



Mathematisch-Naturwissenschaftliche Fakultät



Department of Mathematics

Module Handbook

Mathematics
Master of Science*

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1 Description of the Study Programme

1.1 Programme Concept and Qualification Objectives

The Master of Science Mathematics programme is a research-oriented study programme that prepares students for a career in research and university teaching as well as for a career in business and industry. Graduates are highly capable of familiarising themselves with specific fields of work analysing complex problems and developing solution strategies. They are trained in structured and conceptual thinking and their ability to abstract is particularly well developed. They also have important general qualifications such as creativity, communication, teamwork skills and perseverance.

The degree programme is designed for four semesters and is a consecutive study programme that requires the successful completion of the six-semester Bachelor of Science study programme in mathematics at the University of Tübingen or an equivalent qualification. A specific feature of the Master's degree programme is the combination of mathematical breadth with simultaneous specialisation in a selected mathematical field. Graduates acquire sound knowledge in several different areas of mathematics and mathematical modelling, and they specialise in a selected area to such an extent that they are able to deal with current research questions. The analytical skills they acquired in the Bachelor's study programme are significantly expanded and they are enabled to carry out scientific work. They learn to critically scrutinise and evaluate theories and to develop their own initial approaches. The study programme enables them to adapt openly and creatively to new conditions in their professional life and to critically classify and apply scientific findings in a targeted manner.

When studying maths, students learn to see the world through mathematical glasses. Recognising mathematical structures in the environment and depicting the environment in simplified mathematical models is an essential skill that is taught in mathematics studies and makes graduates attractive for a variety of professional fields. Typical employers for our graduates are research and development departments in industry, service companies such as banks or insurance companies, management consultancies, software development companies and opinion research institutes; less obvious fields of activity such as science journalism or museum education are also open to our graduates. In addition, some of them will go into academia at a national or international university or research institution after completing a doctorate.

1.2 Structure of the Study Programme

The courses offered by the Department of Mathematics in the Master of Science Mathematics programme are each assigned to one or more of the following five areas of specialisation, which are naturally derived from the research areas represented in the department:

- · Algebra and Geometry,
- · Analysis and Differential Geometry,

- · Mathematical Physics,
- Numerical Mathematics and Optimisation
- · Stochastics.

On beginning their Master studies, each student selects a personal field of specialisation, in which they collect 18 credit points by attending specialised lectures and associated exercise classes. They attend a seminar and the modules in the Scientific Work section, which all are related to their chosen field. In this area of mathematics, the student is introduced to questions of current research. It is assumed that the student has already acquired basic knowledge in the area of the specialisation during their Bachelor's degree, as provided in the modules of the respective specialisation on Mathematical General Education (see list of Modules for Mathematical General Education, p. 20). Therefore, in the *Study Focus* section, only specialisation modules (see list of specialisation modules, p. 81) and no modules for Mathematical General Education can be included. If a student does not have the required prior knowledge in the specialisation, they can still acquire it as part of the Master's degree programme and take the corresponding modules in the *Elective Specialisation* section.

The work to be completed in the Master's programme is divided into four sections:

- · Study Focus,
- · Advanced Knowledge in Mathematics,
- · Elective Specialisation,
- · Scientific Work.

As explained, the sections *Study Focus* and *Scientific Work* summarise the achievements in the student's chosen personal study specialisation. In addition, in the section *Advanced Knowledge in Mathematics* 30-33 credit points in at least two other specialisations in the department must also be achieved, whereby the exact rules for this allow students to enter a new mathematical field, but also ensure the desired depth (see section 2, p. 14). In the remaining section *Elective Specialisation*, students can give their degree programme a very individual profile by incorporating selected achievements from courses in other subject areas and thus expanding the expertise they may have acquired in their Bachelor's degree programme in a minor subject or by deepening their skills in certain areas of mathematics, possibly also in their personal study specialisation, by taking further modules from the Master's degree programme (see section 3, p. 14). In order to ensure that the choice can be made solely from the point of view of defining an individual profile of the degree programme, the grades of the modules in the *Elective Specialisation* are not included in the calculation of the final grade, unlike the grades in the modules of the other three sections.

