



Mathematisch-Naturwissenschaftliche Fakultät



Department of Mathematics

Module Handbook Mathematical Physics Master of Science

Winter Semester 2024

Version: 16th December 2024

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1 Program description

1.1 Study Concept

The Master of Science Mathematical Physics is an international research-oriented two year master's program offered jointly by the departments of Mathematics and Physics within the Faculty of Science of the University of Tübingen starting every year in the winter semester. It is geared towards students with a solid background in Mathematics as well as in Physics, and it requires a bachelor's degree in physics or mathematics or an equivalent degree. The scientific discipline "Mathematical Physics" is concerned with the mathematically rigorous formulation and analysis of physical theories and models. In this master's program students will thus deepen and broaden their knowledge of Mathematics and Physics in interdisciplinary courses in Mathematical Physics as well as in disciplinary courses in Mathematics and Theoretical Physics. At the end of the program they are particularly well prepared for jobs where the typical competences of mathematicians are needed in combination with applications of physics. The program is international and cannot be pursued without a solid knowledge of the English language. Language skill on the level of B2 according to the European Framework of Reference for Languages are therefore required. All mandatory modules and a large number of facultative modules are offered only in English. Some facultative modules may sometimes be offered only in German.

1.2 Qualification Goals

Students deepen and broaden their theoretical knowledge of different areas of mathematical physics, mathematics and theoretical physics. They become proficient in general and specific methods and principles in these areas. They can connect problems and questions from physics with their counterparts in mathematical models and are able to judge and critically question the relevance and adequacy of mathematical models and the derived consequences. They are able to report on and scrutinize the current state of research in the area of their specialisation. Graduates can apply their expanded knowledge in order to develop and successfully handle their own research projects. They are able to present, discuss, and defend the results of their research in writing and orally in front of a scientific audience. In the course of the Mathematical Physics Colloquium students practice scientific collaboration and discourse in interdisciplinary and internationally mixed groups.

Their education enables graduates in mathematical physics to successfully and professionally tackle complex mathematical modelling problems in physics and, after an appropriate familiarization with the subject, also in other areas of technology, finance or economics. They are moreover well prepared for interdisciplinary and international collaborations in mixed teams of different specialists from different cultural backgrounds, as are common nowadays in all areas of research and development.

1.3 Program Structure

The Master's Program is a two year (four terms) consecutive study program with a modular structure. Based on the foundational modules "Geometry in Physics", "Functional Analysis in Geometry", "Mathematical Quantum Theory", and "Mathematical Relativity", to be attended during the first year, students can specialise rather freely according to their personal preferences in one or more areas of Mathematical Physics, Mathematics and/or Theoretical Physics. The few restrictions are that every student must take at least one module from the Mathematics master's program and one module from the Theoretical Physics master's program, as well as a seminar. As a consequence, all graduates of the Master's Program have proven their ability to successfully conduct mathematical studies and theoretical physics studies at the master's level. A Scientific Project in the third term typically serves as a preparation for the Master Thesis (M.Sc. Thesis, 30 ECTS-points) written during the final term. During the second year students are also required to attend the Mathematical Physics Colloquium. This is a weekly colloquium where specialists lecture about recent developments in Mathematical Physics, and students have the opportunity to meet and discuss with international guest scientists and local researchers about current topics. The prescribed period of study is two years corresponding to a total of 120 ECTS points.

1.4 Mentoring

At the start of the program every student will be assigned to a mentor from the group of professors involved in the master's program for the whole duration of his/her studies. Students meet their mentor at the beginning and later at least once per term in order to plan and discuss the progress of their studies. In particular, at these meetings the study and examination plan in compliance with the examination regulations is discussed. The module selection is documented and passed on to the head of the examinations board for approval. During the first meeting possible gaps in the knowledge should be discussed in order to fill them by taking appropriate courses within the area of elective specialisation. The study and examination plan is then updated every semester during the meetings with the mentor. The mandatory mentoring program assures that students specialise in a purposeful way and select accordingly goal-oriented combinations of modules from mathematics and physics.

During the meetings with the mentor also possible time slots for a study period at a university abroad can be discussed. In principle, every semester is suitable, depending on the study progress of the student and the courses avaliable at the other institution. It is also possible to write the master's thesis during a stay abroad under the cosupervision of a scientist there.

1.5 Information for students with a bachelor's degree in Physics at the University of Tübingen

Graduates of the 4-year degree program Bachelor of Science in Physics at the University of Tübingen can already gain up to 60 credit points for the degree program Master of Science in Mathematical Physics during their bachelor studies.

In particular,

• the module BMTPKFT Klassische Feldtheorie from the bachelor's program can be credited with

9 credit points for the module MAT-40-32 Advanced Topics in Theoretical Physics in the master's program, and

• up to 21 credit points in the section Vertiefungsfach in the bachelor's program can be credited in the section Elective Studies, provided the choice is suitable.

Moreover,

- up to 27 credit points in the section Ergänzungsmodule in the bachelor's program can be gained via the modules MAT-65-11 Geometry in Physics, MAT-65-12 Mathematical Quantum Theory, MAT-65-13 Mathematical Relativity or MAT-65-14 Mathematical Statistical Physics from the master's program, and
- the bachelor's thesis can be credited with 9 credit points in the module Scientific Project.

In order to finish the Master of Science in Mathematical Physics subsequently to the bachelor's degree in Physics at the University of Tübingen it is recommended to choose in the section Vertiefungsfach in the bachelor's program courses in theoretical physics, which can be credited in the section Elective Studies in the master's program in Mathematical Physics. Moreover, it is recommended to choose in the section Ergänzungsmodule in the bachelor's program at least two of the modules MAT-65-11, MAT-65-12, MAT-65-13 or MAT-65-14 from the master's program in Mathematical Physics. Good choices would be the combinations MAT-65-11 + MAT-65-13 and MAT-65-12 + MAT-65-14. Also the combination MAT-65-11 and MAT-65-12 would be suitable.

2 Study Plans

2.1 Overview by Modules

We provide here an overview of the study plan as a table showing the modules to be taken.

Suggested Term	Module Number	Module Title	Type of Course	Type of Module	Assign- ments	Type of Exam	ECTS- Points
Section 1: I	oundations						
1	MAT-65-11	Geometry in Physics	L+E	PM	EC	wr. o. or.	9
1	MAT-65-12	Mathematical Quantum Theory	L+E	PM	EC	wr. o. or.	9
2	MAT-65-13	Mathematical Relativity	L+E	PM	EC	wr. o. or.	9
Section 2: I	Knowledge E	xpansion					
1–3	MAT-40-31	Advanced Topics in Mathematics	L+E	PMW	EC	wr. o. or.	9
1–3	MAT-40-32	Advanced Topics in Theoretical Physics	L+E	PMW	EC	wr. o. or.	9
2–3	MAT-40-33	Seminar Knowledge Extension	S	PMW	s.M.	Pr	3
Section 3: I	Elective Spec	ialisation					
1-3		Modules from the master's programmes of the Department of Mathematics or Physics according to Section 3.		WPM			30
Section 4: 9	Section 4: Scientific Work						
3	MAT-40-41	Scientific Project	Р	PM	s.M.	-	9
3–4 MAT-40-42 Mathematical Physics Colloquium			C+C	PM	-	-	3
4	MAT-40-43	Master Thesis M.Sc. Mathematical Physics	MT	PM	s.M.	MT	30

Abbreviations:

Type of Module : PM=compulsory module, WPM=compulsory module with choice, WM=elective module Examination Type : MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=Seminar, IC=inverted classroom

Course Work : EC=exercise certificate

Other : h=hours, o.=or, s.M.=see module description

2.2 Overview by the Course of Studies

We first provide a general study plan showing the distribution of credit points over the different areas and the general time line. On the following pages example study plans for different types of specialisation are provided, where possible courses are assigned to the modules MAT-40-31 and MAT-40-32 as well as the modules from the area of Elective Specialisation.

Term	СР	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientific Work
1.	27	27 CP			
2.	30	27 01	21 CP	30 CP	
3.	31			30 01	42 CP
4.	32				1 2 01

Figure 2.1: General Study Plan

2.3 Example Study Plans

The example study plans shown below shall give an idea how the individual study in the different specialisations could look like. They are not meant as a recommendation, and it is neither guaranteed that the courses listed will be offered each year, nor that they all will be given in English.

Example Study Plan without Specialisation

Term	СР	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientif	ic Work	
		Geometry in Physics (9 CP)	Linear Partial				
1.	27	Mathematical Quantum Theory (9 CP)	Differential Equations (9 CP)				
		Mathematical		Advanced Topics in Mathematical Quantum Theory (9 CP)			
2.	30	Relativity (9 CP)	Seminar(3 CP)	Mathematical Statistical Physics (9 CP)			
			Quantum Field	Advanced Topics in Mathematical Relativity (6 CP)			
3.	31		Theory and Particle Physics (9CP)	Advanced Topics in Mathematical Statistical Physics (6 CP)	Mathe- matical Physics	Scientific Project (9 CP)	
4.	32				Colloquium (3 CP)	Master Thesis (30 CP)	

Figure 2.2: The program Mathematical Physics can be completed to a large extent also without choosing a particular specialisation. In this case we recommend taking all four foundational modules and also all advanced courses offered. The modules from the area Knowledge Expansion should then be chosen in accordance with the planned specialisation in the Scientific Project and the Master Thesis, cf. e.g. the following study plans.

Example Study Plan Quantum Theory

Term	СР	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientif	ic Work
		Geometry in Physics (9 CP)				
1.	27	Mathematical Quantum Theory (9 CP)	Operator Theory (9 CP)			
2.	30	Mathematical Relativity (9 CP)	Quantum Field Theory and Particle Physics (9 CP)	Functional Analysis (9 CP)		
			Seminar(3 CP)			
				Advanced Topics in Mathematical Quantum Theory (9 CP)		
3.	31			Computational Methods in Physics / Astrophysics (6 CP)	Mathe-	Scientific Project
				Theoretical Condensed Matter Physics (6 CP)	matical Physics Colloquium (3 CP)	(9 ČP)
4.	32					Master Thesis (30 CP)

Figure 2.3: The mathematical foundations of quantum theory are predominantly allocated to areas of analysis. Thus we recommend that those specialising in one of the areas Mathematical Quantum Theory, Quantum Field Theory, Condensed Matter, Many-Body Quantum Systems, or Quantum Information attend mathematical courses from analysis, e.g. Operator Theory, Partial Differential Equations, Calculus of Variations, and Numerical Analysis.

Example Study Plan Relativity

Term	СР	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientif	ic Work
		Geometry in Physics (9 CP)	Astronomy and			
1.	27	Mathematical Quantum Theory (9 CP)	Astrophysics (9 CP)			
2.	30	Mathematical Relativity (9 CP)	Introduction to Partial Differential Equations (9 CP)	Riemannian Geometry (9 CP)		
			Seminar(3 CP)			
				Advanced Topics in Mathematical Relativity (9 CP)		
3.	31			Theoretical Astrophysics (6 CP)	Mathe-	Scientific Project
			Computational methods in Physics / Astrophysics (6 CP)	matical Physics Colloquium (3 CP)	(9 CP)	
4.	32					Master Thesis (30 CP)

Figure 2.4: The mathematical foundations of relativity are predominantly allocated to areas of geometry and analysis. Thus we recommend that those specialising in one of the areas Mathematical Relativity, Astronomy, Cosmology, or Astro Physics attend mathematical courses from geometry, e.g. Riemannian Geometry and Lorentz Geometry, and from analysis, e.g. Partial Differential Equations, Calculus of Variations, and Numerical Analysis.

Example Study Plan Statistical Physics

Term	СР	Foundations of Mathematical Physics	Knowledge Expansion	Elective Specialisation	Scientif	ic Work
		Geometry in Physics (9 CP)				
1.	27	Mathematical Quantum Theory (9 CP)	Probability Theory (9 CP)			
		Mathematical	Advanced Statistical	Mathematical Statistical Physics (9 CP)		
2.	30	Relativity (9 CP)	Physics (9 CP)	Density Functional Theory (6 CP)		
				Advanced Topics in Mathematical Statistical Physics (6 CP)		Scientific
3.	31		Seminar (3CP)	Mathematical Statistics (9 CP)	Mathe- matical Physics	Project (9 CP)
4.	32				Colloquium (3 CP)	Master Thesis (30 CP)

Figure 2.5: The mathematical foundations of statistical physics are predominantly allocated to areas of probability. Thus we recommend that those specialising in one of the areas Mathematical Statistical Physics, Soft Matter, or Density Functional Theory attend mathematical courses from probability, e.g. Probability Theory and Mathematical Statistics.

2.4 Overview by Study Progress and Credit Requirements

		I	F.,,											
			Exam	ı	I		Teaching				allocation of exams S points to semeste recommendation on pulsory allocations			
		Exam	Duration (min)		Weight in the final grade	Course			Points (CP)	is a recomposite are material allocate to countries or co	points to commer ulsory all arked as ion of Erses is followed upon	o semes ndation c	ters only. s he nts a- nly	
		Type of Exam	Duratio	Grading	Weight	Type of (Status	SWS	ECTS	1. CP	2. CP	3. CP	4. CP	
Fou	ndations of Mathematical Pl	nysics:							27					
MAT	-65-11 Geometry in Physics							6	9					
1.	Lecture	Wr.	90–120	_	9	L	0	4		6				
2.	Exercises	or Or.	or 20–30	g	9	Е	0	2		3				
MAT	-65-12 Mathematical Quantun	n Theor	У					6	9					
1.	Lecture	Wr.	90–120	g	9	L	0	4		6				
2.	Exercises	or Or.	or 20–30	9		E	0	2		3				
MAT	-65-13 Mathematical Relativity	/						6	9					
1.	Lecture	Wr. or	90–120 or	g	9	L	0	4			6			
2.	Exercises	Or.	20–30	9		E	0	2			3			
Kno	wledge Expansion:								21					
MAT	-40-31 Advanced Topics in Ma	athemat	ics					6	9					
1.	Lecture	Wr. or	90–120 or	g	9	L	O	4		6				
2.	Exercises	Or.	20–30			E	0	2		3				
MAT	-40-32 Advanced Topics in Ph	ysics			ı			6	9			1		
1.	Lecture	Wr. or	90–120 or	g	9	L	0	4			6			
2.	Exercises	Or.	20–30			E	0	2			3			
MAT	-40-33 Seminar			ı	I			2	3			1		
1.	Seminar	Pres.	45–90	g	3	S	0	2				3		
Elec	tive Specialisation:								30					
ľ	Here the modules MAT-65-15 Master's Programs in Mathem be discussed and agreed upor poard.	atics, P	hysics, and	d Astro	o and	Partic	cle Physics	s, can	be cl	nosen. 1	The choi	ces nee	d to	
MAT	-65-14 Mathematical Statistica	cs					6	9						
1.	Lecture	Wr.	90–120	g	9	L	f	4			6			
2.	Exercises	or Or.	or 20–30	9		Е	f	2			3			
MAT	-65-21 Advanced Topics in Ma	athemat	ical Quantı	ım Th	eory			6	9					
		Wr.	90-120			L	f	4			6			

			Exam				Teaching				Те	rm	
		Type of Exam	Duration (min)	D	Weight in the final grade	f Course			Points (CP)	is a recomposite are material allocate to countries on the countries of th	points to commenulsory all arked as ion of Ed rses is fo ily. Cred	of examo semes dation of location of such. TCTS point or informatics are occupled	ters only. s he nts a- nly
		be o	ıratic	Grading	eigh.	Type of	Status	SMS	ECTS	1.	2.	3.	4.
		Ţ	ă	ত্র	>	1≥	S.	S	Ш	CP	CP	CP	CF
2.	Exercises					E	f	2			3		
MAT	-65-22 Advanced Topics in M	T		ım Th	eory	(short	version)	4	6			Г	
1.	Lecture	Wr. or	90–120 or	g	6	L	f	2			3		
2.	Exercises	Or.	20–30			E	f	2			3		
MAT-65-23 Advanced Topics in Mathematical Relativity		I	ı		6	9				1			
1.	Lecture	Wr. or	90–120 or	g	9	L	f	2				3	
2.	Exercises	Or.	20–30			E	f	2				3	
MAT	-65-24 Advanced Topics in M	athemat	ical Relativ	ity (sh	ort ve	ersion)	4	6				
1.	Lecture	Wr. or	90–120 or	g	6	L	f	2				3	
2.	Exercises	Or.	20–30			Е	f	2				3	
Scie	entific Work								42				
MAT	-40-41 Scientific Project								9				
1.	Project	Proj.		ng	9		0					9	
MAT	-40-42 Mathematical Physics	Colloqu	ium				1		3				
1.	Colloquium			ng			0					1	2
MAT-40-43 Master Thesis									30				
1.	Thesis	Thes.		g	30		0						30

: o=obligatory, f=fakultative : o.=or, SWS=hours in class per week, CP=credit points=ECTS points Status Other

3 Module Descriptions

Section 1: Foundations

In the case that some of the mandatory modules in this section or modules, which are essentially identical as far as the contents and competences are concerned, have been part of the Bachelor studies, which are the prerequisite for this Master's Degree Program, according to the examination regulations these modules cannot be taken in the Master's Degree Program any more. They have to be replaced by other suitable modules in the framework of the studies and examination plan.

Module Number: MAT-65-11	Module Title: Geometry in Physics		Type of Module: Compulsory Module					
ECTS-Points	9							
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h					
Duration	1 Semester							
Frequency	regularly in Winter Semeste	r						
Term	1							
Language of Instruction	English	nglish						
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	Classes 2 SWS, Homework A	ssignements					
Content	relevance for physics. Particle and associated notions of co	cular topics are manifolds, diff	ods of differential geometry and their erential forms, Riemannian metrics ry of submanifolds, real vector bun- Physics are discussed.					
Objectives	of differential geometry. The integral calculus and experie applied within physical theor and concepts from the lecture put it into a larger framework. Through homework assignment independent acquaintal lectures. They learn how to develop solution strategie	y develop, in particular, a deep nce through examples how the ies. Students are able to name re as well as to explain the cor c. nents and exercise classes stu- nce with the notions, stateme to transfer these methods to no	nce with the use of the listed notions per understanding of differential and emathematical notions are naturally and prove the essential statements attent developed in the lecture and to adents develop a confident, precise, ents, and methods explained in the ew problems, to analyse them and roup. They are able to present their dessary.					

Requirements for Obtaining Credit, Grading, Weight if applicable	Title Geometry in Physics In this module students need	ans of Type of Course	o o Status	SMS 4 2	S ECTS	yes Assignments yes	wr. o. or.	Ont. of Exam (min) 90-180 0. 20-30	g Grading	00 Weight for Grade
Literature	the exam. The type of examin Exemplary Literature:	allon	15 56	et by	uie i	nstruct	01.			
	 John Lee: Introduction John Lee: Riemannian Chris Isham: Modern of Mikio Nakahara: Geom 	man liffere	ifolds ntial	s: An geoi	intro metry	oductio y for ph	n. Springer nysicists. Wo	orld Scientifi		
Transfer	ativity. Successful completion	Participation in the module is a prerequisite for participation in the module Mathematical Relativity. Successful completion of the module may be a prerequisite for participation in the module Seminar Knowledge Extension and is so for the participation in the module Scientific Project.								
Prerequisites	-									
Responsible Persons	Christoph Bohle, Carla Ceder	baum	ı, Ste	efan '	Teufe	el				
Abbreviations:										

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-12	Module Title: Mathematical Quantum Theo	ory						of Module: ulsory Modu	le	
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:		
Duration	1 Semester						·			
Frequency	regularly in Winter Semester									
Term	1									
Language of Instruction	English	nglish								
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	Classe	s 2 S	SWS	, Hor	meworl	(Assignem	ents		
Content	The module provides an intrest the formulation and analysis butions, Hilbert spaces, units operators, spectral theorem, erators. In addition, basic ic perturbation theory, Hartree theory, adiabatic theory or smatical methods and areas examples from quantum theoretic theory.	of qua ary gro tensor leas fr resp. emicla are mo	intun oups or prod om r Harti issica	n the and ducts nore ree-F al an	ories their s, PO spec ock alysi	s. Topic gener WMs, s cific me theory, s can I	s include thators, spectpectral meanthods such the Fock spectos discussed	ne Fourier tra tral theory of asures, and n as Rayleig pace formalied. The mer	ansforr of self-a trace of h-Sch ism, so ntioned	m, distri- adjacent lass op- rödinger cattering mathe-
Objectives	Students know and understate to analyse known and new quexplain the statements and and their mathematical modelling and assignments and exercise cacquaintance with the notion how to transfer these methods trategies on their own and stand for them in a critical distance.	uestio proofs elling the r lasses s, state ods to within	ns from and and nather students and nather men	om che le are emat dents hts, a pro-	uant ecture able ical ical dev and n blem	tum theme. Further to que results velop and thodes, to a sey are	hermore, the stion the rederived fro confident, as explained nalyse ther	are able to uney link physelevance and it. Throuprecise, and in the lecture and to de	nderst sical p d adec ugh ho d inde es. Th evelop	and and roblems quacy of mework pendent ey learn solution
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Mathematical Quantum Theory	L E	0	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module students need the exam. The type of exami							s in order to	be adr	mitted to
Transfer	Successful completion of mo ticipation in the module Adva pletion of one of the modules prerequisite for the participat	nced Math	Topic emat	s in tical	Math Quar	nemation Intum T	al Quantun neory and N	า Theory. Sเ	ıccess	ful com-
Prerequisites	-									
Responsible Persons	Stefan Teufel									

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-13	Module Title: Mathematical Relativity							of Module: ulsory Modu	le		
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		lass	:		Self-St 180 h	tudy:			
Duration	1 Semester										
Frequency	regularly in Summer Semest	er									
Term	2										
Language of Instruction	English										
Forms of Teaching and Learning	Lectures 4 SWS + Exercise (Classe	es 2 9	SWS	, Hor	meworł	(Assignem	ents			
Content	are Newton's theory of gravitions, the Schwarzschild sparmatter models, black holes,	the module provides an introduction to the mathematical theory of relativity. Particular topics as Newton's theory of gravity, special theory of relativity, relativistic effects, Einstein's equants, the Schwarzschild spacetime. Optionally, other topics such as cosmological models, latter models, black holes, Cauchy problem and ADM decomposition, singularity theorems gravitational waves can be discussed.									
Objectives	Students obtain knowledge use them to analyse known interrelate physical problems through methods from differe mathematical model and the on methods and subjects ga 65-11. Students are able to lecture as well as to explain framework. Through homework assignm and independent acquaintar lectures. They learn how to to develop solution strategies solutions and to stand for the	and no contial gresul ined to the content and the content and trans on the content and trans and	ew p smoleome ts de hrough and each and each th the fer the	roble ogy etry a riveo ghou orove xt de xerci e not ese wn a	ms f and to and to I from It the e the evelope se cl tions meth	rom the astroph o quest o quest o quest o quest o first se essen ped in asses o , statel nods to within a	e theory of nysics and to the relementary, they emester, in tial statementhe lecture students dements, and new problement. The	relativity. The their mather wance and a renhance the particular irents and con and to put evelop a contents, to ana	ney are matical dequa neir kno modu cepts it into fident, kplaine lyse th	e able to models cy of the owledge ale MAT- from the a larger precise, d in the eem and	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Mathematical Relativity	ш Гуре of Course	o o Status	SMS 4	S B ECTS	sh Assignments	Type of Exam or. or.	Our. of Exam (min) 0. 20-30	ص Grading	Weight for Grade	
	In this module students need the exam. The type of exami							s in order to	be adı	mitted to	
Transfer	Successful completion of mo in the module Advanced Top the modules Mathematical F the participation in the modu	ics in Relativ	Mat ity o	nema Ma	atical them	l Relati	vity. Succe	ssful comple	etion c	f one of	
Prerequisites	Participation in the module G	Participation in the module Geometry in Physics is a prerequisite.									
Responsible Persons	Carla Cederbaum, Gerhard I	Huiske	en, Fr	ank	Loos	e					

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Section 2: Knowledge Expansion

Module Number:	Module Title:							f Module:				
MAT-40-31	Advanced Topics in Mathema	tics					Compu	ılsory Modu	le with	Choice		
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:				
Duration	1 Semester											
Frequency	Every Semester											
Term	1–3											
Language of Instruction	English or German	nglish or German										
Forms of Teaching and Learning	ectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements											
Content	the correspondent SWS-cove mended subjects are for insta- tions, Harmonic analysis, Lie tic processes, Calculus of va- geometry. Further details car	is required to attend one or more lectures as well as the respective exercise classes with e correspondent SWS-coverage from the Master's degree program in Mathematics. Recomended subjects are for instance Partial differential equations, Numerics of differential equations, Harmonic analysis, Lie groups, Nonlinear functional analysis, Operator theory, Stochast processes, Calculus of variations, Symplectic geometry, Algebraic topology or Algebraic cometry. Further details can be found in the catalogue of mathematical modules starting at age 42 and in the module handbook of the degree program M.Sc. Mathematics.										
Objectives	of physical applications. They the methods at hand to tackle ticular the concrete content re	The students aquire deepend knowledge in one selected area of mathematics independently of physical applications. They broaden the basis of their mathematical knowledge and extend the methods at hand to tackle mathematical problems. The further qualification goals, in particular the concrete content related qualifaction goals, will follow from the module description of the chosen course in the module handbook for the M.Sc. Mathematics.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Advanced Topics in Mathematics	L E	0	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module students need the exam. The type of examir							in order to	be adr	nitted to		
Transfer	The module may be a prerequ	uisite	for th	ie m	aster	thesis						
Prerequisites	See prerequisites in the Modu	ıle Ha	ındbo	ook N	M.Sc	. Mathe	ematics.					
Responsible Persons	The dean of study affairs in the	ie dep	artm	ent	of ma	athema	itics					
Examination Type: M Teaching Format: L= T: Status: m	=graded, ng=not graded IT=Master's thesis, or.=oral exa =lecture, LE=lecture with inte =tutorial, P=project, S=Seminal =mandatory, o=optional =hours, o.=or, s.M.=see module	egrate r, IC=i	d ex nver	ercis ted c	ses, dassi	SL=se	minar or I	ecture, E=e	•			

Module Number: MAT-40-32	Module Title: Advanced Topics in Theoreti	cal Ph	vsics					of Module: ulsory Modu	le with	Choice		
ECTS-Points	9		yoloc	•			Compt	Jisory Wiodd	ic with	Onoice		
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	_	lass	:		Self-St	tudy:				
Duration	1 Semester											
Frequency	Every Semester											
Term	1–3											
Language of Instruction	English or German											
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	ctures 4 SWS + Exercise Classes 2 SWS, Homework Assignements										
Content	physics as well as the resp from the Master's degree pro- ticls Physics. Recommended physics, Theoretical astrophysics, Advanced statistical physics, tum optics, Quantum information	t is required to attend one or more advanced-level lectures from the field of theoretical physics as well as the respective exercise classes with the correspondent SWS-coverage rom the Master's degree program in Physics or the Master's degree program Astro and Particle Physics. Recommended subjects are for instance Quantum field theory and Particle physics, Theoretical astrophysics, Relativistic astrophysics, Many-particle quantum systems, Advanced statistical physics, Yang-Mills theory, Condensed matter physics, Theoretical quantum optics, Quantum information theory, Cosmology, Numerical methods in physics and astrophysics, Current topics in theoretical physics. Further details can be found in the module										
Objectives	The students aquire deeper pendently of rigorous mathe theoretical physics and exter qualification goals, in particu the module description of the the M.Sc. Astro and Particle	maticand the lar the chos	l fori meth cond en c	malis lods crete	m. 1 at ha cont	They brand to ta tent rela	oaden the b ackle proble ated qualifa	pasis of their ems in physic tion goals,	r know cs. The will foll	ledge in e further low from		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Advanced Topics in Theoretical Physics	L E	0	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module students need the exam. The type of exami	l to sun	cces	sfully et by	con	nplete a	assignments or.	s in order to	be adr	nitted to		
Transfer	The module may be a prerec	uisite	for th	ne m	aste	r thesis						
Prerequisites	See prerequisites in the Mod	ule Ha	ndbo	ok N	1.Sc.	Physic	s or M.Sc.	Astro and Pa	article	Physics.		
Responsible Persons	Die Studiendekanin oder der	Die Studiendekanin oder der Studiendekan des Fachbereichs Physik										
Abbroviations												

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-40-33	Module Title: Seminar Knowledge Extensi	on						Type of Module: Compulsory Module with Choice				
ECTS-Points	3						·					
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	lass	:		Self-S	tudy:				
Duration	1 Semester											
Frequency	Every Semester	Every Semester										
Term	2–3											
Language of Instruction	English or German											
Forms of Teaching and Learning	Seminar: Presentation, Disc	ussion	, Tea	ımwo	ork, F	Handou	t					
Content	Various topics from various Physics.	Various topics from various areas of Mathematical Physics, Mathematics or Theoretical Physics.										
Objectives	vanced topic in Mathematics form of an oral presentation.	The students have learnt to develop independently or in team an acquaintance with an advanced topic in Mathematics or Physics by applying scientific methods and to present it in form of an oral presentation. They have improved their skills in the presentation of mathematical or physical results and are able to argue for these results in critical discussions.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Seminar	S	0	2	3	yes	Pr	45–90	g	100		
Transfer	The module may be a prered	uisite	for th	ne m	aste	thesis				1		
Prerequisites	Successful completion of on Physics".	e of th	e mo	odule	es fro	m the	section "Fo	undations o	f Math	ematical		
Responsible Persons	Stefan Teufel											
Examination Type : N	=graded, ng=not graded //T=Master's thesis, or.=oral ex :=lecture, LE=lecture with int							•	•			

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Section 3: Elective Specialisation

Within the study area Elective Specialisation students can choose modules from the Master Programs Mathematical Physics, Mathematics, Physics, and Astro and Particle Physics according to their individual interests. In particular, courses listed in the module descriptions MAT-40-31 and MAT-40-32 but not chosen there, the module MAT-65-13 respectively MAT-65-14 not yet chosen in the area Foundations, the modules MAT-65-15 and MAT-65-21 to MAT-65-24, as well as other appropriate advanced modules from the programs Mathematical Physics, Mathematics (see ??), Physics, and Astro and Particle Physics are available. Note that not all modules can be offered every year, but there is always a broad choice. Also note that some modules from other programs might be offered only in German, but also here a choice of English courses is ensured. The selection of modules within the area Elective Specialisation must be discussed and decided together with the mentor. Each module can be selected only once. In agreement with the mentor and upon request at the examinations board, 9 ECTS points within the area of Elective Specialisation can be allocated for modules that serve to close knowledge gaps either in mathematics or physics.

Within the area of Elective Specialisation students obtain relevant skills. They learn to independently judge which additional qualifications and competences are relevant to their studies and to select courses accordingly. They are able to acquire specific knowledge also beyond the mandatory parts of the study program. Within the area of their specialisation they can report on and scrutinize the current state of research. In the exercise classes students learn to work confidently, precisely and independently with the notions, statements and methods presented during the lectures. They also learn how to apply methods to new problems and to analyse and solve them alone or in groups.

Advanced Topics in Mathematical Quantum Theory (MAT-65-21, 9 CP)	27
Advanced Topics in Mathematical Quantum Theory (short version) (MAT-65-22, 6 CP)	29
Advanced Topics in Mathematical Relativity (MAT-65-23, 9 CP)	31
Advanced Topics in Mathematical Relativity (short version) (MAT-65-24, 6 CP)	33
Foundations of Quantum Mechanics (MAT-65-15, 9 CP)	25
Mathematical Statistical Physics (MAT-65-14, 9 CP)	23
Quantum Shannon Theory and Beyond (MAT-65-35, 9 CP)	35

Module Number: MAT-65-14	Module Title: Mathematical Statistical Phy	sics	Type of Module: Elective Module
ECTS-Points	9		
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h
Duration	1 Semester		
Frequency	not regularly, in Summer Se	mester	
Term	2-3		
Language of Instruction	English		
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	Classes 2 SWS, Homework A	ssignements
Content	concepts of probability theor bles, thermal equilibrium, E cesses, Wiener process), la phase transitions), statistica tion to thermal equilibrium, I	y, classical statistical mechani Boltzmann equation, entropy), Ittice models (Ising model, Gil al quantum mechanics (quant Bose-Einstein condensate). O t phenomena, renormalizatior	istical physics. Particular topics are cs of gases (equivalence of ensem-Brownian motion (stochastic probbs measure, thermodynamic limit, um mechanical ensembles, transiptionally, other topics such as open a group theory and the fluctuation-

Objectives Students obtain knowledge and understanding of the listed notions and methods and can use them to analyse known and new problems from statistical physics. They are able to interrelate fundamental physical concepts, such as equilibrium, irreversability and entropy, and their mathematical models vie probabilistic methods and to question the relevance and adequacy of the mathematical model and of the results derived from it. Thereby, they enhance their knowledge on methods and subjects gained throughout the first semester, in particular on probability theory. Students are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary. Exam (min) Weight for Grade Type of Course Requirements Type of Exam Assignments for Obtaining Credit, Grading, Grading Dur. of I Status ECTS Weight if SWS applicable Title Mathematical Statistical L 4 6 90-180 wr. o. 100 yes g **Physics** o. 20-30 or. 2 Ε 3 In this module students need to successfully complete assignments in order to be admitted to the exam. The type of examination is set by the instructor. **Transfer** Successful completion of module is a prerequisite for the participation in the module Advanced Topics in Mathematical Statistical Physics. **Prerequisites** Responsible Roderich Tumulka Persons Abbreviations: Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

Lieutie, Lieutie with integrated exercises, Siesenman of fedure, Liexen

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-15	Module Title: Foundations of Quantum Me	chanio	cs					of Module: e Module				
ECTS-Points	9						·					
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		lass	:		Self-St 180 h	tudy:				
Duration	1 Semester											
Frequency	regularly every two years											
Term	2-3											
Language of Instruction	English											
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	ectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements										
Content	ing its mathematical and phil Bohmian mechanics, many w sented and analysed mather berg's uncertainty principle,	the module provides an introduction to fundamental questions of quantum mechanics, includ- g its mathematical and philosophical aspects. Various interpretations such as Copenhagen, ohmian mechanics, many worlds and the collapse of the spontaneous wave function are pre- ented and analysed mathematically and physically. Other topics include Born's rule, Heisen- erg's uncertainty principle, the quantum measurement problem, Bell's non-locality theorem, entical particles and theorems without hidden variables.										
Objectives	Students know and can applunderstand several important matical knowledge relevant to mathematical treatment with surprising phenomena and properties of the lecture as well in the exercise classes they the terms, statements and mon new problems, to analyse They are able to present their	t theological the poarado dox in the second of the second	ries of application of the student of the student of the student of the service o	of how cation cal m of quaretation dents dents ired a ired a he le	w the eani leani l	e quant these rung. The um med why capab xplaining they are the they are the the they are the they	um world walles and the ey will famile chanics. The and will be e of naming the prese precise and have learn strategie	orks. They a cories and colliarise thems ney will apprese able to foll g and provinented connect d independented to transfers s on their ow	acquire an con selves reciate ow the g the e ctions. ent har er the r	e mathe- nect the with the what is current essential adling of nethods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Foundations of Quantum Mechanics	L E	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	The type of examination is se	et by t	he in	struc	tor.							
Transfer	the chosen personal Study Advanced Knowledge in Ma	The module belongs to the <i>Study Specialisation Mathematical Physics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.										
Prerequisites	The basic modules on Analysis and Linear Algebra are required.											
Responsible Persons	Roderich Tumulka											

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-21	Module Title: Advanced Topics in Mathema	atical (Quan	ıtum	Theo	ory		of Module: e Module					
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass			Self-St 180 h	udy:					
Duration	1 Semester												
Frequency	not regularly												
Term	2-3												
Language of Instruction	English												
Forms of Teaching and Learning	Lectures 4 SWS + Exercise (ectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements											
Content	The module provides an intrilike Hartree and Hartree-Formathematical models in quatems. It will present both the particular area, as well as propen problems.	ck the ntum to e fund	ory, field ame	BCS theo ntal	theery arm	ory, ad nd trans ematic	iabate theo sport in inte al results a	ry, renorma erdependent .nd physical	lisatior fermin notion	group, on sys- s of the			
Objectives	Students obtain knowledge a able to apply them in the ana ematical Quantum Theory. S concepts from the lecture as it into a larger framework. The of research in the specific are Through homework assignment and independent acquaintar lectures. They learn how to to develop solution strategies solutions and to stand for the	llysis of tudent well and are are are are transfer on the contractions on the contraction of the contractions on the contractions of the contracti	of knows are stored about the stored abo	own a able explained to with a contract of the	and retorning to the total the total the	new proname a e conto ribe an asses , state nods to within a	oblems from nd prove the ext developed of critically of students de ments, and new problements. The	n the specific e essential sed in the lec challenge the velop a contempt methods ex ems, to ana	tarea of tatement and tatement	of Math- ents and d to put nt state precise, d in the em and			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Advanced Topics in Mathematical Quantum	L	0	4	6	yes	wr. o.	90-180 o. 20-30	g	100			
	In this module students need the exam. The type of exami						 assignments		be adr	nitted to			
Transfer	The module may be a prerec	uisite	for th	ne m	aster	thesis							
Prerequisites	Knowledge from the module Mathematical Quantum Theory is assumed.												
Responsible Persons	Stefan Teufel												

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-22	Module Title: Advanced Topics in Mathema version)	tical C	Quan	tum ⁻	Γheo	ry (sho		of Module: e Module				
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h		lass	:		Self-St 120 h	udy:				
Duration	1 Semester						·					
Frequency	not regularly, in Summer Sen	nester	•									
Term	2											
Language of Instruction	English											
Forms of Teaching and Learning	Lectures 2 SWS + Exercise (Classe	s 2 S	SWS	, Hor	mework	Assignem	ents				
Content	theory, like Hartree and Har group, mathematical models systems. It will present both t	The module provides a short introduction to an advanced topic of mathematical quantum neory, like Hartree and Hartree-Fock theory, BCS theory, adiabate theory, renormalisation group, mathematical models in quantum field theory and transport in interdependent ferminon systems. It will present both the fundamental mathematical results and physical notions of the particular area, as well as provide an insight into the current state of research and the existing upon problems.										
Objectives	Students obtain knowledge a able to apply them in the ana ematical Quantum Theory. S concepts from the lecture as it into a larger framework. The current state of research in the Through homework assignment and independent acquaintant lectures. They learn how to to develop solution strategies solutions and to stand for the	lysis of tudent well a ney are speents a ce with transfer on the contract of t	of knoods are as to decifice and each the the fer the	own a explain explain area exercing exe	and retorning to the total the total the	new proname a e conteribe ar asses : , state and to within a	blems from nd prove the ext developed in parts a students de ments, and new proble group. The	n the specific e essential s ed in the lec also critically velop a cont methods ex ems, to ana	tatement ture ar challe fident, cplaine	of Math- ents and id to put enge the precise, d in the em and		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Advanced Topics in Mathematical Quantum Theory	L E	0	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module students need the exam. The type of exami							s in order to	be adr	nitted to		
Transfer	The module may be a prereq	uisite	for th	ne m	aster	thesis						
Prerequisites	Knowledge from the module Mathematical Quantum Theory is assumed.											
Responsible Persons	Stefan Teufel											

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-23	Module Title: Advanced Topics in Mathematics	atical I	Relat	ivity				of Module:					
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-Si 180 h	tudy:					
Duration	1 Semester												
Frequency	not regularly, in Winter Seme	ster											
Term	3												
Language of Instruction	English												
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	ectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements											
Content	It will present both the fundar	the module provides an introduction to an advanced topic of mathematical theory of relativity. Will present both the fundamental mathematical results and physical notions of the particular rea, as well as provide an insight into the current state of research and the existing open roblems.											
Objectives	Students obtain deepend kn learn analytic and geometric equations and to examine th mathematical solutions. Stuconcepts from the lecture as it into a larger framework. The of research in the specific and Through homework assignment and independent acquaintar lectures. They learn how to to develop solution strategies solutions and to stand for the	e technesse. Note that the technology are the techn	nique Morecare a s to e abl nd e th the fer the	es in over, able expla e to xerci e no lese own a	orde they to na ain th desc se cl tions meth and v	er to produce do under do unde	ove existenderstand the destand the developed critically estudents dements, and new problegroup. The	ce of solution of ce physical representations are essential seed in the leconallenge the evelop a continuation of methods exems, to ana	ons of elevand tateme ture and e curre fident, kplaine lyse th	Einstein e of the ints and d to put ent state precise, d in the em and			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Advanced Topics in Mathematical Relativity	L	0	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100			
	In this module students need the exam. The type of exami	to su	cces	sfully	con			s in order to	be adr	nitted to			
Transfer	The module may be a prerec	uisite	for th	ne m	aste	r thesis							
Prerequisites	Knowledge from the module Mathematical Relativity is assumed.												
Responsible Persons	Carla Cederbaum, Gerhard I	Huiske	n, Fı	ank	Loos	e							

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-24	Module Title: Advanced Topics in Mathen sion)	natical	l Rel	ativit	y (sl	hort ve		of Module: e Module				
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass			Self-St 120 h	udy:				
Duration	1 Semester						·					
Frequency	not regularly, in Winter Seme	ster										
Term	3											
Language of Instruction	English											
Forms of Teaching and Learning	Lectures 2 SWS + Exercise (ectures 2 SWS + Exercise Classes 2 SWS, Homework Assignements										
Content	relativity. It will present both t	The module provides a short introduction to an advanced topic of mathematical theory of elativity. It will present both the fundamental mathematical results and physical notions of the articular area, as well as provide an insight into the current state of research and the existing pen problems.										
Objectives	Students obtain deepend kn learn analytic and geometric equations and to examine the mathematical solutions. Studencepts from the lecture as it into a larger framework. The current state of research in the Through homework assignment and independent acquaintant lectures. They learn how to to develop solution strategies solutions and to stand for the	e techi ese. Ments well a ney arme spe ents a ice wittransi s on th	nique Morec are a s to e able cific and e th the fer the	es in over, able explained to area exercing exer	orde they to na in th desc se cl tions meth	er to produce to under the control of the control o	ove existenderstand the derstand the developed in parts a students dements, and new proble group. The	ce of solution of	ons of elevance tatementure ar challed fident, coplaine lyse th	Einstein e of the ents and id to put enge the precise, d in the em and		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Advanced Topics in Mathematical Relativity	Type of Course	o Status	SWS 2	ε ECTS	se Assignments	Type of Exam o. o.	Dur. of Exam (min) 081-09 0-05-09	ص Grading	Weight for Grade		
	In this module students need the exam. The type of exami can be offered by the lecture for the module instead of 6.	nation	is s	et by	the	instruct	or. – In exc	eptional cas	es the	module		
Transfer	The module may be a prerec	uisite	for th	ne m	aste	r thesis						
Prerequisites	Knowledge from the module	Mathe	emati	cal F	Relati	ivity is	assumed.					
Responsible Persons	Carla Cederbaum, Gerhard I	Huiske	en, Fı	ank	Loos	se						

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-35	Module Title: Quantum Shannon Theory a	ınd Be	yonc	l				of Module: e Module						
ECTS-Points	9													
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		Class	:		Self-St 180 h	udy:						
Duration	1 Semester													
Frequency	not regularly													
Term	2-3													
Language of Instruction	English	inglish												
Forms of Teaching and Learning	Lectures 4 SWS + exercise of	Lectures 4 SWS + exercise classes 2 SWS, homework assignments												
Content	Contents:													
	 Basic concepts about the universal quantum computer: quantum gates, quantum circuits, universality and measurements. 													
	Quantum algorithms: Deutsch-Jozsa, Shor and Grover.													
	Quantum communication: no-cloning theorem, quantum teleportation and superdense coding. Quantum key distribution													
	Physical realisations:	 Physical realisations: DiVincenzo criteria, Cirac-Zoller quantum computer, circuit QED. 												
	Decoherence and operations	en qua	ıntun	n sys	tems	i.								
	Quantum error correct	tion. F	ault-	toler	ant q	uantun	n computing	J .						
	Alternative models of	quanti	um c	omp	uting	: Adiab	atic quantu	m computat	ion.					
	Introduction to the the entanglement, multipart					nt: de	finition, crit	eria and me	easure	ment of				
Objectives	In this course, the students quantum communication cha for several quantum informat timation and quantum hypoth essential results of the lectur In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	annel. ion pronesis teles as when a second teles as when a second teles are a second tele	They cesting ell as acqu s of the	knothing to knothing. The sassified area in the letter to wo	w how asks e stu essir a cor ecture rk on	w to us is, such idents a ng and infident, is. They is solution	e diverse quas quantum are capable explaining to precise an have learn on strategie.	uantum entru tomography of naming a he presente d independe ed to transfe s on their ow	opic m y, quar und pro d conn ent har er the r vn or in	easures ntum es- loving the lections. Indling of methods a team.				
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade				
	Quantum Shannon Theory and Beyond	L E	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100				
	In this module an exercise or examination the coursework oral is decided by the instruc	must I	have	bee	n acc	uired.	Whether th	e examination						

Literature	Exemplary Literature:
	 Michael A. Nielsen, Isaac L. Chuang: Quantum Computation and Quantum Information. CUP 2010.
	Mark M. Wilde: From Classical to Quantum Shannon Theory. arXiv 2019.
	John Watrous: The theory of quantum information. CUP 2018.
	Eric A. Carlen: Trace inequalities and quantum entropy. Rutgers 2009.
	Michael A. Wolf: Quantum Channels and Operations Guided Tour. Lecture Notes 2012.
Transfer	The module belongs to the <i>Study Specialisation Mathematical Physics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	The basic modules on Analysis and Linear Algebra are required.
Responsible Persons	Angela Capel Cuevas
Abbroviations	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{ Teaching Format : L=lecture, \ LE=lecture \ with \ integrated \ exercises, \ SL=seminar \ or \ lecture, \ E=exercise \ class, \ T=tutorial, \ P=project, \ S=Seminar, \ IC=inverted \ classroom }$

Status : m=mandatory, o=optional

Section 4: Scientific Work

Module Number: MAT-40-41	Module Title: Scientific Project							of Module: oulsory Mod		
ECTS-Points	9	9								
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 255 h									
Duration	1 Semester						·			
Frequency	Every Semester									
Term	3									
Language of Instruction	English									
Forms of Teaching and Learning	Individual supervision by a m	entor	stuc	ly of	scie	ntific w	orks.			
Content	Content: • Definition of an advan	Content: • Definition of an advanced scientific project in coordination with the mentor.								
	Formulation of specifi	 Independent search and study of the relevant scientific literature. Formulation of specific problems and methodical approach to their solution. Written presentation of the project in conext of current state of research on 5-10 pages. 								
Objectives	develop skills to syste learn to work critically judgement, acquire qualifications problems and appropring proposal.	and and	to fo	rm a	sub	stantia literatu	ted, profes	ssional and h, identifica	interdise	relevant
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Scientific Project	т Type of Course	o Status	SMS 1	Φ ECTS	Assignments	Type of Exam	Dur. of Exam (min)	g Grading	Weight for Grade
	·									
Transfer	Successful completion of this sis.	mod	ıle is	a pr	ereq	uisite f	or participa	ation in mod	ule Mas	ter The-
Prerequisites	Successful completion of mo cal Quantum Theory or Math					hysics	and of one	of the mode	ules Ma	themati-
Responsible Persons	Stefan Teufel, Werner Vogels	ang.								

