoretical contents of the lecture ModAna1.
6	**Learning objectives and skills**	Students • 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**	Recommended: • module ModAna1
8	**Integration into curriculum**	2nd or 3rd semester, after ModAna1
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics
10	**Method of examination**	oral presentation (90 minutes) and presentation document (4-8 pages)
11	**Grading procedure**	80% based on oral presentation, 20% based on presentation document
12	**Module frequency**	Winter semester or summer semester
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	The literature will be determined depending on the chosen topic.

1	**Module name 65954**	**Module 54: NumOptCont: Numerics of Optimal Control (Numerik der Optimalsteuerungen)**	**5 ECTS**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Tutorial: 2 semester hrs/week	**Opti/NASi**
3	**Lecturers**	**Prof. Dr. H. Meindlschmidt**	

4	**Module coordinator**	**Prof. Dr. H. Meindlschmidt**
5	**Content**	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. 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. By default, the lecture will be given in English (in German only if all participants agree).
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 into curriculum**	2nd (or 4th) semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • M.Sc. Mathematics, specialization Modeling, Simulation and Optimization • M.Sc. Economics and Mathematics, specialization Optimization and process management
10	**Method of examination**	oral exam (20 min)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	Summer semester
13	**Workload**	Contact hours: 60 hrs Independent study: 90 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	M. Gerdts, Optimal Control of ODEs and DAEs, De Gruyter, 2012.

1	**Module name** **65273**	**Module 55:** **SemiGroups: Semigroups of Linear Operators**	**10 ECTS**
2	**Courses/lectures**	a) Lectures: 4 semester hrs/week b) Tutorial: 2 semester hrs/week	**MApA**
3	**Lecturers**	**Prof. Dr. E. Bänsch**	

4	**Module coordinator**	**Prof. Dr. E. Bänsch**
5	**Content**	• Unbounded, closed operators • generators and semigroups • resolvent of a semigroup • Hille-Yosida-Theorem; Lumer-Phillips-Theorem; evolution equations • perturbation and approximation
6	**Learning objectives and skills**	Students are familiar with unbounded operators. They understand the interlink between semigroups and operators. Furthermore, they can apply semigroup theory to the solution of evolution equations.
7	**Prerequisites**	Strongly recommended: knowledge in functional analysis. Recommended: some basics about PDEs and maybe some notion of stochastic processes.
8	**Integration into curriculum**	arbitrary semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • M.Sc. Mathematics • M.Sc. Economics and Mathematics
10	**Method of examination**	oral exam (20 min)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	irregularly
13	**Workload**	Contact hours: 75 hrs Independent study: 225 hrs Total: 300 hrs, corresponding to 10 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English (German, if desired by the audience)
16	**Recommended reading**	• David Applebaum: Semigroups of linear operators (can be donwloaded through https://www.cambridge.org/core/books/semigroups-of-linear-operators/) • Ronald Schnaubelt: Lecture Notes on Evolution Equations (pdf will be made available for the participants) • Klaus-Jochen Engel; Rainer Nagel: A short course on operator semigroups, Universitext, Springer 2006

1	**Module name** **65894** (replaces 65067)	**Module 56:** **CtrlMaLearn: Mathematical Foundations of Control and Machine Learning** (replaced the expired module Introduction to Control and Machine Learning)	**5 ECTS**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Tutorial: 0.5 semester hrs/week	**Opti**
3	**Lecturers**	**Prof. Dr. E. Zuazua, D. Lopez-Montero**	