1.3 Mentoring

The exact rules for the selection of courses in the four sections of the study programme can be found at the beginning of the respective section in chapter 3 on module descriptions. To ensure that students make sense of their studies from the outset and adhere to all rules, each student is assigned a mentor, preferably from their chosen study specialisation, when they start the degree programme. The student meets with this mentor at the beginning of the degree programme in order to

draw up a personal study and examination plan that includes all the modules planned for the degree programme. The study and examination plan must be submitted to the head of the examination board for approval; in the case of participation in a double-degree programme (see chapter 4), other persons or committees may be involved in the approval process. In the following semesters, the student meets with their mentor at least once to adjust the study and examination plan. The adjusted study and examination plans must be resubmitted for approval. A change to the chosen personal study specialisation is also possible as part of the change to the study and examination plan upon application.

When creating or adapting the study and examination plan, a sensible time slot can also be planned for a study component at a foreign university. In principle, every semester is suitable for this. The decision will depend on the student's previous achievements and the programme offered at the chosen foreign university.

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	Course- work	Type of Exam	ECTS- Points
Section 1: 9	Study Focus						
1-3	In addition to the modu Seminar Study Focus s cialisation modules tota 18 LP in accordance w more detailed regulatio Module descriptions			PMW			18
2-3	MAT-40-01	Seminar Study Focus	S	PMW	s.M.	Pr	3
Section 2: A	Advanced Kn	owledge in Mathematics					
1-3				PMW			30-33
Section 3: E	Elective Spec	ialisation					
1-3		Modules from the degree programmes of the Department of Mathematics or other departments (for more detailed regulations see below. 3 Module descriptions)		WPM			27-30
Section 4: 9	Scientific Wo	rk					
3	MAT-40-02	Introduction to Scientific Work	Р	PM	s.M.	-	9
4	MAT-40-03	Master Thesis M.Sc. Mathematics	MT	PM	s.M.	MT	30

Abbreviations:

Type of Module : PM=compulsory module, PMW=compulsory module with choice, WPM=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 that shows the distribution of credit points by section. On the following pages you will find examples of study plans for different personal study specialisations.

Sch	Schematic Study Plan												
FS	СР	Core Area of	Core Area of Mathematics										
1	30	Study Focus	Advanced Knowledge										
2	30	(21 CP)	in Mathematics (30-33 CP)	Elective Specialisation (27-30 CP)									
3	30	Scientific Work	(00 00 01)										
4	30	(39 CP)											
		on of the Abbreviations: ster, CP=credit points (ECTS points)										

2.3 Selection of Possible Courses of Studies

Unspecific Exemplary Study Plan

The following exemplary study plan shows how the coursework to be completed could be distributed over the four semesters without naming specific modules.

Uns	pecifi	c Exemplary Study Plar	1										
FS	СР	c	Core Area of Mathematics										
1	30	Study Focus: Advanced Lecture (9 CP)	Advanced Knowledge in Mathematics: Introductory Lecture (9 CP)	Advanced Knowledge in Mathematics: Advanced Lecture (3 CP)	Free								
2	30	Study Focus: Advanced Lecture (9 CP)	Study Focus: Seminar (3 CP)	Advanced Knowledge in Mathematics: Advanced Lecture (9 CP)	Elective Area (27-33 CP)								
3	30	Introduction to Scientific Work (9 CP)	Advanced Knowledge in Mathematics: Advanced Lecture (9 CP)	Advanced Knowledge in Mathematics: Advanced Lecture (3 CP)									
4	30	Master Thesis (30 CP)											

Exemplary Study Programme Plans for the Personal Study Specialisation

We would now like to list an exemplary study plan for each of the study focusses to show what such a study programme could look like in concrete terms. However, as the choice of modules depends on a large number of factors (previous knowledge from the Bachelor's degree programme, current range of courses, personal interests), these should not be seen as recommendations and and generally cannot be studied in exactly this combination.

Stud	dy pla	n with Personal Study S	specialisation Algebra a	nd Geometry								
FS	СР	С	Core Area of Mathematics									
1	33	Algebraic Geometry (9 CP)	Probability Theory (9 CP)	Geometry in Physics (9 CP)	Advanced Module: Written Communication and Translation (B.A. Anglistik) (6 CP)							
2	30	Computer Algebra (9 CP)	Study Focus: Seminar (3 CP)	Partial Differential Equations (9 CP)	Algebraic Transformation Groups (9 CP)							
3	27	Introduction to Scientific Work (9 CP)	Percolation Theory (3 CP)	Geometric Evolution Equations (3 CP)	Descriptive Linguistics (M.A. English Linguistics) (12 CP)							
4	30		Master T (30 C									