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-40-42	Module Title: Mathematical Physics Colloquium							of Module: ulsory Modu	ıle	
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 30 h									
Duration	2 Semester	2 Semester								
Frequency	Every Semester	Every Semester								
Term	3–4									
Language of Instruction	English	English								
Forms of Teaching and Learning	Presentations, discussions. Specific form of study: during	Presentations, discussions. Specific form of study: during the final semester students present their Master thesis.								
Content	During each semester on 15 appointed dates (2 h each) there will take place presentations and discussions on current topics in mathematical physics. Speakers are the researchers of the involved departments, guest scientists and master's students, who present the results of their Master Thesis.									
Objectives	area of their own specializati to discuss and challenge the	Students gain an insight into the current development of mathematical physics beyond the area of their own specialization. They develop the ability to follow scientific presentations and to discuss and challenge them within a larger group of scholars. They therefore also obtain interdisciplinary and intercultural competencies through regular cooperation and discussion in mixed groups.								
Requirements for Obtaining Credit, Grading, Weight if	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
applicable	Colloquium Winter Semester	С	0	2	1	no	-	-	ng	-
	Colloquium Summer Semester	С	0	2	2	no	-	-	ng	-
Transfer	-	1		1	1		I		1	l
Prerequisites	-									
Responsible Persons	Carla Cederbaum, Stefan Te	ufel								

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-40-43	Module Title:Type of Module:Master Thesis M.Sc. Mathematical PhysicsCompulsory Module										
ECTS-Points	30										
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 900 h										
Duration	1 Semester										
Frequency	Every Semester	every Semester									
Term	4										
Language of Instruction	English or German	English or German									
Forms of Teaching and Learning	Master thesis										
Content	Students are assigned to workgroups and participate in seminars of the group. Under the supervision of the mentor students have to handle a concrete problem from mathematical physics by applying scientific methods and present it in written form in English or German. In particular this includes: • Definition of an advanced scientific task in coordination with the mentor; • Independent search and study of the relevant scientific literature; • Formulation of appropriate questions and methodical approach to their answers; • Independent execution and written presention of the project and the results in the context of the current state of research; • Presentation of the results in English in Mathematical Physics Colloquium.										
Objectives	Students are able to develop acquaintance increasing independe develop acquaintance critically interpret scie present their results in	nce by with s ntific r	app cien esuli	tific I s an	scie iterat d inte ased	entific n ture on egrate on prii	nethods; a new topi them into the	ic; neir state of Good Scienti	knowle	dge;	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Master Thesis	Type of Course	o Status	SWS	% ECTS	S Assignments	Type of Exam	Dur. of Exam (min)	ص Grading	Weight for Grade	
Transfer	-										

Prerequisites	
	27 CP from the compulsory elective section Foundations of Mathematical Physics,
	a total of 18 CP from the sections Knowledge Expansion and Elective Specialisation,
	Successful completion of module Scientific Project.
Responsible Persons	Stefan Teufel, Werner Vogelsang.

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Catalogue of Mathematics Modules

This section lists modules from the M.Sc. Mathematics programme that can be included in the area Elective Specialisation and which are not yet listed in Section 3.

•	Abstract Dynamical Systems (MAT-55-33, 9 CP))4
•	Algebraic Curves (MAT-45-14, 9 CP)	58
•	Algebraic Curves and Riemannian Surfaces (MAT-50-29, 9 CP)	12
•	Algebraic Geometry (MAT-45-11, 9 CP)	52
•	Algebraic Geometry and Toric Varieties (MAT-45-12, 9 CP)	54
•	Algebraic Groups (MAT-45-16, 9 CP)	32
•	Algebraic Number Theory (MAT-45-21, 9 CP)	'C
•	Algebraic Topology 1 (MAT-50-21, 9 CP)	26
•	Algebraic Topology 2 (MAT-50-22, 9 CP)	28
•	Algebraic Topology 3 (MAT-50-23, 3 CP)	30
•	Algebraic Transformation Groups (MAT-45-13, 9 CP)	56
•	Algorithms of Numerical Mathematics (MAT-70-01, 9 CP)	31
•	Applied Topology 2 (MAT-50-26, 3 CP)	36
•	Applied topology 1 (MAT-50-25, 3 CP)	34
•	Area Minimising Flows (MAT-55-43, 5 CP))2
•	Automorphic Forms (MAT-55-53, 5 CP)	20
•	Calculus of Variations (MAT-55-49, 5 CP)	4
•	Cohomology and Sheaves (MAT-55-61, 9 CP)	24
•	Combinatorics (MAT-75-02, 9 CP)	9
•	Commutative Algebra (MAT-45-02, 9 CP)	18
•	Computer Algebra (MAT-45-03, 9 CP)	50
•	Consistency Proofs (MAT-55-62, 6 CP)	26
•	Control Theory (MAT-55-06, 9 CP)	30
•	Convex Geometry (MAT-50-02, 9 CP))4
•	Cox Rings (MAT-45-18, 9 CP)6	34
•	Elastic Curves (MAT-55-46, 3 CP))8
•	Elementary Number Theory (MAT-45-25, 6 CP)	78
•	Elliptic Curves and Cryptography (MAT-45-27, 9 CP)	32
•	Elliptic Curves and Taniyama-Shimura (MAT-45-28, 9 CP)	34
•	Elliptic Functions and Elliptic Curves (MAT-45-24, 9 CP)	⁷ 6
•	Ergodic Theory (MAT-55-05, 9 CP)	58
•	Explicit Mathematics (MAT-55-65, 6 CP)	31
•	Foundations of Discrete Mathematics (MAT-75-12, 9 CP)	39
•	Fuctional Analysis (MAT-55-01, 9 CP)	50
•	Fully Non-Linear Elliptic Equations (MAT-55-27, 5 CP)	38

•	Fully Non-Linear Elliptic and Parabolic Partial Differential Equations (MAT-60-36, 3 CP)	263
•	Game Theory (MAT-70-40, 3 CP)	316
•	Geometric Evolution Equations (MAT-60-01, 3 CP)	237
•	Geometric Group Theory (MAT-50-30, 9 CP)	144
•	Geometric Measure Theory (MAT-55-42, 9 CP)	200
•	Geometric Measure Theory – Flows (MAT-55-48, 5 CP)	212
•	Geometric Measure Theory – Varifolds (MAT-55-47, 5 CP)	210
•	Geometric Variation Problems (MAT-60-02, 3 CP)	239
•	Geometry of Manifolds 1 (MAT-50-10, 9 CP)	104
•	Geometry of Manifolds 2 (MAT-50-11, 9 CP)	106
•	Graph Theory (MAT-75-10, 9 CP)	335
•	Gravitational Collapse and Singularities in General Relativity (MAT-60-30, 3 CP)	259
•	Gromov-Witten Theory (MAT-50-40, 6 CP)	146
•	Groups and Representations (MAT-65-05, 9 CP)	265
•	Hamiltonian Systems (MAT-65-38, 9 CP)	277
•	Harmonic Analysis in Euclidean Space (MAT-55-12, 9 CP)	172
•	Harmonic Analysis on Abelian Groups (MAT-55-13, 9 CP)	174
•	Harmonic Analysis on General Groups (MAT-55-14, 9 CP)	176
•	Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP)	148
•	Information Geometry (MAT-50-12, 3 CP)	108
•	Information Geometry and Neural Data Processing 2 (MAT-50-13, 3 CP)	110
•	Information Theory (MAT-75-07, 9 CP)	329
•	Integrable Systems (and Infinite Dimensional Lie Algebras) (MAT-50-18, 9 CP)	120
•	Introduction to Analytic Number Theory (MAT-45-26, 3 CP)	. 80
•	Introduction to Berkovich Geometry (MAT-45-20, 3 CP)	. 68
•	Introduction to Combinatorial Birational Geometry (MAT-45-40, 9 CP)	. 90
•	Introduction to Combinatorial Mirror Symmetry (MAT-45-41, 6 CP)	. 92
•	Introduction to Commutative Algebra and Algebraic Geometry (MAT-45-01, 9 CP)	. 46
•	Introduction to Dynamical Systems (MAT-55-34, 3 CP)	196
•	Introduction to Geometric Measure Theory (MAT-55-41, 9 CP)	198
•	Introduction to Geometric Measure Theory – Measure Theoretic Methods (MAT-55-44, 5 CP)	204
•	Introduction to Geometric Measure Theory – Varifolds (MAT-55-45, 5 CP)	206
•	Introduction to Harmonic Analysis (MAT-55-11, 9 CP)	170
•	Introduction to Integrable Systems (Classical Mechanics, Riemann Surfaces, and Spectral Theory) (MAT-50-CP)	
•	Introduction to K-theory (MAT-50-24, 3 CP)	132
•	Introduction to Modular Forms (MAT-45-29, 3 CP)	. 86
	Introduction to Optimisation (MAT-70-20, 6 CP)	300

•	Introduction to Partial Differential Equations (MAT-55-21, 9 CP)	180
•	Introduction to Partial Differential Equations – Part 1 (MAT-55-25, 5 CP)	186
•	Introduction to Riemannian Surfaces (MAT-50-15, 5 CP)	114
•	Introduction to Set Theory (MAT-55-63, 3 CP)	228
•	Introduction to Stochastic Differential Equations - Part 1 (MAT-70-12, 5 CP)	295
•	Introduction to Tropical Enumerative Geometry (MAT-50-05, 5 CP)	100
•	Introduction to the Mathematical Logic (MAT-55-60, 3 CP)	222
•	Lie Groups (MAT-55-51, 9 CP)	216
•	Limits of Spaces (MAT-60-05, 6 CP)	245
•	Linear Control Theory (MAT-55-07, 6 CP)	162
•	Markov Chains and Applications (MAT-75-11, 9 CP)	337
•	Mathematical Aspects of Neuronal Information Processing 1 (MAT-50-14, 3 CP)	112
•	Mathematical Aspects of Neuronal Information Processing 2 (MAT-50-19, 3 CP)	122
•	Mathematical Aspects of the Quantum Hall Effect (MAT-65-32, 6 CP)	269
•	Mathematical Methods for Condensed Matter Physics (MAT-65-31, 6 CP)	267
•	Mathematical Population Genetics (MAT-75-08, 6 CP)	331
•	Mathematical Statistics (MAT-75-03, 9 CP)	321
•	Matrix Analysis and Applications (MAT-65-37, 6 CP)	275
•	Modular Forms (MAT-45-23, 9 CP)	. 74
•	Morse Theory (MAT-55-28, 3 CP)	190
•	Non-Commutative Ergodic Theory (MAT-55-09, 9 CP)	166
•	Non-Linear Elliptic and Parabolic Partial Differential Equations (MAT-60-35, 6 CP)	261
•	Non-Linear Functional Analysis (MAT-55-02, 9 CP)	152
•	Non-Linear Optimisation (MAT-70-21, 9 CP)	302
•	Nonlinear Elliptic Partial Differential Equations in Minimal Surface Theory (MAT-55-24, 9 CP)	184
•	Null Geometry in General Relativity (MAT-60-08, 5 CP)	251
•	Number Theory and Cryptography (MAT-45-22, 9 CP)	. 72
•	Numerical Optimisation (MAT-70-25, 5 CP)	306
•	Numerics of Differential Equations of Surfaces (MAT-70-06, 6 CP)	291
•	Numerics of Instationary Differential Equations (MAT-70-03, 9 CP)	285
•	Numerics of Stationary Differential Equations (MAT-70-02, 9 CP)	283
•	Numerics of Stochastic Differential Equations (MAT-70-15, 3 CP)	297
•	Operator Algebras (MAT-55-04, 9 CP)	156
•	Operator Algebras and their Applications to Statistical Mechanics (MAT-55-71, 6 CP)	235
•	Operator Theory (MAT-55-03, 9 CP)	154
•	Optimal Control Theory with Ordinary Differential Equations (MAT-70-05, 5 CP)	289
•	Optimisation with Differential Equations (MAT-70-22, 9 CP)	304
	Ordinary Differential Equations - Analysis and Numerics (MAT-70-04, 9 CP)	287

•	Partial Differential Equations (MAT-55-22, 9 CP)	182
•	Percolation Theory (MAT-75-05, 3 CP)	325
•	Point Processes (MAT-75-09, 6 CP)	333
•	Probability Sistances for Sata Science (MAT-75-20, 6 CP)	341
•	Probability Theory (MAT-75-01, 9 CP)	317
•	Propagation of Chaos (MAT-65-39, 9 CP)	279
•	Pseudo Differential Operators (MAT-55-10, 3 CP)	168
•	Quantum Information Theory (MAT-65-36, 9 CP)	273
•	Real Algebraic Geometry (MAT-45-19, 6 CP)	. 66
•	Representation Theory of Finite Groups (MAT-45-31, 6 CP)	. 88
•	Riemannian Geometry (MAT-50-16, 6 CP)	116
•	SL2(R) (MAT-55-52, 3 CP)	218
•	Selected Chapters from Dynamical Systems Theory (MAT-55-32, 3 CP)	192
•	Selected Chapters from Functional Analysis (MAT-55-70, 6 CP)	233
•	Selected Chapters from Operator Theory (MAT-55-15, 9 CP)	178
•	Space-Like Hypersurfaces in Lorentzian Manifolds (MAT-60-04, 6 CP)	243
•	Special Relativity (MAT-60-07, 3 CP)	249
•	Special Topics in Evolution Equations for Submanifolds (with Exercise Class) (MAT-60-10, 6 CP)	255
•	Special Topics in Evolution Equations for Submanifolds (without Exercise Classes) (MAT-60-11, 3 CP)	257
•	Spectral Theory of Positive Operators (MAT-55-08, 6 CP)	164
•	Statistical Learning Theory for Nonparametric Regression 1 (MAT-70-31, 9 CP)	310
•	Statistical Learning Theory for Nonparametric Regression 2 (MAT-70-32, 9 CP)	312
•	Stochastic Analysis (MAT-75-06, 9 CP)	327
•	Stochastic Differential Equations (MAT-70-11, 9 CP)	293
•	Stochastic Optimal Control in Infinite Dimensions (MAT-70-16, 3 CP)	299
•	Stochastic Processes (MAT-75-04, 9 CP)	323
•	The Einstein Constraint Equations (MAT-60-09, 6 CP)	253
•	The Ricci Flow of Riemannian Metrics (MAT-60-06, 6 CP)	247
•	Theoretical Aspects of Machine Learning (MAT-70-30, 6 CP)	308
•	Theory and Numerics for Constrained Optimisation Problems (MAT-70-33, 9 CP)	314
•	Theory of Mathematical Proofs (MAT-55-64, 6 CP)	229
•	Topics in Mathematical Relativity (MAT-60-03, 3 CP)	241
•	Topological Vector Spaces and Distributions (MAT-50-27, 6 CP)	138
•	Topology (MAT-50-20, 6 CP)	124
•	Toric Varieties and Mori Dream Spaces (MAT-45-15, 9 CP)	. 60
•	Tropical Enumerative Geometry (MAT-50-04, 9 CP)	. 98
•	Tropical Enumerative Geometry - Part 2 (MAT-50-06, 5 CP)	102
•	Tropical Geometry (MAT-50-03, 9 CP)	. 96
•	Uniformisation of Riemannian Surfaces (MAT-50-28, 5 CP)	140
_	Wave Equations of Relativistic Quantum Mechanics (MAT-65-33, 6 CP)	271

Module Number: MAT-45-01	Module Title: Introduction to Commutative ometry		of Module: ulsory Modu	le with	Choice						
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		Class	:		Self-St 180 h	tudy:			
Duration	1 Semester										
Frequency	regularly in Winter Semester										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SW	S							
Content	 Rings and ideals. Gröbner bases. Localization. Noetherian rings and Integral ring extension Krull's principal ideal Hilbert's zeros theore Affine varieties, Zarisi 	ns. theore m and	m ar Noe	ether	norm	nalisatio	-				
Objectives	The students have become for tative algebra and affine algoretween algebra and geome students understand how accent as the simultaneous to students are capable of national assessing and explaining the line the exercise classes they the terms, statements and mon new problems, to analyst team. They are capable of prediscourse.	ebraic etry the dopting eatme ming a prese have a nethods e ther	geo g a h nt a nd p entec acqu s of t	metr gh th ighe nd re orovir d con ired the le d to	y. The example of the	ney have ample spective tion of e esse fons. Infident, and so so so the medium of the	e experien of affine va e - namely, seemingly ntial results precise an have learn lution strate	ced the prof arieties. Fur abstracting unrelated q s of the lect d independent ed to transfer egies on the	found in the properties the properti	nterplay ore, the roblem - ns. The well as adling of nethods or in a	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Introduction to Commutative	Type of Course	J Status	SMS 4	e ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Algebra and Algebraic Geometry In this module an exercise of examination the coursework	E ertifica	f te is	2 to be	3 e acq		or. s coursewo	o. 20-30 ork. For part			
	examination the coursework oral is decided by the instruc								on is w	ritten or	

Literature	Exemplary Literature:
	 Michael Francis Atiyah, Ian G. Macdonald: Introduction to commutative algebra. Addison Wesley 1969.
	 David A. Cox, John B. Little, Donal O'Shea: Ideals, varieties, and algorithms. Springer 2008.
	 David Eisenbud: Commutative algebra with a view toward algebraic geometry. Springer 1995.
	 Ernst Kunz: Einführung in die kommutative Algebra und algebraische Geometrie. Vieweg 1980.
	Miles Reid: Undergraduate Commutative Algebra. Cambridge University Press 1997.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Commutative Algebra' due to the large overlap in content.
Prerequisites	There are no further prerequisites.
Responsible Persons	Jürgen Hausen

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-02	Module Title: Commutative Algebra		of Module: ulsory Modu	le with	Choice						
ECTS-Points	9						l l				
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:			
Duration	1 Semester										
Frequency	regularly in Winter Semester	regularly in Winter Semester									
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	3							
Content	Content:							·			
	Rings and Ideals.										
	Localisation and loca	l rings.									
	Noetherian and Artini	an ring	gs an	d mo	duls						
	Integral ring extension	ns and	Coh	en-S	eide	nberg t	heorems.				
	Krull's principal ideal	theore	m an	d dir	nens	ion the	ory.				
	Primary decomposition	n.									
	Normality, regularity a	and dis	crete	valu	uatior	n rings.					
	Hilbert's Nullstellensa	ıtz and	Noe	ther	norm	nalizatio	on.				
Objectives	The students are familiar walgebra, which are essential They recognise how adopting the simultaneous treatment a capable of naming and provexplaining the presented corn in the exercise classes they the terms, statements and monnew problems, to analysteam. They are capable of prediscourse.	for stugg a high and resting the innection have a nethods se then	udyin her p solution e essons. acqui s of to n and	g the ersp on of entia red a he le d to	e field ective seer al res a cor ecture work	ds of all e - name mingly cults of mident, e. They on so	gebra, geo nely, abstrac unrelated q the lecture precise an have learn lution strate	metry, and reting the prouestions. The as well as dindepended independed in transfered to argue for the second control of the control of the second in the s	number blem - ne stud assess ent har er the r eir own	r theory. enables ents are sing and adling of nethods or in a	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Commutative Algebra	L E	f	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise c examination the coursework oral is decided by the instruc	ertifica must h	te is	to be	acq acq	juired.	Whether th	e examination			

Literature	Exemplary Literature:
	 Michael Francis Atiyah, Ian G. Macdonald: Introduction to commutative algebra. Addison Wesley 1969.
	 David A. Cox, John B. Little, Donal O'Shea: Ideals, varieties, and algorithms. Springer 2008.
	David Eisenbud: Commutative algebra with a view toward algebraic geometry. Springer 1995.
	 Ernst Kunz: Einführung in die kommutative Algebra und algebraische Geometrie. Vieweg 1980.
	Miles Reid: Undergraduate Commutative Algebra. Cambridge University Press 1997.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Introduction to Commutative Algebra and Algebraic Geometry' due to the large overlap in content.
Prerequisites	There are no further prerequisites.
Responsible Persons	Victor Batyrev, Thomas Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-03	Module Title: Type of Module: Computer Algebra Compulsory Module with Choi									Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	S						
Content	Content:									
	Canonical forms and a	standa	ırd ba	asis f	for id	eals ar	nd modules.			
	Computation of impor	tant op	oerat	ions	for ic	leals a	nd modules			
	Syzygies, free resolut	ions a	nd th	e pro	oof o	f the B	uchberger c	riterion.		
	Calculation of the prin	nary re	esolu	tion	of ide	eals.				
	Hilbert functions.									
Objectives	Students are familiar with im gebraic geometry as well as familiar with the theory of sta familiarised themselves with and will have implemented a ing and proving the essential presented connections. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the They also learnt about important money implemented algorithms.	algoriandard impor lgorithial result have a ethods them a eir solurtant s	ithmill bas tant ms ir lts of acquis of tand tand tand tand tand tand tand tand	c apples a software the software per apple	proad nd the vare se the lecture cture rk on d, if re	ches to leir divergence divergenc	esolving the erse applicates in the fit es. The stude well as assented precise and have learned ary, defend	em. In particulations. They eld of symbodents are casessing and dindepended to transfess on their ow them in critical forms.	cular, to will all olic co apable explained that the render or in ical discussion.	they are so have mputing of naming the adding of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Computer Algebra	L	f	4	6	yes	wr. o.	90-180	g	100
		Е	f	2	3	,00	or.	o. 20-30	9	100
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.								

Literature	Exemplary Literature:
	 Gert-Martin Greuel, Gerhard Pfister: A SINGULAR Introduction to Commutative Algebra. Springer 2008.
	 Wolfram Decker, Christoph Lossen: Computing in algebraic geometry. A quick start using SINGULAR. Springer 2006.
	 Wolfram Decker, Gerhard Pfister: A first Course in computational algebraic geometry. Cambridge University Press 2013.
	David A. Cox, John B. Little, Donal O'Shea: Ideals, varieties, and algorithms. Springer 2008.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the modules commutative algebra and algebraic geometry are helpful however not absolutely necessary for participation in the module computer algebra
Responsible Persons	Hannah Markwig, Thomas Markwig
Abbreviations:	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-11	Module Title: Algebraic Geometry Type of Module: Compulsory Module with Che							Choice			
ECTS-Points	9	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 90 h 180 h										
Duration	1 Semester	1 Semester									
Frequency	regularly in Summer Semes	er									
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ecture 4 SWS + Exercise Class 2 SWS									
Content	Content:	Content:									
	Prevarieties and varie	Prevarieties and varieties.									
	Projektive varieties ar	Projektive varieties and homogeneous spectrum.									
	Finite and proper more	phism	S.								
	Blow-up and Grassman	ann va	rietie	es.							
	 Rational mapping. 										
	Divisors and line bund	dels, cl	ass	grou	o and	d Picar	d group.				
Objectives	they develop a deepened ungebra. The students are cap well as assessing and explain the exercise classes they the terms, statements and monnew problems, to analyse	The students learn central terms, results and methods of modern Algebraic Geometry and they develop a deepened understanding of the interconnections between Geometry and Algebra. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Algebraic Geometry	L	f	4	6	yes	wr. o.	90-180	g	100	
		E	f	2	3	, 55	or.	o. 20-30	9		
	In this module an exercise context examination the coursework oral is decided by the instruc	must I	nave	bee	n acc	uired.	Whether th	e examination			

Literature	Exemplary Literature:
	Robin Hartshorne: Algebraic geometry. Springer 2006.
	Klaus Hulek: Elementare algebraische Geometrie. Vieweg 2012.
	Ernst Kunz: Einführung in die algebraische Geometrie. Vieweg 1997.
	David Mumford: The red book of varieties and schemes. Springer 1999.
	Miles Reid: Undergraduate algebraic geometry. Cambridge University Press 1988.
	Igor R. Shafarevich: Basic algebraic geometry. Springer 1994.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
	The module cannot be taken together with the module 'Algebraic Geometry and Toric Varieties' due to the large overlap in content.
Prerequisites	Essential knowledge from the module Commutative Algebra is assumed.
Responsible Persons	Victor Batyrev, Hannah Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title: Algebraic Geometry and Tor	ic Varie	atios					f Module:	a with	Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h									
Duration	1 Semester									
Frequency	regularly in Summer Semest	er								
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	6						
Objectives	Products and separate Projektive varieties are Divisors and line bund Toric varieties. Students learn the central control they develop an advanced ure Using the example of the control capable of naming and provexplaining the presented cord in the exercise classes they	 Projective space. Prevarieties, morphisms, tangent space and singularities. Products and separation. Projektive varieties and Grassmannians. Divisors and line bundels, class group and Picard group. 								
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Algebraic Geometry and Toric Varieties	п Type of Course	t Status	SMS 4	σ eCTS	Assignments	Type of Exam o. o.	Onr. of Exam (min) 90-180 o. 20-30	Grading	Weight for Grade
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	ave	beer	n acq	uired.	Whether the	e examinatio		

Literature	Exemplary Literature:
	 David A. Cox, John B. Little, Henry K. Schenck: Toric varieties. American Mathematical Society 2011:
	Robin Hartshorne: Algebraic geometry. Springer 2006.
	Klaus Hulek: Elementare algebraische Geometrie. Vieweg 2012.
	Ernst Kunz: Einführung in die algebraische Geometrie. Vieweg 1997.
	David Mumford: The red book of varieties and schemes. Springer 1999.
	Miles Reid: Undergraduate algebraic geometry. Cambridge University Press 1988.
	Igor R. Shafarevich: Basic algebraic geometry. Springer 1994.
Transfer	The module belongs to the Study Specialisation Algebra and Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Algebraic Geometry' due to the large overlap in content.
Prerequisites	Essential knowledge from the module Introduction to Commutative Algebra and Algebraic Geometry is assumed.
Responsible Persons	Jürgen Hausen
Abbreviations:	

Grading System : g=graded, ng=not graded

Examination Type : MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio

Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-13	Module Title: Type of Module: Algebraic Transformation Groups Compulsory Module with Choice									Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SW	S						
Content	 Elements of the struction Elements of the representation Quotients in algebraich Classical invariant the Geometrical invariant tients. 	 Operations of algebraic groups on algebraic varieties, homogeneous spaces. Elements of the structure theory of affine-algebraic groups and their Lie algebras. Elements of the representation theory of affine-algebraic groups and their Lie algebras. Quotients in algebraic geometry. Classical invariant theory: Hilbert's finiteness theorem. calculation of invariants. Geometrical invariant theory: Mumford's construction of quotients. variation of quo- 								
Objectives	The students learn basic me tures. At the same time, the example from group and ring ing and proving the essential presented connections. In the exercise classes they the terms, statements and me	- Spheric varieties. The students learn basic methods for mathematical work with symmetries on geometric structures. At the same time, they experience the interaction of different algebraic concepts, for example from group and ring theory, in algebraic geometry. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team.								
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Algebraic Transformation Groups	L E	f	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.								

Literature	Exemplary Literature:
	Armand Borel: Linear algebraic groups. Springer 1991.
	Jean A. Dieudonne, James B. Carrell: Invariant theory. Academic Press 1971.
	David Mumford: Geometric invariant theory. Springer 1965.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Algebraic Groups' due to the large overlap in content.
Prerequisites	Knowledge of the Commutative Algebra and Algebraic Geometry modules is helpful, but not a prerequisite for participation in the Algebraic Transformation Groups module.
Responsible Persons	Victor Batyrev, Jürgen Hausen

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{ Teaching Format : L=lecture, \ LE=lecture \ with \ integrated \ exercises, \ SL=seminar \ or \ lecture, \ E=exercise \ class, \ T=tutorial, \ P=project, \ S=Seminar, \ IC=inverted \ classroom }$

Status : m=mandatory, o=optional

Module Number: MAT-45-14	Module Title: Type of Module: Algebraic Curves Compulsory Module w								le with	Choice
ECTS-Points	9	Э								
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ass 2	SW	S						
Content	Content:									
	Projective curves, divi	sors, ⁻	Thec	rem	of Ri	emann	-Roch.			
	Ramified coverings, T	heore	m of	Hun	vitz.					
	Linear systems, embe	Linear systems, embeddings, Castelnuovo inequality.								
	Singularities of plane	Singularities of plane curves, Puiseux expansions.								
	Classification and mod	duli sp	aces	s, Ja	cobi v	variety.				
Objectives	Students have familiarised the selected sub-area of algebra oped an in-depth understand capable of naming and proving explaining the presented confunction in the exercise classes they the terms, statements and mon new problems, to analyse They are able to present their	tic ged ing of ng the nection have a ethods them	ometalge e essons. acques of tand	try. febraic sention ired the letto wo	amilia c curred al res a cor ecture ork or	arised ves and sults of nfident, e. They n solution	themselves I their class the lecture precise an have learn on strategie	with it. The ification. The as well as dindependent of transfers on their ow	ey have stude assessent har er the root or in or in	e devel- ents are sing and adling of methods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Algebraic Curves	L E	f	4 2	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise ce examination the coursework oral is decided by the instruc	must l	nave	bee	n acc	uired.	Whether th	e examination		
Literature	Exemplary Literature:		_	_						
	Robin Hartshorne: Alç	gebrai	c ge	omet	ry. S	pringer	2006.			
	Gerd Fischer: Ebene	algebr	aisc	he K	urver	n. View	eg 1994.			
	Rick Miranda: Algebra	ic Cui	rves	and	Riem	nann Sı	ırfaces. AM	IS 1995.		

Transfer	The module belongs to the Study Specialisation Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Essential knowledge from the module Commutative Algebra as well as basic knowledge from Algebraic Geometry and Complex Analysis is required.
Responsible Persons	Victor Batyrev, Hannah Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-15	Module Title: Toric Varieties and Mori Dream Spaces Type of Module: Compulsory Module with Choice									Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:			
Duration	1 Semester	1 Semester									
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	3							
Content	Content: In the lecture Moreties:	ri Drea	m Sp	oace	s are	consi	dered as ge	eneralisation	s of to	ric vari-	
	Geometry and combine	natoria	I the	ory fo	or tor	ic varie	eties and M	ori Dream S	paces.		
	Divisors on toric varie	ties an	nd Mo	ori D	ream	Space	es.				
	Quotient representation	on and	Cox	ring	for to	oric va	rieties and I	Mori Dream	Space	S.	
	Sheaves of divisorial	Sheaves of divisorial algebras.									
	Cox sheaves and cha										
	Quotients of H-factori	al affin	e vai	rietie	S.						
	Shaded rings.										
	Varieties with torus op	peratio	ns.								
Objectives	and methods of modern alg With the class of Mori drean varieties and their investigat added another important m geometry. The students are as well as assessing and ex In the exercise classes they the terms, statements and m on new problems, to analyse	Students have deepened their knowledge and understanding of the central concepts, results and methods of modern algebraic geometry in its interplay between geometry and algebra. With the class of Mori dream spaces, they have become familiar with a generalisation of toric varieties and their investigation using methods of convex geometry. In doing so, they have added another important methodological component to the interplay between algebra and geometry. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Toric Varieties and Mori Dream Spaces	L E	f	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	nave	beer	n acc	uired.	Whether th	e examination			

Literature	Exemplary Literature:
	 Ivan Arzhantsev, Ulrich Derenthal, Jürgen Hausen, and Antonio Laface. Cox rings. Cambridge University Press 2014.
	Yi Hu, Sean Keel. Mori dream spaces and GIT. Michigan Math. J. 48: 331-348, 2000.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Essential knowledge from the modules Introduction to Commutative Algebra and Algebraic Geometry as well as Algebraic Geometry and Toric Varieties is assumed.
Responsible Persons	Jürgen Hausen

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-16	Module Title: Algebraic Groups		Type of Module: Compulsory Module with Choice								
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h								
Duration	1 Semester		,								
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS									
Content	Content:										
	Definition and examp	les of algebraic groups.									
	Hopf algebras.										
	Operations of algebra	ic groups on varieties.									
	Linearisation of algeb	raic groups.									
	Group closure.										
	Resolvable and nilpot	ent groups.									
	The Lie algebra of an	algebraic group.									
	Examples of Lie algel	oras.									
	 Convolutions and cor 	nmutators.									
	The adjoint represent	ation and its differential.									
	The Jordan decompo	sition in affine algebraic group	OS.								
	Characters of an alge	- '									
	Semi-invariants of a r										
		uction of quotients with applica	ations.								
	Diagonalisable group										
	Rigidity of diagonalisa										
	Theorem of Lie-Kolch										
	Structure of affine res										
		imple elements of algebraic gr	oups.								
	Borel subgroups and										
	Structure and classification	cation of semisimple algebraic	groups.								

Objectives	Students have learnt about a large class of important groups and algebraic varieties that play an essential role in many mathematical fields. They have learnt how methods of group theory and algebraic geometry complement each other and can lead to a deeper understanding. They have learnt about the approach to classifying mathematical objects using an important example class and have acquired knowledge of methods that also play a key role in classification in completely different mathematical areas. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.																	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade								
	Algebraic Groups	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100								
	In this module an exercise context examination the coursework oral is decided by the instruction	must I	nave	bee	n acc	uired.	Whether th	e examination										
Literature	Exemplary Literature: James E. Humphreys 1981. Armand Borel: Linear					·	, -	1975. 21, S	pringe	r-Verlag								
Transfer	The module belongs to the state chosen personal Study Advanced Knowledge in Mastrictive requirements of the The module cannot be taken to the large overlap in conter	Special sthematic respect togetl	alisat atics ctive	ion, or <i>E</i> secti	it ca <i>lectiv</i> on.	n be ir e Spec	ncluded in t cialisation, i	the sections n accordance	Study ce with	/ Focus, the re-								
Prerequisites	Knowledge of the modules C a prerequisite for participation	ommu n in th	ıtativ e Alç	e Alg gebra	jebra aic G	and A	lgebraic Ge nodule.	ometry are I	nelpful	, but not								
Responsible Persons	Victor Batyrev, Jürgen Hause	en								Victor Batyrev, Jürgen Hausen								
1 6130113							_											

: h=hours, o.=or, s.M.=see module description, SWS=contact hours per week

Other

Module Number: MAT-45-18	Module Title: Cox Rings		Type of Module: Compulsory Module with Choice								
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h								
Duration	1 Semester										
Frequency	not regularly	oot regularly									
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Class 2 SWS									
Content	Content:										
	Divisorial algebras.										
	Cox rings.										
	Charakteristic spaces	S.									
	Good quotients.										
	Geometric invariant the second content of the second content	neory.									
	Gale-duality.										
	Connections to toric	geometry.									
	Defining data for variegations	eties with finitely generated Co	ox ring.								
	Singularities.										
	Picard group.										
	Basis locus.										
	Ampleness.										
	Kanonical class.										
	Intrinsic quadrics.										
	k*-surfaces.	akt a a									
	Varieties with torus actions	ction.									
Objectives	and methods of modern alge combinatorics. They have fa investigating special classes tween algebra and geometry are capable of naming and and explaining the presented in the exercise classes they the terms, statements and mon new problems, to analyse	Students have deepened their knowledge and understanding of the central concepts, results and methods of modern algebraic geometry in its interplay between geometry and algebra and combinatorics. They have familiarised themselves with the Cox ring as an algebraic object for investigating special classes of geometric spaces. In doing so, they expand the interplay between algebra and geometry with another important methodological component. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									

Requirements for Obtaining Credit, Grading, Weight if applicable	Title Cox Rings	п Туре of Course	t Status	SMS 4	e ects	Assignments	Type of Exam o. o.	Dur. of Exam (min) 0. 20-30	Grading	Weight for Grade
	In this module an exercise cer examination the coursework n oral is decided by the instructor	nust ł	nave	beer	n acc	uired.	Whether the	e examinatio		
Literature	Ivan Arzhantsev, Ulrich 2014.	n Der	entha	al, Jü	irger	ı Haus	en, Antonio	Laface: Co	x Ring	s. CUP
Transfer	The module belongs to the Si the chosen personal Study S Advanced Knowledge in Mati strictive requirements of the re	Specia hema	alisat <i>tics</i> (ion, or <i>El</i>	it ca <i>lectiv</i>	n be ir	ncluded in t	he sections	Study	Focus,
Prerequisites	Knowledge of commutative alguments duction to commutative algebra								modu	le Intro-
Responsible Persons	Jürgen Hausen									

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-19	Module Title: Real Algebraic Geometry							of Module: ulsory Modul	le with	Choice	
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h										
Duration	1 Semester										
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lecture 3 SWS										
Content	varieties. This involves quest of topological types for real a	Content: This course aims to dive into different aspects of the study of the topology of real algebraic varieties. This involves questions related to the 16th Hilbert problem: we look at obstructions of topological types for real algebraic varieties and at the realisation of topological types via different construction techniques, with special emphasis to low dimensional cases.									
Objectives	and real numbers. They are f to the study of real algebraic to investigate and answer un- are capable of naming and p and explaining the presented In the exercise classes they the terms, statements and me	Students learn about some fundamental differences in algebraic geometry over the complex and real numbers. They are familiar with the application of topological and algebraic methods to the study of real algebraic varieties. They have learnt how modern methods can be used to investigate and answer unsolved scientific questions of the late 19th century. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Real Algebraic Geometry	L ü	f	3	4,5 1,5	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise ce examination the coursework oral is decided by the instruct	must h	nave	bee	n acq	uired.	Whether th	e examination			
Literature	Frederice Mangolte: F Robert Silhol: Real Alg Riccardo Benedetti, J Editions Herrmann 19 Alex Degtyarev, Viatcl eties: du côté de chez	gebrai ean-Ja 90. neslav	c Su acqu Kha	rface es f urlam	es. Sp Risler nov: -	oringer : Rea Topolo	· 1989. I Algebraic gical prope	and Semi-a			

Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge in algebraic geometry or algebraic topology is helpful, but not mandatory.
Responsible Persons	Hannah Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-20	Module Title: Introduction to Berkovich Ge	ometr	у					Type of Module: Compulsory Module with Choice				
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h											
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	English											
Forms of Teaching and Learning	Lecture 3 SWS											
Content	Content:											
Objectives	Ultrametric triangle in Affinoid domains. Berkovich affine and Analytification of alge The students have become fields and their induced top	 Non-Archimedean fields, valuations, and absolute value functions. Ultrametric triangle inequality and induced topology. Affinoid domains. Berkovich affine and projective line. Analytification of algebraic varieties. The students have become familiar with the most important examples of non-Archimedean										
	challenges in developing a Berkovich's approach to add line in Berkovich's framework they have encountered a typencountered in their studies familiar with the connections students are capable of nar assessing and explaining the In the exercise classes they the terms, statements and more to new problems, to analysteam. They are capable of prodiscourse.	ressin k in d e of ge (such s to al ming a e prese have a hethod e then	g the etail, come as very gebra pented acques of the ended acques	se is both tric so ecto aic go rovir d con ired in the lead to	sues a set- pace r spate eome ag the nection a core ecture work	the section . The section . The section . They on so	students have tically and mentally differentially differential results precise and have learned that the strategy and the str	we examined topologically ferent from comanifolds). Inalytification of the lected independent to transferigies on the	I the provided the	ojective bing so, camples are also or. The well as adling of nethods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Introduction to Berkovich Geometry	L	f	3	4,5	yes	wr. o. or.	90-180 o. 20-30	g	100		
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	cided I	by the instru	uctor with a	pprova	I by the		

Literature	Exemplary Literature:
	Annette Werner: Nichtarchimedische Geometrie. Vorlesungsskript.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge of topological concepts is assumed.
Responsible Persons	Hannah Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-21	Module Title: Type of Module: Algebraic Number Theory Compulsory Module with Choice											
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h											
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German	German										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Cl	ass 2	SW	S								
Content	content:											
	Rings of integers.											
	Class numbers.											
	Dirichlet's unit theoren	٦.										
	Extension of Dedeking	l rings	i.									
	 Valuation theory. 											
	Local fields.											
	Adeles and ideles.											
Objectives	The students have learned the The students are capable of a assessing and explaining the In the exercise classes they the terms, statements and more on new problems, to analyse They are able to present their	namin prese nave a ethods them a	g and entect acqu s of t and t	d pro l con ired : he le o wo	oving necti a cor ecture rk or	the essions. ofident, e. They of solution	precise an have learn on strategies	Its of the lec d independe ed to transfe s on their ow	ture as ent har er the r n or in	dling of nethods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Algebraic Number Theory	L E	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise ce examination the coursework oral is decided by the instruct	must ł	nave	bee	n acc	uired.	Whether the	e examination				
Literature	Exemplary Literature:											
	Jürgen Neukirch: Alge	braiso	che Z	Zahle	nthe	orie. S	pringer 200	7.				
	Alexander Schmidt: E	nführı	ung i	n die	alge	ebraisc	he Zahlenth	eorie. Sprin	ger 20	07.		
	Andre Weil: Basic nun	nber th	neor	y. Sp	ringe	er 1995						

Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Victor Batyrev, Anton Deitmar, Jürgen Hausen

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-22	Module Title: Number Theory and Cryptog	ıraphy						of Module: ulsory Modu	le with	Choice			
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German or English												
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS												
Content	Content:												
	RSA cryptosystec, pri	mality	tests	s, Ak	(S alg	gorithm							
	Factorisation methods	s, num	ber f	ield s	sieve								
	Quadratic reciprocity	in cryp	togra	aphy.									
	Evaluation of the disc	rete lo	garitl	hm.									
	Dynamical systems a	nd the	Polla	ard's	rho a	algorith	ım.						
	Elliptic curve cryptogr	aphy.											
	Grille and post-quanti	um cry	ptog	raph	y.								
	Zero-knowledge proo	fs, digi	tal si	gnat	ures	and ha	sh function	S.					
Objectives	The students got to know the cations in cryptography. The bouring disciplines: They end acquainted with elliptic curving graphic protocolls are working solutions may suprisingly concluded by the lecture as well as assess they the terms, statements and mon new problems, to analyst team. They are capable of produced by the terms of the problems of the produced by the terms of the problems of the problems.	ey have counted as over the counted as over th	re de re me er finitough om re ts are	eepe thod ite fid n stud most e cap plain ired he le d to	ned as of the lds. dying distinct the last of the last	and ex he theo They many nct bra of nan ne pres nfident, e. They	tended theicory of dynar understand open proble anches of m ning and pre- cented conn precise an have learn lution strate	ir knowledge nical system I how funda ems of cryto nathematics oving the ce ections. d independe ed to transfe egies on the	e abours and last and	t neigh- become crypto- c, whose students esults of adling of nethods or in a			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Number Theory and Cryptography	L E	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100			
	In this module an exercise or examination the coursework oral is decided by the instruc	ertifica must h	nave	to be	e acq	uired.	Whether th	e examination					