4	**Module coordinator**	**Prof. Dr. E. Zuazua**
5	**Content**	This course provides a unified mathematical perspective on control theory and machine learning. It introduces key concepts from the analysis of dynamical systems governed by Ordinary and Partial Differential Equations (ODEs and PDEs), including controllability, observability, and stability. Building on these principles,the course explores how control-theoretic and optimization-based methods provide insight into the dynamics of state-of-the-art machine learning systems, including deep neural networks, federated learning frameworks, and large language models (LLMs).
6	**Learning objectives and skills**	By the end of the course, students will have developed a solid understanding of the mathematical and dynamical foundations underlying control and learning systems. They will be able to analyze the optimization and stability properties of deep learning algorithms, and explain how control-theoretic principles extend to large-scale models such as large language models (LLMs). Furthermore, students will be trained to deliver clear and rigorous scientific presentations of technical concepts and research results.
7	**Prerequisites**	Strongly recommended: Basic knowledge of calculus, linear algebra, ODEs and PDEs.
8	**Integration into curriculum**	1st-4th semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • M.Sc. Data Science, specialization Simulation and Numerics
10	**Method of examination**	oral exam (20 min)
11	**Grading procedure**	100% based on oral exam
12	**Module frequency**	irregularly
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• L. Bottou, F. E. Curtis, and J. Nocedal, Optimization methods for large-scale machine learning. SIAM Review, 60 (2) (2018) , 223-311. • J. M. Coron, Control and Nonlinearity, Mathematical Surveys and Monographs, 143, AMS, 2009. • I. Goodfellow, Y. Bengio, & A. Courville, Deep Learning. MIT press, 2016. • C. F. Higham, and D. J. Higham, Deep learning: An introduction for applied mathematicians. SIAM Review, 61 (4) (2019), 860-891. • J. Nocedal, and S. Wright, Numerical Optimization. Springer Science & Business Media, 2006. • D. Ruiz-Balet, and E. Zuazua, Neural ODE control for classification, approximation and transport. arXiv preprint arXiv:2104.05278, (2021).

		• E. Zuazua, Propagation, observation, and control of waves approximated by finite difference methods, SIAM Review, 47 (2) (2005), 197-243. • 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.

1	**Module name** **65075**	**Module 57:** **PrimerFA: A primer on functional-analytic methods for PDEs**	**5 ECTS**
2	**Courses/lectures**	Seminar: 2 semester hrs/week	**MApA**
3	**Lecturers**	**Prof. Dr. S. Metzger**	

4	**Module coordinator**	**Prof. Dr. G. Grün**
5	**Content**	Basics and foundations in the following topics: • 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**	Students are able to: • 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 into curriculum**	1st or 2nd semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% oral exam
12	**Module frequency**	Only in summer semester
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• 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

1	**Module name 65887**	**Module 58: ConsL: Modul Conservation Laws**	**5 ECTS**
2	**Courses/lectures**	Seminar: 2 semester hrs/week	**MApA**
3	**Lecturers**	**Prof. Dr. E. Wiedemann, Dr. L. Pflug**	

4	**Module coordinator**	**Dr. L. Pflug**
5	**Content**	• (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**	Recommended: some basic knowledge in PDEs is of advantage, Sobolev spaces
8	**Integration into curriculum**	1st semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • MSc Mathematics specialization modelling, simulation and optimization • MSc Mathematics and Economics
10	**Method of examination**	oral exam (15 minutes)
11	**Grading procedure**	100% oral exam
12	**Module frequency**	irregular
13	**Workload**	Contact hours: 30 hrs Independent study: 120 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• A. Bessan: Hyperbolic systems of conservation laws: the one-dimensional Cauchy problem. Vol. 20. Oxford University Press on Demand, 2000 • A. Keimer, L. Pflug: Existence, uniqueness and regularity results on nonlocal balance laws, Journal of Differential Equations 263.7 (2017): 4023-4069 • G.M. Coclite et al.: 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 (2022) • S. Blandin, Sebastien, Paola Goatin. Well-posedness of a conservation law with non-local flux arising in traffic flow modeling, Numerische Mathematik 132.2 (2016): 217-241 • A. Aggarwal, R. M. Colombo, Paola Goatin.Nonlocal systems of conservation laws in several space dimensions, SIAM Journal on Numerical Analysis 53.2 (2015): 963-983

1	**Module name** **65887**	**Module 59:** **MFCFL: Mathematical Foundations of Control and Machine Learning**	**5 ECTS**
2	**Courses/lectures**	a) Lectures: 2 semester hrs/week b) Tutorial: 0.5 semester hrs/week	**Opti**
3	**Lecturers**	**Prof. Dr. E. Zuazua, Dr. Zh. Ji**	