Stud	ly Pla	n with the Personal Stu	dy Specialisation Analy	rsis and Differential Geo	ometry								
FS	СР	С	Core Area of Mathematics										
1	30	Harmonic Analysis on Abelian Groups (9 CP)	Commutative Algebra (9 CP)	Seminar Advanced Knowledge in Mathematics (3 CP)	Nuclear and Particle Physics (B.Sc. Physics) (9 CP)								
2	30	Harmonic Analysis on General Groups (9 CP)	Study Focus: Seminar (3 CP)	Algebraic Geometry (9 CP)	Physics of Nanostructures (B.Sc. Physics) (9 CP)								
3	30	Introduction to Scientific Work (9 CP)	Mathematical Quantum Theory (9 CP)	Numerics of Stochastic Differential Equations (3 CP)	Mathematical Relativity (9 CP)								
4	30		Master 7 (30 C										

Stud	Study Plan with the Personal Study Specialisation Mathematical Physics												
FS	СР	c	Core Area of Mathematics										
1	30	Mathematical Quantum Theory (9 CP)	Convex Geometry (9 CP)	Seminar Advanced Knowledge in Mathematics (3 CP)	Condensed Matter (B.Sc. Physics) (9 CP)								
2	30	Mathematical Relativity (9 CP)	Study Focus: Seminar (3 CP)	Numerics of Stationary Differential Equations (9 CP)	Classical Field Theory (B.Sc. Physics) (9 CP)								
3	30	Introduction to Scientific Work (9 CP)	Numerics of Instationary Differential Equations (9 CP)	Selected Chapters from the Theory of Dynamical Systems (3 CP)	Probability Theory (9 CP)								
4	30		Master Thes	is (30 CP)									

Stud	ly Pla	n in the Personal Study	Specialisation Numeric	cal Mathematics and Op	otimisation							
FS	СР	С	Core Area of Mathematics									
1	30	Optimisation with Differential Equations (9 CP)	Introduction to the Partial Differential Equations (9 CP)	SL ₂ (ℝ) (3 CP)	Algorithms (B.Sc. Computer Science) (9 CP)							
2	30	Stochastic Differential Equations (9 CP)	Study Focus: Seminar (3 CP)	Algebraic Number Theory (9 CP)	Machine Learning: Algorithms and Theory (M.Sc. Computer Science) (9 CP)							
3	30	Introduction to Scientific Work (9 CP)	Mathematical Statistics (9 CP)	Elastic Curves (3 CP)	Modelling and Simulation (M.Sc. Computer Science) (9 CP)							
4	30		Master Thes	is (30 CP)								

Stud	dy Pla	n with the Personal Stu	dy Specialisation Stoch	astics	
FS	СР	С	ore Area of Mathematic	es	Elective Specialisation
1	30	Stochastic Processes (9 CP)	Functional Analysis (9 CP)	SL ₂ (ℝ) (3 CP)	Introduction to the Partial Differential Equations (9 CP)
2	30	Mathematical Statistics (9 CP)	Study Focus: Seminar (3 CP)	Computer Algebra (9 CP)	Microeconomics (B.Sc. Economics and Business Administration) (9 CP)
3	30	Introduction to Scientific Work (9 CP)	Operator Algebras (9 CP)	Geometric Variation Problems (3 CP)	Microeconomics (B.Sc. Economics and Business Administration) (9 CP)
4	30		Master Thes	is (30 CP)	