Literature	Exemplary Literature:
	 Jeffrey Hoffstein, Jill Pipher, Joseph H. Silverman: An introduction to mathematical cryptography. Springer 2008.
	 Stefan Müller-Stach, Jens Piontkowski: Elementare und algebraische Zahlentheorie. Vieweg+Teubner 2011.
	Joseph H. Silverman, John T. Tate: Rational points on elliptic curves. Springer 1992.
	 Nigel Smart: Cryptography: An introduction. McGraw-Hill 2003. (online version: https://www.cs.bris.ac.uk/~nigel/Crypto_Book/).
	 Lawrence C. Washington: Elliptic curves: Number theory and cryptography. Chaman & Hall/CRC 2008.
Transfer	The module belongs to the Study Specialisation Algebra and Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Elliptic Curves and Cryptography' due to the large overlap in content.
Prerequisites	The contents of the module algebra from the study program Bachelor of Science are presumed.
Responsible Persons	Elena Klimenko, Thomas Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-23	Module Title:Type of Module:Modular FormsCompulsory Module with Choice										
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 90 h 180 h										
Duration	1 Semester										
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise 0	Lecture 4 SWS + Exercise Class 2 SWS									
Content	Content:										
	Examples: Eisenstein Modular curves as R	 Modular forms for the modular group and its congruence subgroups. Examples: Eisenstein series, Dedekind eta function, theta series. Modular curves as Riemann surfaces. Arithmetic applications and conjectures. 									
Objectives	The students know and under mental techniques for working geometry and they have least fully in algebraic geometry. results of the lecture as well in the exercise classes they the terms, statements and not onew problems, to analyst team. They are capable of prodiscourse.	ng ther trned, I The s as ass have a nethoda	n. The now of tude sessi acques of the normal session of the normal session of the normal session of the normal session and the normal session of the norm	ney he concerned and and and and and and and and and an	ave repts are cand executed a correcture work	reache from capable apable aplainin fident, e. They on so	d a deependombinatoric of naming g the prese precise an have learn lution strate	d understands can be applied and proving and proving and connected independed to transfergies on the	ding of plied so the ections. ent har er the rein own	convex uccess- essential adling of nethods or in a	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Modular Forms	L	f	4	6	VAS	wr. o.	90-180		100	
	iviouulai i oiilis	Е	f	2	3	yes	or.	o. 20-30	g	100	
	In this module an exercise of examination the coursework oral is decided by the instruc	must	have	beei	n acc	uired.	Whether th	e examinatio			

Literature	Exemplary Literature:
	 Henri Cohen, Fredrik Stromberg: Modular forms. A classical approach. AMS Graduate Studies of Mathematics 2017.
	Fred Diamond, Jerry Shurman: A first course in modular forms. Springer 2005.
	Max Koecher, Aloys Krieg: Elliptische Funktionen und Modulformen. Springer 2007.
	Toshitsune Miyake: Modular forms. Springer 1989.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites. Basic knowledge from algebra and complex analysis is helpful, however.
Responsible Persons	Anton Deitmar, Anna von Pippich

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:continuous} \begin{tabular}{ll} Teaching Format : L=lecture, & LE=lecture & with integrated exercises, & SL=seminar & or lecture, & E=exercise & class, & T=tutorial, & P=project, & S=Seminar, & IC=inverted & classroom & IC=inverted & Class$

Status : m=mandatory, o=optional

Module Number: MAT-45-24	Module Title: Elliptic Functions and Elliptic	Curve	es					of Module: ulsory Modu	le with	Choice
ECTS-Points	9						'			
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	Class	:		Self-St 180 h	udy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SW	S						
Content	Plane projective curve Curves over finite field Applications in crypto Additionally a selectio Modular forms; Classification of Moduli spaces.	 Elliptic functions, Weierstrass-P-function, Riemann surfaces, complex tori. Plane projective curves, Theorem of Bezout, elliptic curves. Curves over finite fields, rational points. Applications in cryptography. Additionally a selection of the following: Modular forms; Classification of elliptic curves; 								
Objectives	The students have expanded have learnt about elliptic cursive relevance in a wide spontions, methods and result Number Theory, Topology ar understand their mutual interessential results of the lectur. In the exercise classes they the terms, statements and rods to new problems, to ana team. They are capable of prodiscourse.	rves as ectrum ts from the Cryper trelation to the test with the test wi	s a of of the otogroups. The of as acquired as of the of t	class math dis- raphy The s ass ired the and t	of mema ciplin v, whi stud essir a cor lectu	athem tical are ch are ents and fident, re. The rk on s	atical objecteas. The semplex Calcorelevant in the capable of explaining the precise and ey have least colution stra	ts, which has tudents have ulus, Algebrathe given coof naming a he presented independente to transtegies on the to argue for the sto argue for the students.	es come ve stude raic Ge ntext, a nd prod d connent har esfer th eir own	prehendied the cometry, and they ving the ections. Indiing of the methon or in a
Requirements for Obtaining Credit, Grading, Weight if applicable	Type of Course Status Sws ECTS Assignments Type of Exam (min) Dur. of Exam (min) Weight for Grade								Weight for Grade	
	Elliptic Functions and Elliptic Curves	L E	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise context examination the coursework oral is decided by the instruction	must l	nave	bee	n acc	uired.	Whether th	e examination		

Literature	Exemplary Literature:
	Wolfgang Fischer, Ingo Lieb: Funktionentheorie. Vieweg 2005.
	Gerd Fischer: Ebene algebraische Kurven. Vieweg 1994.
	Joseph H. Silverman: The arithmetic of elliptic curves. Springer 2009.
	Ian Blake, Gadiel Seroussi, Nigel Smart: Elliptic curves in cryptography. CUP 1999.
Transfer	The module belongs to the <i>Study Specialisations Algebra and Geometry</i> and <i>Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the lecutre Introduction to Complex Analysis is needed.
Responsible Persons	Jörg Zintl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-25	Module Title: Elementary Number Theory							of Module: ulsory Modu	le with	Choice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass	-		Self-Si 120 h	tudy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SWS	S						
Content	Content:									
	Divisibility in the integ	ers.								
	Prime numbers.									
	Congruences.									
	Quadratic remainders	i.								
	Arithmetic functions.									
	Multiplicative function	S.								
	Classical sets.									
	Applications.									
Objectives	Students deepen their basic mathematical problems of varies essential results of the lectur Students will be able to reflect area. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	e as we at and of the and of the and of the and of the and the	tinds ell as critica cqui cqui and t	s. The assally a lired he le o wo	e studes essirandy: a corecture ecture rk on	dents and and se the confident, e. They a solution	are capable explaining to current state precise and have learn on strategie	of naming a the presente e of research d independe ed to transfe s on their ow nem in critica	ind produced connumbers in the ent har er the run or in	ving the sections. e subject adling of methods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Elementary Number Theory	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise of examination the coursework oral is decided by the instruc	ertificat must h	e is	to be	e acq	uired.	Whether th	e examinati		

Literature	Exemplary Literature:
	Friedhelm Padberg: Elementare Zahlentheorie. Spektrum Akademischer Verlag 2001.
	 Stefan Mueller-Stach, J. Piontkowski: Elementare und algebraische Zahlentheorie. Vieweg 2006.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, only basic knowledge of groups and rings from linear algebra is required.
Responsible Persons	Victor Batyrev, Thomas Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-26	Module Title: Introduction to Analytic Numb	er Th	eory					f Module: Isory Modul	le with	Choice
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	lass	:		Self-Sti 120 h	udy:		
Duration	1 Semester	Semester								
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS								
Content	Prime number theorer	 Content: Arithmetic functions and Dirichlet series, Prime number theorem and Dirichlet's prime number theorem, Zeros of the Riemannian zeta function, Riemann hypothesis and the explicit formula. 							rmula.	
Objectives	analytical methods to numbe ical continuation through inte to other cases, such as auto Riemann hypothesis, which stand its depth. They are able the lecture as well as to explain	The students understand the interplay between analysis and number theory. They can apply analytical methods to number theoretic problems. They understand the mechanism of analytical continuation through integral representation and have learned to independently transfer it to other cases, such as automorphic L-functions. They have gained an understanding of the Riemann hypothesis, which is considered the most difficult problem of all math, and understand its depth. They are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. They are able to describe and critically challenge the current state of research in							f analyt- ransfer it ng of the d under- pts from a larger	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Analytic Number Theory	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	cided	by the instru	uctor with a	pprova	l by the
Literature	Exemplary Literature: • Komaravolu Chandra: 1968.	sekha	ran:	Intr	oduc	tion to	Analytic N	umber The	ory.	Springer
Transfer	The module belongs to the Differential Geometry. Takin be included in the sections Specialisation, in accordance	g into Study	Foc	ount us, A	the d A <i>dvai</i>	chosen nced K	personal S nowledge ir	tudy Specia Mathemat	ilisatio <i>ics</i> or	n, it can <i>Elective</i>
Prerequisites	There are no further prerequ	sites								

Other

Responsible Persons	Anton Deitmar
Abbreviations:	
Grading System : g	=graded, ng=not graded
Examination Type : M	T=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio
	=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, =tutorial, P=project, S=Seminar, IC=inverted classroom
Status : m	n=mandatory, o=optional

ECTS-Points		Module Title: Elliptic Curves and Cryptography Type of Module: Compulsory Module with Choice										
	9											
Ti i Ol	Workload: 270 h	Time i 90 h	in Cl	ass:			Self-St 180 h	udy:				
Duration 1	1 Semester						•					
Frequency r	not regularly											
Term 1	1-3											
Language of Instruction	German or English											
Forms of Teaching Land Learning	Lecture 4 SWS + Exercise C	lass 2 S	sws	}								
Content	Content:											
	Basic concepts of cryp	otograp	hy.									
	Symmetric cryptosyste	ems, pu	ublic	key	syste	ems, di	screte loga	rithm, RSA.				
	Factorisation into prim	es, atta	acks	on c	rypto	osyster	ns.					
	Basic concepts of plai	n projed	ctive	geo	metr	y.						
	Elliptic curves as Abel	ian gro	ups.									
	Curves over finite field	ls, Frob	eniu	s m	orphi	sm, en	domorphisi	m ring.				
	Counting points, Hass	e boun	ıd, W	eil c	onje	ctures,	Schoof's a	lgorithm.				
	Cryptosystems on ellip	otic cur	ves,	algo	rithn	ns and	attacks.					
c a lu a a I t	Students are familiar with the cryptographically motivated of advanced algebraic and geor lenges of algorithmic implem are capable of naming and pand explaining the presented in the exercise classes they the terms, statements and mon new problems, to analyse They are able to present their	question metric to entation proving connection according to the entation at the entation at the entation and the entation are the entation and entation are entation and entation are entation and entation are entation and entation are entat	ns re echn n and the ection equir of the	elatir nique d are esse ns. red a ne lee	ng to es for e fam entia a con cture rk on	elliptic answe niliar wi result fident, . They solutic	c curves an ering them. th standard s of the leconomic precise and have learned at strategies.	d have an in They unders I algorithms. It is a well dindepended to transfers on their ow	nsight stand the seas as as ent han er the ner in or in	into the ne chal- tudents sessing adling of nethods a team.		
E	Title Elliptic Curves and	г Type of Course	J Status	SMS 4	e ECTS	Assignments	Type of Exam	Dur. of Exam (min)	ت Grading	Weight for Grade		
1	Cryptography In this module an exercise ce examination the coursework					uired a			cipatio			

Literature	Exemplary Literature:
	 Albrecht Beutelspacher, Jörg Schwenk, Klaus-Dieter Wolfenstetter: Moderne Verfahren in der Kryptographie. Springer 2015.
	Joseph H. Silverman: The arithmetic of elliptic curves. Springer 2009.
	Ian Blake, Gadiel Seroussi, Nigel Smart: Elliptic curves in cryptography. CUP 1999.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the modules 'Number Theory and Cryptography' due to the large overlap in content
Prerequisites	There are no further requirements.
Responsible Persons	Jörg Zintl
Abbreviations:	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{ Teaching Format : L=lecture, \ LE=lecture \ with \ integrated \ exercises, \ SL=seminar \ or \ lecture, \ E=exercise \ class, \ T=tutorial, \ P=project, \ S=Seminar, \ IC=inverted \ classroom }$

Status : m=mandatory, o=optional

Module Number: MAT-45-28	Module Title: Elliptic Curves and Taniyama	-Shim	ura					of Module: ulsory Modu	le with	Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass			Self-Si 180 h	tudy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS									
Content	 Group-law, arithmetic Modular curves and formation Riemann surfaces, ab Geometric version of a plained. 	 A selection of the following topics will be covered: Group-law, arithmetic of elliptic curves. Modular curves and forms. Riemann surfaces, abelian differentials, Jacobian. Geometric version of Taniyama-Shimura-conjecture (i.e. Wiles' modularity theorem) explained. Connection to Fermat's last theorem. 									
Objectives	The students have learnt and and geometry to answer profe of Taniyama-Shimura and its capable of naming and provexplaining the presented concurrent state of research in the exercise classes they the terms, statements and monnew problems, to analyse They are able to present their	ound named applied app	nathecation e essens. So ject acques of t	emat n to sentia Stude area ired ired he le o wo	ical c the p al res ents v a cor cture rk or	question proof of sults of will be a nfident, e. They n solution	ns using the fermat's to the lecture able to reflew precise and have learn on strategie	e example of heorem. Th as well as ct and critica d independe ed to transfe s on their ow	the cone student assessed assessed assessed and and and and and and and and and an	njecture ents are sing and lyse the adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Elliptic Curves and Taniyama-Shimura	L E	f f	4 2	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise context examination the coursework oral is decided by the instruction	must l	nave	beei	n acc	uired.	Whether th	e examination			
Literature	Exemplary Literature: • Joseph H. Silverman:	The A	Arithn	netic	of E	lliptic C	Curves. Spri	nger 2009.			

Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the modules Introduction to Riemann surfaces and Algebraic number theory are assumed.
Responsible Persons	Ivo Radloff

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-29	Module Title: Introduction to Modular Forn		Type of Module: Compulsory Module with Choice								
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h										
Duration	1 Semester										
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS									
Content	Content: The study of mode century with Gauss, Eisens algebra. They have many sure of Lagrange's four square the 1995. This course aims to git • Modular forms for the • Examples: Eisenstein • Arithmetic application • Hecke operators and	tein ar rprisir eorem ve an Modu serie s and	nd Rang application and introduced introduce	amar plica the q ducto roup Rar ectur	nujan tions grour ory u and manu	i, and i to nun nd-brea ndersta congru	is a fascination and the street theory, aking proof canding of this sence subgreence subgreence	ting blend o including a of Fermat's l s broad topi oups.	f analy beautit ast the	vsis and ful proof	
Objectives	Students have learnt the bas lar forms. They are familiar v The students are capable o as assessing and explaining critically analyse the current	<i>i</i> ith an f nami the p	alytic ng a rese	al, a nd p nted	lgebr rovin conr	raic and g the e nection	d geometric essential res s. Students	aspects of r sults of the	nodula lecture	r forms. as well	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Modular Forms	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	cided	by the instru	uctor with a	pprova	l by the	

Literature	Exemplary Literature:
	 Henri Cohen, Fredrik Stromberg: Modular forms. A classical approach. AMS Graduate Studies of Mathematics 2017.
	Fred Diamond, Jerry Shurman: A first course in modular forms. Springer 2005.
	Max Koecher, Aloys Krieg: Elliptische Funktionen und Modulformen. Springer 2007.
	Toshitsune Miyake: Modular forms. Springer 1989.
	 Lloyd James Peter Kilford: Modular forms: A classical and computational introduction. Imperial College Press 2015.
	Deitmar Anton: Automorphic forms. Springer 2013.
Transfer	The module belongs to the Study Specialisation Algebra and Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Modular Forms' due to the large overlap in content.
Prerequisites	There are no further prerequisites, but basic knowledge of algebra and function theory is helpful.
Responsible Persons	Anton Deitmar
Abbreviations:	g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-31	Module Title: Representation Theory of Fi	nite Gr	oups	3				Type of Module: Compulsory Module with Choice					
ECTS-Points	6							<u>_</u>					
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h												
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German												
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	Lecture 2 SWS + Exercise Class 2 SWS											
Content	Content:	Content:											
	Groups and group effects.												
	Representations, irreducibility, Schursch's lemma.												
	Semisimplicity, Masch	nke's th	neore	em.									
	Characters, orthogon	ality re	latio	ns.									
	Isotypical decomposit	ion, ch	arac	ter ta	ables								
	Representations of th	e symr	metri	c gro	up.								
	Semi-simple Artinian	algebra	as.										
Objectives	In the lecture, students learn understanding for the interact are capable of naming and and explaining the presented In the exercise classes they the terms, statements and m on new problems, to analyse They are able to present the	tion of proving done of the conne of the con	georgeone geotion acqui s of t	metri ess ns. ired a he le o wo	c and entia a corecture rk on	d algeb I resultificent, e. They I solution	precise an have learn strategies	ds. methods cture as well d independe ed to transfe s on their ow nem in critica	The second as	students sessing adling of methods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Representation Theory of Finite Groups	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100			
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	nave	beei	n acc	uired.	Whether th	e examination					

Literature	 Exemplary Literature: William Fulton, Joe Harris: Representation theory. Springer 1991. Bertram Huppert: Character theory of finite groups. De Gruyter 1998. Serge Lang: Algebra. Springer 2002. Jean-Pierre Serre: Linear representations of finite groups. Springer 1977.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . It can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Group Representations in Physics' due to the large overlap in content.
Prerequisites	In terms of content, only basic knowledge of linear algebra is required.
Responsible Persons	Victor Batyrev, Jürgen Hausen, Milena Wrobel
	graded, ng=not graded IT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio

Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

: m=mandatory, o=optional Status

Module Number: MAT-45-40	Module Title: Introduction to Combinatoria	l Birational Geometry	Type of Module: Compulsory Module with Choice								
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h								
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	class 2 SWS									
Content	Content:										
	map for surfaces X o divisors. The divisor of the divisor of the divisors, line variety. Ample and vertical divisors of the di	 Smooth projective toric surfaces P_Δ associated with lattice polygons Δ. The moment map for surfaces X over the complex numbers. The rational equivalence on boundary divisors. The divisor class group Cl(X) and the bilinear intersection pairing on Cl(X). Cartier divisors, line bundles, invertible sheaves. The canonical divisor of a normal variety. Ample and very ample divisors. Nondegenerate algebraic curves in toric surfaces. Blow ups of toric surfaces. Birational 									
		es via blow ups and blow dow f a surface. The Zariski decom									
	 The cone of curves of a surface. The Zariski decomposition. Birational Cremona transformations. Desingularization of nondegenerate curves D on smooth toric surfaces X via blow ups. Combinatorial constructing minimal models of pairs (X, D) for normal toric surfaces X. Cyclic quotient surface singularities and their combinatorial minimal desingularization. Finite subgroups of SU(2) and surface Du Val singularities and their minimal desingularization. 										
		on of nondegenerate surfaces) of their Newton polytopes Δ .	in 3-dimensional toric varieties via								
	The Kodaira dimensic els of nondegenerate		inatorial constructing minimal mod-								
	Combinatorial formula	as for the Hodge numbers of n	ninimal models.								
Objectives	In the lecture, students learn how to apply concepts, results and methods of convex geometric in order to analyse important classes of algebraic surfaces. They learn to recognise calculate complex algebro-geometric constructions. They are familiarised with an interest and deep classification problem, the minimal models for algebraic surfaces. The students capable of naming and proving the essential results of the lecture as well as assessing explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handlir the terms, statements and methods of the lecture. They have learned to transfer the methon new problems, to analyse them and to work on solution strategies on their own or in a term of the present their solutions and, if necessary, defend them in critical discours										

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Combinatorial Birational	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.										
Literature	Exemplary Literature:										
	 Laurent Buse, Fabrizio History of Shapes. Spr Klaus Hulek: Elementa Tadao Oda: Convex Bo Toric Varieties. Springe Robin Hartshorne: Alg 	inger re Algodies er 198	2023 gebra and 38.	3. aisch Alge	ne Ge ebraic	eometri Geom	ie. Springer netry: An Int	2012.			
Transfer	The module belongs to the State chosen personal Study State Advanced Knowledge in Matastrictive requirements of the results.	specia hema	alisat <i>tics</i> (ion, or <i>E</i>	it ca <i>lectiv</i>	n be ir	ncluded in t	he sections	Study	Focus,	
Prerequisites	Knowledge of commutative alg									essen-	
Responsible Persons	Victor Batyrev										
Abbreviations:											

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-45-41	Module Title: Introduction to Combinatoria	l Mirror Symmetry	Type of Module: Compulsory Module with Choice								
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: 180 h	Time in Class: 60 h	Self-Study: 120 h								
Duration	1 Semester										
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS										
Content	Content:										
	Quintic 3-folds in proju	ective 4-space and their mirror	S.								
	Toric varieties associal ated with lattice polyh		edral cones. Toric varieties associ-								
	Resolution of singularities. Cohomology rings of smooth projective toric varieties.										
	 Construction of Calab reflexive polyhedra. 	oi-Yau varieties as hypersurfac	es in toric varieties associated with								
	A combinatorial form correspondence.	ula for Hodge numbers of Ca	llabi-Yau 3-folds. Monomial-divisor								
	Combinatorial mirror of Calabi-Yau varieties.	construction for Calabi-Yau cor	mplete intersections. Mirrors of rigid								
	Computation of period functions.	ds of Calabi-Yau hypersurfaces	s using generalized hypergeometric								
	Stringy Hodge number	ers of singular Calabi-Yau varie	eties.								
	 Moduli spaces. Bour secondary polytopes. 		s of Calabi-Yau hypersurfaces and								
	Computation of Grom	ov-Witten invariants of Calabi	-Yau complete intersections.								
	A combinatorial appro	oach to Berglund-Hübsch mirro	or symmetry.								
	based on polar duality in the the most famous examples of dodecahedron. In combination considered reflexive polyhedra Δ^* below lattice of characters of an atone-parameter subgroups in is the theory of toric varieties symmetry discovered by physic N and from Δ to Δ^* . The aim of the module is to	e class of reflexive lattice poly of polar dual pairs of polyhedr orial mirror symmetry, an esse dra Δ are elements of the latt ng to the dual lattice N . The latting to the dual lattice N . The latting to the dual lattice N and the dual T . For this reason, the main is. Combinatorial mirror symmetricists for 3-dimensional Calater explain the connection between derstandable way possible at	atorial approach to mirror symmetry stopes. The Platonic solids provide a: Cube-octahedron, icosahedronantial fact is that the vertices of the ice M and the vertices of the dual lattice M can be identified with the all lattice N becomes the lattice of tool of the combinatorial approach stry allows us to interpret the mirror abi-Yau manifolds by going from M ten reflexive polyhedra and Calabination to inform students about further								

Objectives	Students are familiar with the complex issues of mirror symmetry, which establishes a duality between manifolds of symplectic and algebraic geometry and was first postulated by physicists. They have learnt how methods of toric geometry and discrete mathematics can be used for very important classes of Calabi-Yau varieties in order to calculate the mirrors of the manifolds and their invariants in concrete terms. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Introduction to Combinatorial Mirror Symmetry	ш Г Type of Course	t Status	SWS a	s s ECTS	Assignments	Type of Exam o. o.	Dur. of Exam (min) 0. 20-30	Grading	Weight for Grade
	In this module an exercise cer examination the coursework n oral is decided by the instructor	tifica nust h	te is	to be beer	acq acc	juired.	Whether the	e examinatio		
Literature	Exemplary Literature:									
	 Victor Batyrev: Dual Portic Varieties. J. Alg. 0 							labi-Yau Hy	persur	faces in
	 Victor Batyrev, Duco va curves on Calabi-Yau of 168:3 (1995), 493–533 	comp								
	 Victor Batyrev and Lev Calabi-Yau manifolds. Soc., Providence, RI (1 	Mirro	r Syı	mme						
	 David Cox, Sheldon K Surveys and Monograp 						d Algebraic	Geometry.	Mathe	ematical
	 Israil Gelfand, Mikhail K tidimensional Determin 							nants, Resul	tants a	ınd Mul-
	 Masao Jinzenji: Classi Band 29, 2018. 	cal M	1irror	Syn	nmet	ry. Sp	ringerBriefs	in Mathema	atical F	Physics,
Transfer	The module belongs to the St the chosen personal Study S Advanced Knowledge in Math strictive requirements of the re	pecia nema	alisat <i>tics</i> (ion, or <i>El</i>	it ca <i>ectiv</i>	n be ir	ncluded in t	he sections	Study	Focus,
	Knowledge of the modules commutative algebra and algebraic geometry are assumed.									
Prerequisites	· · · · · · · · · · · · · · · · · · ·									

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-02	Module Title: Convex Geometry							Type of Module: Compulsory Module with Choice				
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass			Self-Si 180 h	tudy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise CI	ass 2	SWS	3								
Content	Content:	Content:										
	Cones, polytopes, poly	Cones, polytopes, polyhedra, fans, polyedral complexes.										
	Normal fans of polygon	ns.										
	Triangulations, subdivi	Triangulations, subdivisions, secondary fans, diskriminants.										
Objectives	In the lecture the students leadevelope a deepened unders example of polytopes and far sense. The students are cap well as assessing and explair In the exercise classes they the terms, statements and me on new problems, to analyse team. They are capable of prediscourse.	tandirns. Be able on the able of the able	ng for eside of na ne pr acqu s of t n an	the sthe ming esen fred the lead to	cond ey er and ted d a con cture work	cept of on thance I proving connect onfident, e. They on so	duality of m their geom g the centrions. precise an have learn lution strate	ethematical etric view ar al results of d independe ed to transfe egies on the e to argue fo	object nd thei the le ent har er the r eir owr	s on the r spatial cture as adding of methods a or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Convex Geometry	L E	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise ce examination the coursework oral is decided by the instruct	nust l	nave	bee	n acc	quired.	Whether th	e examination				
Literature	Exemplary Literature: • Günter M. Ziegler: Lec	tures	on F	Polyto	pes	. Sprinç	ger 1998.					
Transfer	The module belongs to the S the chosen personal Study S Advanced Knowledge in Mat strictive requirements of the r	Specia <i>hema</i>	alisat <i>tics</i>	ion, or <i>E</i>	it ca <i>lecti</i> v	n be ir	cluded in	the sections	Study	/ Focus,		

Other

Responsible Persons	Hannah Markwig									
Abbreviations:										
Grading System : g	=graded, ng=not graded									
Examination Type : M	T=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio									
, ,	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, etutorial, P=project, S=Seminar, IC=inverted classroom									
Status : m	n=mandatory, o=optional									

Module Number: MAT-50-03	Module Title: Tropical Geometry							of Module: ulsory Modu	le with	Choice					
ECTS-Points	9						·								
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:							
Duration	1 Semester	1 Semester													
Frequency	not regularly														
Term	1-3														
Language of Instruction	German or English														
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ecture 4 SWS + Exercise Class 2 SWS													
Content	Content:	Content:													
	Tropical numbers and polynomials.														
	Tropical hypersurface	s and	varie	ties.											
	Tropical toric varieties	3.													
	Matroid fans and trop	ical ab	strac	t var	ieties	S.									
	Tropical modifications	, stabl	e inte	ersec	tions	and ra	ational equi	valence.							
	Tropical curves and li	near s	ysten	ns.											
	• Tropical (p,q) -homolo	gy.													
	Correspondence thec	rems.													
Objectives	The students know and under mental techniques for working geometry and they have leastfully in algebraic geometry. The and they can explain their in the exercise classes they the terms, statements and more to new problems, to analysteam. They are capable of prodiscourse.	ng ther rned, h he stu trinsic have a ethods	n. The now of dents conn acqui s of to n and	ney he concest care to the	epts nan nan ons. a corecture work	reache from cone ne and nfident, e. They on so	d a deepen- ombinatoric prove the c precise an have learn lution strate	d understan s can be ap entral result d independe ed to transfe egies on the	ding of plied so of the ent har er the reir own	convex uccess- e lecture adling of nethods or in a					
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade					
	Tropical Geometry	L E	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100					
	In this module an exercise context examination the coursework oral is decided by the instruction	must I	have	bee	n acc	uired.	Whether th	e examination							

Literature	Exemplary Literature:
	Grigory Mikhalkin, Johannes Rau: Tropical geometry. Manuscript 2018.
	Diane Maclagan, Bernd Sturmfels: Introduction to tropical geometry. AMS 2015.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites. Knowledge from the modules Algebraic Geometry and Differential Geometry is helpful, however.
Responsible Persons	Hannah Markwig, Johannes Rau

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-04	Module Title: Type of Module: Compulsory Module with Cho											
ECTS-Points	9						'					
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		lass	:		Self-St 180 h	udy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS											
	Tropical enumerative Combinatorial method Correspondence thed Tropical and classic Co Real counts, Welschill Hurwitz numbers. Tropical correspondence	 Enumerative geometry of algebraic curves, in particular in the plane. Tropical enumerative problems and multiplicities. Combinatorial methods, floor diagrams and grid paths. Correspondence theorems for curves in the plane through given points. Tropical and classic Gromov-Witten theory in genus 0. Real counts, Welschinger invariants and polynomial invariants. Hurwitz numbers. Tropical correspondences for Hurwitz numbers. Real Hurwitz numbers and Zigzag numbers. 										
Objectives	The students know basic te text of tropical geometry me and limitations of the tropical they deepen their knowledge Gromov-Witten theory. The and they can explain their in In the exercise classes they the terms, statements and m to new problems, to analys team. They are capable of p discourse.	thods. I acce in the stude trinsic have a nethods	The ss in e fiel nts conracques of t	ey de con d of an n ection ired he le	velop necti alget ame ons. a cor ecture work	o a dee on with oraic ge and p nfident, e. They on so	eper unders n more come eometry tow rove the ce precise and n have learn lution strate	tanding of the plex issues. It was a module in trail results dindependent of the period on the period of the period on the period on the period on the period of the period on the period of the period on the period of the perio	ne pos Furth ar spa of the ent har er the r	sibilities ermore, ces and lecture adling of nethods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Tropical Enumerative Geometry	L E	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	have	bee	n acc	uired.	Whether th	e examination				

Literature	Exemplary Literature:
	Grigory Mikhalkin, Johannes Rau: Tropical geometry. Manuscript 2018.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Familiarity with the module Tropical Geometry is assumed.
Responsible Persons	Hannah Markwig, Johannes Rau

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio

Status : m=mandatory, o=optional

Module Number: MAT-50-05	Module Title:Type of Module:Introduction to Tropical Enumerative GeometryCompulsory Module with Choice												
ECTS-Points	5												
Workload - Time in Class - Self-Study	Workload: 150 h	Time 45 h	_	lass	•		Self-St 105 h	Self-Study: 105 h					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German or English												
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 1 SWS												
Objectives	Tropical enumerative p Combinatorial method Correspondence theo Real counts, Welschir	 Enumerative geometry of algebraic curves, in particular in the plane. Tropical enumerative problems and multiplicities. Combinatorial methods, floor diagrams and grid paths. Correspondence theorems for curves in the plane through given points. Real counts, Welschinger invariants and polynomial invariants. The students know basic terms, results and methods of enumerative geometry in the con-											
	text of tropical geometry mer and limitations of the tropica they deepen their knowledge students are capable of nan assessing and explaining the In the exercise classes they the terms, statements and m to new problems, to analyse team. They are capable of p discourse.	l acce in the ning a prese have a ethoda	e field and pented acquis of to	condof a rovir l condition less than the less than the less to see the less than the l	necti algeb ng the necti a cor ecture work	on with raic ge e esse ons. nfident, e. They on so	n more com ometry town ntial results precise an have learn lution strate	plex issues. ards modula of the lect d independa ed to transfe egies on the	Furth ar spac ure as ent har er the r eir own	ermore, es. The well as adling of nethods or in a			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Introduction to Tropical Enumerative Geometry In this module an exercise ce												
	examination the coursework oral is decided by the instruc								on is w	ritten or			
Literature	Exemplary Literature:												
	Grigory Mikhalkin, Joh	anne	s Rai	u: Tr	opica	al geom	etry. Manus	script 2018.					

Transfer	The module belongs to the Study Specialisation Algebra and Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module is conceptually part of the module Tropical Enumerative Geometry and cannot be counted alongside it.
Prerequisites	Familiarity with the module Tropical Geometry is helpful, but not necessary.
Responsible Persons	Hannah Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title:						Туре с	of Module:				
MAT-50-06	Tropical Enumerative Geome	etry - P	art 2				Compu	ulsory Modu	le with	Choice		
ECTS-Points	5											
Workload - Time in Class - Self-Study	Workload: 150 h	Time 45 h	in C	lass	:		Self-St 105 h	udy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 1 SWS											
Content	Content:											
	Plane curves of higher genus.											
	Multiplicities.											
	Welschinger invariant	s.										
	Lattice paths.											
	Floor diagrams.											
	Hurwitz numbers.											
	Tropical moduli space	es.										
Objectives	The students deepen their kacquainted with various met merative problems which caname and prove the central tions. In the exercise classes they the terms, statements and more to new problems, to analysteam. They are capable of prodiscourse.	thods to the same the	o en olved of the acqui s of the	ume d wit he le ired he le	rate the the coture a corecture work	tropica aid of and the and the anfident, a. They on so	I curves, as tropical geney can exp precise an have learn lution strate	s well as with ometry. The olain their into dindepender ed to transfergies on the	h varion student student har the return the return the return town	ents can connec- adling of nethods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Tropical Enumerative	Type of Course	J Status	SWS 2	ω ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Geometry - Part 2	E	f	1	2	yes	or.	o. 20-30	g	100		
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	nave	bee	n acc	uired.	Whether th	e examination				

Literature	Diane Maclagan, Bernd Sturmfels: Introduction to tropical geometry. AMS 2015. Grigory Mikhalkin, Johannes Rau: Tropical geometry. Manuscript 2018.
Transfer	The module belongs to the <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module is conceptually part of the module Tropical Enumerative Geometry and cannot be included alongside it.
Prerequisites	Familiarity with the module Tropical Enumerative Geometry is expected.
Responsible Persons	Hannah Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-10	Module Title: Geometry of Manifolds 1 Type of Module: Compulsory Module with Choice											
ECTS-Points	9							<u> </u>				
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		lass	:		Self-Study: 180 h					
Duration	1 Semester						'					
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS											
Content	Content:											
	Manifolds and subma	nifolds	5.									
	Vector fields and flow	S.										
	Metrics, Foundations	of Rie	manı	nian	geon	netry.						
	Complex structures.											
	Theorem of Gauß-Bo	nnet o	n sui	rface	S.							
Objectives	The students know and under geometry and the basic techning especially of differential arematical concepts are nature proving the essential results connections. In the exercise classes they the terms, statements and in to new problems, to analysteam. They are capable of prediscourse.	niques and inte ally us of the have a nethod e then	s for I egral ed ir lectu acqu s of to	nand calcongeoure a ired a he led to	ling tulus a cometre control to the	hem. Tand hary. The ll as	They have do ve exemplar e students a sessing and precise and have learn lution strate	eepened the rily experient re capable dexplaining dindepende ed to transfered on the eto argue for the received and the recei	eir unde ced ho of nam the pr ent har er the r eir own	erstand- w math- ing and esented adling of nethods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Geometry of Manifolds 1	L	f	4	6	yes	wr. o.	90-180 o. 20-30	g	100		
	-	E	f	2	3		or.	0. 20-30				
	In this module an exercise c examination the coursework oral is decided by the instruc	must	have	bee	n acc	uired.	Whether the	e examination				

Literature	Exemplary Literature:									
	Sylvestre Gallot, Dominique Hulin, Jacques Lafontaine: Riemannian Geometry. Springer 2004.									
	John M. Lee: Introduction to Smooth Manifolds. Springer 2012.									
	Liviu I. Nicolaescu: Lectures On The Geometry Of Manifolds. World Scientific 1996.									
	Clifford Henry Taubes: Differential Geometry: Bundles, Connections, Metrics and Curvature. Oxford University Press 2011.									
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. Due to a significant overlap in contents the module cannot be taken together with either of the modules 'Geometry in Physics' and 'Introduction to Differential Geometry'.									
Prerequisites	There are no further prerequisites.									
Responsible Persons	Christoph Bohle, Frank Loose									
Abbreviations:										
Grading System : g	=graded, ng=not graded									
Examination Type : M	T=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio									
	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,									

: h=hours, o.=or, s.M.=see module description, SWS=contact hours per week

T=tutorial, P=project, S=Seminar, IC=inverted classroom

: m=mandatory, o=optional

Status

Other

Module Number: MAT-50-11	Module Title: Type of Module: Geometry of Manifolds 2 Compulsory Module with Choice											
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	me in Class: Self-Study: 180 h									
Duration	1 Semester											
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS											
Content	Content:											
	Global aspects of Riemannian geometry											
	Cohomology of mani Analysis of differentia		atore	on n	nanifo	olde						
	Applications on Riem	·					lex manifold	ds).				
Objectives	The students are familiar wit geometry. They have deeped they have exemplarily expestudents are capable of national assessing and explaining the line the exercise classes they the terms, statements and not onew problems, to analyst team. They are capable of products of processing the students and not not problems.	ened the rienced ming a present the rient the	eir u d hov nd p entec acqu s of t	nder v loc rovir l con ired he le	stand al an ng the necti a cor ecture work	ding of nd glob e esse ons. nfident e. They on so	methods in al aspects ntial results precise an have learn lution strate	differential in geometry of the lectron dindepende ed to transference to argue for the difference to argue for the edition of the difference to argue for the edition of the difference to argue for the edition of the difference to argue for the difference to th	geome interaure as ent hare er the reir own	etry, and lot. The well as adling of methods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Geometry of Manifolds 2	L	f	4	6	yes	wr. o.	90-180	g	100		
	- Somethy of Marinoldo E	Е	f	2	3	,55	or.	o. 20-30	9			
	In this module an exercise of examination the coursework oral is decided by the instruc	must l	nave	bee	n acc	uired.	Whether th	e examination				

Literature	Exemplary Literature:
	 Sylvestre Gallot, Dominique Hulin, Jacques Lafontaine: Riemannian Geometry. Springer 2004.
	John M. Lee: Introduction to Smooth Manifolds. Springer 2012.
	Liviu I. Nicolaescu: Lectures On The Geometry Of Manifolds. World Scientific 1996.
	 Clifford Henry Taubes: Differential Geometry: Bundles, Connections, Metrics and Curvature. Oxford University Press 2011.
	John Milnor: Morse Theory. PUP 1963.
	Donu Arapura: Algebraic Geometry over the Complex Numbers. Springer 2012.
	Sundararaman Ramanan: Global Calculus. AMS 2005.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the modules 'Geometry on Manifolds' or 'Geometry in Physics' is assumed.
Responsible Persons	Christoph Bohle, Frank Loose

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-12	Module Title: Information Geometry							f Module: Ilsory Modul	le with	Choice	
ECTS-Points	3	3									
Workload - Time in Class - Self-Study	Workload: 90 h							Self-Study: 60 h			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	1-3									
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS									
Content	 Foundations of Information Geometry (e.g. Fisher information metrics and dual relationships for parametric statistical models, Kullback-Leibler divergence, natural gradient). application to neural data processing (in particular supervised learning in artificial neural networks). 										
Objectives	Students have an elementary to problems in information to proving the essential results connections.	neory	and	stat	istics	. The	students ar	e capable o	of nam	ning and	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Information Geometry	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	ecided	by the instru	uctor with a	pprova	al by the	
Literature	 Anthony C. C. Cooled Processing Systems. Shun-Ichi Amari: Nati 1998. Yann Ollivier: Rieman 	 Exemplary Literature: Shun-Ichi Amari, Hiroshi Nagaoka: Methods of Information Geometry. AMS 2001. Anthony C. C. Coolen, Reimer Kuehn, Peter Sollich: Theory of Neural Information Processing Systems. OUP 2005. Shun-Ichi Amari: Natural Gradient works Efficiently in Learning. Neural Computation 								ormation	

Transfer	The module belongs to the Study Specialisations Algebra and Geometry, Analysis and Differential Geometry and Stochastics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge from differential geometry (Riemannian metrics, connections and curvature, geodesics) and from stochastics is assumed.
Responsible Persons	Christoph Bohle

 $Grading \ System \quad : g=graded, \ ng=not \ graded$

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-13	Module Title: Information Geometry and N	eural	Data	Prod	cessi	ng 2		f Module: Ilsory Modul	le with	Choice
ECTS-Points	3									
Workload - Time in Class - Self-Study							Self-St 60 h	udy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German	German								
Forms of Teaching and Learning	Lecture 2 SWS									
Content	Content:	Content:								
Objectives	The students can name and prove the central results of the lecture and they can explain their intrinsic connections.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Information Geometry and Neural Data Processing 2 Whether the examination is	L writte	f n or	2 oral	3 is de	no ecided	wr. o. or.	o. 20-30 uctor with a	g pprova	100 If by the
Literature	 Exemplary Literature: Shun-Ichi Amari, Hiroshi Nagaoka: Methods of Information Geometry. AMS 2001. Anthony C. C. Coolen, Reimer Kuehn, Peter Sollich: Theory of Neural Information Processing Systems. OUP 2005. Shun-Ichi Amari: Natural Gradient works Efficiently in Learning. Neural Computation 1998. Yann Ollivier: Riemannian Metrics for Neural Networks I - Feedforward Networks. Information and Inference, IMA 2015. 									
Transfer	Differential Geometry. Takin be included in the sections	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.								
Prerequisites	The module Information geor	netry	and	neur	al da	ta proc	essing is a	prerequisite		
Responsible Persons	Christoph Bohle									

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-14	Module Title: Mathematical Aspects of Neing 1		of Module: ulsory Modu	le with	Choice					
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h									
Duration	1 Semester	Semester								
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS								
Content	 Artificial neural netwo methods. Dynamic interpretation ics) and the change of Simple neuroscientific Recent work on the themachine learning. In a continuation of the methods. 	 Dynamic interpretation as the flow of data/activations through the network (fast dynamics) and the change of weights during training (slow dynamics). Simple neuroscientific models for the dynamics of neural networks. Recent work on the theoretical foundations of deep learning and biologically plausible 								
Objectives	The students have learned the fundamentals of information processing using artificial neural networks and biologically more plausible alternatives. They are familiar with dynamical systems as a possible framework for theoretical and mathematical investigations. The students can name and prove the central results of the lecture and they can explain their intrinsic connections.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Mathematical Aspects	Type of Course	- Status	SWS 2	ω ECTS	Assignments	Type of Exam	Dur. of Exam (min) 081-06	Grading	Weight for Grade
	of Neuronal Information Processing 1 Whether the examination is Board of Examiners.							o. 20-30 uctor with a		

Literature	Exemplary Literature:					
	Ian Goodfellow, Yoshua Bengio, Aaron Courville: Deep Learning. MIT 2016.					
	 Anthony C. C. Coolen, Reimer Kühn, Peter Sollich: Theory of Neural Information Processing Systems. OUP 2005. 					
	 Dmitry Krotov, John J. Hopfield: Unsupervised learning by competing hidden units. PNAS 2019. 					
	Guan-Horng Liu, Evangelos A. Theodorou: Deep Learning Theory Review - An Optimal Control and Dynamical Systems Perspective. arXiv:1908.10920.					
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.					
Prerequisites						
Responsible Persons	Christoph Bohle					

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=Seminar, IC=inverted classroom \\$

Status : m=mandatory, o=optional

Module Number: MAT-50-15	Module Title: Type of Module: Introduction to Riemannian Surfaces Compulsory Module with Choice									Choice	
ECTS-Points	5						<u> </u>				
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 150 h 105 h										
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	-3									
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	ecture 2 SWS + Exercise Class 1 SWS									
Content	Content:	ontent:									
	Coverings and fundar	nental	grou	ıps.							
	Topological classification	ion of t	the s	urfa	ces.						
	Theorem of Riemann	-Hurwit	Z.								
	Differential forms and	Differential forms and integration.									
	Sheaves and cohomo	Sheaves and cohomology.									
	Theorem of Riemann	Roch.									
	Serre duality.										
	Kobayashi metric.										
	Theorem of Picard.										
Objectives	based on local-to-global reas rigidity resulting from analyti damental questions naturally can ultimately be used to ar terrelated and in many case proving the essential results	Students develop an approach to abstract surfaces and understand classification techniques based on local-to-global reasoning. In the concept of holomorphy, they grasp the principles of rigidity resulting from analytical properties. Using the sheaf concept, students see how fundamental questions naturally lead to increasingly abstract conceptualisations and how these can ultimately be used to answer questions. They learn how geometry and analysis are interrelated and in many cases mutually dependent. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. Students will be able to reflect and critically analyse the current state of research									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Riemannian Surfaces	Introduction to Riemannian L f 2 3 ves wr. o. 90-180 g 10						100			
	In this module an exercise of examination the coursework oral is decided by the instructionally be offered by the awarded for the module in	must h tor with ne lecti	nave h app urer v	beei prova witho	n acc al by	uired. the Bo	Whether th ard of Exar	e examination niners. – Th	on is w e mod	ritten or ule may	

Literature	Exemplary Literature:
	Hershel M. Farkas, Irwin Kra: Riemann Surfaces. Springer 1992.
	Otto Forster: Riemannsche Flächen. Springer 1977.
	Klaus Lamotke: Riemannsche Flächen. Springer 2009.
	Jürgen Jost: Compact Riemann surfaces. Springer 2006.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Riemann surfaces' due to the large overlap in content
Prerequisites	Knowledge from the lecture Introduction to Complex Analysis is required.
Responsible Persons	Anton Deitmar, Reiner Schätzle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title: Riemannian Geometry		of Module:	le with	Choice						
ECTS-Points	6							,			
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h										
Duration	1 Semester	1 Semester									
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SWS	S							
Content	Content:										
	Riemannian manifolds	S.									
	Geodesics.										
	Curvature.										
	Geometry of submani	Geometry of submanifolds.									
Objectives	manifolds from a classical particles. The students were care sufficient to study their renotions of curvature was deferential geometry was achieved the essential statements and veloped in the lecture and tocritically challenge the current Through homework assignment and independent acquaintar lectures. They learn how to	The students have learned and understood definitions and main examples of Riemannian manifolds from a classical point of view. In addition, topics related to geodesics were discussed. The students were exposed to important geometric results involving geodesics which are sufficient to study their role in different areas of differential geometry. Intuition for various notions of curvature was developed by the students and familiarity with computations in differential geometry was achieved in the exercise sessions. They are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. They are able to describe and critically challenge the current state of research in the specific area. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	- Status	SWS 2	ε ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Riemannian Geometry	Е	f	2	3	yes	or.	o. 20-30	g	100	
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	nave	beei	n acc	uired.	Whether the	e examination			

Literature	Exemplary Literature:
	John M. Lee: Riemannian manifolds: An introduction to curvature. Springer 1997.
	Barret O'Neill: Semi-Riemannian geometry. With applications to relativity. Academic Press 1983.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry, Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the module Geometry in Physics is assumed.
Responsible Persons	Carla Cederbaum, Gerhard Huisken

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-17	Module Title: Introduction to Integrable Sy Riemann Surfaces, and Spe	Type of Module: Compulsory Module with Choice							
ECTS-Points	9								
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h						
Duration	1 Semester								
Frequency	not regularly								
Term	1-3								
Language of Instruction	English								
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	class 2 SWS							
Content	group. The course will focus discrete counterparts. Origin during a famous horse ride a and the underlying theory in A fundamental idea for under as spectrum preserving defocase symmetric matrices. We study an important classing algebro-geometric) solutions of Riemann surface theory a ics, Riemann surface theory briefly touch upon an integral algebra. The KdV equation is related interpreted as a dynamical deeply related to the geometric in the lecture are related to the lecture, it	on equations related to the Konally a mathematical model for along a canal, equations of Kd' volves various mathematical derstanding and solving KdV typermations of underlying auxiliants of explicit solutions that in a classical mechanics. The and spectral theory will be explicit systems interpretation of the document of the system on the space of paratry of Lie algebras and Lie group the geometry of Riemann surfacis planed to explain how infinitial	pe equations is their interpretation ry linear operators - in the simplest acludes solitons and finite gap (or be described using a combination relevant parts of classical mechanical plained in the lecture. We will also the QR-algorithm of numerical linear erent ways: for example, it can be metrized curves in the plane; it is ups; the special solutions discussed						
Objectives	The students have seen and understood relations between classical topics like Riemann surfaces, mechanics, and spectral theory – as well as other branches of mathematics – the were discovered mainly in the second half of the twentieth century during the emergence of a branch of mathematics sometimes called <i>soliton theory</i> or <i>integrable mathematics</i> . The students can name and prove the central results of the lecture and they can explain their intrinsiconnections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the method to new problems, to analyse them and to work on solution strategies on their own or in team. They are capable of presenting their results and if applicable to argue for it in a critical discourse.								