4	**Module coordinator**	**Prof. Dr. E. Zuazua**
5	**Content**	This course provides a unified mathematical perspective on control theory and machine learning. It introduces key concepts from the analysis of dynamical systems governed by Ordinary and Partial Differential Equations (ODEs and PDEs), including controllability, observability, and stability. Building on these principles,the course explores how control-theoretic and optimization-based methods provide insight into the dynamics of state-of-the-art machine learning systems,including deep neural networks, federated learning frameworks, and large language models (LLMs).
6	**Learning objectives and skills**	By the end of the course, students will have developed a solid understanding of the mathematicaland dynamical foundations underlying control and learning systems. They will be able to analyze the optimization and stability properties of deep learning algorithms, and explain how control-theoretic principles extend to large-scale models such as large language models (LLMs). Furthermore, students will be trained to deliver clear and rigorous scientific presentations of technical concepts and research results.
7	**Prerequisites**	Recommended: basic knowledge of calculus, linear algebra, ODE and PDE.
8	**Integration into curriculum**	1st - 4th semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • MSc Data Science, field of study Simulation and Numerics
10	**Method of examination**	oral exam (20 minutes)
11	**Grading procedure**	100% oral exam
12	**Module frequency**	irregular
13	**Workload**	Contact hours: 37.5 hrs Independent study: 112.5 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• [1] L. Bottou, F. E. Curtis, and J. Nocedal, Optimization methods for large-scale machine learning. SIAM Review, 60 (2) (2018) , 223-311. • [2] J. M. Coron, Control and Nonlinearity, Mathematical Surveys and Monographs, 143, AMS, 2009. • [3] I. Goodfellow, Y. Bengio, & A. Courville, Deep Learning. MIT press, 2016. • [4] C. F. Higham, and D. J. Higham, Deep learning: An introduction for applied mathematicians. SIAM Review, 61 (4) (2019), 860-891. • [5] J. Nocedal, and S. Wright, Numerical Optimization. Springer Science & Business Media, 2006. • [6] D. Ruiz-Balet, and E. Zuazua, Neural ODE control for classification, approximation and transport. arXiv preprint arXiv:2104.05278, (2021). • [7] E. Zuazua, Propagation, observation, and control of waves approximated by finite difference methods, SIAM Review, 47 (2) (2005), 197-243. • [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.

1	Module name 65838	Module 60: NeuN: Neural Network Theory	5 ECTS
2	Courses/lectures	a) Lectures: 3 semester hrs/week b) Tutorial: 1 semester hrs/week	NASi
3	Lecturers	Dr. C. Schneider	

4	**Module coordinator**	**Dr. C. Schneider**
5	**Content**	In this lecture, we will study deep neural networks. We will focus on a functional analytical and well-founded framework which allows to make rigorous statements which do provide explanations and intuition as to why certain neural network architectures are preferable over others. For example, we will see explanations of why deep neural networks are, in some sense, superior to shallow neural networks or why the neural network architecture can efficiently reproduce high dimensional functions when most classical approximation schemes cannot. The lecture covers the basics of the following topics: • Classical approxmation results by neural networks • ReLU networks • The role of depth • High dimensional approximation • Complexity of sets of networks • Spaces of realisations of neural networks The presentation of the material is in lecture form. The essential terms and techniques are acquired through exercises and homework.
6	**Learning objectives and skills**	Students gain a mathematical understanding of the structure and principles of neural networks.
7	**Prerequisites**	Linear Algebra I and Analysis I & II or Mathematics for Data Science I & II or comparable; Functional Analysis or Higher Analysis are strongly recommended.
8	**Integration into curriculum**	4th semester
9	**Module compatibility**	• Mandatory elective module for MSc in Computational and Applied Mathematics • MSc Mathematics, field of study “Modeling, Simulation, Optimization” • MSc Data Science
10	**Method of examination**	oral exam (20 minutes) or written exam (60 min)
11	**Grading procedure**	100% oral exam or written exam
12	**Module frequency**	irregular
13	**Workload**	Contact hours: 60 hrs Independent study: 90 hrs Total: 150 hrs, corresponding to 5 ECTS credits
14	**Module duration**	One semester
15	**Teaching and examination language**	English
16	**Recommended reading**	• Lecture notes for this module • P. Petersen, J. Zech: Mathematical theory of deep learning, 2024 • I. Goodfellow, Y. Benigo, A. Courville: Deep Learning, MIT Press, 2016 http://www.deeplearningbook.org • M. Anthony and P. L. Bartlett: Neural network learning: theoretical foundations. Cambridge University Press, Cambridge, 1999 • J. Berner, P. Grohs, G. Kutyniok, and P. Petersen: The modern mathematics of deep learning. arXiv:2105.04026, 2021 • M. Telgarsky: Deep learning theory (lecture notes). https://mjt.cs.illinois.edu/dlt