2.4 Overview by Course of Study and Examination Requirements

Ove	rview by Course of Study a	nd Exai	mination R	equir	emen	ts							
			Exam			Т	eachin	g			Sem	ester	
		Type of Exam	Duration (min)	a	Weight in the final grade	Type of Course			Points(CP)	nation semes menda locatio course tive na award	The allocation of examinations / ECTS points to semesters is of a recommendatory nature. The allocation of ECTS points to courses are of an informative nature. Credits are only awarded upon completion of the module.		to m- al- s to ma- only
		Туре о	Duratic	Grading	Weigh	Type o	Status	SWS	ECTS	1. CP	2. CP	3. CP	4. CP
Sec	tion 1: Study Focus								21				
S	addition to the module Semin pecialisation in compliance wi pssible schematic distribution	th the ir	accordance	ce with	h the	requir	ements	on p	age 1	2 must l			
First	t Advanced Module from the F	Persona	Study Spe	cialisa	ation			6	9				
1.	Lecture	Wr.	90–120	g	9	L	0	4		6			
2.	Exercise class	o. Or.	o. 20–30	9		E	0	2		3			
Sec	ond Advanced module from th	e Perso	onal Study	Specia	alisati	on		6	9				
1.	Lecture	Wr.	90–120	g	9	L	f	4			6		
2.	Exercise class	o. Or.	o. 20–30	9		E	f	2			3		
Sen	ninar Study Focus							2	3				
1.	Seminar	R	45–90 3	S	0	2			3				
	tion 2: Advanced Knowledgere, modules amounting to 30				soloci	tod fro	m the l	liet of	30– 33	los offer	ad by the	n Donart	mont
of	Mathematics, taking into accoints across the academic sen	ount the	e guidelines	s on p		_							
Mod	lule from the Mathematical Ge	neral E	ducation se	electio	n			6	9				
1.	Lecture	Wr. o.	90–120 o.	g	9	L	0	4		6			
2.	Exercise class	Or.	20–30			E	0	2		3			
First	t specialisation module (not fro	om the	Personal St	udy S	pecia	lisatio	n	2	3				
1.	Lecture	Or.	20–30	g	3	L	0	2		3			
Sec	ond specialisation module (no	t from t	he Persona	l Stud	y Spe	cialis	ation)	6	9				
1.	Lecture	Wr.	90–120	g	9	L	0	4			6		
2.	Exercise class	o. Or.	o. 20–30	9		Е	0	2			3		
Thir	d specialisation module (not fr	om the	Personal S	Study S	Specia	alisati	on)	6	9				
1.	Lecture	Wr.	90–120	g	9	L	0	4				6	
2.	Exercise class	o. Or.	o. 20–30	9		Е	0	2				3	
	rth specialisation module (not	from th	e Personal	Study	Spec	ialisa	tion)	2	3				
Fou	Till specialisation module (not						/						

Status Other

			Exam			Т	eachin	g			Sem	ester		
		Exam	Duration (min)	0	Weight in the final grade	Type of Course			Points(CP)	nations semes menda locatio course tive na awarde	the allocation of exami- ations / ECTS points to emesters is of a recom- nendatory nature. The al- ocation of ECTS points to ourses are of an informa- ve nature. Credits are only warded upon completion of the module.			
		Type of Exam	Ouratio	Grading	Veight	Type of	Status	SMS	ECTS F	1.	2.	3.	4.	
					_		0)		ш	CP	СР	CP	CP	
Section 3: Elective Specialisation									27–					
	-								30					
Here you can choo Mathematics and o	ose modules t	totalling							dules			epartme	ent of	
Here you can choo	ose modules to other departm	totalling							dules			epartme	ent of	
Here you can choo Mathematics and o Section 4: Scientific	ose modules to other departm	totalling							dules ents c			epartme	ent of	
Here you can choo Mathematics and o Section 4: Scientific ntroduction to Scientific	ose modules to other departm	totalling							dules ents d			epartme	ent of	
Here you can choo Mathematics and o Section 4: Scientific ntroduction to Scienti	ose modules to other departm	totalling ents in		e with	the re		ive req		dules ents d				ent of	
Here you can choo Mathematics and o Section 4: Scientific Introduction to Scientific	ose modules to other departm	totalling ents in		e with	the re		ive req		dules ents c 39				ent of	

: o=obligatory, f=facultative : o.=or, SWS=hours in class per week, CP=credit points=ECTS Points

3 Module Descriptions

Section 1: Study Focus

In the section *Study Focus*, a total of 21 credit points must be earned. Of these, 3 credit points are allocated to the module *Seminar Study Focus*. Within this module, a seminar must be attended that is related to the personal study specialisation.

The remaining 18 credit points are to be earned through modules from the list of *Specialisation Modules*, involving lectures with or without exercises, concluding with oral or written examinations. The modules must be related to the chosen personal study specialisation (see module description). Modules from the list of modules for Mathematical General Education cannot be included here. Additionally, no further seminars or modules that conclude with examinations other than those specified can be included.

Module Number: MAT-40-01	Module Title: Seminar Study Focus							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	Self-Study: 60 h				
Duration	1 Semester						·					
Frequency	Every semester											
Term	2-3											
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Seminar, talk, presentation, of	e-learr	ning,	blen	ded	learning)					
Content	Various topics from the chos	en Pe	rsona	al Stu	udy S	Speciali	sation.					
Objectives	Students work independent Specialisation and prepare the train their presentation techn on the topic chosen, they are Master's thesis.	em in iques	a did and s	dactionsharp	ally en t	appeali heir pro	ng and scie fessional di	entifically so	und for yle. De	m. They pending		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Seminar	s	0	2	3	yes	Pr	60-90	g	100		
	ticipation in the course, for ex or by completing assignment the preparation of a handou	In addition to a successful talk, the acquisition of credit points also requires regular active participation in the course, for example in the form of questions and contributions to the discussion or by completing assignments. In addition, a written elaboration of one's own presentation or the preparation of a handout for the participants may be part of the work to be done. This additional work constitutes the coursework for the module.										
Transfer	The successful completion o Mathematik.	f the m	nodu	le is	a pre	erequisit	te for the m	odule Maste	er Thes	is M.Sc.		