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Integrable Systems	L E	f	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise cer examination the coursework n oral is decided by the instructor	nust ł	nave	beer	n acc	uired.	Whether the	e examination		
Literature	tems. CUP 2004. • Leonid A. Dickey: Solit • Alan C. Newell: Soliton • Sergei P. Novikov, Sergei	Olivier Babelon, Denis Bernard, Michel Talon: Introduction to classical integrable sys-								
Transfer	The module belongs to the Study Specialisations Algebra and Geometry, Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.									
Prerequisites		The module Introduction to Complex Analysis and Ordinary Differential Equations is required. Basic knowledge of differential geometry (manifolds, differential shapes) is helpful, but not necessary.								
Responsible Persons	Christoph Bohle, Frank Loose	Christoph Bohle, Frank Loose								

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-18	Module Title: Integrable Systems (and Inbras)		of Module: ulsory Modu	le with	Choice					
ECTS-Points	9	9								
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	3						
Content	Content: Integrable systems are differential or difference equations with extraordinarily large symmetry group. The course will focus on equations related to the Korteweg de Vries (KdV) equation and discrete counterparts. Originally a mathematical model for the soliton phenomenon discovered during a famous horse ride along a canal, equations of KdV type have now many applications and the underlying theory involves various mathematical disciplines. A fundamental idea for understanding and solving KdV type equations is their interpretation as spectrum preserving deformations of underlying auxiliary linear operators - in the simplest case symmetric matrices. This lecture is the continuation of the lecture called Introduction to Integrable Systems (Classical Mechanics, Riemann Surfaces, and Spectral Theory). This continuation will investigate integrable equations using sl(2,C)—loop algebras. In particular, we will study explicit solutions that can be described using the theory of hyperelliptic Riemann surfaces.									
Objectives	algebra of sl(2,C). The stude can explain their intrinsic cor In the exercise classes they the terms, statements and m to new problems, to analyse	The students have aquired a uniform point of view on integrable equations related to the loop algebra of sl(2,C). The students can name and prove the central results of the lecture and they can explain their intrinsic connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods to new problems, to analyse them and to work on solution strategies on their own or in a team. They are capable of presenting their results and if applicable to argue for it in a critical								
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Integrable Systems (and Infinite Dimensional Lie Algebras)	ш Гуре of Course	t Status	SMS 4	g g ECTS	se Assignments	Type of Exam o. o.	Onr. of Exam (min) 0.20-30	ص Grading	Weight for Grade
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.									

Literature	Exemplary Literature:
	 Olivier Babelon, Denis Bernard, Michel Talon: Introduction to classical integrable systems. CUP 2004.
	Leonid A. Dickey: Soliton equations and Hamiltonian systems. World Scientific 2003.
	Alan C. Newell: Solitons in mathematics and physics. SIAM 1985.
	 Sergei P. Novikov, Sergei V. Manakov, Lev P. Pitaevskii, Vladimir E. Zakharov: Theory of Solitons - The Inverse Scattering Method. Consultants Bureau 1984).
Transfer	The module belongs to the Study Specialisations Algebra and Geometry, Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge from the module Introduction to Integrable Systems (Classical Mechanics, Riemann Surfaces, and Spectral Theory) is assumed.
Responsible Persons	Christoph Bohle, Frank Loose

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:continuous} \begin{tabular}{ll} Teaching Format : L=lecture, & LE=lecture & with integrated exercises, & SL=seminar & or lecture, & E=exercise & class, & T=tutorial, & P=project, & S=Seminar, & IC=inverted & classroom & IC=inverted & Class$

Status : m=mandatory, o=optional

Module Number: MAT-50-19	Module Title: Mathematical Aspects of Nei ing 2	urona	I Info	rmat	ion I	Process		f Module: Ilsory Modu	le with	Choice
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	Advanced applications data. Dynamic interpretation through the network (namics). Simple neuroscientific plausible machine learners.	n of nafast d	eura ynan	data	a pro and	cessing change	g methods a	as flow of d s during trai	ata/act	ivations slow dy-
Objectives	Students have learnt the bas biologically more plausible all framework for theoretical and ing and proving the essential presented connections.	ternat I math	ives. iema	The tical	y are inve	familia stigatio	er with dyna ns. The stud	mic systems dents are ca	s as a _l apable	oossible of nam-
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Mathematical Aspects of Neuronal Information Processing 2	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	ecided I	oy the instru	uctor with a	pprova	I by the
Literature	Ian Goodfellow, Yoshu Anthony C. C. Coolen cessing Systems. OUI Simon Haykin: Neural	, Rein P 200	ner K 5.	(ühn,	Pet	er Sollid	ch: Theory	of Neural In	format	

Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, the module dynamic systems and information processing 1 module is a prerequisite.
Responsible Persons	Christoph Bohle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title:	Module Title: Type of Module: Topology Compulsory Module with Cha								
ECTS-Points	6						Compt	ilsory Wodu	ie with	Choice
Workload - Time in Class - Self-Study	Workload: Time in Class: 60 h							audy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SWS	6						
Content	Content:									
		 Review of metric spaces: Closed sets, environment, continuity, complete metric spaces, compactness in metric spaces metric spaces. 								
	Set-theoretic topology: topological spaces, continuity convergence, compactness, separation axioms.									
	 Spaces of continuous functions: Urysohn's lemma and applications, Stone-Cech compactification, the theorem of Stone-Weierstraß, notions of convergence in functions, compactness in functionsräumen. 									
	 Baires spaces and the application of Baires theory: Baires' function classes, existence sets. 									
	Outlook on algebraic	topolog	gy.							
Objectives	Students have familiarised themselves with the central concepts, results and methods of settheoretical topology and have understood that this theory can be used to describe many phenomena in different areas of mathematics. In this way, they link their knowledge of very different areas of mathematics. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Topology	L E	f f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	ave	beei	n acq	juired.	Whether th	e examination	icipatic on is w	on in the ritten or

Literature	Exemplary Literature:
	Felix Hausdorff: Grundzüge der Mengenlehre. Von Veit & Comp. 1914.
	Boto von Querenburg: Mengentheoretische Topologie. Springer 2001.
	Volker Runde: A Taste of Topology. Springer 2005.
Transfer	The module belongs to the Study Specialisation Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Rainer Nagel

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title:							f Module:		2 1		
MAT-50-21	Algebraic Topology 1						Compu	Ilsory Modul	le with	Choice		
ECTS-Points	9											
Workload - Time in Class - Self-Study							Self-St 180 h	Self-Study: 180 h				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	3								
Content	Content:											
	Set theoretical topolo	ду.										
	Basic concepts of cat	Basic concepts of category theory.										
	The fundamental group of a punctured topological space.											
	Theory of covering spaces.											
	Basic concepts of sin	gular h	omo	logy	theo	ry.						
	Applications.											
Objectives	spaces, into a precise theory how abstract concepts, e.g. ways of speaking that enabstudents are capable of narassessing and explaining the In the exercise classes they the terms, statements and mon new problems, to analyse	The students learn how to realise ideas in topology, e.g. the detection of holes in topological spaces, into a precise theory, even with a sophisticated technique. In particular, they recognise how abstract concepts, e.g. from category theory and homological algebra, provide effective ways of speaking that enable the formation of ideas to be adequately implemented. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Algebraic Topology	L E	f	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	nave	beei	n acc	uired.	Whether the	e examinatio				

Literature	Exemplary Literature:
	Allen Hatcher: Algebraic topology. Cambridge University Press 2009.
	Horst Schubert: Topologie. Teubner 1971.
	Edwin H. Spanier: Algebraic topology. McGraw-Hill 1966.
	Ralph Stöcker, Heiner Zieschang: Algebraische Topologie. Teubner 1994.
Transfer	The module belongs to the Study Specialisation Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Anton Deitmar, Frank Loose

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-22	Module Title: Algebraic Topology 2							of Module: ulsory Modu	le with	Choice
ECTS-Points	9	9								
Workload - Time in Class - Self-Study	Workload: Time in Class: 90 h						Self-St 180 h	tudy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	S						
Content	Content:									
	Further development	of sing	ular	hom	ology	theor	y.			
	Simplicial complexes	and the	eir si	impli	cial h	omolo	gy.			
	CW spaces and their	cellula	r hor	molo	gy.					
	Axiomatic homology.	Axiomatic homology.								
	Homological algebra.									
	Cohomology.									
	 Homology and Cohor 	nology	with	coe	fficie	nts.				
	Product structures in	homolo	ogy a	and o	cohor	nology				
	The Poincaré duality	theorer	m for	topo	ologic	al mar	nifolds.			
Objectives	The students extend their ability to transfer concrete topological problems into algebraic constructions. They deepen their knowledge in abstract mathematical disciplines to accomplish even technically very challenging tasks. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SMS 4	e ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Algebraic Topology 2	E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	nave	bee	n acc	uired.	Whether th	e examination		

Literature	Exemplary Literature:
	Allen Hatcher: Algebraic topology. Cambridge University Press 2009.
	Horst Schubert: Topologie. Teubner 1971.
	Edwin H. Spanier: Algebraic topology. McGraw-Hill 1966.
	Ralph Stöcker, Heiner Zieschang: Algebraische Topologie. Teubner 1994.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Content-wise, the module Algebraic Topology 1 is a prerequisite for participating in this module.
Responsible Persons	Frank Loose
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Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-23	Module Title: Type of Module: Algebraic Topology 3 Compulsory Module with Choice								Choice	
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 90 h 60 h									
Duration	1 Semester									
Frequency	not regularly	ot regularly								
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	 Basic concepts of hon Homotopy group of sp Spectral sequences; K-theory; 	 A selection of the following topics will be covered: Basic concepts of homotopy theory; Homotopy group of spheres; Spectral sequences; 								
Objectives	With the in-depth knowledge introduced to current areas of which can lead to a Master possible doctorate in algebra essential results of the lecture	of rese s thes ic topo	arch sis, follogy	and or ex . The	they amp	tackle le. Th dents a	a small res ey will also re capable	search project lay the formatter of the formatter of the following the f	ect ther undatio and pro	nselves, ns for a ving the
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Algebraic Topology 3	L	f	2	3	no	Р		g	100
	Specifics on the portfolio will	be ex	plain	ed b	y the	exami	ner at the b	eginning of	the co	ırse.
Literature	Allen Hatcher: Algebra Allen Hatcher: Vector John W. Milnor, James 1974. John W. Milnor: Lect 1965.	bundles D. S	es ar tash	nd K- eff: C	theo Chara	ry. Mar acteristi	nuskript 200 c classes.	99. Princeton U		

Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, the modules Algebraic Topology 1 and 2 are prerequisite for participation in this module.
Responsible Persons	Frank Loose

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-24	Module Title:Type of Module:Introduction to K-theoryCompulsory Module with Choic								Choice	
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 90 h 60 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	Content:									
	Vector bundle.									
	Topological K-theory.									
	Künneth formula and	Künneth formula and Bott periodicity.								
	Characteristic classes	Characteristic classes.								
	Chern character.	Chern character.								
	Algebraic K-theory	Algebraic K-theory								
	Plus construction.									
Objectives	The students have learnt an algebra and number theory. different areas. They can un gorical K-groups and apply are capable of naming and and explaining the presented	They derstand them. or ovin	nave ind a They g the	lear nd u / hav ess	nt to se te ve lea	recognerms su arnt to	iise and use ich as vecto think in larç	the connector or fibre buge contexts.	ctions bundles The s	oetween or cate- students
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to K-theory	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100
Literature	Exemplary Literature:	1	1		1	1	I	l	1	1
	Michael Atiyah: K-the	ory. A	ddisc	n-W	esley	/ 1989.				
	Max Karoubi: K-theor	y. Spr	inger	200	8.					
	Emilio Lluis-Puebla, Chigher algebraic K-the							ophe Soule,	Victor	Snaith:

Transfer	The module belongs to the Study Specialisation Algebra and Geometry and Analysis und Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Anton Deitmar

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-25	Module Title: Applied topology 1		Type of Module: Compulsory Module with Choice										
ECTS-Points	3												
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 60 h												
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German	German											
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS											
Content	Content:												
	 Simplicial complexes and their homology. Persistent homology. Basic notions from topological data analysis. 												
Objectives	The students are familiar with basic concepts of algebraic topology and their application in the context of topological data analysis. The students can name and prove the central results of the lecture and they can explain their intrinsic connections.												
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Applied topology 1	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100			
	Whether the examination is Board of Examiners.	writter	n or	oral	is de	cided	by the instru	uctor with a	oprova	I by the			
Literature	Exemplary Literature:												
	Herbert Edelsbrunner	, John	L. H	arer	Cor	nputati	onal Topolo	gy. AMS 20	10.				
	Robert Ghrist: Elemen	ntary A	Appli	ed To	polo	gy. Cre	eate Space	2014.					
	Sergey V. Matveev: Le	ecture	s on	Alge	braic	Topol	ogy. EMS 20	006.					
Transfer	The module belongs to the s Geometry and Stochastics. sections into account, the mo Knowledge Mathematics or E	Takir dule c	ng th an b	e pe	erson signe	al spe d to the	cialisation a	ınd the rest	rictions	s of the			
Prerequisites	There are no further prerequ	isites.											
Responsible Persons	Christoph Bohle												

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-26	Module Title: Applied Topology 2		Type of Module: Compulsory Module with Choice										
ECTS-Points	3												
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 60 h												
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German												
Forms of Teaching and Learning	Lecture 2 SWS												
Content	Content:												
	 Advanced aspects of persistent homology (e.g. stability). Applied Morse theory. Applied sheaf theory. 												
Objectives	The students are familiar with advanced concepts of applied topology and topological data analysis. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.												
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Applied Topology 2	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100			
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	cided	by the instri	uctor with a	pprova	l by the			
Literature	Exemplary Literature:	ntary /	Appli	ed To	polo	gy. Cre	eate Space	2014.	10.				
Transfer	The module belongs to the State the chosen personal Study Advanced Knowledge in Mastrictive requirements of the	Specia thema	alisat atics	ion, or <i>E</i>	it ca <i>lectiv</i>	ın be ir	ncluded in t	he sections	Study	/ Focus,			
Prerequisites	The contents of the module from differential geometry is			polo	gy 1	' are a	ssumed. M	loreover, ba	sic kn	owledge			
Responsible Persons	Christoph Bohle												

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title: Topological Vector Spaces and Distributions Type of Module: Compulsory Module with Cho												
ECTS-Points	6	na Dis	tilbu	10113			Оотпро	ilisory Woodu	ie with	Onoice			
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 180 h 120 h												
Duration	1 Semester						'						
Frequency	not regularly												
Term	1-3												
Language of Instruction	German or English												
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS												
Objectives	Content: A selection of the following to Locally convex topolo Duality: Hahn-Banach Generalised functions Properties of distribut Applications and exame Students master the basic properties of the basic properties of the basic properties. Students are also which classical questions of capable of naming and provexplaining the presented corn the exercise classes they the terms, statements and monnew problems, to analyse	gical von theory of the control of t	ector em, on mo on on mo on mo on on mo on on mo on on on on on on on on on on on on on o	d tec the name	ces, space res a correcture	Freche e, topo and dis- on the ues of try of gramain cs can cults of	he theory o eneralised application be treated the lecture precise an have learn	stributions. f topological functions as of the the with it. The as well as a d independent of the totransfer to transfer to the transfer to transfer to the transfer	vector ccordir ory ar e stude assess ent har er the r	spaces and to L. and show ents are sing and andling of nethods			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Topological Vector Spaces and Distributions												
	In this module an exercise c examination the coursework oral is decided by the instruc	must h	nave	beer	n acc	uired.	Whether th	e examination					

Literature	Exemplary Literature:
	Gerald Folland: Real Analysis. Wiley 1999.
	Helmut H. Schäfer: Topological Vector Spaces. Springer 1999.
	Laurant Schwartz: Theorie des Distributions. Hermann 1998.
	Laurant Schwartz: Mathematics for the Physical Sciences. Dover 2008.
	Francois Trèves: Topological Vector Spaces, Distributions and Kernel. Dover 1967.
Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the module Functional Analysis and basic knowledge of set-theoretical topology is assumed.
Responsible Persons	Ulrich Groh, Rainer Nagel

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{ Teaching Format : L=lecture, \ LE=lecture \ with \ integrated \ exercises, \ SL=seminar \ or \ lecture, \ E=exercise \ class, \ T=tutorial, \ P=project, \ S=Seminar, \ IC=inverted \ classroom }$

Status : m=mandatory, o=optional

Module Number: MAT-50-28	Module Title: Uniformisation of Riemannian		Type of Module: Compulsory Module with Choice									
ECTS-Points	5						'					
Workload - Time in Class - Self-Study	Workload: 150 h	Self-St 105 h	Self-Study: 105 h									
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 1 SWS											
Content	Content:											
	Uniformisation of Riemannian surfaces											
Objectives	The students have learnt how to determine the simply connected Riemann surfaces by successively solving suitable differential equations. They are then able to classify Riemann surfaces under suitable conditions. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. Students will be able to reflect and critically analyse the current state of research in the subject area.											
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Uniformisation of Riemannian Surfaces	L	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise ce examination the coursework oral is decided by the instruc- exceptionally be offered by t points will be awarded for the	must l tor wit he led	nave th ap cture	beei prova r with	n acc al by nout	quired. the Bo exercis	Whether the ard of Exar	e examination niners. – Th	on is w ie mod	ritten or ule may		
Literature	Exemplary Literature:											
	Hershel M. Farkas, Irw	/in Kra	a: Rie	emar	nn Sı	urfaces	. Springer 1	1992.				
Transfer	The module belongs to the Differential Geometry. Taking be included in the sections a Specialisation, in accordance	g into Study	Foc	ount us, <i>A</i>	the d I <i>dvai</i>	chosen nced K	personal S nowledge i	Study Špecia n Mathemat	ılisatioi <i>ics</i> or	n, it can <i>Elective</i>		
Prerequisites	The module Introduction to Bachelor of Science Mathem								/lodule	s of the		
Responsible Persons	Reiner Schätzle											

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-29	Module Title: Algebraic Curves and Ri	emannian Surfaces	Type of Module: Compulsory Module with Choice									
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h									
Duration	1 Semester											
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS											
Content	KCompact Riema											
		orem of plane curves.										
	Topological gende	er.										
	Superpositions.Shapes and integ	ration										
	Sheaves and coh											
	Hodge theory.											
	Arithmetic and ge	ometric gender.										
	Abel's theorem.											
	Riemann-Roch th	eorem.										
	Serre duality.											
	Jacobian and Abe	elian varieties.										
	Riemannian biline	ear relations.										
	Jacobi inverse pro	blem.										
	Elliptic curves and	d functions.										
	J-invariant.											
	Uniformisation.	. =.										
	Topology of non-c	compact Riemann surfaces.										
Objectives	Students develop an approach to abstract surfaces and understand classification techniques based on local-to-global reasoning. In the concept of holomorphy, they grasp the principles of rigidity resulting from analytical properties. Using the concept of trenches, students see how fundamental questions naturally lead to increasingly abstract conceptualisations and how these can ultimately be used to answer questions. They learn how geometry and analysis are interrelated and in many cases mutually dependent. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. Students will be able to reflect and critically analyse the current state of research in the subject area.											

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Algebraic Curves and Riemannian Surfaces	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners. – The module may exceptionally be offered by the lecturer without exercise classes; in this case, only 6 credit points will be awarded for the module instead of 9.											
Literature	Exemplary Literature:											
	Frederice Mangolte: R	eal A	lgebr	aic \	/ariet	ies. Sp	oringer 2020).				
	Robert Silhol: Real Alg	ebrai	c Su	rface	es. S	oringer	1989.					
	Riccardo Benedetti, Je Editions Herrmann 199		acqu	ies F	Risler	: Rea	l Algebraic	and Semi-a	lgebra	ic Sets.		
	Alex Degtyarev, Viatch eties: du côté de chez							ties of real	algebr	aic vari-		
Transfer	The module belongs to the a Differential Geometry. Taking be included in the sections a Specialisation, in accordance The module cannot be taken to the large overlap in content.	into Study with toget	acco Foci the re	ount <i>us, A</i> estric	the c A <i>dvar</i> ctive	chosen nced K require	personal S inowledge in ements of th	tudy Špecia n <i>Mathemat</i> e respective	lisation ics or section	n, it can <i>Elective</i> on.		
Prerequisites	In terms of content, the course to function theory of ordinary							as well as ti	ne intro	duction		
Responsible Persons	Ivo Radloff											
Abbreviations: Grading System : g=graded, ng=not graded Examination Type : MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,												

Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=Seminar, IC=inverted classroom

: m=mandatory, o=optional Status

Module Number: MAT-50-30	Module Title: Geometric Group Theory Type of Module: Compulsory Module with Choice													
ECTS-Points	9						<u> </u>	•						
Workload - Time in Class - Self-Study	Workload: 270 h													
Duration	1 Semester													
Frequency	not regularly													
Term	1-3													
Language of Instruction	German or English													
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS													
Content	Content:													
	Group actions on graphs, free groups.													
	Quasi isometries.													
	Groth types.													
	Hyperbolic groups.													
	• Ends.													
Objectives	Students learn to explore profrom the Cayley graph of the of the Cayley graphs with the to the underlying group. Students about groups. The statements about groups results of the lecture as well in the exercise classes they the terms, statements and mon new problems, to analyst team. They are capable of prodiscourse.	e groune helpudents the information of the stragger as asserted as the median of the m	ip. To of a und-terfactudent session acquired to the control of th	They analy erstace of its an arred arred arche led	are a rtical and had a re cand exact a core	able to metho low alg ebra al apable plainin fident, e. They	investigateds and to vebra and a geometr of naming g the prese precise an have learn lution strate	the geome vork out the nalysis can y that leads and proving nted connect independent to transferies on the	etric proint consisted in the ections. The record in the r	operties nections together eresting essential adling of nethods or in a				
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade				
	Geometric Group Theory	L	f	4	6	yes	wr. o.	90-180	g	100				
		E	f	2	3	, , , ,	or.	o. 20-30	9					
	In this module an exercise context examination the coursework oral is decided by the instruction	must ł	nave	beer	n acc	uired.	Whether th	e examination						

Literature	Exemplary Literature:
	Clara Löh: Geometric Group Theory - an Introduction. Springer 2017.
	 Thorsten Camps, Volkmar Große Rebel, Gerhard Rosenberger: Einführung in die kom- binatorische und die geometrische Gruppentheorie. Heldermann Verlag 2008.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Hannah Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-40	Module Title: Gromov-Witten Theory Type of Module: Compulsory Module with Choice															
ECTS-Points	6															
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h															
Duration	1 Semester															
Frequency	not regularly															
Term	1-3															
Language of Instruction	German or English															
Forms of Teaching and Learning	Lecture 3 SWS + Exercise C	lass 1	SW	S												
Content	Content:															
	Enumerative geometr	у,														
	Moduli spaces of stab	ole curv	es,													
	Moduli spaces of stab	ole map	os,													
	 Universal families, 															
	Forgetful maps,															
	Cluing maps,															
	Gromov-Witten invariant	ants,														
	Computation of Grom	ov-Wit	ten i	nvari	ants,											
	 Divisor equations, 															
	Kontsevich's formula.															
Objectives	research field of Gromov-Wi understand important exam them as cut products on mod Gromov-Witten invariants. results of the lecture as well In the exercise classes they the terms, statements and m on new problems, to analyse	Students are based on their knowledge in Algebraic geometry introduced into the current research field of Gromov-Witten theory and enumerative geometry. The students know and understand important example classes of enumerative invariants and know how to present them as cut products on module spaces. Students master the basic algorithms for calculating Gromov-Witten invariants. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.														
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade						
	Gromov-Witten Theory	L	f	3	4,5	yes	wr. o. or.	90-180 o. 20-30	g	100						
		ertifica	te is	to be	e acq	uired a		In this module an exercise certificate is to be acquired as coursework. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.								

Literature	Exemplary Literature:
	 Joachim Kock, Israel Vainsencher: An invitation to quantum cohomology: Kontsevich's formula for rational plane curves. Birkhäuser 2007.
	 Ravi Vakil: The moduli space of curves and Gromov-Witten theory. Enumerative invariants in algebraic geometry and string theory. Lecture Notes in Mathematics, 1947. Springer 2008.
Transfer	The module belongs to the Study Specialisation Algebra and Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the module Algebraic Geometry is required.
Responsible Persons	Hannah Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-50-50	Module Title: Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic							of Module: ulsory Modu	le with	Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 180 h										
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SW	S							
Content	cepts of incidence and cong oped. After the introduction of end theory. An Euclidean fie	Content: Starting from a system of axioms for plane absolute geometry with the basic concepts of incidence and congruence, the associated Bachmann reflection geometry is developed. After the introduction of the hyperbolic axiom, this is continued with reflection-geometric end theory. An Euclidean field is created from the rotations around an end and the translations along a straight line, with the help of which the hyperbolic plane under consideration is described algebraically.									
Objectives	The students have learnt to I lute and hyperbolic planes) in particular, they have learn etry, which rarely appears in also deepened their knowled are able to name and prove the relationships presented. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	rom c t abou the cu dge of the ma have a ethod them	omplet Backerricularity the ain state acques of tand to the and the arms of th	etely chma um, intentatem atem ired a he le o wo	differnn's and the weaver the contents of the	erent po group- thus de ring of s of the nfident, e. They n solution	erspectives theoreticall epen their geometry a lecture and precise ar have learr on strategie	and to link ly oriented re knowledge o and algebra. d to categori and independened to transfe so on their ow	them to the	ogether. In geomos. They Students I explain	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic	Hyperbolic Geometry: Axiomatic, Reflection L f 4 6 yes wr. o. 90-180 g 1							100		
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.									
Literature	 Exemplary Literature: Friedrich Bachmann: Aufbau der Geometrie aus dem Spiegelungsbegriff. Springer 1959. Robin Hartshorne: Geometry: Euclid and beyond. Springer 2000. Helmut Karzel, Kay Sörensen, Dirk Windelberg: Einführung in die Geometrie. Vandenhoeck und Ruprecht 1973. 										

Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the geometry module is helpful but not required.
Responsible Persons	Hermann Höhl, Hannah Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-01	Module Title: Fuctional Analysis Type of Module: Compulsory Module with Choice											
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 90 h 180 h											
Duration	1 Semester											
Frequency	regelmäßig	regelmäßig										
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise 0	Lecture 4 SWS + Exercise Class 2 SWS										
Content	Content:	Content:										
	 Normed spaces, Ban Hahn-Banach theore Closed graph theorer Compact Operators, 	m, unifo	orm I	boun ppin	idedr	ness pr orem,	Banach-Ala	oglu theorer	m.			
Objectives	The students are aquainted dimensional spaces and car stand the complex of proble analytical problems. The stuthe lecture as well as assess in the exercise classes they the terms, statements and non new problems, to analysteam. They are capable of problems.	n apply ems of idents sing an have a nethods se then	ther spectare of the spectare	n to ctral capal plain ired he le d	probletheore	lems in and finaming presenting the presenting the present the pre	n analysis and can use its and providented connumber precise and practice and the control of the	nd geometry results for ing the esse ections. d independe ed to transfe egies on the e to argue fo	y. They the solution ential re ent har er the re eir own	under- lution of esults of adling of nethods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Functional Analysis	L	f	1 1 100						100		
	E f 2 3 yes o. H o. 20-30 9											
	examination the coursework	n this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.										

Literature	Exemplary Literature:
	Nicolas Bourbaki: Topological vector spaces. Springer 1987.
	 Adam Bowers, Nigel Dalton: An introductory course in functional analysis. Springer 2014.
	Harro Heuser: Funktionalanalysis. Teubner 2006.
	Markus Haase: Functional analysis. American Mathematical Society 2014.
	Peter D. Lax: Functional analysis. Wiley 2002.
	Gert Kjaergaard Pedersen: Analysis now. Springer 1995.
	Walter Rudin: Functional analysis. McGraw-Hill 1991.
	Dirk Werner: Funktionalanalysis. Springer 2011.
	Kosaku Yosida: Functional analysis. Springer 1995.
	Hans Wilhelm Alt: Lineare Funktionalanalysis. Springer 2012.
Transfer	The module belongs to the <i>Study Specialisations Analysis and Differential Geometry</i> and <i>Mathematical Physics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. In combination with one of the modules Numerics of Stationary Differential Equations or Numerics of Non-Stationary Differential Equations, it can be included in the study focus <i>Numerical Mathematics and Optimisation</i> .
Prerequisites	There are no prerequisites.
Responsible Persons	Carla Cederbaum, Anton Deitmar, Gerhard Huisken, Reiner Schätzle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

### Compulsory Module with Choice ### CTS-Points Workload	Module Number:	Module Title:							of Module:					
Workload	MAT-55-02	Non-Linear Functional Analy	sis					Сотр	ılsory Modu	le with	Choice			
Title Prequency 270 h 90 h 180 h 18	ECTS-Points	9	9											
Term	- Time in Class													
Term	Duration	1 Semester												
Lecture 4 SWS	Frequency	not regularly												
Content Content	Term	1-3												
Content Content: Differentiation and integration in Banach spaces. Compact, coercive, proper mappings and gradient mappings. Fredholm mappings. Continuity method. Degree of mapping. Fixed point theorems. Variational inequalities. Monotone operators. Students master the differentiation and integration of non-linear functions and various functional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title Non-Linear Functional Analysis Differentiation and integration in Banach spaces. Compact, coercive, proper mappings and gradient mappings. Predictional analysis and gradient mappi		German or English	German or English											
Differentiation and integration in Banach spaces. Compact, coercive, proper mappings and gradient mappings. Fredholm mappings. Continuity method. Degree of mapping. Fixed point theorems. Variational inequalities. Monotone operators. Students master the differentiation and integration of non-linear functions and various functional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title Non-Linear Functional Analysis Mon-Linear Functional L f 4 6 g yes wr. o. 90-180 g 100		Lecture 4 SWS												
Compact, coercive, proper mappings and gradient mappings. Fredholm mappings. Continuity method. Degree of mapping. Fixed point theorems. Variational inequalities. Monotone operators. Students master the differentiation and integration of non-linear functions and various functional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title Variational Varia	Content	Content:	Content:											
Fredholm mappings. Continuity method. Degree of mapping. Fixed point theorems. Variational inequalities. Monotone operators. Students master the differentiation and integration of non-linear functions and various functional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title Non-Linear Functional L f 4 6 0 0 0 0 0 0 0 0		Differentiation and int	egratio	n in	Bana	ach s	paces.							
Continuity method. Degree of mapping. Fixed point theorems. Variational inequalities. Monotone operators. Students master the differentiation and integration of non-linear functions and various functional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title Non-Linear Functional Analysis Analysis Non-Linear Functional Control of the method of the technical handling of the method of the problems in this field of research. Problems of the method of the technical handling of the method of the problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title Non-Linear Functional Analysis Degree of mapping. Problems of non-linear functions and various functional infinite functions and various functions and various functions and various functions in finite functio		Compact, coercive, p.	roper m	парр	ings	and	gradie	nt mappings	S.					
Degree of mapping. Fixed point theorems. Variational inequalities. Monotone operators. Students master the differentiation and integration of non-linear functions and various functional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title Non-Linear Functional Analysis Analysis Population of non-linear functions and various functions and various functions and various functions and various functions. In the exemption in infinite-dimensional spaces. The students are equations in infinite dimensional spaces. The students are equations in i		Fredholm mappings.												
Fixed point theorems. Variational inequalities. Monotone operators. Students master the differentiation and integration of non-linear functions and various functional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title Non-Linear Functional Analysis Pixed point theorems. Students master the differentiation and integration of non-linear functions and various functions and integration of non-linear functions and various functions in infinite-dimensional spaces. The students assessed in the security of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title Non-Linear Functional Analysis Pixed point in figure functions and integration of non-linear functions and various functions in infinite-dimensional spaces. The students in figure functions in infinite-dimensional spaces		Continuity method.												
Variational inequalities. Monotone operators. Students master the differentiation and integration of non-linear functions and various functional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title Non-Linear Functional Analysis Analysis Analysis Analysis Students master the differentiation and integration of non-linear functions and various functions and integration of non-linear functions and various functions in infinite-dimensional paces. The students of the lecture as well as assessing and various functions in infinite-dimensional paces. The students of the lecture as well as assessing and various functions. Title Analysis Analysis Page 4 4 6 6 6 6 6 6 6 7 7 7 7 7 7 7 7 7 7 7		Degree of mapping.												
Students master the differentiation and integration of non-linear functions and various functional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title		Fixed point theorems.												
Students master the differentiation and integration of non-linear functions and various functional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title		Variational inequalitie	s.											
tional analytical methods for solving non-linear equations in infinite-dimensional spaces. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes, students have acquired confidence in the technical handling of the methods they have learnt and can apply them independently to other problems. They are able to present their problem solutions and participate in discourses on problems in this field of research. Requirements for Obtaining Credit, Grading, Weight if applicable Title		Monotone operators.												
	Objectives	tional analytical methods for students are capable of nar assessing and explaining the In the exercise classes, stu- methods they have learnt an to present their problem sol	solving ming are prese dents h d can a	g nor nd p nted nave apply	n-line rovir I con acq ther	ear e ng the necti uired m ind	quatione esse ons. confid	ns in infinite ntial results lence in the ently to othe	-dimensiona of the lect technical her problems.	al spac ure as nandlin They	es. The well as g of the are able			
analysis ü f 2 3 or. 0. 20-30	for Obtaining Credit, Grading, Weight if	Non-Linear Functional	+					wr. o.	90-180					
examination the coursework must have been acquired. Whether the examination is written or		In this module an exercise c	ertificat	te is	to be	acq	uired a	s coursewo	rk. For part	 icipatio	n in the			

Literature	Exemplary Literature:
	Melvyn Berger: Nonlinearity in Functional Analysis. Elsevier 1977.
	Klaus Deimling: Nonlinear Functional Analysis. Springer 1985.
	Eberhard Zeidler: Nonlinear Functional Analysis and its Applications I. Fixed-Point Theorems. Springer 1986.
Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	The Integration and Measurement Theory module and the Functional Analysis module must have been successfully completed.
Responsible Persons	Reiner Schützle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-03	Module Title: Type of Module: Operator Theory Compulsory Module with Choice												
ECTS-Points	9						·						
Workload - Time in Class - Self-Study	Workload: 270 h												
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German or English	German or English											
Forms of Teaching and Learning	Lecture 4 SWS	Lecture 4 SWS											
Content	Content:												
	Operator semigroups	and at	ostra	ct Ca	auchy	/ probl	ems.						
	Theorem of Hille-Yos	ida.											
	Applications of concre	ete evo	lutio	n eq	uatio	ns.							
	Spectral theory of ser	migrou	ps ar	nd th	eir ge	enerato	ors.						
	Asymptotic of semigroup	oups.											
	Applications:												
	Semigroups ofSemigroups of					differer	itial equatio	ns;					
	- Semigroups of	-			1113,								
Objectives	Students have understood the able to deal with concrete everyosedness using the Hille-Y. The students are capable of assessing and explaining the lin the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	olution osida the naming present the naming and the name	equal heore g and ented acqui s of the	ations em a d pro l con ired a he le o wo	s in that do not ind do not ind do not ind do not ind do not indicate the second second do not indicate the second do not indicate indicate the second do not indicate the second do no	nis abs iscuss the est ons. nfident, e. They solution	tract form. The qualitate sential resurprecise and have learn on strategies.	They are ablorive behavior lts of the lecond independent to transfers on their owners in critical control of the control of th	e to pro ur of so ture as ent har er the r n or in	ove well- plutions. s well as adling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Umber of the large of									100			
	In this module an exercise c examination the coursework oral is decided by the instruc	must h	nave	beei	n acc	uired.	Whether th	e examination					

Literature	Exemplary Literature:
	Bruce Blackadar: Operator algebras. Springer 2006.
	 Klaus Jochen Engel, Rainer Nagel: One-parameter semigroups for linear evolution equations. Springer 2000.
	 Klaus Jochen Engel, Rainer Nagel: A short course on operator semigroups. Springer 2006.
	Gert Pedersen: Analysis now. Springer 1995.
Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	The content of the Functional Analysis module is prerequisite for participation in this module.
Responsible Persons	Anton Deitmar, Rainer Nagel, Reiner Schützle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-04	Module Title: Operator Algebras Type of Module: Compulsory Module with Choice								
ECTS-Points	9								
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h						
Duration	1 Semester								
Frequency	not regularly								
Term	1-3								
Language of Instruction	German or English								
Forms of Teaching and Learning	Lecture 4 SWS								
Content	Content:								
	 Spectral theory in Ba Commutative Banac Gelfand-Naimark. The spectral theorem Operator topologies a Kaplansky's density t Von Neumann algebra struction of examples The axiomatics of C* 	spaces and their spectral proposed algebras. h algebras and the representation of a Hilb and von Neumann's bicommutation heorem. as and their classification according to the space of th	entation theorem of Gelfand and pert space. ant theorem. rding to Murray-von Neumann, con-						
	Applications and outle	•	m of Sakai for W^* -algebras.						
Objectives	The students have familiarised themselves with the central concepts, results and methods of the theory of operator algebras. They have learnt the interplay between algebra and topology using the example of von Neumann algebras and their classification. The students also recognise how taking a higher point of view, i.e. the axiomatic nature of the problem, allows different questions to be dealt with and solved simultaneously. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.								

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Operator Algebras	L ü	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.										
Literature	Bruce Blackadar: Oper Ola Bratelli, Derek Rob Richard Kadison, John IV. AMS 1997. Gert Pedersen: Analys Shoichiro Sakai: C*- a Masamichi Takesaki: T	inson Ring is no W	: Op rose w. Sp *-Alo	erato : Fur pring	or Alg ndam er 19 as. S	gebras nentals 995. Springe	and Quantu of the Theo r 1998.	ry of Operat			
Transfer	The module belongs to the Steematical Physics. Taking into included in the sections Study cialisation, in accordance with	acc Foc	ount <i>us</i> , <i>P</i>	the Idvai	chos nced	en per Knowl	sonal Study edge in Mai	/ Specialisa thematics or	tion, it <i>Electi</i>	can be	
Prerequisites	The content of the Functional	Anal	ysis r	nodı	ule is	prerec	quisite for pa	articipation i	n this r	nodule.	
Responsible Persons	Ulrich Groh, Rainer Nagel										
Abbreviations: Grading System : g	=graded, ng=not graded								· ·		

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, } \mbox{LE=lecture with integrated exercises, } \mbox{SL=seminar or lecture, } \mbox{E=exercise class, } \mbox{T=tutorial, P=project, S=Seminar, IC=inverted classroom}$

Status : m=mandatory, o=optional

Module Number:	Module Title:									01 :			
MAT-55-05	Ergodic Theory						Сотри	Ilsory Modu	e with	Choice			
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	•		Self-St 180 h	udy:					
Duration	1 Semester						'						
Frequency	not regularly												
Term	1-3												
Language of Instruction	German or English												
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS												
Content	Content:												
	Topological and measure-theoretical dynamical systems.												
	Recurrence and mixing properties.												
	Ergodic theorems of von Neumann and Birkhoff.												
	Spectral theory of the	Koopr	man	oper	ator.								
	Operators with discre	te spe	ctrun	n (Ha	almos	s-von N	leumann)						
	Applications in stocha	ıstics a	ınd n	iumb	er th	eory.							
Objectives	The students have familiaris of ergodic theory. They have and topology using the example and topology using the example and topology using the example and topology. The students are cape well as assessing and explain the exercise classes they the terms, statements and more on new problems, to analyse They are able to present the	ve expended exples it possible of ning the have a tethods	erien dyn ssible nam ne pre acqui s of t	nced amic e to ning esen ired he le o wo	the part system of the part of	orofour ems a with a proving connec onfident, e. They a solution	nd interplay and their class and solve va the essentitions. precise and have learned on strategies	between messification. It is proble it is proble it is a results of the independent of the independent is on their own.	easure The fur ms sin the lecent han er the n	e theory nctional- nultane- cture as adling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Ergodic Theory	T Type of Course B Status B SWS B ECTS Assignments Type of Exam OBL: of Exam Grading					Weight for Grade						
	In this module an exercise of	E	f to is	2 to b	3	yes	Or.	o. 20-30	g				
	examination the coursework oral is decided by the instruc	must h	nave	bee	n acc	uired.	Whether the	e examination					

Literature	Exemplary Literature:
	 Manfred Einsiedler, Thomas Ward: Ergodic Theory with a View Towards Number Theory. Springer 2011.
	 Tanja Eisner, Balint Farkas, Markus Haase, Rainer Nagel: Operator Theoretic Aspects of Ergodic Theory. Springer 2015.
	Paul Halmos: Lectures on Ergodic Theory. Martino Fine Books 2013.
	Marcelo Viana, Krerley Oliveira: Foundations of Ergodic Theory. CUP 2016.
Transfer	The module belongs to the Study specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	The content of the Functional Analysis module is Prerequisite for participation in this module.
Responsible Persons	Rainer Nagel
Abbreviations:	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-06	Module Title: Control Theory		of Module: ulsory Modul	le with	Choice								
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German or English	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS												
Content	Content:	Content:											
	 Introduction to finite-dimensional linear control systems with examples from mechanics. Controllability, observability, stabilisability. Kalman criterion. Feedback systems. Stabilisability through feedback. Examples. Introduction to infinite-dimensional control theory. Mathematical framework and examples. 												
Objectives	The students learn importa They are able to use the trare capable of naming and and explaining the presented in the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	eory in proving documents to connect the have a them a them a	n are the ection acqui s of the	eas on easons. It is in the leasons to the leasons	of appentiant of appendix of a	olication I resultificant, e. They solution	n such as its of the led precise an have learn on strategies	mechanics. cture as well d independe ed to transfe s on their ow	The solution I have as	students sessing adling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Control Theory	L E	f f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100			
	In this module an exercise c examination the coursework oral is decided by the instruc	must h	nave	bee	n acc	uired.	Whether th	e examination					

Literature	Exemplary Literature:								
	Hans W. Knobloch: Lineare Kontrolltheorie. Springer 1985.								
	 Hans W. Knobloch, Alberto Isidori, Dietrich Flockerzi: Topics in control theory. Birkhäuser 1993. 								
	 Jerzy Zabczyk: Mathematical Control Theory. Birkhäuser 1992. 								
	Rurth F. Curtain, Hans Zwart: An Introduction to Infinite Dimensional Systems Theory. Springer 1995.								
Transfer	The module belongs to the <i>Study Specialisation Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.								
Prerequisites	There are no further prerequisites.								
Responsible Persons	Rainer Nagel								
Abbreviations: Grading System : g	Abbreviations: Grading System : g=graded, ng=not graded								

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-07	Module Title: Linear Control Theory							of Module: ulsory Modu	le with	Choice	
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass			Self-St 120 h	udy:			
Duration	1 Semester						·				
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS										
Content	Mathematical methods are indispensable for the management and control of complex systems and processes. The underlying theory is not only fascinating due to its diverse applications, but also, in its abstract form, due to the clarity and elegance of its methods and results. In this lecture, finite-dimensional systems are dealt with first, for which a good knowledge of analysis and linear algebra is sufficient. The aims are Kalman's controllability criterion and the resulting criteria for stabilisability. If there is enough time, we will extend the theory to infinite-dimensional systems. In the exercise classes we will apply the theory to concrete examples.										
Objectives	rienced and understood the in analysis and their benefits fo proving the essential results connections. Students will be in the subject area. In the exercise classes they the terms, statements and me	In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Linear Control Theory	L	f	2	3	yes	wr. o.	90-180	g	100	
		Е	f	2	3	,00	or.	o. 20-30	9	100	
	In this module an exercise ce examination the coursework oral is decided by the instruct	must l	nave	beer	acc	uired.	Whether the	e examination			
Literature	Exemplary Literature:										
	Hans Wilhelm Knobloo	h, Hu	ibert	Kwa	kerr	naak: L	ineare Kont	rolltheorie. S	Springe	er 1985.	
	Jerzy Zabczyk: Mathe	matic	al Co	ntrol	The	ory. Bi	khäuser 19	92.			
	Ruth F. Curtain, Hans Springer 1995.	Zwar	t: An	Intro	oduc	tion to	Infinite-Dim	ensional Sy	stems	Theory.	

Transfer	The module belongs to the <i>Study Specialisation Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge of the modules analysis and linear algebra is sufficient.
Responsible Persons	Rainer Nagel

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-08	Module Title: Spectral Theory of Positive C	perat	ors					of Module: ulsory Modu	le with	Choice	
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass	•		Self-St 120 h	udy:			
Duration	1 Semester						·				
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS										
Content	Content: Starting from the classical theorems of Perron and Frobenius on the spectrum of positive matrices, positive linear mappings to C^* - and W^* -algebras and their spectral and algebraic properties are analysed. The ergodic properties of these operators, i.e. the convergence of powers and means, can then be derived from these. We then discuss the generalisation to operator semigroups. Applications of the theory can be found in mathematical physics, among others.										
Objectives	Students learn the basic spectral properties of positive operators on C^* - and W^* -algebras and the connections with non-commutative ergodic theory. In the seminar following the lecture, students can work on topics that lead to a Master's thesis. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. Students will be able to reflect and critically analyse the current state of research in the subject area.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Spectral Theory of Positive Operators	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is Board of Examiners. – The ercise classes; in this case, 5.	writtei modul	e ma	ау ех	cept	ionally	be offered	by the lectu	rer witl	nout ex-	
Literature	Exemplary Literature:										
	Tanja Eisner, Markus Theory. Springer 2015		e, Ra	ainer	Naç	gel : O	perator The	eoretic Aspe	cts of	Ergodic	
	Ulrich Groh: Spectral Preprint.		ry of	Con	nplet	ely Pos	sitive Maps	on C^st - and	W*-A	lgebras.	
Transfer	The module belongs to the Si ematical Physics. Taking int included in the sections Studicialisation, in accordance with	o acc ly Foc	ount <i>us</i> , <i>F</i>	the I <i>dval</i>	chos nced	en per Knowl	sonal Stud <i>edge in Ma</i>	y Specialisa <i>thematics</i> o	tion, it r <i>Electi</i>	can be	
Prerequisites	Knowledge from functional ar	nalysis	s and	l ope	rato	algeb	ras is assur	ned.			

Responsible Persons	Ulrich Groh, Rainer Nagel
Abbreviations:	
Grading System : g	=graded, ng=not graded
Examination Type : M	IT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio
	=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, =tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional
Other : h=hours, o.=or, s.M.=see module description, SWS=contact hours per week

Module Number: MAT-55-09	Module Title: Non-Commutative Ergodic T	heory						Type of Module: Compulsory Module with Choice				
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-S 180 h	tudy:				
Duration	1 Semester											
Frequency	not regularly	not regularly										
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS											
Content	Content: Firstly, the essential basic concepts and properties of C* and W* algebras are introduced and discussed. Then, based on commutative theory, non-commutative dynamical systems are defined. With the help of the so-called cross products it is then shown how such non-commutative dynamical systems can be characterised with the help of the group representation. The significance in mathematical physics is always emphasised.											
Objectives	The students have learnt the central concepts, results and methods of non-commutative ergodic theory, i.e. of dynamical systems on operator algebras. They have experienced the fascinating interplay between the structure of von Neumann algebras and the (asymptotic and spectral-theoretical) behaviour of operators on these algebras. The students realised how an axiomatic and structural point of view makes it possible to treat and solve different problems simultaneously. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.											
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Non-Commutative Ergodic Theory	L ü	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	nave	bee	n acc	uired.	Whether th	ie examinatio				
Literature	Exemplary Literature:											
	Tanja Eisner, Balint Fa of Ergodic Theory. Sp	ringer	201	5.			-	Operator The	oretic	Aspects		
	Bruce Blackadar: Ope Alai Quialandata Qualit		_		-	_		-14.d		\ 7 .4		
	Alai Guichardet: System Distance of Free Lating		-					sterisque 13	-14 19	9/4.		
	Dirk Werner: Funktion Volker Runde: A Taste		-		_							
	Volker Runde: A Taste	; UI 10	μοιο	yy. S	bhi ii lé	yei ∠00						

Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Good knowledge of functional analysis and basic knowledge of topology. Interest in mathematical quantum mechanics.
Responsible Persons	Rainer Nagel

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-10	Module Title: Pseudo Differential Operator	S						of Module: ulsory Modu	le with	Choice			
ECTS-Points	3												
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	lass	:		Self-Study: 120 h						
Duration	1 Semester						'						
Frequency	not regularly												
Term	1-3												
Language of Instruction	German or English												
Forms of Teaching and Learning	Lecture 2 SWS												
Content	Content:												
	Fourier transform and Sobolev spaces.												
	Pseudodifferential operators on manifolds.												
	Finite propagation velocity.												
	Fredholm operators a	nd elli _l	ptic c	comp	lexes	S .							
	The heat conduction I	kernel	and	the l	ocal i	index t	heorem.						
	The Atiyah-Bott-Pator	di theo	rem.										
	Von Neumann algebra	as and	l repi	eser	ntatio	ns.							
	The L2 index theorem	l.											
Objectives	Students learn basic techni geometry. They will unders and how both merge into the the transition from one to the will be able to use theoretica will learn to use modern app The students are capable or as assessing and explaining critically analyse the current	tand to more other al approached naming the processing the processing transport of the	he congression of the congressio	onne eral Its in nes to L2 th nd p nted	ection calcu solu o sol neory rovin conr	tion ted tion ted ve spe to pro g the en nection	een differen pseudo-diffe chniques for cific probler ve deep gro essential res s. Students	tial and interemential oper differential ones in concrept theoretics of the	egral operators a equation ete cas cal stat lecture	perators and how ons. You es. You ements. as well			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Pseudo Differential Operators	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100			
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	cided	by the instr	uctor with a	pprova	I by the			

Literature	Exemplary Literature:
	 Peter B. Gilkey: Invariance theory, the heat equation, and the Atiyah-Singer index theorem. Publish or Perish 1984.
	 Wolfgang Lück: L2-invariants: theory and applications to geometry and K-theory. Springer 2002.
	Michael Taylor: Pseudo differential operators. Springer 1974.
	Man-Wah Wong: An introduction to pseudo-differential operators. World Scientific Publishing 2014.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the module Functional Analysis is assumed.
Responsible Persons	Anton Deitmar
Abbroviations	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-11	Module Title: Introduction to Harmonic Ana	alysis						of Module: ulsory Modul	le with	Choice	
ECTS-Points	9						,				
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	•		Self-St 180 h	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	1-3									
Language of Instruction	German	German									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS									
Content	Content:										
	Fourier series and Fo	urier tr	ansf	orma	tion.						
	Plancherel theorem a	nd inve	erse	theo	rems	i.					
	Poisson summation for	rmula									
	tempered distributions	3.									
	Additionaly a selection	n of the	e foll	owin	g top	ics will	be covered	l:			
	- LCA groups;	tranaf	0 K 100 G	+i o o ı							
	general Fouriernon-abelian gro					ions:					
	Sobolev-spaces	-	10 10	pics	Cintat	.10113,					
	Singular integra										
	Poisson integra	ls.									
Objectives	Students can combine algebrate They recognise the interplay and can apply the knowledg theory. They understand the into various function spaces results of the lecture as well in the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	betwee e gain intera . The as ass have a thods	een the ed from the control of the c	he prom to of gents and an ired and ire	roper his to group are on the condition of the condition	ties of quest theory capable plaining the pl	functions are tions in phy and analy of naming g the prese precise an have learn on strategies	nd their Four sics, analys sis and gain and proving nted connect d independent ed to transfers on their ow	rier trainis and a deep of the ections. The rections or the rection or in	nsforms number insights ssential adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Introduction to Harmonic	Type of Course	Status	SMS 4	e ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Analysis	E	f	2	3	yes	wr. o. or.	o. 20-30	g	100	
	In this module an exercise or examination the coursework oral is decided by the instruc	ertifica must h	nave	to be	e acq	uired.	Whether th	e examination			

Literature	Exemplary Literature:
	Anton Deitmar: A first course in harmonic analysis. Springer 2005.
	 Elias M. Stein: Singular integrals and differentiability properties of functions. Princeton University Press, 1970.
	Elias M. Stein, Guido Weiss: Introduction to fourier analysis on euclidean spaces. Princeton University Press 1971.
Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	The content of the Functional Analysis module is prerequisite for participation in this module.
Responsible Persons	Anton Deitmar

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-12	Module Title: Harmonic Analysis in Euclide	ean Sp	oace					of Module: ulsory Modu	le with	Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 90 h 180 h										
Duration	1 Semester	1 Semester									
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	German	àerman									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ecture 4 SWS + Exercise Class 2 SWS									
Content	Content:										
	Fourier transformation	٦.									
	Covering-, decompos	ition- a	and ir	nterp	olatio	on the	orems.				
	Singular integrals, Po	isson i	nteg	rals.							
	Hardy- and BMO-spa	ces, m	ultip	lier th	neore	ems, Li	ttlewood-Pa	lley theory.			
Objectives	The students got to know to euclidean space. The student lecture as well as assessing In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	nts are and ex have a ethoda them	capa xplain acqu s of t and t	able ning ired a he le o wo	of na the p a cor cture rk on	ming a resent ofident e. They o solution	and proving ed connecti precise an have learn on strategie	the essential ons. d independe ed to transfes on their ow	I resultent hare er the r	ndling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course Status SWS ECTS Assignments Type of Exam Dur. of Exam (min)						Grading	Weight for Grade		
	Harmonic Analysis in	L	f	4	6	yes	wr. o.	90-180	g	100	
Euclidean Space E f 2 3 or. o. 20-30								9			
	In this module an exercise or examination the coursework oral is decided by the instruc	must l	have	beei	n acc	uired.	Whether th	e examination			

Literature	Exemplary Literature:
	• Charles L. Feffermann, Elias M. Stein: ${\cal H}^p$ spaces of several variables. Acta Mathematica 129, pp. 137-193, 1972.
	 Christopher D. Sogge: Fourier integrals in classical analysis. Cambridge University Press 2017.
	 Elias M. Stein: Singular integrals and differentiability properties of functions. Princeton University Press 1970.
	Elias M. Stein: Harmonic analysis. Princeton University Press 1993.
	Elias M. Stein, Guido Weiss: Introduction to Fourier analysis on Euclidean spaces. Princeton University Press 1971.
Transfer	The module belongs to the <i>Study Specialisation Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, the modules functional analysis and introduction to harmonic analysis are a prerequisite for participation in this module.
Responsible Persons	Reiner Schützle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-13	Module Title: Harmonic Analysis on Abelia	n Gro	ups					of Module: ulsory Modul	le with	Choice			
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	Self-Study: 180 h					
Duration	1 Semester												
Frequency	not regularly	not regularly											
Term	1-3												
Language of Instruction	German												
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Cl	ecture 4 SWS + Exercise Class 2 SWS											
Content	Convolution algebras,	 Content: Locally compact groups, existence and uniqueness of Haar algebras. Convolution algebras, Banach algebras, the Gelfand-Neumark theorem. LCA groups, Pontryagin duality, Plancherel theorem, structure theory of LCA groups. 											
Objectives	monic analysis and know ho topological/analytical/geomet braic structures such as C^* -cories. The students are capa well as assessing and explain the exercise classes they the terms, statements and more topological structures.	The students have become familiar with the central concepts and methods of abstract harmonic analysis and know how to use them. They have understood the connection between topological/analytical/geometric concepts such as LCA groups and their expression in algebraic structures such as C^* -algebras and are able to apply this way of thinking to other theories. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team.											
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Harmonic Analysis on Abelian Groups	L E	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100			
	In this module an exercise ce examination the coursework oral is decided by the instruct	must l	nave	bee	n acc	uired.	Whether th	e examination					
Literature	Anton Deitmar: A first Anton Deitmar, Siegfri Edwin Hewitt, Kenneth Walter Rudin: Fourier	ed Ec	hterh	noff: strac	Princ	ciples o	f Harmonic analysis. V	Analysis. S					

Transfer	The module belongs to the <i>Study Specialisation Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, the module functional analysis is a prerequisite for participation in this module.
Responsible Persons	Anton Deitmar

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-14	Module Title: Harmonic Analysis on Gener	al Gro	ups					of Module: ulsory Modul	le with	Choice	
ECTS-Points	9						·				
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	3							
Content	Representation theory	Content: • Representation theory of compact groups, Peter-Weyl theorem. • Representation theory of general groups. • trace formula and applications to the Heisenberg group and $SL_2(\mathbb{R})$.									
Objectives	The students have familiarise harmonic analysis and know understand its far-reaching is are capable of naming and pand explaining the presented in the exercise classes they the terms, statements and mon new problems, to analyse They are able to present their	how mplica proving connection to the connection	to us tions the ection acqui s of t and t	se the se the se essens. I red a he le o wo	em. so for entia a cor ecture rk or	They I r other al result offident, e. They n solution	nave maste areas of m is of the lec precise an have learn on strategies	red the trace athematics. Sture as well dindependent to transfers on their ow	e form The s I as as ent har er the r on or in	ula and students sessing adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Harmonic Analysis on General Groups	L E	f f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise ce examination the coursework oral is decided by the instruc	must h	nave	beei	n acc	quired.	Whether th	e examinatio			
Literature	Anton Deitmar, Siegfri Gerald B. Folland: A cenatics. Boca Raton Michael E. Taylor: Nor	ourse 1995.	in al	ostra	ct ha	armonio	analysis. S	Studies in Ad			

Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, the module harmonic analysis on abelian groups is a prerequisite for participation in this module.
Responsible Persons	Anton Deitmar

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, } \mbox{LE=lecture with integrated exercises, } \mbox{SL=seminar or lecture, } \mbox{E=exercise class, } \mbox{T=tutorial, P=project, S=Seminar, IC=inverted classroom}$

Status : m=mandatory, o=optional

Module Number: MAT-55-15	Module Title: Selected Chapters from Ope	rator 7	Γheo	ry				of Module: ulsory Modu	le with	Choice		
ECTS-Points	9						·					
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS										
Content	Content:	Content:										
	Spectral theory of restricted and unrestricted linear operators, especially spectral calculus.											
	Spectral theory of positive operators – Perron-Frobenius theory.											
	Spectral theory for op	Spectral theory for operators of ergodic theory.										
Objectives	Students master the concept lus. They can then apply this behaviour. They are also a such as stochastics, ergodic and proving the essential resented connections. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	to cor ble to theor sults of have a ethod them	reco ry or of the acqu s of t	e ope gnise num lect ired ired he le o wo	erato e cro ber t ure a co ecture rk or	rs and oss-con theory. as well offident, e. They notice the control of the contro	discuss pro nections to The studer as assessing precise and have learn on strategies	perties such other math other math other math other math other math other math other such as the such that independed to transfers on their ow	as asy ematicable of aining ent har er the r	Imptotic al fields naming the pre- ndling of methods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Selected Chapters from Operator Theory	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise context examination the coursework oral is decided by the instruc	ertifica must l	te is	to be	e acc	quired.	Whether th	e examination				
Literature	Exemplary Literature:											
	Klaus Jochen Engel, equations. Springer 2 Markus Haase: The F	000.										

Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Solid knowledge of operator theory, in particular Hille-Yosida theory for operator semigroups is a prerequisite.
Responsible Persons	Rainer Nagel

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title:							of Module:				
MAT-55-21	Introduction to Partial Differe	ential E	quat	tions			Compi	ulsory Modu	le with	Choice		
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		Class	:		Self-Si 180 h	tudy:				
Duration	1 Semester											
Frequency	regelmäßig	egelmäßig										
Term	1-3	-3										
Language of Instruction	English	English										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ecture 4 SWS + Exercise Class 2 SWS										
Content	Content:											
	Harmonic functions.											
	Maximum principles.											
	Sobolev spaces.											
	• L^2 theory.											
	Important examples (Laplac	e eq	uatio	n, wa	ave eq	uation, hea	t equation).				
	Fundamental solution	ıs (ellip	otic s	ituati	ion).							
	weak solutions of ellip	otic eq	uatio	ns.								
Objectives	The students got to know a mental for many fields, like strong connections to geom central terms, results and m these methods in advanced central results of the lecture In the exercise classes they the terms, statements and m on new problems, to analysteam. They are capable of p discourse.	numer etry, a ethods cours as wel have a nethods e ther	ics of less of less. If as acques of the an	or stome sue inear The asse ired to do to	chas of the part stude ssing a cor ecture work	tics. A e lectu ial diffe ents ar g and e nfident, e. They c on so	Iso evolution in the studerential equipment of the capable of the	enary equation dents are a ations and a ations and a continuation of naming a le presented independent transferegies on the e to argue for the continuation of the con	ons, who can a common to the conner of the c	no have ted with e to use ving the actions. adling of nethods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Introduction to Partial Differential Equations	L E	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise c examination the coursework oral is decided by the instruc	must l	have	bee	n acc	uired.	Whether th	e examinati				

: m=mandatory, o=optional

Status

Other

Literature	Exemplary Literature:
	Lawrence C. Evans: Partial differential equations. American Mathematical Society 2010.
	 David Gilbarg, Neil S. Trudinger: Elliptic partial differential equations of second order. Springer 2001.
	 Olga A. Ladyzenskaja, Vsevolod A. Solonnikov, Nina N. Uralceva: Linear and quasilinear equations of parabolic type. AMS 1968.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. In combination with one of the modules Numerics of Stationary Differential Equations or Numerics of Non-Stationary Differential Equations, it can be included in the study focus Numerical Mathematics and Optimisation.
Prerequisites	There are no further prerequisits.
Responsible Persons	Gerhard Huisken, Reiner Schätzle
Abbreviations:	
Grading System : g	=graded, ng=not graded
Examination Type : M	IT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio
Teaching Format : L	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, etutorial, P=project, S=Seminar, IC=inverted classroom

Module Number:	Module Title: Partial Differential Equations Type of Module: Compulsory Module with Choice									Chaine		
							Compt	lisory Modul	ie with	Choice		
ECTS-Points	9						<u> </u>					
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	•		Self-St 180 h	udy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS											
Content	Content:											
	Schauder estimates.											
	Calderon-Zygmund es	stimate	es.									
	Harnack's inequality.											
	Hölder regularity.											
	Viscosity solutions.											
	Existence of solutions	accor	rding	to P	erron	۱.						
	Evans-Krylov theoren	1.										
Objectives	After the students have learn ferential Equations, this know to current research question results of the lecture as well in the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	wledges. The as ass have a ethods them a	e is of sessing the sessing th	deep dents ng a ired the le	ened are nd ex a cor ecture rk on	. Stud capabl plainin fident, e. They solution	ents are pro e of naming og the prese precise and have learnd on strategies	epared for a and proving nted conned d independe ed to transfe s on their ow	and into g the e ctions. ent har er the n	roduced ssential adling of nethods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Partial Differential Equations	L	f	4	6	yes	wr. o.	90-180	g	100		
	- Salas Emoroniai Equations	ü	f	2	3	,55	or.	o. 20-30	9	100		
	In this module an exercise context examination the coursework oral is decided by the instruction	must l	have	bee	n acc	uired.	Whether the	e examinatio				

Literature	Exemplary Literature:
	 Luis Angel Caffarelli, Xavier Cabre: Fully nonlinear elliptic equations. American Mathematical Society 1995.
	 Michael G. Crandall, Hitoshi Ishii, Pierre-Louis Lions: User's Guide to Viscosity Solutions of second Order Partial Differential Equations. Bulletin of the American Mathematical Society 27, No. 1, pp. 1-67, 1992.
	 David Gilbarg, Neil S. Trudinger: Elliptic partial differential equations of second order. Springer 2001.
	Olga A. Ladyzenskaja, Vsevolod A. Solonnikov, Nina N. Uralceva: Linear and quasilinear elliptic equations.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. In combination with one of the modules Numerics of Stationary Differential Equations or Numerics of Instationary Differential Equations, it can be included in the specialisation Numerical Mathematics and Optimisation.
Prerequisites	The content of the module introduction to partial differential equations is a prerequisite for the participation in this module.
Responsible Persons	Gerhard Huisken, Reiner Schützle
Abbreviations:	-araded na-not graded

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-24	Module Title: Nonlinear Elliptic Partial Diffe Surface Theory	erentia	l Equ	uatio	ns in	Minim		of Module: ulsory Modul	le with	Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS									
Content	Content: The course will consider PDE aspects of minimal surfaces, beginning with the existence theory for minimal graphs with prescribed boundary data. Emphasis will be placed on the De Giorgi-Nash estimate, which is one of the key achievements of 20th Century mathematics, and is foundational in the study of quasilinear elliptic and parabolic equations. We will also explore connections between minimal surfaces and the Allen-Cahn equation, which is a semilinear equation arising in the theory of phase transitions. Here the focus will be on rigidity results for entire solutions (namely the Bernstein problem and closely related De Giorgi conjecture) and their use in proving regularity via rescaling.										
Objectives	The students obtain an adva understanding of connection will acquire an array of new on objects governed by nonl applications of Sobolev theorem Moser iteration, and the use and when these techniques prove the essential statement developed in the lecture and critically challenge the currer In the exercise classes they the terms, statements and mon new problems, to analysteam. They are capable of produced the discourse.	s betwood techninear of the control	veen nique differ caling cond condition it in a condition it in a condition in a	this es for ential grand to a cepts ired a he led do to	theory estail equal compity for a second large archinacture work	y and ablishing attions apactner rmulae given and the lear frammen the shifted and the shifted	profound programments of the profession of the p	roblems in grive and quathniques inclints, Stampas will be abled as to explay are abled to independed to transfered to transfered on the	eometrilitative ude acchia ir e to a e to na ain the o descripent har er the reir own	ry. They control dvanced teration, ssess if me and context ribe and adling of nethods or in a	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Nonlinear Elliptic Partial Differential Equations in Minimal Surface Theory	ш г Type of Course	t Status	SMS 4	S B ECTS	Assignments	wr. o. or.	On: 06 Exam (min) 90-180 0. 20-30	ص Grading	Weight for Grade	
	In this module an exercise context examination the coursework oral is decided by the instruction	must l	nave	bee	n acc	uired.	Whether th	e examination			

Literature	Exemplary Literature:
	Lawrence C. Evans: Partial Differential Equations. AMS 2010.
	 David Gilbarg, Neil Trudinger: Elliptic partial differential equations of second order. Springer 1083.
	 David Kinderlehrer, Guido Stampacchia: An introduction to variational inequalities and their applications. Siam 2000.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basics of linear elliptic PDE (Schauder theory, existence for Dirichlet problem) are desirable but not completely necessary.
Responsible Persons	Gerhard Huisken

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{ Teaching Format : L=lecture, \ LE=lecture \ with \ integrated \ exercises, \ SL=seminar \ or \ lecture, \ E=exercise \ class, \ T=tutorial, \ P=project, \ S=Seminar, \ IC=inverted \ classroom }$

Status : m=mandatory, o=optional

Module Number: MAT-55-25	Module Title: Introduction to Partial Differen	Module Title:Type of Module:Introduction to Partial Differential Equations – Part 1Compulsory Module with Choice										
ECTS-Points	5											
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 150 h 45 h 105 h											
Duration	1 Semester	1 Semester										
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 1 SWS											
Content	Content:	Content:										
	Harmonic functions.	Harmonic functions.										
	Maximum principles.											
	Sobolev spaces.	Sobolev spaces.										
Objectives	The students have familiarist analysis, the concepts and r as numerics and stochastics methods of linear partial difference the more advanced courses. results of the lecture as well as In the exercise classes they let the terms, statements and more on new problems, to analyse they are able to present their	methons. Studerentia The as assenave a ethods	ds o idental eq stude sessi acqu s of t	f where are are are are are are are are are	ich a e far ns a are o nd ex a cor cture rk or	are fund miliar wand can capable oplaining ofident, e. They on solution	damental for ith the cer successfure of naming the prese precise and have learn on strategie	or many other tral concept tral concept the transfer and proving the transfer and transfer and transfer and transfer and their ownem in critical	er area se me g the e ctions. ent har er the r	as, such ults and thods in essential adling of methods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Introduction to Partial Differential Equations – Part 1	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise ce examination the coursework oral is decided by the instruct	rtifica must h	te is	to be	acc acc	quired.	Whether th	e examination				
Literature	Exemplary Literature:											
	 Lawrence C. Evans: 2010. David Gilbarg, Neil S. Springer 2001. 									-		
	Olga A. Ladyzenskaja ear equations of parab						Nina N. Ura	lceva: Linea	r and	quasilin-		

Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. In combination with one of the modules 'Numerics of Stationary Differential Equations' or 'Numerics of Nonstationary Differential Equations', it can be included in the Specialisation Numerical Mathematics and Optimisation. The module is part of the module Introduction to Partial Differential Equations and cannot be taken together with this module.
Prerequisites	There are no further prerequisites.
Responsible Persons	Gerhard Huisken, Reiner Schätzle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-27	Module Title: Type of Module: Fully Non-Linear Elliptic Equations Compulsory Module with Choice								Choice	
ECTS-Points	5									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 150 h 105 h									
Duration	1 Semester									
Frequency	not regularly	not regularly								
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 1 SWS									
Content	 Content: Solution of general fully non-linear equations with elliptic equations. Solution of the Monge-Ampere equation. 									
Objectives	The students learn the techrithe second derivatives of a glearn how the modulus of c Evans-Krylov theorem and solution. In particular, they are and to the special, non-unifor of naming and proving the estimate of research in the subjections.	given sontinutearn earn earn earn earn earn earn earn	ity o the o to ap elliptical res nts v	on of the continuous of the co	fafu sechuity them nge-	ully nor ond de methods nethods Amper e lectur	I-linear elliptorivatives is d, which less to general e equation. The as well as	tic equation. then estimated ads to the uniformly ell The students assessing	The sated us exister iptic ects are and ex	students sing the ace of a quations capable plaining
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Fully Non-Linear Elliptic Equations	L E	f	2	3 2	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise context examination the coursework oral is decided by the instructionally be offered by the points will be awarded for the	must l tor with	nave th ap cture	bee prova r witl	n acc al by hout	uired. the Bo exercis	Whether the ard of Exar	e examination niners. – Th	on is w ie mod	ritten or ule may

Literature	Exemplary Literature:
	 Luis A. Caffarelli, Joseph Kohn, Joel Spruck: The Dirichlet problem for nonlinear second-order elliptic equations. I. Monge-Ampere equation. In: Communications on Pure and Applied Mathematics 37,3 pp. 369-402.
	 Luis A. Caffarelli, Joseph Kohn, Luis Nirenberg, Joel Spruck: The Dirichlet problem for nonlinear second-order elliptic equations. II. Complex Monge-Ampere, and uniformly elliptic, equations. In: Communications on Pure and Applied Mathematics 38,2 pp. 209-252.
	David Gilbarg, Neil S. Trudinger: Elliptic Partial Differential Equations of Second Order. Springer 1998.
Transfer	The module belongs to the <i>Study Specialisation Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module MAT-60-36 'Fully nonlinear elliptic and parabolic partial differential equations' due to the large overlap in content.
Prerequisites	For participation, the modules Introduction to Partial Differential Equations and Partial Differential Equations are required.
Responsible Persons	Reiner Schätzle
Abbreviations:	-graded ng-net graded

Grading System : g=graded, ng=not graded

 $\label{thm:model} \textbf{Examination Type: MT=Master's thesis, or.=oral\ exam,\ wr.=written\ exam,\ Pr=presentation,\ H=essay,\ P=portfolio\ exam,\ Pr=presentation,\ P=portfolio\ exam,\ P=portfolio\$ $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : m=mandatory, o=optional

Module Number: MAT-55-28	Module Title:Type of Module:Morse TheoryCompulsory Module with Choice											
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 90 h											
Duration	1 Semester											
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS										
Content	Content:											
	Topology of differentiable manifolds.											
	Riemannian metrics o	Riemannian metrics on differentiable manifolds.										
	Dynamic systems on a	Dynamic systems on differentiable manifolds.										
	Homotopy type of diffe	erentia	ıble ı	nani	folds							
	Main approaches of N	lorse t	theoi	y.								
	Outlook on Morse hor	nology	/.									
Objectives	Students learn how to analysic using the tools of analysis, in learn how the level surfaces used to obtain statements a to algebraic topology, which The students are capable of assessing and explaining the	n part of nor bout t analy namin	icula n-deg he h ses g an	r the gene omo the t d pro	theorate topy opol	ory of of function type of ogy (of the est	lynamical syns, so-called manifolds. manifolds)	rstems. In p d Morse fun They also using algeb	oarticu ictions build a oraic m	lar, they can be bridge nethods.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Morse Theory	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100		
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	ecided	by the instru	uctor with a	pprova	l by the		
Literature	Exemplary Literature:											
	John Milnor: Morse TI Press 1961.	_										
	Morris W. Hirsch: Diff 1988.	erenti	al To	polo	gy. (aradua	te Texts in I	Mathematics	s 33. S	Springer		

Transfer	The module belongs to the Study Specialisation Studienschwerpunkt Analysis and Differential Geometry and Algebra and Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge of differentiable manifolds and of dynamic systems is helpful.
Responsible Persons	Frank Loose

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-32	Module Title:Type of Module:Selected Chapters from Dynamical Systems TheoryCompulsory Module with Choice										
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h										
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	1-3									
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS									
Content	Content: A selection of the following topics will be covered: • dynamical systems as solution flows of ordinary and partial differential equations; • isomorphic invariants of dynamical systems, especially the discrete spectrum; • linear skew-product flows; • applications in number theory, combinatorics and stochastics.										
Objectives	Students are familiar with qu tial equations and the methor functional analysis, operator applicability of abstract mather proving the essential results connections.	ds us theor emat	ed to y an ical o	o an d er conc	alyse godic epts.	them. theory The	On the bay, they have students are	asis of solid e experience e capable o	knowled the of nam	edge of diverse ing and	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Selected Chapters from Dynamical Systems Theory	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is Board of Examiners.	writter	n or	oral	is de	cided I	by the instru	uctor with a	pprova	I by the	
Literature	Exemplary Literature:										
	 Tanja Eisner, Balint Fa of ergodic theory. Spri Manfred Einsiedler, Th ory. Springer 2011. David Kerr, Hanfeng 2016. 	nger 2 nomas	2015 s Wa	rd: E	rgod	lic thec	ry: with a v	iew towards	Numb	er The-	

Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. It can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, the module Dynamic Systems Prerequisite for participation in this module.
Responsible Persons	Rainer Nagel

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-33	Module Title: Abstract Dynamical Systems							of Module: ulsory Modu	le with	Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	tudy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS										
Content	rence and (topological) ergorare applied to category the Jacobs-deLeeuw-Glicksberg and the Furstenberg-Zimmer current research topics are a	Content: The central properties of topological dynamic systems such as minimality, recurrence and (topological) ergodicity are repeated. Subsequently, the statements proven there are applied to category theoretical foundations. Important structural results such as the Jacobs-deLeeuw-Glicksberg decomposition, the theorem of Halmos-von Neumann's theorem and the Furstenberg-Zimmer structure theory are discussed and generalised. In this context, current research topics are addressed and a category-theoretical perspective is developed. Among other things, the application of ergodic theory to number theory and combinatorics is presented.									
Objectives	can be developed and further can apply the techniques do theoretical or ergodic-theoretical or ergodic-theoretical or ergodic-theoretical or ergodic-theoretical or ergodic-theoretical or ergodic-theoretical respective to the useful new sential respective connections. In the exercise classes they the terms, statements and metallicities.	The students have learnt how abstract theories (here dynamic systems, Koopman systems) can be developed and further abstracted from concrete questions (in number theory). They can apply the techniques developed in these areas, to deal with concrete (e.g. number-theoretical or ergodic-theoretical) problems. The students have thus learnt important examples of the usefulness of abstract mathematical theories. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Abstract Dynamical Systems	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise ce examination the coursework oral is decided by the instruct	must l	nave	beei	n acc	uired.	Whether th	e examination			
Literature	Jan de Vries: Topolog tinuous mappings. De	 oral is decided by the instructor with approval by the Board of Examiners. Exemplary Literature: Tanja Eisner et al.: Operator theoretic aspects of ergodic theory. Springer 2015. Jan de Vries: Topological dynamical systems. An introduction to the dynamics of continuous mappings. De Gruyter 2014. Saunders Mac Lane: Categories for the working mathematician. Springer 1998. 									
	Helmut H. Schaefer: E	Banac	n latt	ices	and	positive	e operators.	Springer 19	978.		

Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Introduction to Dynamical Systems' due to the large overlap in content.
Prerequisites	Solid knowledge of Topology, Functional Analysis and Operator Theory, in particular spectral theory of positive operators is required. operators are assumed. Fundamentals of Ergodic Theory and Category Theory are also very useful, but not strictly necessary.
Responsible Persons	Rainer Nagel

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-34	Module Title: Type of Module: Introduction to Dynamical Systems Compulsory Module with Choice											
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 90 h											
Duration	1 Semester											
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Lecture 2 SWS											
Content	Content: Kepler's laws. Equilibrium positions. Stability. Predator-prey model. Poincaré-Bendixson th Limit sets. Periodic orbits. Celestial mechanics.	 Kepler's laws. Equilibrium positions. Stability. Predator-prey model. Poincaré-Bendixson theorem. Limit sets. Periodic orbits. 										
Objectives	The students can ask and exferential equations, like e.g.: states or periodic orbits? The lecture as well as assessing a	How le	ong o	do ex able	ist m of na	nathem Iming a	atical solution at the state of	ons? Are the the essentia	ere equ	uilibrium		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Introducation to Dynamical	Type of Course	J Status	SMS 2	ω ECTS	S Assignments	Type of Exam o. o.	Dur. of Exam (min)	۵ Grading	Weight for Grade		
	Systems					110	0. 01.	o. 20-30	9			
Literature	Morris W. Hirsch, Step algebra. Academic Pro Vladimir I. Arnold: Ma Carl Ludwig Siegel, Jü	ess 19	974. itical	metl	nods	of clas	sical mecha	unics. Spring	ger 20 ⁻	10.		

Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Dynamical Systems' due to the large overlap in content.
Prerequisites	There are no further prerequisites.
Responsible Persons	Frank Loose

 $Grading \ System \quad : g=graded, \ ng=not \ graded$

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title:							f Module:			
MAT-55-41	Introduction to Geometric M	easure	The	ory			Compu	llsory Modul	e with	Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	_	lass	:		Self-St 180 h	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ecture 4 SWS + Exercise Class 2 SWS									
Content	Content:										
	Measures, Covering theorems, differentiation of measures, Hausdorff measures and densities.										
	Isodiametric inequalit	у.									
	Rademacher's theorem	m and	l Whi	tney	emb	edding	theorem.				
	Surface- and Cosurfa	ce forr	nula.								
	Countable rectifiable	sets, re	ectifia	able '	varifo	olds.					
Objectives	Students have familiarised analysis and geometry and various problems. They ha methods of geometric meas courses. The students are cas well as assessing and ex In the exercise classes they the terms, statements and non new problems, to analyse They are able to present the	whose ye fame the sure the sapable plaining have a nethods	e co niliari eory e of r g the acqu s of t and t	ncep sed t and namir pres ired a the le	ts ar can ng an sente a cor cture rk on	nd met selves succes ad proved conr afident, e. They a solution	hods can be with the basefully applying the essentions. precise and have learned a strategies.	ne successforms of concept of these method independent of the transfers on their owners.	ully ap is, resumods in s of the ent har er the m	plied to ults and a further e lecture adling of nethods a team.	
Redriements Sws Sws ECTS Assignments Type of Exam (min) Dur. of Exam (min)							Grading	Weight for Grade			
	Introduction to Geometric Measure Theory	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise c examination the coursework oral is decided by the instruc	must l	have	beei	n acc	uired.	Whether the	 ork. For parti e examinatio			

Literature	Exemplary Literature:
	 Lawrence C. Evans, Ronald F. Gariepy: Measure theory and fine properties of functions. CRC Press 1992.
	Herbert Federer: Geometric measure theory. Springer 1969.
	Leon Simon: Lectures on geometric measure theory. Australian National University 1984.
Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Reiner Schätzle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-42	Module Title: Geometric Measure Theory							of Module: ulsory Modu	le with	Choice		
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-Si 180 h	tudy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS										
Content	Content:											
	First and second varia	First and second variation for varifolds.										
	Monotonicity formula.											
	Allard's integral comp	actnes	s the	eorei	n.							
	Lipschitz approximation	on.										
	tilt-excess descent.											
	Allard's regularity thee	orem.										
	General and rectifible	flows.										
	Deformation theorem.											
	Surface minimizing flo	WS.										
Objectives	After having learned the basi this knowledge is deepened recent research. The studen lecture as well as assessing In the exercise classes they the terms, statements and m on new problems, to analys team. They are capable of p discourse.	. The ts are and exhave a ethods e then	stude capa cplain acque s of to n an	dents able ning ired he le	will of na the pa core core	be preming a present of the premium	epared for a nd proving ed connect precise ar have learn lution strat	and guided the essential tons. Id independe to transfeed to transfeed to argue for the tone tone to argue for the tone tone tone tone tone tone tone ton	to prob Il resul ent har er the r eir owr	olems of ts of the adling of methods a or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Geometric Measure Theory	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	nave	bee	n acc	uired.	Whether th	e examinati				

Literature	Exemplary Literature:
	Herbert Federer: Geometric measure theory. Springer 1969.
	Enrico Giusti: Minimal surfaces and functions of bounded variation. Birkhäuser 1984.
	Leon Simon: Lectures on geometric measure theory. Australian National University 1984.
Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Regarding to content the module introduction to geometric measure theory is a prerequisite for participation in the module geometric measure theory.
Responsible Persons	Reiner Schätzle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-43	Module Title: Area Minimising Flows							of Module: ulsory Modul	le with	Choice	
ECTS-Points	5										
Workload - Time in Class - Self-Study	Workload: 150 h	Time 45 h	in C	lass	:		Self-Si 105 h	Self-Study: 105 h			
Duration	1 Semester						·				
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Cl	Lecture 2 SWS + Exercise Class 1 SWS									
Content	Content: Compactness theorem for integral flows. Regularity of area minimising flows.										
Objectives	After having learned the essential notions and methods of geometric measure theory, this knowledge is deepened. The students will be prepared for and guided to problems of recent research. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Area Minimising Flows	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise ce tion is written or oral is decide										
Literature	Herbert Federer: Geo Enrico Giusti: Minimal Leon Simon: Lecture: 1984.	surfa	ces a	and f	uncti	ons of	bounded va	ariation. Birk			
Transfer	The module belongs to the S into account the chosen per Study Focus, Advanced Knowith the restrictive requireme	rsonal <i>wledg</i>	Stu e in l	dy S Math	pecia emai	alisatio <i>tics</i> or	n, it can bo <i>Elective Sp</i>	e included in	n the	sections	
Prerequisites	Knowledge from the modules sure Theory is expected.	Intro	ductio	on to	Geo	metric	Measure T	heory and G	eomet	ric Mea-	

Other

Responsible Persons	Reiner Schätzle
Abbreviations:	
Grading System :	g=graded, ng=not graded
Examination Type :	MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio
	_=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=Seminar, IC=inverted classroom
Status :	n=mandatory, o=optional

Module Number: MAT-55-44	Module Title: Introduction to Geometric M Theoretic Methods	Introduction to Geometric Measure Theory – Measure Compulsory Module with Choice									
ECTS-Points	5										
Workload - Time in Class - Self-Study	Workload: 150 h	Time 45 h	in C	lass			Self-S	tudy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	1-3									
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	ecture 2 SWS + Exercise Class 1 SWS										
Content	 Content: Measures, Covering theorems, differentiation of measures, Hausdorff measures and densities. Isodiametric inequality. Rademacher's theorem and Whitney embedding theorem. 										
Objectives	Students have familiarised the analysis and geometry and various problems. They have methods of geometric measurements are carried as well as assessing and explinithe exercise classes they be the terms, statements and meaning on new problems, to analyse to the terms are able to present their	whose famous the theorem in the theorem in the theorem in the	e co iliaris eory e of r g the acqu s of t and t	ncep sed t and amir pres ired a he le o wo	ts and the management of the m	nd met selves succes nd prov ed conr nfident, e. They n solution	hods can limited with the basefully applying the essurections. precise an have learn on strategie	be successfi asic concept y these methential results and independented to transfe s on their ow	ully apts, res nods in s of the ent har er the r	plied to ults and a further e lecture adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Geometric Measure Theory – Measure Theoretic Methods	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise ce examination the coursework oral is decided by the instruct	nust l	nave	beei	n acc	quired.	Whether th	ie examinatio	icipation on is w	on in the ritten or	
Literature	Exemplary Literature:										
	Lawrence C. Evans, F tions. CRC Press 1992		d F. (Garie	py:	Measu	re theory a	nd fine prop	erties	of func-	
	Herbert Federer: George		mea	asure	the	ory. Sp	ringer 1969).			
	• Leon Simon: Lectures 1984.								onal U	niversity	

Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module is part of the module 'Introduction to Geometric Measurement Theory' and cannot be taken together with this module.
Prerequisites	There are no further prerequisites.
Responsible Persons	Reiner Schätzle

 $Grading \ System \quad : g=graded, \ ng=not \ graded$

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-45	Module Title: Introduction to Geometric Me	asure	The	ory -	- Var	ifolds		of Module: ulsory Modu	le with	Choice		
ECTS-Points	5						·					
Workload - Time in Class - Self-Study	Workload: 150 h	Time 45 h	in C	lass	:		Self-St 105 h	tudy:				
Duration	1 Semester	1 Semester										
Frequency	not regularly											
Term	1-3	-3										
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	ecture 2 SWS + Exercise Class 1 SWS										
Content	Content:	Content:										
	Surface- and Cosurface	e forr	nula.									
	Countable rectifiable s	Countable rectifiable sets, rectifiable varifolds.										
Objectives	analysis and geometry and w ious problems. They have fa of geometric measure theory The students are capable of assessing and explaining the In the exercise classes they the terms, statements and m on new problems, to analyse	Students have familiarised themselves with an important mathematical field that combines analysis and geometry and whose concepts and methods can be successfully applied to various problems. They have familiarised themselves with basic concepts, results and methods of geometric measure theory and can successfully apply these methods in further courses. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.							d to varmethods courses. s well as adding of methods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Introduction to Geometric Measure Theory – Varifolds	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise ce examination the coursework oral is decided by the instruct	must l	nave	bee	n acc	quired.	Whether th	e examination				
Literature	Exemplary Literature:											
	Lawrence C. Evans, F tions. CRC Press 199 Herbert Federer: Geo	2. metric	: mea	asure	the	ory. Sp	ringer 1969).				
	• Leon Simon: Lecture 1984.	on (yeom	ietric	1116	asure t	neory. Aus	ualian Natio	ла О	niversity		

Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module is part of the module 'Introduction to Geometric Measurement Theory' and cannot be taken together with this module.
Prerequisites	The module integration and measure theory from the B.Sc. Mathematics or an equivalent module must have been successfully completed during the course of studies.
Responsible Persons	Reiner Schätzle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-46	Module Title: Elastic Curves							of Module: ulsory Modul	e with	Choice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h										
Duration	1 Semester										
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 2 SWS										
Content	Content:										
	Classification of elasti	c curv	es a	ccor	ding	to Lanç	ger and Sing	jer.			
	Order reduction of the	Euler	-Lag	ranç	je eq	uation	of the elastic	c energy of	a curv	e.	
	Qualitative behaviour	of an	elast	ic cı	ırve.						
	Solving the Willmore 6	Solving the Willmore equation under axial symmetry with variational methods.									
Objectives	Students learn how to deal with a geometrically relevant functional and its critical points using the example of the elastic energy of a curve. This gives them an insight into the theory of fourth-order elliptic differential equations where familiar techniques, such as the maximum principle, can no longer be used. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Elastic Curves	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	cided	by the instru	uctor with a	pprova	al by the	
Literature	Exemplary Literature:										
	Filippo Gazzola, Har Value Problems, Sprir	iger 2	010.					-			
	David Gilbarg, Neil S. Springer 1998.	Trudi	nger	: Elli	ptic p	oartial	differential e	equations of	secor	nd order.	
	Joel Langer, David A. ential Geom. Band 20							of closed cu	rves,	J. Differ-	
	John M. Lee: Introduction	tion to	smo	ooth	man	ifolds.	Springer 20	13.			
	Michael Struwe: Varia	tional	Meth	nods	. Spr	inger 2	2008.				

Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, knowledge from the module Introduction to Partial Differential equations and basic knowledge of differential geometry are assumed.
Responsible Persons	Reiner Schützle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-47	Module Title: Geometric Measure Theory	– Varif	olds				-	of Module: ulsory Modul	le with	Choice		
ECTS-Points	5											
Workload - Time in Class - Self-Study	Workload: 150 h	Time 45 h	in C	Class	:		Self-St 105 h	udy:				
Duration	1 Semester	I Semester										
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	Lecture 2 SWS + Exercise Class 1 SWS										
Content	Content:	Content:										
	First and second varia	ation fo	or va	rifold	S.							
	Monotonicity formula.											
	Allard's integral comp	actnes	s the	eorei	n.							
	Lipschitz approximation	on.										
	tilt-excess descent.											
	Allard's regularity the	orem.										
Objectives	After the students have lear Measure Theory, this knowl prepared for and introduced ing and proving the essential presented connections. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	edge i to curr al resu have a tethoda thema	rent rent related to the second to the secon	eperesea f the ired the le	ned varch of lection a corecture or	with a requestion ure as a solution of the sol	view to vari ns. The stu well as ass precise an have learn on strategie	abilities. St dents are ca essing and d independe ed to transfe s on their ow	udents apable explain ent har er the r on or in	s will be of nam- ning the adling of nethods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Geometric Measure Theory – Varifolds	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise or examination the coursework oral is decided by the instruc	must I	nave	bee	n acc	uired.	Whether th	e examination				

Literature	Exemplary Literature:
	Herbert Federer: Geometric measure theory. Springer 1969.
	Enrico Giusti: Minimal surfaces and functions of bounded variation. Birkhäuser 1984.
	Leon Simon: Lectures on geometric measure theory. Australian National University 1984.
Transfer	The module belongs to the <i>Study Specialisation Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module is part of the geometric measurement theory module and cannot be taken together with it.
Prerequisites	In terms of content, the module Introduction to Geometric Dimension Theory is a is a prerequisite for participation.
Responsible Persons	Reiner Schätzle
Abbreviations: Grading System : g	=graded, ng=not graded

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-48	Module Title: Geometric Measure Theory -	- Flow	s					of Module: ulsory Modul	le with	Choice	
ECTS-Points	5										
Workload - Time in Class - Self-Study	Workload: 150 h	Time 45 h	in C	lass			Self-St 105 h	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	ass 1	SWS	3							
Content	Content:	Content:									
	General and rectifiable	e flows	i.								
	Deformation theorem.										
	Surface minimizing flo	ws.									
Objectives	After the students have learn Measure Theory, this knowled prepared for and introduced ting and proving the essential presented connections. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present their	edge is controlled to curred the controlled the con	s de ent r Its of acqui s of t and t	eperesea the reda ne le o wo	led valued value	with a valuestion ure as a solution of the sol	view to vari ns. The stu- well as ass precise and have learned on strategies	abilities. St dents are ca essing and d independe ed to transfe s on their ow	apable explaine expla	will be of nam- ning the adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Geometric Measure Theory – Flows	L E	f f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise ce examination the coursework oral is decided by the instruc	must h	nave	beer	acc	quired.	Whether the	e examinatio			
Literature	Exemplary Literature:										
	Herbert Federer: Geo	metric	mea	sure	the	ory. Sp	ringer 1969				
	Enrico Giusti: Minimal	surfac	ces a	ınd fı	uncti	ons of	bounded va	riation. Birk	häusei	1984.	
	Leon Simon: Lecture 1984.	s on g	jeom	etric	mea	asure t	heory. Aus	tralian Natio	onal Ui	niversity	

Transfer	The module belongs to the <i>Study Specialisation Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module is part of the geometric measurement theory module and cannot be taken together with it.
Prerequisites	In terms of content, the module Introduction to Geometric Dimension Theory is a is a prerequisite for participation.
Responsible Persons	Reiner Schätzle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-49	Module Title: Calculus of Variations							f Module:	le with	Choice
ECTS-Points	5							<u> </u>		
Workload - Time in Class - Self-Study	Workload: 150 h	Time 45 h	in C	lass	:		Self-St 105 h	udy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English	German or English								
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 1	SWS	S						
Content	Content:									
	Direct method of calc	ulus of	varia	ation	S.					
	Euler-Lagrange equation	ions.								
	Palais-Smale conditio	n.								
	Mountain-Pass Lemm	a acco	ordin	g to i	Ambı	osetti-	Rabinowitz.			
Objectives	In the first part of the course which is primarily used to probut also has applications in ebasics from functional analydifferent context, e.g. geomabout a so-called mountainin the existence of solutions naming and proving the ess the presented connections. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	ve the e.g. differs and etric a pass for pass ential have a ethods them a	exist ferend par nalys lemn artial resul acquis of t	tence itial of tial of sis. I na. ' diffe Its of ired a he le o wo	e of w geom different n the With erenti the the cture rk on	reak so etry. T ential e e secon its hel al equallecture offident, e. They a solution	lutions of paney have als quations and part of the p, they can ations. The as well as precise and have learned as strategies	artial differer so acquired at can also ne course, so analyse no estudents a assessing a dindepende ed to transfers on their owner in critical	ntial eq the ne use the student on-unic are cap and ex ent har er the r	uations, cessary ese in a selearnt queness bable of plaining adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ecrs	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Calculus of Variations	L E	f	1	2	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise context examination the coursework oral is decided by the instruction	ertifica must h	te is	to be	acq acq	uired.	Whether the	e examination		

Literature	Exemplary Literature:
	Michael Struwe: Variational Methods, Springer 2008.
	 David Gilbarg, Neil S. Trudinger: Elliptic Partial Differential Equations of Second Order, Springer 1998.
	Walter Rudin: Functional Analysis, Mc Graw Hill Education 1991.
Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge of the modules Introduction to Partial Differential Equations and Functional Analysis is an advantage, but not essential.
Responsible Persons	Reiner Schätzle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title:						Туре о	f Module:			
MAT-55-51	Lie Groups						Compu	Ilsory Modu	le with	Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	udy:			
Duration	1 Semester										
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS									
Content	Content:										
	Manifolds and Lie gro	ups,									
	Lie algebras and expo	nentia	ıl ma	p,							
	Covering spaces and	classif	icatio	on of	Lie	groups	by their Lie	algebras,			
	Classical Lie groups,										
	Operations of Lie group	ıps an	d ho	moge	eneo	us spa	ces.				
Objectives	Lie groups lie at the interface describing the symmetries of differential equations, in particular learn from a prominent of mathematics can work tog developed that can precisely capable of naming and provexplaining the presented confin the exercise classes they the terms, statements and monnew problems, to analyse They are able to present their	f geomicular examplether descring the nection have a ethods them a	netrice if the ole he extreme to	c objese sow demely a varientia ired a he le o wo	ects, symmiffere y such iety al research	but also netries ent disc ccessfu of sym sults of nfident, e. They a solution	so algebraic form a con iplines of m lly and how metry phen the lecture precise and have learned in strategies	e equations tinuous set. athematics a convincin omena. The as well as a dindepende ed to transfer on their owners in critical	or solu The s can dis g form e stude assess ent han er the n	tions of students ciplines alism is ents are ing and adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	- Status	SMS 4	e ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Lie Groups	E	f	2	3	yes	or.	o. 20-30	g	100	
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	nave	beei	acq acq	uired.	Whether the	e examination			

Literature	Exemplary Literature:								
	Joachim Hilgert, Karl-Hermann Neeb: Liegruppen und Lie-Algebren. Vieweg 1991.								
	Gerhard P. Hochschild: The structure of Lie groups. Holden-Day 1965.								
	Frank W. Warner: Foundations of differentiable manifolds and Lie groups. Springer 1983.								
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.								
Prerequisites	There are no further prerequisites.								
Responsible Persons	Anton Deitmar, Frank Loose								

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-52	Module Title: SL2(R)								f Module: Ilsory Modu	le with	Choice
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	lass	:			Self-St 60 h	udy:		
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	Deutsch und Englisch										
Forms of Teaching and Learning	Lecture 2 SWS										
Content	Content: • Structure theory of the Lie group $SL_2(\mathbb{R})$. • Introduction to the representation theory of $SL_2(\mathbb{R})$. • Computation of the unitary dual. • Proof of the explicit Plancherel formula.										
Objectives	With the $SL_2(\mathbb{R})$ the student have become familiar with the with the basics of hyperbolic classify representations. More Lie groups, and they have gaunderstand the analysis lying The students are capable of assessing and explaining the	ne bas geome eover thered unde namir	sics of etry. , they d a do rneating ar	of th The are eepe th th	e rep stude able er und e The roving	ents ha to tranderstandersemed the corem	ation we lead sfer ding of Pla	theory arned their ki of the the	of Lie grout to construct nowledge to theory of Lie and apply	ups as , to spl analy group it succ	well as it and to se other os. They essfully.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam		Dur. of Exam (min)	Grading	Weight for Grade
	$SL_2(\mathbb{R})$	L	f	2	3	no	wr.	o. or.	90-180 o. 20-30	g	100
Literature	Exemplary Literature:				ory of	semis	imple	group	s. PUP 200	1.	1
Transfer	The module belongs to the Differential Geometry. Takin be included in the sections Specialisation, in accordance	g into <i>Study</i>	Foc	ount us, 7	the d A <i>dvai</i>	chosen nced K	pers nowle	onal S edge ii	tudy Specia <i>Mathemat</i>	ilisatio <i>ics</i> or	n, it can <i>Elective</i>
Prerequisites	There are no further prerequ	sites.									
Responsible Persons	Anton Deitmar										

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-53	Module Title:							of Module:	lo with	Chaina	
	Automorphic Forms						Compt	lisory iviodu	ie with	Choice	
ECTS-Points	5										
Workload - Time in Class	Workload:	Time	in C	lass			Self-St	udy:			
- Self-Study	150 h	45 h					105 h				
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise 0	Class 1	SW	S							
Content	Content:										
	Module forms for the module group and its congruence subgroups.										
	Examples: Eisensteir	Examples: Eisenstein series, Ramanujan delta function, theta series.									
	Modulus curves.										
	Arithmetic application	s and	conie	ectur	es.						
	Hecke operators.		.,.								
	The L-function of a m	odular	form	and	lite o	onnool	tions with al	lintia auruas			
	THE L-IUNCTION OF A IN	odulai	10111	i aiiu	i its C	OHHEC	ions with ei	iiptic cui ves	•		
Objectives	Students have familiarised to fautomorphic forms in exconnection between modula are capable of naming and and explaining the presente. In the exercise classes they the terms, statements and non new problems, to analyse They are able to present the	amples r, real proving d conne have a nethods them a	s and represent the control of the c	d are esent	ation entia a cor cture rk on	e to us theory I result fident, E. They solution	se them. To and adelic the lector of the lector of the lector of the learn on strategies.	They have under the Left of th	nderst . The s I as as ent har er the r n or in	ood the students sessing adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Automorphic Forms	L	f	2	3	yes	K o. mP o. H	90-180 o. 20-30	g	100	
		E	f	1	2						
	In this module an exercise c examination the coursework oral is decided by the instruc-	must l	nave	beei	n acc	uired.	Whether the	e examination			

Literature	Exemplary Literature:							
	Deitmar, Anton: Automorphic Forms. Springer 2012.							
	Goldfeld, Dorian: Automorphic forms and L-functions for the group GL(n,R). Cambridge University Press 2015.							
	Serre, Jean-Pierre: A course in arithmetic. Springer 1973.							
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module is part of the module Introduction to Geometric Measurement Theory and cannot be taken together with this module.							
Prerequisites	Basic knowledge of function theory is assumed.							
Responsible Persons	Anton Deitmar							
Abbreviations: Grading System : g	=graded, ng=not graded							

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{ Teaching Format : L=lecture, \ LE=lecture \ with \ integrated \ exercises, \ SL=seminar \ or \ lecture, \ E=exercise \ class, \ T=tutorial, \ P=project, \ S=Seminar, \ IC=inverted \ classroom }$

Status : m=mandatory, o=optional

Module Number: MAT-55-60	Module Title: Introduction to the Mathemat	ical Lo	ogic					f Module: Ilsory Modul	le with	Choice
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	Class	:		Self-Sti 60 h	udy:		
Duration	1 Semester						·			
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	Content:									
	Propositional logic.									
	Languages of the first									
	 Completeness and compactness. 									
	Theory of computations:Register machines;Gödelisation.									
	 Incompleteness of ari 	thmeti	c:							
	 First and secon 	d inco	mple	tene	ss th	eorem.				
	Set theory:									
	Ordinal- and caIncompleteness				;					
	- incompleteness	01 301	illo	Ji y.						
Objectives	Students are able to underst ematical logic. They underst the difference between truth mathematical content. The sof the lecture as well as asset	tand tand p and p tuden	the li roval ts ar	imits oility e cap	of p and pable	ossible can ap e of nar	mathemati ply basic the ning and pr	cal knowled eoretical mo oving the es	lge, re del thi	cognise nking to
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to the Mathe- matical Logic	L	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
Literature	Exemplary Literature:	1	1	1	1	I	I	l	<u>I</u>	'
	Rautenberg, Wolfgan 2008.Ziegler, Martin: Mathe							Logik. Vie	eweg+	Teubner

Transfer	The module is not assigned to a specialisation. It can be included in the sections <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Anton Deitmar

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-61	Module Title:Type of Module:Cohomology and SheavesCompulsory Module with Choice									
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 180 h	Time in 0	Class:		Self-Si 120 h	tudy:				
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Cl	Lecture 4 SWS + Exercise Class 2 SWS								
Content	 Content: It is shown how different cohomology theories (singular, de Rham, Cech) can all be understood as derivatives of the intersection functor from sheaf theory and thus their equality (after coefficient expansion) can be shown very easily: Introduction to category theory. Presentation of the current cohomology theories. Sheaves, derived functors, sheaf cohomology. Comparison of cohomology theories. 									
	The students see and understand the connections between seemingly widely divergent theories. They understand mechanisms that combine algebraic, geometric and analytic methods. They have learned to abstract arbitrary mathematical theories using category theory, to appreciate cohomology theory as a general obstacle theory in applications and to use sheaves as generalisations of function spaces for topological questions. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. Students will be able to reflect and critically analyse the current									
Objectives	ries. They understand mecha They have learned to abstract preciate cohomology theory as as generalisations of function naming and proving the esse	unisms that of arbitrary as a gene of spaces f ential resu Students v	at combing y mathem ral obstact or topolog lits of the	e algeb latical t le theo gical qu lecture	raic, geome heories usi ry in applic estions. The as well as	etric and ana ng category ations and to ne students assessing a	theory theory use sare ca	nethods. y, to ap- sheaves pable of plaining		
Requirements for Obtaining Credit, Grading, Weight if applicable	ries. They understand mecha They have learned to abstract preciate cohomology theory as as generalisations of function naming and proving the esset the presented connections.	unisms that of arbitrary as a gene of spaces f ential resu Students v	at combing y mathem ral obstact or topolog lits of the	e algeb latical t le theo gical qu lecture	raic, geome heories usi ry in applic estions. The as well as	etric and ana ng category ations and to ne students assessing a	theory theory use sare ca	nethods. y, to ap- sheaves pable of plaining		
Requirements for Obtaining Credit, Grading, Weight if	ries. They understand mecha They have learned to abstract preciate cohomology theory as as generalisations of function naming and proving the esset the presented connections. So state of research in the subjection	anisms that arbitrary as a gene a spaces frontial results at a gene a spaces frontial results at area.	at combine y mathem ral obstact for topolog lits of the will be abl	e algeb satical tele theo gical que lecture e to rei	raic, geome heories usi ry in applic estions. The as well as flect and cr	etric and analy grade and analy ations and to be students assessing a litically analy by the beautiful analy analy analy analy by the beautiful analy by the beautiful analy analy analy analy by the beautiful analy analy analy analy by the beautiful analy ana	alytic m theory o use: are ca and ex se the	Meight for Grade Weight for G		
Requirements for Obtaining Credit, Grading, Weight if	ries. They understand mecha They have learned to abstract preciate cohomology theory as as generalisations of function naming and proving the esset the presented connections. So state of research in the subjection	Anisms that the cit arbitrary as a gene of spaces of ential results and the cit area.	SMS SLOE	e algeb latical t le theo gical qu lecture e to re	raic, geome heories usi ry in applic estions. The as well as flect and cr	petric and analog category ations and to students assessing attically analy	alytic m theory theory to use sare ca and ex se the	nethods. y, to ap- sheaves pable of cplaining current		
Requirements for Obtaining Credit, Grading, Weight if	ries. They understand mecha They have learned to abstract preciate cohomology theory as as generalisations of function naming and proving the esset the presented connections. So state of research in the subjection	anisms that arbitrary as a gene of spaces for arbitrary arbi	or topologilts of the will be able or a solution of the will be able of the will be able or a solution of the will be able o	e algeb natical t ele theo gical qu lecture e to rei	raic, geome heories usi ry in applice estions. The as well as flect and creations and creations were estioned by the instruction of the conferred by the instruction of the conferred by the conf	etric and analy getric and analy getric and analy getric and analy attempts assessing a sitically analy go 20-30 90-180 0. 20-30 uctor with ally the lecture	alytic m theory use sare ca and ex se the bulbago g pprova r without	Methods. y, to apsheaves pable of current Application of the policy of		
Requirements for Obtaining Credit, Grading, Weight if	ries. They understand mecha They have learned to abstract preciate cohomology theory as generalisations of function naming and proving the esset the presented connections. State of research in the subjective Cohomology and Sheaves Whether the examination is a Board of Examiners. – The means of the control of the contro	anisms that arbitrary as a gene of spaces for arbitrary arbi	or topologilts of the will be able or a solution of the will be able of the will be able or a solution of the will be able o	e algeb natical t ele theo gical qu lecture e to rei	raic, geome heories usi ry in applice estions. The as well as flect and creations and creations were estioned by the instruction of the conferred by the instruction of the conferred by the conf	etric and analy getric and analy getric and analy getric and analy attempts assessing a sitically analy go 20-30 90-180 0. 20-30 uctor with ally the lecture	alytic m theory use sare ca and ex se the bulbago g pprova r without	Methods. y, to apsheaves pable of current Application of the policy of		
Requirements for Obtaining Credit, Grading, Weight if applicable	ries. They understand mecha They have learned to abstract preciate cohomology theory as generalisations of function naming and proving the esset the presented connections. State of research in the subject the subject that the subject that the presented connections is state of research in the subject that the su	anisms that arbitrary as a gene of spaces for the s	at combine y mathem ral obstace for topologists of the will be able of the will be away exception.	e algeb eatical t ele theo gical qu lecture e to rei stue unisse yes ecided I enally b arded for	raic, geome heories usi ry in applic estions. The as well as flect and creations with the control of the mode of the mode.	getric and analy grategory ations and to be students assessing a sitically analy grategory assessing a sitically analy grategory gratego	alytic m theory theory or use sare ca and exise the bulpped g	nethods. y, to apsheaves pable of explaining current ppz. 0 ppz. 0 100 al by the out exer-		
Requirements for Obtaining Credit, Grading, Weight if applicable	ries. They understand mecha They have learned to abstract preciate cohomology theory as generalisations of function naming and proving the esset the presented connections. State of research in the subject that the presented connections is state of research in the subject that t	anisms that arbitrary as a gene of spaces of ential results for area. L f E f written or nodule madit points of a spaces of spaces.	or topologists of the will be able or a soral is de y exception will be aw	e algeb eatical t ele theo gical qu lecture e to rei strueurbissy yes ecided t bonally b arded fo	raic, geome heories usi ry in applic estions. The as well as flect and created wro and control of the mode mathematic mathematic mathematic records as well as flect and created by the instruction of the mode mathematic mathematic mathematic records as well as we	etric and analy grategory ations and to be students assessing a itically analy by a point of the students of t	alytic m theory theory or use sare ca and exise the bulpped g	nethods. y, to apsheaves pable of explaining current open 100 all by the out exer-		
Requirements for Obtaining Credit, Grading, Weight if applicable	ries. They understand mecha They have learned to abstract preciate cohomology theory as generalisations of function naming and proving the esset the presented connections. State of research in the subject that the presented connections are state of research in the subject that	anisms that arbitrary as a gene of spaces of ential results for area. L f E f written or nodule madit points which are specified area.	or topologists of the will be able or al is de y exception will be aways. Cambro carbon carbo	e algeb eatical t ele theo gical qu lecture e to rei stue ubissy yes ecided t onally b arded fo	raic, geome heories using in applicestions. The as well as flect and creations are well as flect and creations. Wr. o. or. by the instruction of the mode mathematical and creating are offered by the instruction of the mode mathematical and creating are well as the mode mathematical and creating are also as the mode mathematical and creating are also as the mode mathematical and creating are also as the creating are	etric and analy grategory ations and to be students assessing a itically analy by a point of the students of t	alytic m theory theory or use sare ca and exise the bulpped g	nethods. y, to apsheaves pable of explaining current ppz. 0 ppz. 0 100 al by the out exer-		

Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.	
Prerequisites	In terms of content, only basic knowledge from the analysis and linear algebra is required.	1
Responsible Persons	Anton Deitmar	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-62	Module Title: Consistency Proofs							of Module: ulsory Modul	le with	Choice	
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass	:		Self-St 120 h	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SWS	3							
Content	Content:						·				
	 Historical examples of the question of consistency (limits; parallel axiom; set-theoretic paradoxes). Philosophical foundational programs (logicism; formalism; intuitionism). 										
	 Philosophical foundational programs (logicism; formalism; intuitionism). The Hilbert program and Gödel's theorems. 										
	Gentzen's transfinite						or thoory				
	Alternative approache						•				
	Current situation of co					Juding	doders 1).				
Objectives	Students learn about the his formal mathematical theories ing this question mathematic in mathematics both historics ematical tools to be able to to a certain extent, to carry proving the essential results connections. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	s aroses ally. The ally and compression them of the have a sethods them a	e, as ney a d phil ehen out the lecture acquires of the lecture acquires of the lecture acquires of the lectures acquires and to the lecture acquires and the lecture acquires and the lecture acquires a	well losor d the nems are are the le o wo	as the ble to oblicate corselves well a correcture rk on	ne releved categorally. In a resport of the second as as a responding the second as a responding the second as a responding to	vant moderr orise the pro- addition, the ading proofs students a sessing and precise an- have learn on strategies	n techniques oblem of nor ey have acquar of non-con re capable d explaining d independe ed to transfe s on their ow	for invalued the tradiction of name the properties of the properties of the name of the na	restigat- adiction e math- on and, ing and esented adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Consistency Proofs	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	nave	beer	n acq	juired.	Whether the	e examination			

Literature	Exemplary Literature:
	 Kurt Gödel: Über formal unentscheidbare Sätze der Principia Mathematica und verwandter Systeme I. Monatsh. f. Mathematik und Physik 38, 173-198 (1931).
	 Gerhard Gentzen: Die Widerspruchsfreiheit der reinen Zahlentheorie. Math. Ann. 112, 493-565 (1936).
	 Reinhard Kahle, Michael Rathjen (Hrsg.): Gentzen's Centenary: The quest for consistency. Springer 2015.
	Reinhard Kahle, Michael Rathjen (Hrsg.): The Legacy of Kurt Schütte. Springer 2020.
Transfer	The module belongs to the Study Specialisation Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic mathematical knowledge to the extent of the basic lectures is assumed. Previous knowledge of mathematical logic is helpful, but not necessary.
Responsible Persons	Reinhard Kahle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:continuous} \begin{tabular}{ll} Teaching Format : L=lecture, & LE=lecture & with integrated exercises, & SL=seminar & or lecture, & E=exercise & class, & T=tutorial, & P=project, & S=Seminar, & IC=inverted & classroom & IC=inverted & Class$

Status : m=mandatory, o=optional

- Time in Class - Self-Study Duration 1 Frequency	Vorkload: 10 h Semester not regularly	Time 30 h	in C	lass	:													
- Time in Class - Self-Study Duration 1 Frequency	Semester oot regularly	_	in C	lass			3											
Frequency no	not regularly		90 h 30 h 60 h															
Term 1	-3																	
	1-3																	
Language of Instruction	German																	
Forms of Teaching Loand Learning	ecture 2 SWS																	
Content C	Content:																	
	•																	
	The students can The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.																	
Requirements for Obtaining Credit, Grading, Weight if applicable	- itle	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade								
Ir	ntroduction to Set Theory	L	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100								
Literature	exemplary Literature:	1	ı	I					I									
K	The module is not assigned in the module in Mathematics of the respective in the res	or <i>Ele</i>	ctive															
Prerequisites T	here are no further prerequi	sites.																
Responsible Fersons	rank Loose																	
Examination Type : MT= Teaching Format : L=ler T=tu	Abbreviations: Grading System : g=graded, ng=not graded Examination Type : MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=Seminar, IC=inverted classroom																	

Module Number: MAT-55-64	Module Title: Theory of Mathematical Prod	ıfs						of Module: ulsory Modu	le with	Choice	
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass	:		Self-St 120 h	tudy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	Lecture 2 SWS + Exercise Class 2 SWS									
Content	Content:										
	Axiomatic theories, income	Axiomatic theories, incompleteness.									
	Gentzen's proof of consistency for arithmetic.										
	Ordinal number analysis.										
	Provable recursive functions.										
	Predicative analysis.	Predicative analysis.									
	Theories of inductive	definiti	ons.								
Objectives	Students are familiar with the calculations for mathematica are capable of naming and prexplaining the presented concurrent state of research in the lin the exercise classes they the terms, statements and mon new problems, to analyse They are able to present their	I theo oving nection sub have a ethods	ries a the e ns. S ject acqu s of t and t	and tesser Stude area ired a he le o wo	their ntial rents v a cor ecture rk or	metamesults of the control of the co	athematica of the lecturable to reflect precise and have learn on strategie	I properties. e as well as et and critica d independe ed to transfe s on their ow	The sassessally ana ent har er the r	students sing and lyse the adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Theory of Mathematical Proofs	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise context examination the coursework oral is decided by the instruction	must l	nave	beer	n acc	uired.	Whether th	e examinati			
Literature	Exemplary Literature:										
	Wolfram Pohlers. Produced in the second	of The	ory.	Sprir	nger :	2009.					

Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic mathematical knowledge to the extent of the basic lectures is assumed. Previous knowledge of mathematical logic is helpful, but not necessary.
Responsible Persons	Reinhard Kahle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-65	Module Title: Explicit Mathematics							of Module: ulsory Modul	e with	Choice			
ECTS-Points	6												
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass			Self-St 120 h	udy:					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3	1-3											
Language of Instruction	German												
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS												
Content	Content:												
	Applicative theories.												
	Explicit mathematics.												
	Universes in explicit n	nathen	natic	S.									
	Applications in proof t	heory.											
Objectives	Students are familiar with ar systems of analysis and are students are capable of nam sessing and explaining the pranalyse the current state of In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	familia ing an resente esearc have a ethods them a	or with did property of the contract of the co	h the oving onned the s ired ine le	eir fur the ctions subje a cor cture rk on	nction i essent s. Stud ect area nfident, e. They n solution	n proof-theo ial results o ents will be a. precise an have learn on strategies	oretical investif the lecture able to reflect independent in transfers on their owner in critical investigation.	stigatio as we ct and o ent har er the n	ns. The ll as as- critically adling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Explicit Mathematics	L E	f	2	3	yes	mP	90-180 o. 20-30	g	100			
	In this module an exercise or examination the coursework offered by the lecturer withouthe module instead of 6.	must	have	bee	n ac	quired.	- The mo	dule may ex	ceptio	nally be			

Literature	Exemplary Literature:
	 Solomon Feferman: A language and axioms for explicit mathematics, in Algebra and Logic. Lecture Notes in Mathematics, 450, pp. 87-139, Springer-Verlag, Berlin, 1975.
	 Solomon Feferman: Constructive theories of functions and classes. In Logic Colloquium ?78, (Proc. Mons Colloq.), pp. 159-224, North-Holland, Amsterdam, 1979.
	 Gerhard Jäger, Reinhard Kahle, Thomas Strahm: On applicative theories. In Andrea Cantini, Ettore Casari, and Pierluigi Minari, editors, Logic and Foundations of Mathematics, pages 83–92, Kluwer, 1999.
	 Reinhard Kahle: The applicative realm. Textos de Matematica, 40, Departamento de Matemática, Universidade de Coimbra, 2007.
	 Gerhard Jäger, Reinhard Kahle, Thomas Studer: Universes in explicit mathematics. Annals of Pure and Applied Logic, 109(3),141-162, 2001.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge of mathematical logic.
Responsible Persons	Reinhard Kahle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-70	Module Title: Selected Chapters from Fun	ctional	Ana	lysis				of Module:	le with	Choice			
ECTS-Points	6						<u> </u>	<u> </u>					
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass			Self-St	tudy:					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German or English	German or English											
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	Lecture 2 SWS + Exercise Class 2 SWS											
Content	Content: A selection of the following to	A selection of the following topics will be covered:											
	Topological vector spaces and duality theory.												
	(LB) and (LF) spaces	(LB) and (LF) spaces and distributions.											
	Compactness concep	ts (Eb	erleir	i's th	eore	m, Bar	ach-Alaogl	u, Krein-Milr	nan, S	mulian).			
	Theorems from topolo tional analysis.	ogy (Ti	etze,	Ury	sohn	, Stone	e-Cech) and	d their applic	ations	in func-			
	Uniform spaces.												
Objectives	Students are familiar with the to apply their methods and resuch as the theory of distribution connections to other parts of are capable of naming and pexplaining the presented concurrent state of research in the exercise classes they the terms, statements and monnew problems, to analyse They are able to present the	results butions froutions froutions innection the subtention the subtention from the froution them are subtential them are subtential them are subtential to the subtential the subtenti	to co The emati the e ns. S ject a acqui s of the	oncreey had cs, sesser Stude area. The le common term of the le co	ete ex ave r uch a itial r ents v ents v cture rk on	ecognias mea esults ovill be a nfident, solution	s from the sed and un sure theory of the lecturable to reflect precise an have learn on strategies.	field of funct nderstood the or topology e as well as ct and critical d independent ed to transfers on their ow	ional are mand and the mand assess ally and and are the rear the rear or in	analysis, y cross- students sing and allyse the adling of methods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Selected Chapters from	L	f	2	3	no	wr. o.	90-180	g	100			
	Functional Analysis	Е	f	2	3	/10	or.	o. 20-30	9	100			
	In this module an exercise context examination the coursework oral is decided by the instruc	must l	nave	beer	n acc	uired.	Whether th	e examination					

Literature	Exemplary Literature:
	Gerald Folland: Real Analysis. Wiley 1999.
	Helmut H. Schäfer: Topological Vector Spaces. Springer 1999.
	Volker Runde: A Taste of Topology. Springer 2005.
	Gert K. Pedersen: Analysis Now. Springer 1989.
	Paul R. Halmos: Measure Theory. Springer 1950.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the Functional Analysis module is assumed.
Responsible Persons	Ulrich Groh, Rainer Nagel

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-55-71	Module Title: Operator Algebras and the Mechanics		Type of Module: Compulsory Module with Choice									
ECTS-Points	6						·					
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h		Class	:		Self-Si 120 h	tudy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	English											
Forms of Teaching and Learning	Lecture 3 SWS + Exercise Class 1 SWS											
Content	Content:											
	• Basics on operator algebras (C*-algebras, algebraic states, inductive limits);											
	 Introduction to algebraic deformation quantization (general set-up, coherent states, examples); 											
	 Applications to the classical limit of quantum mechanics and statistical mechanics including asymptotic emergence (phase transitions, large deviations (entropy), spontaneous symmetry breaking). 											
Objectives	The students have obtained theory with an emphasis on classical limit of quantum metechniques in order to developed they are familiar with technicoded by algebraic states, exthey understand the physical equilibrium thermodynamics. They are able to describe the name and prove the central tions. In the exercise classes they the terms, statements and meteories to analysteam. They are capable of predictions.	algebechanion absilipments algebechanion absilipments absilipments algebechanism algeb	raic cs and tract to prove the same as pent since as of the same acquary and the same acquary are	deformed structures, a of the heart term of the learn term of the	matic atistic cture existe nd pu e res trans of res ecture a core ecture work	on qua cal me s enco ence re ut them ults an sitions earch e and the infident, e. They on so	ntisation and chanics. The ding the feat esults of line into a general and spontation the specimey can experience are have learn lution strate.	nd their appiney have lead atures of a pinits of seque eral perspector relate them neous symnific area. The blain their in ad independed to transfered to transfered son the	ication rned a hysica hysica ences/rive. Man to fea hetry be stude trinsic ent har er the reir own	s to the Igebraic I theory. nets en- oreover, stures of reaking. ents can connec- ndling of nethods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Operator Algebras and their Applications to Statistical Mechanics	L E	f	3	4,5 1,5	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise c examination the coursework oral is decided by the instruc	must l	have	bee	n acc	uired.	Whether th	e examinati				

Literature	Exemplary Literature:
	Klaas Landsman: Foundations of Quantum Theory, From Classical Concepts to Operator Algebras. Springer 2017.
Transfer	The module belongs to the <i>Study Specialisations Analysis and Differential Geometry, Mathematical Physics</i> and <i>Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus, Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge of C*-algebras and functional analysis as well as in thermodynamics are assumed.
Responsible Persons	Andreas Prohl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:continuous} \begin{tabular}{ll} Teaching Format : L=lecture, & LE=lecture & with integrated exercises, & SL=seminar & or lecture, & E=exercise & class, & T=tutorial, & P=project, & S=Seminar, & IC=inverted & classroom & IC=inverted & Class$

Status : m=mandatory, o=optional

Module Number: MAT-60-01	Module Title: Geometric Evolution Equation	ns						f Module: Ilsory Modu	le with	Choice		
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	lass			Self-St 60 h	udy:				
Duration	1 Semester						•					
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 2 SWS											
Content	Parabolic maximum pr Regularity theory for p Rescaling techniques	 Examples of geometric evolution equations such as Mean curvature flow, Ricci flow, Inverse mean curvature flow. Parabolic maximum principles. Regularity theory for parabolic evolution equations. Rescaling techniques and description of singularities. Asymptotic behavior of solutions. 										
Objectives	Students learn to combine the equations and apply it to spellearn techniques for checking to start their first own research to a doctorate. The students lecture as well as assessing a	cific p solut h proj are c	oroblions ect, apal	ems of no for each	in se on-lin xamp f nar	elected lear evo ble as p ming ar	geometric of the second graph of a Mart of a Mart of the second growing gr	evolution ed tions, which ster's thesis he essentia	quation enable or with	s. They es them n a view		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Geometric Evolution Equations	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100		
	Whether the examination is Board of Examiners.	writter	n or	oral	is de	ecided I	by the instru	uctor with a	pprova	I by the		
Transfer	The module belongs to the S into account the chosen per Study Focus, Advanced Know with the restrictive requireme In combination with one of th Numerics of Differential Equa Numerical Mathematics and	sonal vledgents of e mo tions	Stude in the idules on S	dy S Math espe s Nu urfac	pecia ema ective merio	alisation tics or a e section cs of N	n, it can be <i>Elective Spe</i> n. onstationar	e included i ecialisation, y Differentia	n the s in acco	sections ordance ations or		
Prerequisites	Knowledge from the module I of differential geometry are re			n to F	Partia	al Differ	ential Equa	tions and ba	sic kno	owledge		

Other

Responsible Persons	Gerhard Huisken								
Abbreviations:									
Grading System : g	=graded, ng=not graded								
Examination Type : M	T=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio								
	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, etutorial, P=project, S=Seminar, IC=inverted classroom								
Status : m	n=mandatory, o=optional								

Module Number: MAT-60-02	Module Title: Geometric Variation Problems	3						f Module: Ilsory Modu	le with	Choice		
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	lass			Self-St 60 h	udy:				
Duration	1 Semester						,					
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 2 SWS											
Content	Content:	ontent:										
	 harmonic mappings ar Direct methods of calc Regularity theory for s Relationship between 	 Examples of geometric variation problems such as minimal surfaces, capillary surfaces, harmonic mappings and associated boundary value problems. Direct methods of calculating variations. Regularity theory for solutions of variational problems. Relationship between variational problems and partial differential equations. Stability properties of solutions. 										
Objectives	Students learn to combine the it to specific problems in sele proving solutions to various which provide a basis for ind students are capable of name assessing and explaining the	cted sariation epending a	geon nal p dent nd p	netrio probl scier rovir	variems ems ntific ng th	iational and for work, f e esse	problems. analysing to example	They learn he propertie in a Maste	technices of sor's thes	ques for olutions, sis. The		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Geometric Variation Prob- lems	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100		
	Whether the examination is a Board of Examiners.	writtei	n or	oral	is de	cided	by the instru	uctor with a	pprova	I by the		
Transfer	The module belongs to the S into account the chosen per Study Focus, Advanced Know with the restrictive requirement	sonal <i>vledg</i>	Stu e in i	dy S <i>Math</i>	pecia <i>ema</i> :	alisatio <i>tics</i> or	n, it can be <i>Elective Sp</i> e	included i	n the s	sections		
Prerequisites	Knowledge from the module i of differential geometry are re			n to	oartia	al differ	ential equat	ions and ba	sic kno	owledge		
Responsible Persons	Carla Cederbaum, Gerhard F	luiske	n									

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-03	Module Title: Topics in Mathematical Relati	vity						f Module: Ilsory Modu	le with	Choice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	lass	:		Self-St 60 h	udy:			
Duration	1 Semester										
Frequency	regelmäßig										
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lecture 2 SWS										
Content	Content:										
	 selection of concrete models of Mathematical Relativity, such as black holes, static metrics, physical invariants of isolated systems, positivity estimates for energy and mass. Geometric and analytical structure of the models, existence and properties of concrete models as solutions to Einstein's equations. 										
Objectives	Students acquire in-depth kn tivity. They learn analytical a to Einstein's equations and a results. The lecture introduce in a Master's thesis. The stud the lecture as well as assessi	nd ge re abl es stud dents	ome e to dents are o	tric t cate s to t capal	echn goris heir ole o	iques f e the p first ind f namir	or proving a hysical relev lependent s ng and provi	and investig vance of the cientific wor ing the esse	ating s mather k, for e	olutions ematical example	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Topics in Mathematical Relativity	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is Board of Examiners.	writter	n or	oral	is de	ecided I	by the instru	uctor with a	pprova	l by the	
Transfer	The module belongs to the St ematical Physics. Taking int included in the sections Stud cialisation, in accordance with	o acc <i>y Foc</i>	ount <i>us</i> , A	the I <i>dva</i>	chos nced	en per <i>Knowl</i>	sonal Study edge in Mai	/ Specialisa thematics o	tion, it r <i>Elect</i>	can be	
Prerequisites	In terms of content, the modu Equations are assumed.	les Ma	ather	natio	al R	elativity	and Introdu	uction to Par	tial Dif	ferential	
Responsible Persons	Carla Cederbaum, Gerhard F	luiske	n								

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-04	Module Title: Space-Like Hypersurfaces in		f Module: Ilsory Modul	e with	Choice							
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h		lass	:		Self-St 120 h	udy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS											
Content	Content: Space-like hypersurfaces of a Lorentzian manifold play a crucial role in the study of solutions to Einstein's equations modelling some phenomenon in General Relativity. The course explores how geometric choices of space-like hypersurfaces such as maximal surfaces, constant mean curvature surfaces or solutions of mean curvature flow and inverse mean curvature flow can be used to achieve a splitting of space and time that is suitable for the study of both isolated gravitating systems and cosmological spacetimes.											
Objectives	The students obtain deepe They learn analytic and geo stein equations and to exam of the mathematical solution and concepts from the lectu to put it into a larger framew state of research in the spec Through homework assignmand independent acquaintal lectures. They learn how to to develop solution strategie solutions and to stand for the	metric ine the s. Stue re as v ork. Th ific are ents a nce wi trans s on th	techese. dents well a hey a ea. and e th th fer th	nique More s are as to are al xerci e no nese own a	es in eover able explole to se clations methand w	order to nan ain the descriasses to state to vithin a	to prove exido understane and prove context de the and critical students dements, and new proble group. The	stence of so and the physe the essent veloped in the cally challer velop a contamethods ex ems, to ana	olutions sical retial state he lecting the fident, plained by the fident of the fident	s of Ein- levance rements ure and current precise, d in the em and		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Space-Like Hypersurfaces	L	f	2	3	yes	wr. o.	90-180	ď	100		
	in Lorentzian Manifolds	Е	f	2	3	yes	or.	o. 20-30	g	100		
	In this module an exercise c examination the coursework oral is decided by the instruc	must	have	bee	n acc	uired.	Whether the	e examinatio				

Literature	Exemplary Literature:
	 Barrett O'Neill: Semi-Riemannian Geometry - With applications to Relativity. Academic Press 1983.
	 Andrejs E. Treibergs: Entire space-like hypersurfaces of constant mean curvature in Minkowski space. Inventiones Math. 66, (1982) 39–56.
	 Klaus Ecker, Gerhard Huisken: Parabolic methods for the construction of spacelike slices of prescribed mean curvature in cosmological spacetimes. Comm. Math. Phys. 135 (1991), 595–613.
	 Helmut Friedrich, Alan Rendall: The Cauchy Problem for the Einstein Equations. In: Schmidt B.G. (eds) Einstein's Field Equations and Their Physical Implications. Lecture Notes in Physics, vol 540. Springer 1999.
	 Hans Ringström: The Cauchy Problem in General Relativity. European Math. Society 2009.
Transfer	The module belongs to the <i>Study Specialisation Mathematical Physics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the module Mathematical Relativity is expected.
Responsible Persons	Gerhard Huisken

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-05	Module Title: Limits of Spaces							of Module: ulsory Modul	le with	Choice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass	:		Self-St 120 h	udy:		
Duration	1 Semester						'			
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 3 SWS + Exercise 0	Lecture 3 SWS + Exercise Class 1 SWS								
Content	Content:									
	 Basic concepts of metric geometry, e.g. geodesics, doubling property and Hausdorff measure. Generalized curvature conditions in the sense of Alexandrov and Busemann. Gromov-Hausdorff and ultra convergence. Gromov's Precompactness Theorem and stability theorems. 							ausuom		
Objectives	Students generalise their knowledge in analysis and know how to apply the methods to particular problems in metric geometry. They get to know different convergence notions and learn which properties are stable in the limiting process. In addition, the students are familiar with synthetic and concrete curvature notions, which help to better understand curvature notions in differential geometry and general relativity. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are capable of presenting their results and if applicable to argue for it in a critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Limits of Spaces	L E	f	3	4,5 1,5	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise certificate is to be acquired as coursework. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.									