	Participation in the module requires the successful acquisition of at least 9 ECTS points from modules in the Study Specialisation.
Responsible Persons	The dean of studies at the department of mathematics

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 : o=obligatory, f=facultative

Section 2: Advanced Knowledge in Mathematics

In the section *Advanced Knowledge in Mathematics*, credit points ranging from 30 to 33 must be earned through modules from the lists for Mathematical General Education or Specialisation Modules. The following requirements must be observed:

- The modules must be assignable to areas other than the personal study specialisation (see module description);
- At least 27 credit points must be earned through modules involving lectures with or without exercises, concluding with oral or written exams;
- Modules worth at least 9 credit points each must be included from at least two specialisations, which are different from both each other and from the chosen personal study specialisation;
- · A maximum of 18 credit points can be included from the list of modules for Mathematical General Education.

These requirements ensure that the programme profile reflects both the necessary breadth in terms of the mathematical areas studied and the necessary depth within each area studied. In addition, this approach allows students to design their studies flexibly and individually, while also enabling the department to continually adjust to current developments in mathematics by offering new modules.

Section 3: Elective Specialisation

In the section *Elective Specialisation*, credit points ranging from 27 to 30 must be earned. Upon request, modules from all degree programmes of the University of Tübingen, including the Master of Science in Mathematics programme, can be included. When designing the study and examination plan, it is essential to ensure that the planned choices contribute to a meaningful overall profile of the programme. Additionally, the following notes must be observed:

- · At least 9 credit points should come from modules offered by departments other than mathematics;
- Modules from a maximum of two other departments may be included; exceptions can be approved by the Examination Board in justified cases;
- The modules from other departments should build on those included in the Bachelor of Science;
- Modules from the Master of Science in Mathematics programme can also be included from the list of modules for Mathematical General Education and from the chosen personal study specialisation;
- The grades of graded modules in the Elective Specialisation are not included in the calculation of the final grade.

These requirements are intended to ensure that students, throughout their combined studies, comprising both the Bachelor and Master of Science, acquire competencies beyond their core subject of mathematics in other scientific fields and potential applications of mathematics, while also allowing them to set meaningful focal points. Depending on individual objectives, students should also have the opportunity to expand their intra-mathematical knowledge and make up for any missing prerequisites in the chosen personal study specialisation from the Bachelor's programme, which may arise, for example, from transferring from another university, during the Master's programme.

Which modules are offered in other degree programmes can generally be found in the module handbook of the respective programme, along with the information related to the specific module. If modules from subjects that have not yet been studied as part of the Bachelor's programme are selected, the module handbook for the Bachelor of Science in Mathematics provides recommendations for the most frequently chosen subjects, indicating which modules may be suitable as an introduction to the respective field. Further information can be obtained from the Faculty Course Advisors of the respective programmes; see also:

The following is a list of some of the modules offered by the Department of Mathematics that can only be taken in this section.

Module Number: MAT-00-14	Module Title: Science Communication in S	Type of Module: Elective Module								
ECTS-Points	1	1								
Workload - Time in Class - Self-Study	Workload: 30 h	Time in Class: 15 h	Self-Study: 15 h							

Duration	1 Compoter									
	1 Semester									
Frequency	not regularly									
Term	3-4									
Language of Instruction	English									
Forms of Teaching and Learning	Presentation, group work, blended learning, practical exercises									
Content	Introduction to vocational fields in science communication.									
	Practical training in science communication.									
Objectives	The students know the current situation of science communication and different career paths in this field. They are familiar with the challenges of different formats and media (print media, museum pedagogy, interactive formats, etc.). Moreover, the students have learned about practical aspects which are relevant for science communicators, like free licensing and employment arrangements. They have trained science communication skills that are relevant to different science communication formats by means of oral and written practical exercises.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Science communication in STEM Ffields	S	f	1	1	yes	none	-	ng	-
	Within the module a coursework project is required. There is no			forn	n of a	active p	articipation	and a writte	en ess	ay on a
Literature	Possible References: • Sam Illingworth, Grant Allen: Effective science communication IOP Publishing 2016. • Beatrice Dernbach, Christian Kleinert, Herbert Münder: Handbuch Wissenschaftskommunikation. Springer 2013.									
Transfer	The module can be assigned	to the	Sec	ction	Elec	tive Sp	ecialisation.	•		
Prerequisites	No further prerequisites are re	quire	ed.							
Responsible Persons	Carla Cederbaum									
Examination Type : M	Abbreviations:									

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 : o=obligatory, f=facultative

Section 4: Scientific Work

The section Scientific Work particularly prepares students for academic work. It contains two modules.