Literature	Exemplary Literature:
	 Jeff Cheeger, David Ebin: Comparison Theorems in Riemannian Geometry. AMS 1975.
	Dimitri Burago, Yuri Burago, Sergei Ivano: A Course in Metric Geometry. AMS 2001.
	Mikhail Gromov: Metric Structures for Riemannian and Non-Riemannian Spaces. Springer 2007.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge in analysis and measure theory is assumed.
Responsible Persons	Carla Cederbaum, Gerhard Huisken

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-06	Module Title: The Ricci Flow of Riemannian Metrics							Type of Module: Compulsory Module with Choice		
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: Time in Class: 60 h					Self-St 120 h	Self-Study: 120 h			
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	Content: The lecture introduces the basic properties of the Ricci flow and develops the necessary techniques, e.g. tensor maximum principles and regularity estimation. The long-term existence of solutions and resulting classifications for metrics of positive curvature are presented. Finally, the monotonicity of functionals according to Perelman is derived and used for the classification of possible singularities, with an outlook on the surgery methods of Hamilton and Perelman, which have led to the proof of the Poincaré and geometrisation conjectures.									
Objectives	The students have learnt basic methods for the treatment of geometric evolution equations in Riemannian geometry. At the same time, they have experienced the interplay of local geometric assumptions on the curvature properties of a metric with analytic techniques for the study of parabolic equations and have learnt and understood how the local assumptions have global consequences for the geometry and topology of the underlying manifolds. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.				of local s for the ns have students					
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	The Ricci Flow of Riemannian Metrics	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100
	Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners. – The module may exceptionally be offered by the lecturer without exercise classess; in this case, only 3 credit points will be awarded for the module instead of 6.						nout ex-			
Literature	Exemplary Literature:									
	Simon Brendle: Ricci-flow and the sphere theorem. AMS 2010.									
	Peter Topping: Lectures on the Ricci-Flow. Lecture Notes 2006.									
	Richard Hamilton: Riemannian 3-manifolds with positive Ricci curvature. J. Diff. Geom. 17, 1982.					Geom.				
Transfer	The module belongs to the Sematical Physics. Taking intincluded in the sections Stuccialisation, in accordance with	o acc ly Foc	ount us, A	the I <i>dvai</i>	chos nced	en per <i>Knowl</i>	sonal Study edge in Ma	y Specialisa thematics or	tion, it <i>Electi</i>	can be

Prerequisites	Knowledge from the module Introduction to Partial Differential Equations as well as fundamental knowledge in differential geometry is required.
Responsible Persons	Carla Cederbaum, Gerhard Huisken

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-07	Module Title: Special Relativity							Type of Module: Compulsory Module with Choice			
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	ad: Time in Class: 30 h				Self-St 60 h	Self-Study: 60 h				
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lecture 2 SWS										
Content	Content:										
	 Derivation of the Minkowski metric from basic physical assumptions. Physical consequences of relativity such as length contraction, time dilation and sor popular paradoxes. 					d some					
Objectives	Students have learnt and understood the derivation of the special theory of relativity and important concepts such as length contraction and time dilation. They are familiar with important paradoxes that arise. Students have developed an intuition for various aspects of the theory of relativity. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.				nportant neory of						
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Special Relativity	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.					I by the					
Literature	 Exemplary Literature: Albert Einstein: Relativity: the special and general theory. Public domain 1920. Thomas A. Moore: Six ideas that shaped physics: unit R. McGraw-Hill 2003. Robert Resnick: Introduction to Special Relativity. Wiley 2007. Bernard Schutz: A First Course in General Relativity. Cambridge University Press 2009. 										
Transfer	The module belongs to the <i>S</i> ematical <i>Physics</i> . Taking in included in the sections <i>Stuccialisation</i> , in accordance with	o acc ly Foc	ount us, A	the A <i>dva</i>	chos nced	en per Knowl	sonal Study edge in Ma	/ Specialisa thematics or	tion, it <i>Electi</i>	can be	

Prerequisites	Knowledge from the module Introduction to Partial Differential Equations and basic knowledge of differential geometry are required.
Responsible Persons	Carla Cederbaum, Gerhard Huisken

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-08	Module Title: Null Geometry in General Relativity							of Module: ulsory Modu	le with	Choice
ECTS-Points	5									
Workload - Time in Class - Self-Study	Workload: 150 h	Time 45 h	in C	lass	:		Self-Si 105 h	tudy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	of light-like vector fields and carry a degenerate induced r surfaces in higher codimens	Content: This module provides an introduction to null geometry. Topics include the properties of light-like vector fields and curves, as well as the geometry of light-like hypersurfaces that carry a degenerate induced metric. Another major topic is the extrinsic curvature of space-like surfaces in higher codimension, which are considered in particular along light-like hypersurfaces. Optionally, geometric flows along light-like hypersurfaces can also be treated.								
Objectives	Students know and understand the concepts and methods mentioned and can use them to analyse known and new questions from null geometry. Furthermore, they link physical problems in cosmology and astrophysics and their mathematical modelling using differential geometric methods and are able to question the relevance and adequacy of mathematical modelling and the mathematical results derived from it. In particular, they expand on the methods learnt in the MAT-65-11 module and connect their methodological and specialist knowledge. They are able to name and prove the main statements of the lecture and to categorise and explain the relationships presented. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Null Geometry in General Relativity	L ü	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners. – The module may exceptionally be offered by the lecturer without exercise classes; in this case, only 3 credit points will be awarded for the module instead of 5.							ritten or ule may		
Literature	Barrett O'Neill: Semi- Johannes Sauter: Fol tation (ETH Zürich), 500.11850/150826.	iations	of N	lull h	ıyper	surface	s and the I	Penrose Inec		

Transfer	The module belongs to the Study Specialisation Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	The content of the Geometry in Physics module is a prerequisite.
Responsible Persons	Carla Cederbaum

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-09	Module Title: The Einstein Constraint Equ	ations	Type of Module: Compulsory Module with Choice								
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: 180 h	Time in Class: 60 h	Self-Study: 120 h								
Duration	1 Semester		·								
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	English	English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	Lecture 2 SWS + Exercise Class 2 SWS									
Content	- The Einstein ed - The Cauchy pro • The constraint equation - The conformal - Overview of the - Classification of • Asymptotically Euclid - AE manifolds a	GR and the Einstein equations: ein equations, special solutions and geometric constructions; hy problem for the Einstein equations. quations and the conformal method: rmal method; of the elliptic theory on closed manifolds; cion of constant mean curvature on closed manifolds. Euclidean (AE) initial data: olds and elliptic operators; ons of AE initial data sets.									
Objectives	liptic partial differential equal equations and analyse propersions between the theory problem and the Yambe propersion in geometry, geometric at The students are capable of as assessing and explaining critically analyse the current In the exercise classes they the terms, statements and necessions and explaining critically analyse the current in the exercise classes they	rmal methods to transform Einstein's constraints into a system of el quations and thus describe parts of the solution spaces of Einstein's properties of the associated solutions. They have learnt about convergence of the associated solutions. They have learnt about convergence of the associated solutions. They have learnt about convergence and questions of geometric analysis such as the scalar curvature problem and are familiar with the interplay of methods of Rieman c analysis and physics for answering questions of general relativity le of naming and proving the essential results of the lecture as we may be presented connections. Students will be able to reflect and the entity of the research in the subject area. They have acquired a confident, precise and independent handling of the methods of the lecture. They have learned to transfer the methods by the mand to work on solution strategies on their own or in a team									

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	The Einstein Constraint	L	f	2	3	yes	wr. o.	90-180 o. 20-30	g	100
	Equations	Е	f	2	3	-	or.	0. 20-30		
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners. – The module may exceptionally be offered by the lecturer without exercises; in this case, only 3 credit points will be awarded for the module instead of 5.									
Transfer	The module belongs to the seminatical Physics. Taking be included in the sections Semination, in accordance	j into Study	acco Foci	ount <i>us</i> , <i>A</i>	the d Idvar	chosen nced K	personal S nowledge in	tudy Specia <i>Mathemat</i>	lisation ics or	n, it can <i>Elective</i>
Prerequisites	Basic knowledge of differenti- knowledge of partial differenti- edge of general relativity is a lecture.	al equ	ıatioı	ns is	an a	dvanta	ge, but not	essential. P	revious	knowl-
Responsible Persons	Carla Cederbaum									
Abbreviations:										

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio

Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-10	Module Title: Special Topics in Evolution (with Exercise Class)	Equat	ions	for S	Subm	nanifolo		of Module: ulsory Modul	le with	Choice	
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass			Self-Si 120 h	tudy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	English	English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SWS	3							
Content	Students learn about recent results from the theory of geometric evolution equations that deform curves, hypersurfaces and other submanifolds of an ambient space. Examples are the flow of hypersurfaces along the mean curvature or flows with other geometrically defined velocities.										
Objectives	equations, which will enable of a Master's thesis or with proving the essential results connections. In the exercise classes they the terms, statements and mon new problems, to analyse	The students have learnt techniques for controlling solutions of non-linear parabolic evolution equations, which will enable them to start their first own research project, for example as part of a Master's thesis or with a view to a doctorate. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Special Topics in Evolution Equations for Submanifolds	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise context examination the coursework oral is decided by the instruction	ertifica must l	te is	to be beer	acq acq	uired.	Whether th	e examination	icipation on is w	on in the ritten or	
Literature	Exemplary Literature:										
	Klaus Ecker: Regular	ty the	ory fo	or me	ean c	urvatu	re flow. Birk	khäuser 2004	4.		
Transfer	The module belongs to the S ematical Physics. Taking in included in the sections Studies cialisation, in accordance with	to acc	ount us, A	the I <i>dvai</i>	chos nced	en per Knowl	sonal Stud edge in Ma	y Specialisa <i>thematics</i> or	tion, it Elect	can be	
Prerequisites	Knowledge from the module of differential geometry is red			n to F	Partia	al Differ	ential Equa	tions and ba	ısic kn	owledge	
Responsible Persons	Gerhard Huisken										

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-11	Module Title: Special Topics in Evolution (without Exercise Classes)	Equat	ions	for S	Subn	nanifolo		Type of Module: Compulsory Module with Choice				
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass	:		Self-St 120 h	udy:				
Duration	1 Semester						·					
Frequency	not regularly											
Term	1-3											
Language of Instruction	English											
Forms of Teaching and Learning	Lecture 2 SWS											
Content	Inhalte: Students learn about recent results from the theory of geometric evolution equations that deform curves, hypersurfaces and other submanifolds of an ambient space. Examples are the flow of hypersurfaces along the mean curvature or flows with other geometrically defined velocities.											
Objectives	The students have learnt techniques for controlling solutions of non-linear parabolic evolution equations, which will enable them to start their first own research project, for example as part of a Master's thesis or with a view to a doctorate. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.											
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Special Topics in Evolution Equations for Submanifolds	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100		
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	ecided	by the instr	uctor with a	pprova	l by the		
Literature	Exemplary Literature: • Klaus Ecker: Regulari	ty the	ory fo	or me	ean c	curvatu	re flow. Birk	häuser 200	4.			
Transfer	The module belongs to the <i>S</i> ematical Physics. Taking intincluded in the sections <i>Stuccialisation</i> , in accordance with	o acc	ount us, A	the I <i>dva</i>	chos nced	en pei Knowi	rsonal Study <i>ledge in Ma</i>	y Specialisa thematics o	tion, it	can be		
Prerequisites	Knowledge from the module of differential geometry is rec			n to F	Partia	al Diffe	rential Equa	tions and ba	sic kno	owledge		
Responsible Persons	Gerhard Huisken											

 $Grading \ System \quad : g=graded, \ ng=not \ graded$

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-30	Module Title: Gravitational Collapse and Stivity	Singula	arities	s in (Gene	ral Rela		of Module: ulsory Modu	le with	Choice	
ECTS-Points	3						·				
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h		Class	:		Self-St 60 h	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS									
Content	Content: The course is divided into the in general relativity, the cause we will study singularities are And finally we will study Petholes, the phenomenon of singularities, and some exact cosmic censorship conjecture. Causality theory: Time orientation. Singularities: Raychoudhuri's. Black holes: Cosmic censors.	isal hind the inrose' gravita mples e. The	erard cele s cos ations of gr e con	chy a brate smic al co avita tent ierar	and ved sir censellaps tionatis as chy, q	rarious ngularit sorship e, whi il collap follows global h	theorems ry theorems ry theorems conjecture, ch is the reset that apps: hyperbolicity s, singularity	related to carby Penrose some propersion for the parently does the	ausality and F erties e form s not d	y. Then lawking. of black lation of	
Objectives	Students have acquired in-c general relativity. They will le ing singularity theorems. Th naked singularities. They ar well as categorise and expla and critically scrutinise the c	earn to ey will e able in the	app also to n relat	ly to get ame ionsh	oolog an ov and nips p	jical me verview prove present	ethods in ca of cosmic the main sta ed. Student	usality theo censorship of atements of is will be abl	ry and conject the le e to re	in prov- ture and cture as produce	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	b ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Gravitational Collapse and Singularities in General Relativity		f	2	3	no	wr. o. or.	o. 20-30	g	100	
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	ecided	by the instr	uctor with a	pprova	al by the	

Literature	Exemplary Literature:
	Robert M. Wald: General Relativity. The University of Chicago Press 1984.
	 Stephen W. Hawking and George F. R. Ellis: The large scale structure of spacetime. Cambridge Monographs on Mathematical Physics 1973.
	 Pankaj S. Joshi: Gravitational collapse and spacetime singularities. Cambridge University Press 2007.
	Barret O'Neill: Semi-Riemannian Geometry with applications to relativity. Academic Press 1983.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge of relativity is required to follow the course.
Responsible Persons	Carla Cederbaum, Gerhard Huisken

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-35	Module Title: Non-Linear Elliptic and Performance Equations	arabol	ic P	artia	l Dif	ferentia		of Module: ulsory Modu	le with	Choice		
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	_	lass	:		Self-St 120 h	udy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	English											
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS											
Content	Content:											
	Semilinear and quasil Minimum surface ope Parabolic geometric e Hölder continuity acco Inner regularity and b	rator a quatio ording	and s ons, e to De	urfac e.g. fl e Gic	es of ow a	f prescilong the	ribed mean e mean cui sh;	curvature;	tions;			
Objectives	Students have learnt analytic differential equations of second amples of partial differential techniques were learnt to provide the students are capable of assessing and explaining the line the exercise classes, students they have learnt and to present their problem sol research.	ond or equat ove th namin prese dents l	der dions le ex grander de ex	of the from isten d pro I con acquater ther	e ellip mat ce a eving necti uired m ind	otic and hemation regulation the essential confider the essential confider the endotes the	d parabolic cal physics ularity of so sential resu ence in the ently to other	type. Using and different olutions to so lits of the lect extending the technical her problems.	g cond ntial ge uch eq ture as nandlin They	rete ex- cometry, uations. well as g of the are able		
Requirements for Obtaining Credit, Grading, Weight if applicable Title Non-Linear Elliptic and Parabolic Partial Differential Title Non-Linear Elliptic and Parabolic Partial Differential								Dur. of Exam (min) 90-180 0. 20-30	ے Grading	Weight for Grade		
	In this module an exercise or examination the coursework oral is decided by the instruc	must l	have	beei	n acc	uired.	Whether th	ork. For part e examinatio	icipation on is w	on in the ritten or		

Literature	Exemplary Literature:
	 Lawrence C. Evans, Partial Differential Equations: Chapters on Sobolev Spaces and elliptic PDEs. AMS 1998.
	Gary Lieberman: Second order parabolic differential equations. World Scientific 1996.
	Fritz John: Introduction to Partial Differential Equations. Springer 1982.
	Jürgen Jost: Partielle Differentialgleichungen. Springer 1998.
	David Kinderlehrer, Guido Stampacchia: An introduction to variational inequalities and their applications, Pure and Applied Mathematics, Vol. 88. Academic Press 1980.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, the module Introduction to Partial Differential Equations is a prerequisite.
Responsible Persons	Gerhard Huisken

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-60-36	Module Title: Fully Non-Linear Elliptic and Equations	Parab	olic	Parti	al Di	fferenti		of Module: ulsory Modu	le with	Choice			
ECTS-Points	3												
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h		lass	:		Self-St 60 h	udy:					
Duration	1 Semester	1 Semester											
Frequency	not regularly												
Term	1-3	1-3											
Language of Instruction	English												
Forms of Teaching and Learning	Lecture 2 SWS												
Content	Content: The lecture investigates fully non-linear elliptic and parabolic partial differential equations of second order. Classical examples are the Monge-Ampère equation, the equation of prescribed Gaussian curvature or, more general, equations of prescribed other scalar invariants of curvature together with their parabolic analogues. They also arise in problems of stochastic control and optimal transport. The course establishes basic techniques for solving Dirichlet- and Neumann boundary value problems for such equations, in particular techniques for deriving the necessary a priori estimates for solutions.												
Objectives	The students have learnt and linear partial differential equation of such differential equation of solutions of such equation apply the methods they have The students are capable of assessing and explaining the In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present their	ations s, tech ns and e learn namin prese have a ethod	of the niques of the grant to grant ecception of the control of th	e ellipies vassiothed produced a confined in the legarithm.	ptic avere ociater proportion proportion of the	and par learnt ed bou blems the estions. nfident, e. They n solution	abolic type. to prove the ndary value and related sential resurprecise an have learn on strategies	Using conce existence problems. I equations lts of the lec d independent on their ow	erete ex and re Stude indepe ture as ent har er the r	camples egularity ents can ndently. It well as adding of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Fully Non-Linear Elliptic and Parabolic Partial Differential Equations	L	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100			
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	ecided	by the instr	uctor with a	pprova	I by the			

Literature	Exemplary Literature:
	 David Gilbarg, Neil S. Trudinger: Elliptic partial differential equations of second order. Springer 2001.
	 Lawrence C. Evans, Partial Differential Equations: Chapters on Sobolev Spaces and elliptc PDEs. AMS 1998.
	Gary Lieberman: Second order parabolic differential equations. World Scientific 1996.
	 Ilya J. Bakelman: Convex functions and nonlinear geometric elliptic equations. Springer 1994.
	Luis Caffarelli, Xavier Cabrè: Fully nonlinear elliptic equations. AMS 1995.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'MAT-55-27 Fully Nonlinear Elliptic Equations' due to the large overlap in content.
Prerequisites	At least one course on partial differential equations, basic concepts of differential geometry.
Responsible Persons	Gerhard Huisken
Abbreviations:	

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title:		Type of Module:								
MAT-65-05	Groups and Representation	S	Compulsory Module with Choice								
ECTS-Points	9										
Workload	Workload:	Time in Class:	Self-Study:								
- Time in Class - Self-Study	270 h	90 h	180 h								
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	3									
Language of Instruction	English	English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise 0	Class 2 SWS									
Content	Content:										
		• Groups: subgroups, homomorphisms, isomorphisms, group actions, orbits, stabilisers, equivalence classes, normal subgroups, cosets, factor groups.									
	 Representations: faithful, unitary and irreducible representations, reducibility, characters, Schur's lemma(s), orthogonality of irreducible representations. 										
	Applications: symme	tries and degeneracies in qua	antum mechanics, selection rules.								
	 Representations of fi potents. 	nite groups: group algebra,	regular representation, ideals, idem-								
	Symmetric groups: Yes	oung tableaux, Young operat	ors, dimensions and characters.								
	Applications: identications	al particles in quantum theorie	es.								
	Lie groups: Haar mea	asure, representations, Lie al	gebras.								
	Tensor representation	ns of classical groups: symm	etry classes, Young tableaux.								
	Applications: SU(2) a	and SU(3) in particle physics	(spin, isospin, flavour)								
	Moreover a selection	-									
	·	resentations of the Lorentz ar	<u> </u>								
		otion of particles in quantum	tneories. tion of semi-simple Lie algebras								
	- Hoots and weig	grits, Milling-Oartair Glassificat	tion of semi-simple Lie algebras								
Objectives	The studens know the basic concepts of group and representation theory. They are able apply these abstract algebraic concepts in the context of theoretical physics and have, the developed a deepend understanding for the connections between mathematics and physic. The students are familiar with a number of complex examples of applications of the rep sentation theory of groups in physics. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connection in the exercise classes they have acquired a confident, precise and independent handling the terms, statements and methods of the lecture. They have learned to transfer the method on new problems, to analyse them and to work on solution strategies on their own or in a teal. They are able to present their solutions and, if necessary, defend them in critical discourse										

Requirements for Obtaining Credit, Grading, Weight if applicable	Title Groups and	Type of Course	- Status	SMS 4	e ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Representations	E	f	2	3	yes	or.	o. 20-30	g	100
	In this module an exercise cer examination the coursework n oral is decided by the instructe	nust ł	nave	beer	n acc	uired.	Whether the	e examinatio		
Literature	Irene Verona Schenste Mechanics. NEO Press Barry Simon: Represe Wu-Ki Tung: Group The	s 197 ntatio	6. ns o	f Fini	te ar	nd Com	npact Group	s. AMS 199		uantum
Transfer	The module belongs to the S Physics. Taking into account the sections Study Focus, Ad accordance with the restrictive The module cannot be take Groups' due to the large overl	the cl vance e requ n tog	hose ed Kr uirem ethe	n pe nowle nents r wit	rson: edge of th	al Stud <i>in Mat</i> ne resp	ly Specialisa hematics or pective secti	ation, it can <i>Elective Sp</i> on.	be incl ecialis	luded in ation, in
Prerequisites	There are no further prerequis	sites.								
Responsible Persons	Stefan Keppeler									
Abbreviations:	_aradod_na_not aradod									

 $\label{eq:model} \mbox{Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio \\ \mbox{Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, }$

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-31	Module Title: Mathematical Methods for Condensed Matter Physics							Type of Module: Compulsory Module with Choice				
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h											
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	English	English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SWS	S								
Content	ematical tools necessary to topological insulators. In part Direct integrals on Hill Stability theorems for Bloch-Floquet transfortor. Introduction to the the	 Content: The course provides an introduction, with an analytic perspective, to the basic mathematical tools necessary to have a deeper understanding of the mathematical theories of topological insulators. In particular, the course will cover the following topics: Direct integrals on Hilbert spaces. Stability theorems for relatively bounded perturbations. Bloch-Floquet transformations and their application to the periodic Schrödinger operator. Introduction to the theory of vector bundles and Chern classes. Definition of the Bloch bundle. 										
Objectives	The students know, understathey have developed a deep a natural way in solid state essential results of the lecture. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present their	er uno physic e as w have a ethods them a	derstes. The ell as acquires of the ell as acquires of the ell and	andi he s ass ired he le o wo	ng o stude sessir a cor ecture erk or	f how rents are ng and nfident, e. They	mathematic e capable of explaining to precise and have learn on strategies	al concepts of naming and the presente of independe ed to transfe on their ow	are apond provent har the reference of t	oplied in ving the ections. Indling of methods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Mathematical Methods for Condensed Matter Physics	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise ce examination the coursework oral is decided by the instruc	must l	nave	bee	n acc	quired.	Whether th	e examination				
Transfer	The module belongs to the Mathematical Physics. Takin be included in the sections Specialisation, in accordance	ig into <i>Study</i>	Foci	ount us, A	the d Advai	chosen nced K	personal S nowledge i	itudy Specia n <i>Mathemat</i>	ılisatio <i>ics</i> or	n, it can <i>Elective</i>		
Prerequisites	In terms of content, only kno Mathematik are required.	wledg	e fro	m th	e ba	sic cou	rses of the	first two yea	rs in th	ne B.Sc.		

Responsible Persons	Stefan Teufel						
Abbreviations:							
Grading System : g	=graded, ng=not graded						
Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio							
Teaching Format : L	electure. LE=lecture with integrated exercises. SL=seminar or lecture. E=exercise class.						

Status : m=mandatory, o=optional

Other : h=hours, o.=or, s.M.=see module description, SWS=contact hours per week

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Module Number: MAT-65-32	Module Title: Type of Module: Mathematical Aspects of the Quantum Hall Effect Compulsory Module with Choice								Choice		
ECTS-Points	6	6									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h										
Duration	1 Semester	1 Semester									
Frequency	not regularly										
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Cl	ass 2	SW	S							
Content	Hall effect. In particular, the control of the classica Review of the classica Analysis of the Landau Linear response theor Wannier functions and Magnetic perturbation The students have learned, upper the lectures. In particular, the	 ontent: The course is focused on the description of mathematical models for the quantum all effect. In particular, the course will cover the following topics: Review of the classical Hall effect and historical introduction on the quantum Hall effect. Analysis of the Landau Hamiltonian and of the geometry of the Landau levels. Linear response theory and derivation of the Kubo formula. Wannier functions and their relations to the Hall conductivity. Magnetic perturbations and Streda formula. ne students have learned, understood, and become familiar with the concepts explained in the lectures. In particular, they have developed a deep understanding of the mathematical									
	aspects of the quantum Hall of and concepts from the lectur to put it into a larger framework state of research in the specion Through homework assignment and independent acquaintan lectures. They learn how to to develop solution strategies solutions and to stand for the	e as vork. The fic are ents a ce with transfer transfer transfer to the fire transfer transfe	well aney anea. Ind eal Ind the	as to are at xerci e not nese own a	exploie to se clations methand w	ain the description description asses to the description asses to the description as to the description as t	context de be and criti students de ments, and new proble group. The	eveloped in to cally challer evelop a continued methods ex ems, to ana	he lect nge the fident, kplaine lyse th	ure and current precise, d in the em and	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Mathematical Aspects of the Quantum Hall Effect	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise ce examination the coursework oral is decided by the instruct	must l	nave	beei	n acc	uired.	Whether th	e examination			
Transfer	The module belongs to the matical Physics. Taking the account, the module can be a Mathematics or Elective Specific Control of the module can be a mathematics.	perso assign	nal s ed to	speci the	alisa	tion an	d the restri	ctions of the	e secti	ons into	

Prerequisites	It is strongly recommended that the students have attended the course mathematical methods for condensed matter physics.
Responsible Persons	Stefan Teufel

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-33	Module Title: Wave Equations of Relativis		of Module:	le with	Choice						
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h										
Duration	1 Semester	1 Semester									
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SWS	S							
Content Objectives	Dirac equation. Representation Theo Relativistic Many-Par The students obtain knowled mechanics. They learn and solutions of the Klein-Gordot their properties. The studenty	Klein-Gordon equation.									
	results. They are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. They are able to describe and critically challenge the current state of research in the specific area. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their solutions and to stand for them in a critical discourse if necessary.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Wave Equations of Relativistic Quantum Mechanics	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise c tion is written or oral is decid										

Literature	Exemplary Literature:
	Bernd Thaller: The Dirac equation. Springer 1992.
	 Silvan S. Schweber: An introduction to relativistic quantum field theory, Chap. 2-4. Dover Books 2005.
	Paul R. Garabedian: Partial differential equations. AMS 1998.
	Erich Zauderer: Partial differential equations of applied mathematics. Wiley 2006.
Transfer	The module belongs to the <i>Study Specialisation Mathematical Physics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge in Quantum Mechanics and Special Relativity Theory is expected. Moreover, basic knowledge of Functional Analysis and Partial Differential Equations would be helpful but is not mandatory.
Responsible Persons	Roderich Tumulka
Abbreviations	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-36	Module Title: Quantum Information Theory Type of Module: Compulsory Module with Cho									
ECTS-Points	9	9								
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h							
Duration	1 Semester	1 Semester								
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS									
Content	Content:									
	universality and meas		outer: Quantum gates, quantum circuits,							
			, quantum teleportation and superdense							
	coding. Quantum key		, quantum teleportation and superdense							
	Physical realizations:	DiVincenzo criteria, Cira	c Zoller quantum computer, Circuit QED.							
	Decoherence and op	en quantum systems.								
		ction. Fault tolerant quant								
	·		patic quantum computation.							
	Introduction to the the entanglement, multip		Definition, criteria and measurement of							
Objectives	Students are familiar with the basic concepts and theoretical tools of quantum information processing. They understand the concept of quantum algorithms and quantum circuits and have learnt how to program a quantum computer. They understand how important quantum algorithms work and can describe quantum channels. They know the principles of quantum error correction and entanglement theory and also understand the most advanced concepts of physical realisations of quantum computers. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Quantum Information	L	f	4	6	yes	wr. o.	90-180	g	100
	Theory	ü	f	2	3		or.	o. 20-30		
	In this module an exercise cer examination the coursework n oral is decided by the instructo	nust l	nave	beer	n acc	uired.	Whether the	e examinatio		
Literature	Exemplary Literature:									
	tion. http://mmrc.ams • Ronald de Wolf: Quan ~rdewolf/qcnotes.pd • John Preskill: Quantur	 Michael A. Nielsen, Isaac L. Chuang: Quantum Computation and Quantum Information. http://mmrc.amss.cas.cn/tlb/201702/W020170224608149940643.pdf Ronald de Wolf: Quantum Computing: Lecture Notes. https://homepages.cwi.nl/~rdewolf/qcnotes.pdf John Preskill: Quantum Computation. Lecture Notes. http://theory.caltech.edu/~preskill/ph219/index.html 						cwi.nl/		
Transfer	The module belongs to the S the chosen personal Study S Advanced Knowledge in Matistrictive requirements of the re	pecia hema	alisat <i>tics</i> (ion, or <i>El</i>	it ca <i>lectiv</i>	n be ir	ncluded in t	he sections	Study	Focus,
Prerequisites	There are no prerequisites.									
Responsible Persons	Angela Capel Cuevas									
Abbreviations: Grading System : g=graded, ng=not graded Examination Type : MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=Seminar, IC=inverted classroom										

Status : m=mandatory, o=optional

Module Number: MAT-65-37	Module Title:Type of Module:Matrix Analysis and ApplicationsCompulsory Module with 0									
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 180 h 120 h									
Duration	1 Semester					·				
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 3 SWS + Exercise C	class 1 S	WS							
Content	Content: Foundations of opera Mappings and algebra Positive matrices. Functional calculus a Matrix monotone func Matrix means and ine Applications in quanti	as. nd deriva ctions and qualities.	ations. d conve	exity.		matrices an	d tensor pro	ducts.		
Objectives	Students have acquired incoming tional analysis. They have I matrices, including topics surentropies, quantum Markov tions of matrix analysis in quand proving the essential resented connections. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	become to the comment of the comment	familianonoton etc. The information the lector of the lead to wo	with e mainey a tion to ture a correcture or the correct or the correcture or the correct or the corre	some trix fun re also heory. s well dident, . They solution	aspects of ctions, mat o familiar w The stude as assession precise an have learn on strategie	analysis in rix averages ith several to the several	the co ypical able of aining ent har er the r	ntext of risation, applicanaming the prediction of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Marix Analysis and Applications In this module an exercise of examination the coursework	L f			uired a					

Literature	Exemplary Literature:
	 Fumio Hiai, Denes Petz: Introduction to Matrix Analysis and Applications. https://math.bme.hu/~petz/matrixPD.pdf
	• Denes Petz: Matrix Analysis with some Applications. https://math.bme.hu/~petz/matbme.pdf
	Rajendra Bhatia: Matrix Analysis. Springer 1997.
	Rajendra Bhatia, Positive Definite Matrices. Princeton University Press 2007.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge of functional analysis is desirable.
Responsible Persons	Angela Capel Cuevas
Abbreviations:	

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-65-38	Module Title:Type of Module:Hamiltonian SystemsCompulsory Module with Cho									Choice					
ECTS-Points	9														
Workload - Time in Class - Self-Study	Workload: Time in Class: 90 h							udy:							
Duration	1 Semester														
Frequency	not regularly	not regularly													
Term	1-3														
Language of Instruction	German or English														
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SW	S											
Content	in classical mechanics. This plectic geometry and dyname the lecture are: Symplectic manifolds Darboux-Moser theor Lagrangian and Hami Integrable systems are Moment mappings. Symplectic reduction.	 Symplectic manifolds and the canonical 1-form of the cotangent bundle. Darboux-Moser theorem. Lagrangian and Hamiltonian systems. Integrable systems and Arnold-Liouville theorem. 													
Objectives	methods of symplectic geom of different areas of mathen theoretical physics. The stuthe lecture as well as assess in the exercise classes they the terms, statements and mon new problems, to analyse	The students are familiar with the theory of Hamiltonian systems and their investigation using methods of symplectic geometry. They are familiar with the interplay of methods and questions of different areas of mathematics (differential geometry, geometry, dynamical systems) and theoretical physics. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.													
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade					
	Hamiltonian Systems	L E	f	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100					
	examination the coursework	must l	have	bee	n acc	juired.	Whether th	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.							

Literature	Exemplary Literature:
	Vladimir I. Arnold: Mathematical methods of classical mechanics. Springer 1989.
	Ana Cannas da Silva: Lectures on symplectic geometry. Springer 2001.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, knowledge from the Geometry in Physics module is assumed.
Responsible Persons	Carla Cederbaum

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:continuous} \begin{tabular}{ll} Teaching Format : L=lecture, & LE=lecture & with integrated exercises, & SL=seminar & or lecture, & E=exercise & class, & T=tutorial, & P=project, & S=Seminar, & IC=inverted & classroom & IC=inverted & Class$

Status : m=mandatory, o=optional

Module Number: MAT-65-39	Module Title: Propagation of Chaos							Type of Module: Compulsory Module with Choice			
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		lass			Self-St 180 h	Self-Study: 180 h			
Duration	1 Semester										
Frequency	regelmäßig										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS										
Content	 Content: Interacting many body systems (quantum and classical), importance of correlations. Mean-field situations (e.g., Vlasov) and collisions (Boltzmann). Explicit treatment of correlations. Large deviations from the expected value. 										
Objectives	Students learn how different kinds of many-body systems can be described by effective, non-linear equations. They are able to distinguish and compare different types of convergence of microscopic many-body systems against the effective theory, both in classical and quantum mechanical situations. Based on an argument similar to the law of large numbers, they understand how the independence of particles leads to the effective equation. They learn to prove that independence is indeed preserved - at least approximately - under the evolution of time (propagation of chaos). Building on this, they understand various proof strategies adapted to the respective situation. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Propagation of Chaos	L ?	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.									
Literature	Exemplary Literature: Louis-Pierre Chaintron, Antoine Diez: Propagation of chaos: a review of models, methods and applications. arXiv:2203.00446. Francois Golse: Mean-Field Limits in Statistical Dynamics. arXiv:2201.02005.										

Transfer	The module belongs to the <i>Study Specialisations Mathematical Physics</i> and <i>Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	In addition to the basics of analysis and linear algebra, the content of the Stochastics module is a prerequisite.
Responsible Persons	Peter Pickl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-01	Module Title: Algorithms of Numerical Mat		Type of Module: Compulsory Module with Choice								
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	Self-Study: 180 h			
Duration	1 Semester										
Frequency	regelmäßig										
Term	1-3	1-3									
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS										
Content	 Content: Advanced, big algorithms of numerics (without differential equations) such as: Fast Fourier transformation; QR algorithms for the calulation of eigenvalues; Method of conjugated gradients and more general Krylov space methods as iterative methods in numeric linear algebra and in non-linear optimisation; Simplex method and interior point methods in linear optimisation. 										
Objectives	The students have learned the key concepts, results, and methods of algorithmic numerical mathematics. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Algorithms of Numerical L f 4 6 yes wr. o. 90-180 o. 20-30 g 100 In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or										
Literature	oral is decided by the instructor with approval by the Board of Examiners. Exemplary Literature: • Peter Deuflhard, Andreas Hohmann: Numerische Mathematik 1. De Gruyter 2008. • Martin Hanke-Bourgeois: Grundlagen der Numerischen Mathematik und des Wissenschaftlichen Rechnens. Vieweg 2009.										
Transfer	The module belongs to the Study Specialisation Numerical Mathematics and Optimisation. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.										

Prerequisites	There are no further prerequisites.
Responsible Persons	Christian Lubich, Andreas Prohl
Abbreviations:	

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ $SSeminar, } \mbox{ IC=inverted classroom}$

Status : m=mandatory, o=optional

Module Number: MAT-70-02	Module Title: Numerics of Stationary Differ		Type of Module: Compulsory Module with Choice								
ECTS-Points	9						'				
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	Self-Study: 180 h			
Duration	1 Semester										
Frequency	regelmäßig										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS										
Content	Content: Numerical covering of boundary value problems of stationary (i.e. time independent) ordinary and elliptic partial differential equations, with emphasis to the methods of finite elements.										
Objectives	The students have learned the central terms, results and methods of the numerical treatment of boundary value problems of stationary differential equations. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Numerics of Stationary Differential Equations	L ü	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise context examination the coursework oral is decided by the instruction	must l	nave	beer	n acc	uired.	Whether th	e examination			
Literature	Dietrich Braess: Finite Elemente. Springer Spektrum 2013. Wolfgang Hackbusch: Theorie und Numerik elliptischer Differentialgleichungen. Teubner 1986.										
Transfer	The module belongs to the <i>Study Specialisation Numerical Mathematics and Optimisation</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.										
Prerequisites	Knowledge of the numerical	algorit	hms	mod	ule is	s helpfı	ul, but not n	nandatory.			
Responsible Persons	Christian Lubich										

 $Grading \ System \quad : g=graded, \ ng=not \ graded$

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-03	Module Title: Numerics of Instationary Differential Equations							Type of Module: Compulsory Module with Choice			
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	•		Self-Si 180 h	Self-Study: 180 h			
Duration	1 Semester										
Frequency	regelmäßig										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS										
Content	Content: Numerical treatment of transient (i.e. time-dependent) differential equations, such as: stiff ordinary differential equations, stochastic differential equations, parabolic and hyperbolic partial differential equations.										
Objectives	The students have learned the central terms, results and methods of the numerical treatment of boundary value problems of instationary differential equations. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Numerics of Instationary Differential Equations	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise ce examination the coursework oral is decided by the instruc	must l	nave	beei	n acc	uired.	Whether th	ie examinatio			
Literature	Exemplary Literature:										
	 Ernst Hairer, Gerhard Wanner: Solving Ordinary Differential Equations II. Stiff Problems. Springer 1996. Vidar Thomee: Galerkin Finite Element Methods for Parabolic Problems. Springer 1997. 										
Transfer	The module belongs to the Taking into account the chos tions Study Focus, Advanced dance with the restrictive req	en pe d <i>Kno</i> v	rson vledg	al St ge in	udy : <i>Mati</i>	Specia hemati	lisation, it c cs or <i>Electi</i>	an be includ	led in	the sec-	
Prerequisites	Knowledge from the module absolutely necessary.	Nume	erics	of S	tatior	nary Di	fferential E	quations is h	nelpful,	but not	
Responsible Persons	Christian Lubich										

 $Grading \ System \quad : g=graded, \ ng=not \ graded$

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-04	Module Title: Ordinary Differential Equatio		of Module: ulsory Modu	le with	Choice							
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-S 180 h	Self-Study: 180 h				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS											
Content	Content:						·					
	Non-linear ordinary differential equations: Theorems of Hartman-Grobman and Poincare-Bendixson, bifurcation theory.											
	 Numerical approximation: linear multi-step processes, adaptive processes, geometric integration. 											
Objectives	Students are familiar with the basic methods for studying qualitative behavior and for simulating solutions of non-linear ordinary differential equations. They have learned constructive methods for solving them and are in principle able to implement these with the help of the computer. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.											
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Ordinary Differential Equations - Analysis and Numerics	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.											
Literature	Exemplary Literature: Lawrence Perko: Differential equations and dynamical systems. Springer 1993. David Griffiths, Desmond J. Higham: Numerical methods for ordinary differential equations. Springer 2010.											
Transfer	merical Mathematics and Opticalisation, it can be included	The module belongs to the <i>Study Specialisations Analysis and Differential Geometry</i> and <i>Numerical Mathematics and Optimisation</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective										

Prerequisites	Basic knowledge of the theory of the ordinary differential equations are required, such as those taught in the module algorithms of numerical mathematics.
Responsible Persons	Andreas Prohl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-05	Module Title: Optimal Control Theory with tions		of Module: ulsory Modu	le with	Choice					
ECTS-Points	5									
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		lass	:		Self-St 180 h	udy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS								
Content	Content:	Content:								
	Brief overview of exist	ence	and ı	uniqu	ienes	ss theo	ry for ODEs	S.		
	 Numerical solutions to 	Numerical solutions to ODEs.								
	Introduction to optimal control problems with ODEs.									
	 Existence and uniqueness theory for linear quadratic optimal control problems (LQ problems). 									
	Pontryagin's maximum principle.									
	Numerical approxima	ion of	LQ	orobl	ems.					
Objectives	Students are familiar with the tions and various approaches statements on unambiguous essential results of the lectur. In the exercise classes they the terms, statements and mon new problems, to analyse. They are able to present the	s to s solva e as w have ethod them	olvin bility ell as acqu s of t and t	g the The s ass ired he le to wo	e pro e stud essir a cor ecture rk or	blem. dents a ng and nfident, e. They n solution	They are al re capable explaining to precise an have learn on strategies	so familiar of naming a he presented independed to transfes on their ow	with qu nd prod d conn ent har er the n	alitative ving the ections. adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Optimal Control Theory with Ordinary Differential Equations	L ü	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise context examination the coursework oral is decided by the instruction	must	have	bee	n acc	quired.	Whether th	e examinati		
Literature	Exemplary Literature:					_				
	Matthias Gerdts: Opti	mal C	ontro	ol of (DDE	and D	AEs. De G	ruyter 2012.		

Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Numerical Mathematics and Optimisation. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the module Analysis and the sub-module Introduction to Ordinary Differential Equations is assumed.
Responsible Persons	Andreas Prohl

 $Grading \ System \quad : g=graded, \ ng=not \ graded$

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-06	Module Title: Numerics of Differential Equa	ations	of Sı	urfac	es			of Module: ulsory Modul	e with	Choice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h		lass	:		Self-Si 120 h	tudy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3	1-3								
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS								
Content	Semi- and fully discre face finite elements an	 Numerical treatment of differential equations on moving (or stationary) surfaces. Semi- and fully discretization of elliptic and parabolic equations on surfaces using surface finite elements and efficient time integrators. Implementation of the algorithms. 								
Objectives	Students have learned the basic methods and techniques of numerics for problems on (moving) surfaces. In particular, they are familiar with the discussed energy techniques, which are very strong, general and rich in application, even in surface-independent areas of numerics. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Numerics of Differential Equations of Surfaces	c: Type of Course	t Status	SMS 2	s ECTS	s Assignments	Type of Exam o. o.	Our. of Exam (min) 90-180 0. 20-30	Grading	Weight for Grade
	In this module an exercise ce examination the coursework oral is decided by the instruc	ertifica must l	te is	to be	e acc	quired.	Whether th	ie examinatio		
Literature		oral is decided by the instructor with approval by the Board of Examiners. Exemplary Literature: Gerhard Dziuk: Finite elements for the Beltrami operator on arbitrary surfaces. 1988. Gerhard Dziuk, Charles M. Elliott: Finite elements on evolving surfaces. 2007.								
Transfer	The module belongs to the Taking into account the chostions Study Focus, Advanced dance with the restrictive requirements.	en pe d <i>Kno</i> v	rson vled	al St ge in	udy <i>Mati</i>	Special hematic	lisation, it o es or <i>Electi</i>	an be includ	led in	the sec-

Prerequisites	Knowledge of the numerical algorithms module is helpful, but not mandatory.
Responsible Persons	Christian Lubich
Abbreviations:	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ $SSeminar, } \mbox{ IC=inverted classroom}$

Status : m=mandatory, o=optional

Module Number: MAT-70-11	Module Title: Stochastic Differential Equation	ons						of Module: ulsory Modu	le with	Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass			Self-St 180 h	tudy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS	ecture 4 SWS								
Content	Wiener process, randoDiffusion semigroup, ItSolution of a stochasti	 Stochastic processes, filtrations, martingales. Wiener process, random walk, Donsker's theorem. Diffusion semigroup, Itos integral. Solution of a stochastic differential equation. Markov property, Malliavin calculus, rough path theory. 								
Objectives	Students master the basic pridifferential equations. The strong of the lecture as well as asserting the exercise classes they be the terms, statements and many on new problems, to analyse to They are able to present their	udent ssing nave a ethods them a	s are and acquis of t and t	e cap expla ired a he le o wo	able aining a cor cture rk or	of nang the position of the po	ning and pr resented co precise an have learn on strategie	oving the estions. Indicate the discrepance of the transfers on their own.	ssentia ent har er the r n or in	I results Indling of the second seco
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Stochastic Differential Equations	Lü	f	4 2	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise ce examination the coursework oral is decided by the instruct	must ł	nave	beer	acc	quired.	Whether th	e examinati		
Literature	Exemplary Literature: • Bernt Oksendal: Stoch	nastic	diffe	rtial e	equa	tions. S	Springer 20	00.		
Transfer	The module belongs to the <i>St</i> Stochastics. Taking into acco in the sections <i>Study Focus</i> , in accordance with the restrict	unt th Advar	e ch	osen <i>Kno</i> i	pers	sonal S ge in M	tudy Specia <i>lathematics</i>	alisation, it c or <i>Elective</i>	an be i	ncluded

Prerequisites	Knowledge of the modules Stochastics and Introduction to Integration and Measurement Theory from the Bachelor of Science programme is assumed.
Responsible Persons	Andreas Prohl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-12	Module Title: Introduction to Stochastic Diff	erenti	ial Ed	quati	ons -	Part 1		of Module: ulsory Modul	le with	Choice
ECTS-Points	5									
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-Si 180 h	tudy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise CI	ass 1	SWS	S						
Content	Content:					· ·				
	Introduction to Brownia	Introduction to Brownian motion and stochastic integration.								
	Solution concepts for stochastic differential equations.									
	Stability of stochastic differential equations.									
	Numerical approximation of stochastic differential equations.									
Objectives	Students master the basic principles and techniques for constructing solutions of stochastic differential equations. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Stochastic Differential Equations - Part	L	f	2	3	yes	wr. o.	90-180	g	100
	1	Е	f	1	2	,00	or.	o. 20-30	9	100
	In this module an exercise ce examination the coursework oral is decided by the instruct	nust ł	nave	bee	n acc	uired.	Whether th	e examination		
Literature	Exemplary Literature:									
	Bernt Oksendal: Stoch	nastic	diffe	renti	al eq	uations	s. Springer	2000.		
Transfer	The module belongs to the S and Stochastics. Taking into included in the sections Studicialisation, in accordance with	acco y Foc	ount us, A	the I <i>dva</i>	chos nced	en per <i>Knowl</i>	sonal Study <i>edge in Ma</i>	y Specialisa thematics or	tion, it <i>Elect</i>	can be
Prerequisites	Knowledge from the modules from the Bachelor of Science						on to Integr	ation and M	easure	e Theory

Other

Responsible Persons	Andreas Prohl							
Abbreviations:								
Grading System : g	=graded, ng=not graded							
Examination Type : N	IT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio							
	=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, =tutorial, P=project, S=Seminar, IC=inverted classroom							
Status : n	n=mandatory, o=optional							

Module Number: MAT-70-15	Module Title: Numerics of Stochastic Differ	ential	Equ	atio	ns			f Module: Ilsory Modul	le with	Choice
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h	Time in Class: 30 h					Self-St 60 h	Self-Study: 60 h		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS								
Content	Content:									
	 Random number generator, Ito-Taylor expansion. Strong and weak approximation, consistency. Euler-Maruyama method, Milstein method, stochastic Runge-Kutta method. Approximation of stopped diffusion processes. 									
Objectives	Students master the basic pr tions of stochastic differential essential results of the lecture	equa	tions	. Th	ne stu	dents a	re capable	of naming a	nd pro	ving the
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Numerics of Stochastic Dif- ferential Equations	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	ecided	by the instru	uctor with a	pprova	I by the
Literature	Peter E. Kloeden, Ecktions. Springer 1999.	khard	Plate	en:	Nume	erical s	olution of st	ochastic dif	ferentia	al equa-
Transfer	The module belongs to the Si Stochastics. Taking into accoin the sections Study Focus, in accordance with the restrict	unt th <i>Advar</i>	e ch	ose Kna	n pers	sonal S ge in M	tudy Specia <i>lathematics</i>	lisation, it ca or <i>Elective</i>	an be i	ncluded
Prerequisites	Knowledge from the Stochas	tics m	odul	e in	the B	achelo	r of Science	is required		
Responsible Persons	Andreas Prohl									

 $Grading \ System \quad : g=graded, \ ng=not \ graded$

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-16	Module Title: Stochastic Optimal Control in	Infini	te Di	men	sions	6		f Module: Ilsory Modu	le with	Choice		
ECTS-Points	3	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	lass	:		Self-St 60 h	Self-Study: 60 h				
Duration	1 Semester											
Frequency	not regularly	not regularly										
Term	1-3											
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS										
Content	Content: The course covers aspects of stochastic optimal control, an interdisciplinary subject at the overlap of analysis, optimisation, partial differential equations and stochastics, which lead the participants to topics in current research. The choice of contents takes the knowledge of the participants into consideration.											
Objectives	The students aquire deepend knowledge in stochastic optimal control that introduce them to a current area of research and that allow them to start a small research project. The students can name and prove the central results of the lecture and they can explain their intrinsic connections.											
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Stochastic Optimal Control in Infinite Dimensions	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100		
	Whether the examination is value Board of Examiners.	writte	n or	oral	is de	ecided	by the instru	uctor with a	pprova	l by the		
Transfer	The module belongs to the sand Stochastics. Taking into included in the sections Studicialisation, in accordance with	acco y Foc	ount us, A	the I <i>dva</i>	chos ncea	en per <i>Knowi</i>	sonal Study <i>ledge in Ma</i> i	Specialisa Specialisa	tion, it <i>Elect</i>	can be		
Prerequisites	The contents of the module N	lumer	ics a	re a	ssum	ned.						
Responsible Persons	Andreas Prohl											
Abbreviations:												

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-20	Module Title: Introduction to Optimisation							of Module: ulsory Modu	le with	Choice	
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass	:		Self-St 120 h	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 3 SWS + Exercise C	Lecture 3 SWS + Exercise Class 1 SWS									
Content	 problems with constra Foundations of the the Duality theory for converse 	 Optimality theory for smooth, convex and linear optimisation problems optimisation problems with constraints. Foundations of the theory of convex sets and functions. Duality theory for convex and linear optimisation problems. Solution methods for linear optimisation problems. 									
Objectives	Students know and underst timisation problems. They he economics, technology or pherimitations of using the method tial results of the lecture as we in the exercise classes they the terms, statements and mon new problems, to analyse They are able to present their	nave leads. The second	earnt The he st asse acqui s of t and t	to a ey wi tuder essin ired a he le o wo	ipply If be nts ar g and a cor ecture rk or	the manager able to the capa dexplain a capa d	ethods to s critically as ble of nami ining the pr precise an have learn on strategies	imple problessess the peng and provesented cord independent of transfess on their ow	ems re ossibiliting the nnection ent har er the r	lated to ties and e essen- ns. adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Optimisation	L E	f	3	4,5 1,5	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise context examination the coursework oral is decided by the instruction	must l	nave	beei	n acc	uired.	Whether th	e examination			
Literature	Exemplary Literature:										
	 Florian Jarre, Joseph Methoden. Springer 2 Jorge Nocedal, Steph 	019.			_		-			orie und	

Transfer	The module belongs to the <i>Study Specialisation Analysis and Differential Geometry</i> and <i>Numerical Mathematics and Optimisation</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Only basic knowledge of linear algebra and analysis is required.
Responsible Persons	Christian Lubich

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-21	Module Title:Type of Module:Non-Linear OptimisationCompulsory Module with Choice									
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	regelmäßig									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS									
Content	method. Restricted optimisatio Abadie CQ, KKT cond Linear programme, du Penalty and barrier m	Finite-dimensional optimisation, gradient method with Armijo's rule, globalised Newton								
Objectives	Students master the basic proptimisation problems. The softhe lecture as well as asserting the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	studen essing have a ethoda them	ts are and acqui s of thand to	e cap expla red a he le o wo	pable aining a cor cture rk on	e of nar g the profident, e. They n solution	ning and presented co precise an have learn on strategie	oving the estinnections. d independented to transfers on their own	ssentia ent har er the r n or in	I results adling of methods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Non-Linear Optimisation	L	f	4	6	yes	mP	20-30	g	100
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.								
Literature	Exemplary Literature:									
	Carl Geiger, Christiar gaben. Springer 2002		ow:	The	orie u	und Nu	merik restr	ingierter Op	timieru	ıngsauf-

Transfer	The module belongs to the <i>Study Specialisation Numerical Mathematics and Optimisation</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Andreas Prohl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-22	Module Title:Type of Module:Optimisation with Differential EquationsCompulsory Module with Choice									
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS									
Content	Content:									
	Direct method in the c	alculu	s of v	varia	tions	, Euler	-Lagrange e	equation.		
	Brouwer-Minty theore	n, nor	n-line	ar e	voluti	on equ	ations.			
	Gateaux and Frechet	differe	ntiab	ility.						
	Proof of existence of controls	Proof of existence of optimal controls, necessary optimality conditions.								
	Adjoint, convergent op	timisa	ation	meth	nods	in Ban	ach spaces			
	Variational discretisati	on coi	ncept	ts.						
Objectives	Students master the basic pr totypical control problems w students are capable of nan assessing and explaining the In the exercise classes they the terms, statements and m on new problems, to analyse They are able to present thei	th coining a present the prese	nstra nd p ented acqui s of t and t	ints rovir con red he le o wo	in the ng the nection a core core	e form e esse ons. nfident, e. They n solution	of partial on the precise and have learn on strategies	lifferential ea of the lection d independent ed to transfe s on their ow	quatior ure as ent har er the r vn or in	well as adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Optimisation with Differential	L	f	4	6	yes	wr. o.	90-180	g	100
	Equations	ü	f	2	3	,	or.	o. 20-30		
	In this module an exercise ce examination the coursework oral is decided by the instruc	must l	nave	bee	n acc	uired.	Whether th	e examination		
Literature	Exemplary Literature:									
	Michael Hinze, Rene constraints. Springer 2		u, M	icha	el Ull	orich, S	Stefan Ullric	h: Optimiza	ation w	ith PDE

Transfer	The module belongs to the <i>Study Specialisations Analysis and Differential Geometry</i> and <i>Numerical Mathematics and Optimisation</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	The content of the Functional Analysis module is prerequisite for participation in this module.
Responsible Persons	Andreas Prohl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-25	Module Title: Numerical Optimisation		f Module: Ilsory Modul	le with	Choice					
ECTS-Points	5									
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass			Self-St 180 h	udy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	Content: An introduction to and technology with a focus									science
	Basic concepts of opt	imizatio	on.							
	Unconstrained optimi	zation a	and I	New	on-ty	/pe alg	orithms.			
	Optimization with equ	ations	as c	onsti	aints	S.				
	Optimization with inection	qualities	s as	cons	train	ts.				
	Applications:									
	Economy: resoScience: mode				•				ovno	rimontal
	design.	i esiiii	allUl	ı and	auc	ιριαιιοι	i to measui	emeni uaia	, ехре	illielilai
	 Engineering: digital airplanes, digital 				ation	of tech	nical syste	ms such as	bridge	es, cars,
Objectives	are capable of naming and and explaining the presented in the exercise classes they the terms, statements and mon new problems, to analyse	Students are familiar with the problems and numerical methods of optimization. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.								
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Numerical Optimisation	L ü	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise context examination the coursework oral is decided by the instruction	ertificat must h	ave	beer	acq acc	uired.	Whether the	e examination		

Literature	Exemplary Literature:
	Jorge Nocedal, Stephen J. Wright: Numerical Optimization. Springer 2006.
	 Stephen Boyd, Lieven Vandenberghe: Convex Optimization. Cambridge University Press 2004.
Transfer	The module belongs to the <i>Study Specialisation Numerical Mathematics and Optimisation</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further requirements.
Responsible Persons	Andreas Prohl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-30	Module Title:Type of Module:Theoretical Aspects of Machine LearningCompulsory Module with Choice									
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: 180 h	d: Time in Class: Self-Study: 120 h								
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SW	S						
Content	Content: The lecture covers	some	rece	ent a	spec	ts of th	eoretical m	achine learn	ing su	ch as:
	The theory of Reprod	ucing	Kern	el Hil	bert	Space	s (RKHS).			
	Applications of RKHS mean embeddings.	theory	/ suc	h as	SVM	ls, kerr	nel regressi	on, kernel P	CA, an	d kernel
	Approximation capable	lities c	of ne	ural r	etwo	orks.				
	Dynamics of neural	etwork	s an	d the	neu	ral tanç	gent kernel.			
	Recent advances in I generalisation.	 Recent advances in high dimensional statistics, in particular overparametrisation and generalisation. 								
Objectives	works, support vector mach modern topics in machine leand conceptual tools as need able to name and prove the explain the context developed able to describe and critically. Through homework assignment independent acquaintar lectures. They learn how to	The students learn the mathematical foundations of supervised learning theory, neural networks, support vector machines and kernel methods. They are familiar with fundamental modern topics in machine learning and with their theoretical basis, mathematical approach and conceptual tools as needed for the discussion and justification of algorithms. They are able to name and prove the essential statements and concepts from the lecture as well as to explain the context developed in the lecture and to put it into a larger framework. They are able to describe and critically challenge the current state of research in the specific area. Through homework assignments and exercise classes students develop a confident, precise, and independent acquaintance with the notions, statements, and methods explained in the lectures. They learn how to transfer these methods to new problems, to analyse them and to develop solution strategies on their own and within a group. They are able to present their								
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Theoretical Aspects of	L	f	2	3	yes	wr. o.	90-180	g	100
	Machine Learning	E	f	2	3	,	or.	o. 20-30		
	In this module an exercise of examination the coursework oral is decided by the instruction of the exceptional cases, be offer only 3 credit points are awar	must I tor wit ed wit	nave h ap hout	beei prova exer	n acc al by cises	quired. the Bo	Whether th ard of Exar	ie examination miners. – Th	on is w e mod	ritten or ule may,

Literature	Exemplary Literature:
	Mehryar Mohri, Afshin Rostamizadeh, Ameet Talwalkar: Foundations of Machine Learning. MIT Press 2012.
	 Shai Shalev-Shwartz, Shai Ben-David: Understanding Machine Learning: From Theory to Algorithms. CUP 2014.
	 Peter L. Bartlett, Andrea Montanari, Alexander Rakhlin: Deep learning: a statistical viewpoint. Acta Numerica 2021.
	 Daniel A. Roberts, Sho Yaida, Boris Hanin: The Principles of Deep Learning Theory: An Effective Theory Approach to Understanding Neural Networks. Cambridge University Press 2022.
Transfer	The module belongs to the Study Specialisations Numerical Mathematics and Optimisation and Stochastics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge in linear algebra, analysis and probability theory is needed as well as some knowledge in elementary Hilbert space theory.
Responsible Persons	Andreas Prohl
Abbreviations: Grading System : g	=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-31	Module Title: Statistical Learning Theory for Nonparametric Regression 1 Type of Module: Compulsory Module with Choice									Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS									
Content	Content:									
	Non-parametric regre	ssion,	regre	essio	n es	timator				
	(Universal) consistence	y.								
	Rate convergence.									
	Stone's theorem.									
	 Kernel estimator, k-NI 	N estir	nator	-						
	Slow rate convergenc	e, min	imax	con	verge	ence ra	tes.			
Objectives	Students are familiar with ba universal consistency and ra methods of stochastic learni are capable of naming and and explaining the presented In the exercise classes they the terms, statements and m on new problems, to analyse They are able to present the	te corng as proving connected have a ethod them are the them are th	requirection of the control of the c	ence ired ess ns. red a he le o wo	e. The for no ential correcture or the formal correction of the formal correction the formal	ney are nachine al result nfident, e. They n solution	familiar with the learning at soft he learning at soft the learning precise and have learn on strategies	th the basic applications. Sture as weld independent of transfers on their own.	princip The solution The soluti	oles and students sessing adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Statistical Learning Theory for Nonparametric	L	f	4	6	yes	wr. o.	90-180	g	100
	Regression 1	ü	f	2	3		or.	o. 20-30	9	
	In this module an exercise context examination the coursework oral is decided by the instruction	must l	nave	beer	n acc	uired.	Whether the	e examination		
Literature	Exemplary Literature:									
	 Laslo Györfi, Michael nonparametric regres 						rro Walk: A	distribution	-free tl	neory of

Transfer	The module belongs to the <i>Study Specialisation Numerical Mathematics and Optimisation</i> and <i>Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge of the Stochastics and Probability Theory modules is assumed.
Responsible Persons	Andreas Prohl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-32	Module Title: Statistical Learning Theory sion 2	for N	onpa	rame	etric	Regres		of Module: ulsory Modu	le with	Choice
ECTS-Points	9	9								
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 90 h 180 h									
Duration	1 Semester						·			
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS									
	 Abstract (strong) consproximating) function Examples, in particula neural networks estimates 	 The uniform law of large numbers on function classes (Vapnik-Chervonenkis theory). Abstract (strong) consistency theory for <i>least-squares</i> regression estimators on (approximating) function classes. Examples, in particular the <i>data dependent partitioning</i> estimator and the <i>least squares neural networks</i> estimator. Rate convergence for <i>least-squares</i> estimators. 								
Objectives	quired for machine learning a essential results of the lecture In the exercise classes they the terms, statements and m	Students are familiar with in-depth methods of stochastic learning and their analysis, as required for machine learning applications. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team.								
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Statistical Learning Theory for Nonparametric Regression 2	L ü	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise context examination the coursework oral is decided by the instruction	must l	have	beei	n acc	uired.	Whether th	ne examination		
Literature		Exemplary Literature: Laslo Györfi, Michael Kohler, Adam Krzyzak, Harro Walk: A distribution-free theory of nonparametric regression. Springer 2002.								
Transfer	The module belongs to the Single Stochastics. Taking into account the sections Study Focus, in accordance with the restrict	unt th <i>Advar</i>	e ch nced	osen <i>Kno</i>	pers wled	sonal S ge in M	tudy Special Sathematics	alisation, it c or <i>Elective</i>	an be i	ncluded

Prerequisites	Knowledge from the module Statistical Learning 1 is assumed.			
Responsible Persons Andreas Prohl				
Abbreviations: Grading System : g	=graded, ng=not graded			

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:lecture} \begin{tabular}{ll} Teaching Format : L=lecture, & LE=lecture & with integrated exercises, & SL=seminar & or lecture, & E=exercise & class, & T=tutorial, & P=project, & S=Seminar, & IC=inverted & classroom & IC=inverted & Classroo$

Status : m=mandatory, o=optional

Module Number: MAT-70-33	Module Title: Theory and Numerics for Co lems	nstrain	ied (Optim	isati	on Prol		of Module: ulsory Modu	le with	Choice
ECTS-Points	9	9								
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 90 h 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 4 SWS	ecture 4 SWS								
Content	gradient method with step siz minimum, as well as its varia Central to this is the convex of a minimum with (necessa Abadie condition, Karush-Kı	content: We start with the unconstrained convex minimisation problem (on spaces), and the radient method with step size control according to Armeijo for the approximate calculation of a ninimum, as well as its variants. The simplex method solves linear programmes on polyhedra. Sentral to this is the convex (non-linear) minimisation task on sets, and the characterisation of a minimum with (necessary) optimality conditions (tangent cone, linearised tangent cone, badie condition, Karush-Kuhn-Tucker conditions). In addition, numerical solution methods assed on these theoretical concepts (interior points method, penalty methods, SQP method) are presented and analysed.								
Objectives	The participants have become constrained optimisation prosimplex method, interior point be able to analyse the algornaming and proving the essenth the presented connections. In the exercise classes they the terms, statements and monnew problems, to analyse They are able to present the	blems: at methithms ential have a ethods them	the nods and resu acqu s of t	se incomplets of the letter would be incompleted and the letter work in the letter would be incompleted and the letter would be incomplete	cludenalisation control the control cturent or	e gradie ation me their co lecture nfident, e. They n solution	ent methods ethods and omplexity. It as well as precise an have learn on strategie	s with step s the SQP me ne students assessing d independent ed to transfers on their ow	ize corethod. are call and exent hare returned in the return or in	etrol, the You will pable of plaining adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Theory and Numerics for Constrained Optimisation Problems	L ü	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	examination the coursework oral is decided by the instruct exceptionally be offered by	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners. – The module may exceptionally be offered by the lecturer without exercise classes; in this case, only 6 credit points will be awarded for the module instead of 9.								
Literature	Exemplary Literature:									
	Carl Geiger, Christiar gaben. Springer 2002		ow:	The	orie	und Nu	merik restr	ingierter Op	timieru	ingsauf-

Transfer	The module belongs to the <i>Study Specialisation Numerical Mathematics and Optimisation</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further requirements.
Responsible Persons	Andreas Prohl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-70-40	Module Title: Game Theory							f Module:	le with	Choice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time in Class:					Self-St 60 h	Self-Study: 60 h			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS										
Content	Content: The focus is on Nash and ge	Content: The focus is on Nash and generalised Nash equilibrium problems and their numerical solution.									
Objectives	Students are familiar with the fundamental issues of game theory. They are familiar with analytical and numerical approaches to analysing them. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Game Theory	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is Board of Examiners.	writte	n or	oral	is de	ecided	by the instru	uctor with a	pprova	l by the	
Literature	Exemplary Literature: • Christian Kanzow, Ale										
Transfer	Taking into account the chost tions Study Focus, Advance	The module belongs to the Study Specialisation Numerical Mathematics and Optimisation. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.									
Prerequisites	Basic knowledge of analysis dents of related fields with base							ule is also s	uitable	for stu-	
Responsible Persons	Andreas Prohl										
Abbreviations:											

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title: Type of Module:						OI :			
MAT-75-01	Probability Theory									
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	_	lass	:		Self-St 180 h	udy:		
Duration	1 Semester	ı								
Frequency	regularly in Winter Semeste	•								
Term	1-3									
Language of Instruction	German	German								
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS									
Content	Content:									
	Characteristic functio	ns and	lame	endm	ents	to the	central limit	theorem.		
	Conditional expectation	ons an	d fur	ther	meas	sure-th	eoretic foun	dations.		
		 Markov chains and martingales in discrete time, classification, asymptotic behaviour, stopping times, stationarity, ergodicity. 								
	Introduction to procestion.	Introduction to processes in contiuous time like Poisson processes and Brownian motion.							ian mo-	
Objectives	The students got to know the can model, analyse and intermeasure theoretically found central results of the lecture. The students are capable of assessing and explaining the lin the exercise classes they the terms, statements and mon new problems, to analyst team. They are capable of prediscourse.	rprete and man as we finaming prese have a have a hethods	stoch nner. Ill as ng ar entec acqu s of t n an	The assend produced in the least term of the lea	e depe studes student	endendents ag and of the cons. ons. officent, ons. officent, ons.	cy structure re capable explaining the entral result precise and have learn plution strate	s of random of naming a ne presented sof the lected independent of transferies on the	quantind produced conniture as ent hare returned to the connitude to the connituation to the connitude to th	ties in a ving the ections. well as adding of nethods or in a
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Probability Theory	L	f	4	6	yes	wr. o.	90-180	a	100
	1 TODADIIITY THEOTY	Е	f	2	3	yes	or.	o. 20-30	g	100
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.								

Literature	Exemplary Literature:
	 Heinz Bauer: Wahrscheinlichkeitstheorie und Grundzüge der Maßtheorie. De Gruyter 2010.
	Richard Durrett: Probability, Theory and Examples. Cambridge University Press 2010.
	Hans-Otto Georgii: Stochastik. De Gruyter 2009.
	Jean Jacod, Philip E. Protter: Probability essentials. Springer 2004.
	 Olav Kallenberg. Foundations of Modern Probability. Springer 2002.
	Achim Klenke: Wahrscheinlichkeitstheorie. Springer 2013.
	David Meintrup, Stefan Schäffler: Stochastik. Springer 2005.
	Albert N. Shiryaev: Probability-1. Springer 2016.
Transfer	The module belongs to the <i>Study Specialisation Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Martin Möhle, Martin Zerner

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-75-02	Module Title: Type of Module: Combinatorics Compulsory Module with Choice									Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 90 h 180 h									
Duration	1 Semester	1 Semester								
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS								
Content	Content:									
	Basic combinatorial o	bjects.								
	Generating functions.									
	Semi-orders, Möbius	inversi	on.							
	Method of Polya and	Method of Polya and Redfield.								
	Symbolic combinatori	CS.								
	Transfer matrix methor	Transfer matrix method.								
	Euler-Maclaurin sumr	nation	form	ula.						
	Asymptotic methods.									
Objectives	The students have learned to discrete structures and cour mon identities and handling proving the essential results connections. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	nting pr counti of the have a nethods them a	roblering collectured to the collecture of the c	ms. pefficience as red a ne le po wo	Furth cients s well a corecture rk on	nermor s. The II as as nfident, e. They I solution	e they are f students a sessing and precise an have learn on strategies	amiliar with re capable of explaining dindepende ed to transfes on their owner in critical	applyir of nam the pro ent har er the n	ing coming and esented adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Combinatorics	L E	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	nave	beer	n acc	uired.	Whether th	e examination		

Literature	Exemplary Literature:
	Martin Aigner: Combinatorial theory. Springer 1997.
	Martin Aigner: A Course in Enumeration. Springer 2007.
	Richard P. Stanley: Enumerative combinatorics. Volume 1. Cambridge University Press 2011.
	 Francois Bergeron, Gilbert Labelle, Pierre Leroux. Combinatorial species and tree-like structures. Cambridge University Press 1998.
	Philippe Flajolet, Robert Sedgewick. Analytic Combinatorics. Cambridge University Press 2009.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Stochastics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge of algebra (group effects), function theory (Cauchy's integral formula) and the foundations of discrete mathematics are expected.
Responsible Persons	Martin Mühle, Martin Zerner, Elmar Teufl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-75-03	Module Title: Mathematical Statistics							of Module: ulsory Modul	le with	Choice
ECTS-Points	9	9								
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 180 h									
Duration	1 Semester									
Frequency	regelmäßig									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS								
Content	Content:									
	Statistical models, exp	onent	ial fa	milie	s, su	ufficien	t statistics.			
	Rao-Blackwell theore	m, Leh	man	n-Sc	heffe	theor	em, Cramer	-Rao theore	m.	
	Estimation methods, l tors.	 Estimation methods, UMVU estimator, quality criteria, asymptotic behaviour of estimators. 								
	Hypothesis testing, co	onfiden	ice ir	nterv	al, N	eyman	-Pearson le	mma.		
	Testing methods, UMI	PU tes	ts, 1	- and	l 2-sa	ample 1	ests.			
	Models with growing of	density	quo	tient	s, no	n para	metric mode	els.		
	Introduction in regress	sion ar	nd va	ıriand	ce an	alysis.				
Objectives	Students can model statistic struct, analyse, compare and results. The students are can as well as assessing and explication in the exercise classes they the terms, statements and modern on new problems, to analyse They are able to present the	d apply pable blaining have a thousand the thousand the market a the m	of nate of nate of the	tistica amin pres ired a he le o wo	al est g and sente a cor cture rk on	timatio d provi ed conr nfident, e. They n solution	n and test n ng the essenections. precise and have learn on strategies	nethods and ential results d independe ed to transfe s on their ow	interp of the ent har er the r or in	ret their lecture adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Mathematical Statistics	L	f	4	6	yes	wr. o.	90-180	a	100
	mathematical oldustics	Е	f	2	3	yes	or.	o. 20-30	g	100
	examination the coursework	n this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.								

Literature	Exemplary Literature:
	 Peter J. Bickel, Kjell A. Doksum: Mathematical Statistics: Basic Ideas and Selected Topics. Chapman & Hall 2016.
	Hans-Otto Georgii: Stochastik. De Gruyter 2009.
	Erich L. Lehmann, Joseph P. Romano: Testing statistical hypotheses. Springer 2005.
	Erich L. Lehmann, George Casella: Theory of point estimation. Springer 1998.
	Wiebe R. Pestman: Mathematical Statistics. De Gruyter 2009
	Helmut Pruscha: Vorlesungen über Mathematische Statistik. Springer Vieweg 2000.
	Mark J. Schervish: Theory of Statistics. Springer 1995.
Transfer	The module belongs to the <i>Study Specialisation Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge of the probability theory module is helpful, but is not mandatory.
Responsible Persons	Martin Mühle, Martin Zerner
, , ,	graded, ng=not graded IT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

 $Status \qquad \qquad : m{=}mandatory, \, o{=}optional$

Module Number: MAT-75-04	Module Title: Stochastic Processes						of Module: ulsory Modul	e with	Choice	
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 90 h 180 h									
Duration	1 Semester									
Frequency	regelmäßig									
Term	1-3									
Language of Instruction	German	German								
Forms of Teaching and Learning	Lecture 4 SWS	ecture 4 SWS								
Objectives	 arkov processes; Martingale; Brownian motion, Poi Gaussian processes. Among other things, exister these processes are analysed. The students have learnt the stochastic processes in contare capable of naming and and explaining the presented.	Stochastic processes in continuous time, such as • arkov processes; • Martingale; • Brownian motion, Poisson processes and general Levy processes;								
	In the exercise classes they the terms, statements and m on new problems, to analyse They are able to present the	ethods them a	s of t and t	he le o wo	cture rk on	e. They solution	have learne on strategies	ed to transfe s on their ow nem in critica	er the n	nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Stochastic Processes	L ü	f	4 2	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.								

Literature	Exemplary Literature:
	 Heinz Bauer: Wahrscheinlichkeitstheorie und Grundzüge der Maßtheorie. De Gruyter 2010.
	Joseph L. Doob: Stochastic Processes. Wiley 1990.
	 Samuel Karlin, Howard Taylor: A First Course in Stochastic Processes. Academic Press 1975.
	 Samuel Karlin, Howard Taylor: A Second Course in Stochastic Processes. Academic Press 1981.
	Götz Kersting, Anton Wakolbinger: Stochastische Prozesse. Birkhäuser 2014.
	Achim Klenke: Wahrscheinlichkeitstheorie. Springer 2013.
	James R. Norris: Markov Chains. Cambridge University Press 1997.
Transfer	The module belongs to the <i>Study Specialisation</i> Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	A sound knowledge of the Probability Theory module is assumed.
Responsible Persons	Martin Mühle, Martin Zerner

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-75-05	Module Title: Percolation Theory							f Module: Ilsory Modu	le with	Choice		
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h		lass	:		Self-St 60 h	udy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 2 SWS											
Content	Content:	Content:										
	Edge percolation on g	Edge percolation on graphs, especially on multidimensional grids.										
	Phase transitions.	Phase transitions.										
	Number of clusters and cluster sizes.											
	Special features in two dimensions.											
	Alternative percolation models.											
Objectives	Students can interpret special spatially indexed families of random variables as random geometric structures and apply probability theory methods to analyse them. Using simple models, they learn how microscopic changes can result in macroscopic phase transitions. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.											
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Percolation Theory	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100		
Literature	Exemplary Literature: • Béla Bollobás, Oliver • Geoffrey Grimmett: P						l bridge Unive	ersity Press	2006.			
Transfer	The module belongs to the Physics and Stochastics. To can be included in the section tive Specialisation, in according	aking ons <i>St</i>	into into into into into into into into	acco Focu	ount t is, A	he cho dvance	sen person d Knowledg	al Study Sp e in Mather	ecialis natics	sation, it or <i>Elec</i> -		
Prerequisites	Knowledge of the Probability	Theo	ry m	odul	e is h	elpful,	but not esse	ential.				
Responsible Persons	Elmar Teufl, Martin Zerner											

 $Grading \ System \quad : g=graded, \ ng=not \ graded$

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-75-06	Module Title: Stochastic Analysis									Choice		
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St 180 h	tudy:				
Duration	1 Semester						1					
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS										
Objectives	 Martingales and stopp Doléans measure, con Stochastic integral for martingales). Semimartingales, tran Itô formula (in particul Stochastic differential The students know the main and they know how to handle the lecture and they can explin the exercise classes they	 Martingales and stopping times in continuous time. Doléans measure, compensator, Doob-Meyer decomposition. Stochastic integral for square integrable martingales (in particular for non-continuous martingales). Semimartingales, transformation of stochastic integrals. Itô formula (in particular for processes with jumps). Stochastic differential equations . The students know the main notions, results, methods and examples from stochastic analysis and they know how to handle them. The students can name and prove the central results of the lecture and they can explain their intrinsic connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods										
Requirements for Obtaining Credit, Grading, Weight if	discourse.	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		

Literature	Exemplary Literature:
	Fabrice Baudoin: Diffusion Processes and Stochastic Calculus. EMS 2014.
	 Kai Lai Chung and Ruth J. Williams: Introduction to Stochastic Integration. Birkhäuser 1990.
	Richard Durrett: Stochastic Calculus. CRC Press 2006.
	Albrecht Irle: Finanzmathematik. Teubner 2003.
	 Ioannis Karatzas, Steven Shreve: Brownian Motion and Stochastic Calculus. Springer 1991.
	Michel Métivier: Semimartingales. De Gruyter 1982.
	Bernt Oksendal: Stochastic Differential Equations. Springer 2007.
	 Nicolas Privault: Stochastic Analysis in Discrete and Continuous Settings. Springer 2009.
	Daniel Revuz, Marc Yor: Continuous Martingales and Brownian Motion. Springer 1999.
	Heinrich von Weizsäcker, Gerhard Winkler: Stochastic Integrals, Vieweg 1990.
Transfer	The module belongs to the <i>Study Specialisation Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	A solid knowledge on probability theory is a prerequisite.
Responsible Persons	Martin Möhle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-75-07	Module Title: Information Theory							of Module:	le with	Choice				
ECTS-Points	9							•						
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass:			Self-St 180 h	tudy:						
Duration	1 Semester	1 Semester												
Frequency	not regularly													
Term	1-3													
Language of Instruction	German													
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	class 2	SWS	3										
Content	Content:													
	Entropy and entropy rates in the discrete case.													
	Theorem of Shannon-McMillan-Breiman.													
	Entropy rates of Markov chains.													
	Kolmogorov complex	ty.												
	Data compression.													
	Chanel capacity.													
	Differential entropy.													
Objectives	Students learn to describe in the basic theory to concrete also apply the theoretical or capable of naming and provexplaining the presented con in the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	e rando oncepto ring the nnection have a nethoda	om e s to s e ess ons. acqui s of t and t	experispections in the legal with the legal work in the legal with the legal work in the legal with the legal work in th	imen ific p al res a cor cture rk on	ts and roblem sults of nfident, e. They solution	stochastic s in coding the lecture precise an have learn on strategie	processes. theory. The as well as a dindependent of transfess on their ow	Stude e stude assess ent har er the r or in	ents can ents are sing and adling of nethods a team.				
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade				
	Information Theory	L	f	4	6	yes	wr. o.	90-180	g	100				
		Е	f	2	3	,55	or.	o. 20-30	9					
	In this module an exercise c examination the coursework oral is decided by the instruc	must l	nave	beer	n acc	uired.	Whether th	e examination						

Literature	Exemplary Literature:
	Robert B. Ash: Information Theory. Wiley. 1965.
	Thomas M. Cover, Joy A. Thomas: Elements of Information Theory. Wiley 2006.
	 David J.C. MacKay: Information Theory, Inference and Learning Algorithms. Cambridge 2003.
	Claude Shannon, Warren Weaver: The Mathematical Theory of Communication. University of Illinois Press 1949.
Transfer	The module belongs to the <i>Study Specialisation Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	In terms of content, knowledge from the modules Stochastics and Probability Theory is assumed.
Responsible Persons	Martin Mühle, Martin Zerner, Elmar Teufl
Abbreviations:	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

 $\label{eq:total_project} T = tutorial, \ P = project, \ S = Seminar, \ IC = inverted \ classroom$

Status : m=mandatory, o=optional

Module Number: MAT-75-08	Module Title: Mathematical Population Ge	netics						of Module: ulsory Modul	e with	Choice			
ECTS-Points	6												
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass	:		Self-St 120 h	udy:					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German	German											
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	Lecture 2 SWS + Exercise Class 2 SWS											
Content	Content:												
	Exchangeable population models.												
	Probability of extinction.												
	Descendants and ancestors.												
	Duality of Markoff pro	cesses	3.										
	Coalescent processes	s and a	essoc	ciate	d cor	nverge	nce rates.						
	Simple mutation mod	els, Ew	ens	sam	pling	formu	a.						
	Statistical applications	s, e.g. (estin	natin	g the	mutat	ion rate.						
Objectives	In the lecture, students lear an understanding for the int capable of naming and provexplaining the presented concurrent state of research in the exercise classes they the terms, statements and monnew problems, to analyse They are able to present the	eraction ing the inection he subj have a rethods them a	n of essons. Since the second in the second	georentia Stude area red a he le o wo	metri al res ents v a cor cture rk on	c and sults of vill be a fident, e. They a solution	algebraic m the lecture able to reflect precise and have learn on strategies	ethods. The as well as a ct and critica d independe ed to transfe s on their ow	e stude assess Ily ana ent har er the r	ents are sing and lyse the adling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Mathematical Population Genetics	L E	f f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100			
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	nave	beer	n acc	uired.	Whether the	e examinatio					

Literature	Exemplary Literature:
	Jean Bertoin: Random Fragmentation and Coagulation Processes. Cambridge 2006.
	Stewart N. Ethier, Thomas G. Kurtz: Markov Processes. Wiley 1986.
	Warren J. Ewens: Mathematical Population Genetics. Springer 2004.
	Jim Pitman: Combinatorial Stochastic Processes. LNM 1875. Springer 2006.
	John Wakeley: Coalescent Theory. Roberts & Company Publishers 2008.
Transfer	The module belongs to the <i>Study Specialisation Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	A sound knowledge of probability theory is assumed.
Responsible Persons	Martin Mühle

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-75-09	Module Title: Point Processes							of Module: ulsory Modul	e with	Choice				
ECTS-Points	6													
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass			Self-St 120 h	udy:						
Duration	1 Semester													
Frequency	not regularly													
Term	1-3	1-3												
Language of Instruction	German	German												
Forms of Teaching and Learning	Lecture 2 SWS													
Content	Content:													
	Random measures, point processes, Poisson processes.													
	Factorial measure, Mecke equation.													
	Transformation, labelling, thinning.													
	Characterisation of po	oint pro	cess	ses.										
	Stationary Poisson pr	ocesse	es.											
	Poisson integrals.													
	Cox processes.													
Objectives	The students have familiaris examples of the theory of po are capable of naming and p explaining the presented con current state of research in t In the exercise classes they the terms, statements and m on new problems, to analyse They are able to present the	int prod roving inection he sub have a tethods them a	cessons. Since the constant of	es aresser Stude area ired a he le o wo	nd cantial rents vonts v	in hand esults ovill be a nfident, e. They n solution	lle them ma of the lectur able to reflect precise and have learn on strategies	thematically e as well as contact and critical dindependent to transfers on their ow	The sassessally ana ent har er the r	students sing and lyse the adling of nethods a team.				
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade				
	Point Processes	L ü	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100				
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	nave	beei	n acc	uired.	Whether the	e examinatio						

Literature	Exemplary Literature:
	 Daryl John Daley, David Vere-Jones: An Introduction to the Theory of Point Processes. Springer 2008.
	Martin Jacobsen: Point Process Theory and Applications. Birkhäuser 2006.
	 Olav Kallenberg: Foundations of Modern Probability. Springer 2002.
	John F. C. Kingman: Poisson Processes. Clarendon Press 1993.
	Günter Last, Mathew D. Penrose: Lectures on the Poisson Process. Cambridge 2016.
Transfer	The module belongs to the <i>Study Specialisation Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	A sound knowledge of probability theory is assumed.
Responsible Persons	Martin Mühle
Abbroviotiono	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio $\label{eq:continuous} \begin{tabular}{ll} Teaching Format : L=lecture, & LE=lecture & with integrated exercises, & SL=seminar & or lecture, & E=exercise & class, & T=tutorial, & P=project, & S=Seminar, & IC=inverted & classroom & or lecture, & E=exercise & class, & SL=seminar & or lecture, & E=exercise & class, & SL=seminar & or lecture, & E=exercise & class, & SL=seminar & or lecture, & E=exercise & class, & SL=seminar & or lecture, & E=exercise & class, & SL=seminar & or lecture, & SL=seminar & or$

Status : m=mandatory, o=optional

Module Number:	Module Title:	Module Title: Graph Theory											
ECTS-Points	9						Compt	ulsory Modu	ie with	Choice			
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	:		Self-St	udy:					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German												
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS											
Content	Content:												
	Basic concepts in graph theory,												
	Basic graph theory algorithms,												
	Flows, cuts, connectedness, matchings,												
	Cycle and intersecting space (cohomology theory),												
	Spectral graph theory, matrix tree theorem,												
	 Planar graphs, theore 	em of K	urato	owsk	i and	Wagn	er,						
	Planar embeddings,												
	Graph colorings,												
	Theory of minors.												
Objectives	Students know the basic couse graph theory methods in algebra and be able to beneficial results of the lecture. In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	n practifit from Te as we have a nethods The them a	ce. Themell as acquired to the second to the	They a. The ass red he le o wo	will a e stu essir a cor cture rk on	also redents and	cognise cor are capable explaining t precise an have learn on strategies	nnections to of naming a he presente d independe ed to transfe s on their ow nem in critica	geome and pro d conn ent har er the n	etry and ving the ections. Idling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Graph Theory	L E	f	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100			
	In this module an exercise c examination the coursework oral is decided by the instruc	must h	nave	beei	n acc	uired.	Whether th	e examination					

Literature	Exemplary Literature:
	Bela Bollobas: Modern graph theory, Springer, 1998.
	John Adrian Bondy, Uppaluri Siva Ramachandra Murty: Graph theory, Springer, 2008.
	Reinhard Diestel: Graph theory, Springer, 2018.
	 Jonathan L. Gross, Jay Yellen, Mark Anderson: Graph theory and its applications, CRC Press, 2019.
Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Stochastics. Taking into account the chosen personal Study Specialisation, it can be included in the sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Elmar Teufl
	=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-75-11	Module Title: Markov Chains and Applicati	ons						of Module: ulsory Modul	e with	Choice		
ECTS-Points	9						·					
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		lass:			Self-St 180 h	udy:				
Duration	1 Semester											
Frequency	not regularly	not regularly										
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS											
Content	Content: Fundamentals and advanced topics on Markov chains and related stochastic models are discussed. In particular, the long-term behaviour of Markov chains is examined. Furthermore, applications of Markov chains, such as Markov chain Monte Carlo simulation, randomised search algorithms, graphical models, entropy rates of Markov chains, are discussed.											
Objectives	The students have learnt the basic concepts of the theory of Markov chains and related models. They are also familiar with applications of the theory and have experienced the interaction of probability theory and algorithms. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.											
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Markov Chains and Applications	L E	f	4 2	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise ce examination the coursework oral is decided by the instruc	must l	nave	beer	n acc	uired.	Whether th	e examinatio				
Literature	oral is decided by the instructor with approval by the Board of Examiners. Exemplary Literature: Pierre Bremaud: Discrete Probability Models and Methods. Springer 2017. Pierre Bremaud: Markov Chains. Springer 1999. Olle Häggström: Finite Markov Chains and Algorithmic Applications. Cambridge University Press 2002. Kevin Murphy: Machine Learning: A Probabilistic Perspective. MIT Press 2012. James Spall: Introduction to Stochastic Search and Optimization. Wiley 2003.											
Transfer	The module belongs to the sen personal Study Specialis Knowledge in Mathematics quirements of the respective	ation, or <i>Ele</i>	it ca ctive	ın be	incl	uded ir	the section	ns <i>Study Foo</i>	cus, Ad	dvanced		

Prerequisites	Good knowledge of linear algebra and stochastics is required. Knowledge from the probability theory module is helpful, but is not required.
Responsible Persons	Elmar Teufl

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number:	Module Title:						Type of Module:				
	Foundations of Discrete Mathematics Compulsory Module with Choice										
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in C	lass	•		Self-St 180 h	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS										
Content	Content:										
	• Logic.										
	Sets, relations, functions.Semi-orders.										
	Combinatorics. Number theory.										
	Graph theory.										
	Algorithms and formal languages.										
	Discrete optimization.										
Objectives	Students have learned how to use basic methods of discrete mathematics. They can analyze discrete structures and identify discrete structures in different contexts. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods on new problems, to analyse them and to work on solution strategies on their own or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Foundations of Discrete	L	f	4	6	yes	wr. o.	90-180	g	100	
	Mathematics	E	f	2	3	_	or.	o. 20-30			
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.										

Literature	Exemplary Literature:
	 Ronald Graham, Donald Knuth, Oren Patashnik: Concrete Mathematics. Addison-Wesley 1994.
	Kenneth H. Rosen: Discrete Mathematics and Its Application. McGraw-Hill 2019.
	Ralph P. Grimaldi: Discrete and Combinatorial Mathematics. Addison-Wesley 2004.
	Norman L. Biggs: Discrete Mathematics. Oxford University Press 2002.
Transfer	The module belongs to the <i>Study Specialisations Algebra and Geometry</i> and <i>Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Martin Mühle, Martin Zerner, Elmar Teufl
Abbassistions	

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional

Module Number: MAT-75-20	Module Title: Probability Sistances for Sata Science					Type of Module: Compulsory Module with Choice				
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass	:		Self-St 120 h	udy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS									
Content	Content: We study different concepts of distances between probability measures aimed at applications in data science. The classes of distances which are studied include optimal transport distances, f-divergences and integral probability metrics. The focus is on fundamental mathematical properties of these distances, like duality, famous inequalities, geometric aspects, and quantisation. Several applications in the area of data science and machine learning are illustrated throughout, for instance related to clustering, autoencoders, GANs, image processing, and compression.									
Objectives	Students are familiar with commonly used distances on the space of probability measures, particularly optimal transport distances, divergences, and integral probability metrics. They understand key mathematical results in this area, for instance related to duality, geometric aspects, and quantisation, as well as the interplay between different distances. They have further obtained an understanding of computational aspects and applicability in selected areas of data science. They are able to name and prove the main statements of the lecture as well as categorise and explain the relationships presented. Students will be able to reproduce and critically scrutinise the current state of research in the specialist area addressed. In the exercises, they have developed a confident, precise and independent approach to the concepts, statements and methods from the lecture. They have learned to transfer the methods to new problems, to analyse them and to develop solution strategies alone or in a team. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Assignments	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Probability Sistances for Sata Science	L E	f f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.									

Literature	Exemplary Literature:
	 Gabriel Peyre, Marco Cuturi: Computational optimal transport: with ap- plications to data science. Foundations and Trends in Machine Learning 11.5-6 (2019): 355-607.
	 Alison L. Gibbs, Francis Edward Su: On choosing and bounding probability metrics. International Statistical Review 70.3 (2002): 419-435.
	Cedric Villani: Topics in optimal transportation. American Mathematical Society, 2003.
	 Imre Csiszar, Paul C. Shields: Information theory and statistics: a tutorial. Foundations and Trends in Communications and Information Theory 1.4 (2004). 417-528.
	 Ily Tolstikhin et al.: Wasserstein auto-encoders. 6th International Conference on Learning Representations (ICLR 2018)
	 Siegfried Graf, Harald Luschgy: Foundations of quantization for probability distributions. Springer, 2007.
Transfer	The module belongs to the <i>Study Specialisations Numerical Mathematics and Optimisation</i> and <i>Stochastics</i> . Taking into account the chosen personal Study Specialisation, it can be included in the sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	The course is mostly self-contained, but students benefit from basic knowledge in analysis, probability theory, optimisation, and Python.
Responsible Persons	Stephan Eckstein

Grading System : g=graded, ng=not graded

Examination Type: MT=Master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

T=tutorial, P=project, S=Seminar, IC=inverted classroom

Status : m=mandatory, o=optional