In the module *Introduction to Scientific Work*, students are introduced to the thematic environment of their master's thesis. They become familiar with the essential principles of independent literature research in a scientific context and learn the main aspects of writing scientific mathematical texts. The project work and the reading course, which involves guided reading of scientific texts, are essential teaching and learning forms. The *Master Thesis M.Sc. Mathematics* module provides the framework for preparing the master's thesis and concludes with it as an assessment. Topics from the chosen personal study specialisation must be addressed in both modules.

Module Number: MAT-40-02	Module Title: Introduction to Scientific Wor		of Module: oulsory Modu	ule							
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 240 h										
Duration	1 Semester										
Frequency	Every semester										
Term	3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Individual supervision by a mentor, study of scientific works.										
Content	Independent search a Formulation of specifi	 Definition of an advanced scientific project in coordination with the mentor. 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 system learn to work critically judgement, acquire qualifications problems and approper proposal.	y and in su	to fo	rm a	sub	stantia literatu	ted, profes	ssional and i	interdise	relevant	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Scientific Project	ъ Type of Course	o Status	SWS 1	Φ ECTS	Sex	Type of Exam	Dur. of Exam (min)	g Grading	Weight for Grade	
Transfer	Successful completion of this sis.	s mod	ule is	a pi	rereq	uisite f	or participa	ition in modi	ule Mas	ter The-	

Prerequisites	Successful completion of modules worth at least 30 ECTS in the Sections Specialisation and Advanced Knowledge in Mathematics.
Responsible Persons	The dean of studies at the department of mathematics

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 : o=obligatory, f=facultative

Module Number: MAT-40-03	Module Title: Master Thesis M.Sc. Mather		of Module: ulsory Modu	le									
ECTS-Points	30												
Workload - Time in Class - Self-Study	Workload: 900 h	Time in Class: 0 h					Self-S 900 h	Self-Study: 900 h					
Duration	1 Semester												
Frequency	Every semester	Every semester											
Term	4												
Language of Instruction	German or English												
Forms of Teaching and Learning	Master thesis												
Content	The master thesis brings the master studies to a close. The students have to work under instruction of an advisor on a defined task from mathematics, which will lead up to the current state of research, with scientific methods and present the results in written form. In detail this includes: • the formulation of a scientific question in accordance with the advisor; • the independent search for and the study of relevant scientific literature; • the formulation of suited questions and methodical approaches for their solution; • the independent realisation of the project, the written presentation of the project and the results in the context of the current state of research. The results shall contribute to scientific knowledge. In the master thesis, a question should be be worked on, which belongs to the mathematical area of the chosen personal specialisation.												
Objectives	The students are capable of familiar research topics, till a consistency of the capable of familiar research topics, till a consistency of the capable	deadlir fic me ppropr rk on a ge,	ne ar thod riate a scie	nd to s wit form entifi	inde h gro , c top se a	pender owing in ic and and can	ntly developenden are capable transfer the	o a solution so ce and can e of using the ir methodolo	strategy presen eir matl	t the re- nemtical			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Master Thesis	M Type of Course	o Status	SWS	90 ECTS	Coursework	Type of Exam	Dur. of Exam (min)	ص Grading	Weight for Grade			
Transfer	-			1		1	I						

Prerequisites	Subject specific prerequisite for admission to the module Master Thesis is besides the general part of the examination regulations the successful completion of the module Introduction to Scientific Work and of the modules in the specialisation as well as the aquisiton of at least further 30 credit poins.
Responsible Persons	The dean of studies at the department of mathematics

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 : o=obligatory, f=facultative

Modules of Type Mathematical General Education

The modules for *Mathematical General Education* are predominantly introductory courses in various advanced areas of mathematics. Many of these areas can be further specialised within the offered specialisation modules. The courses underlying these modules can also be included in the modules of the third year of the Bachelor of Science in Mathematics programme again. If the courses have already been included in the framework of a module in the Bachelor of Science in Mathematics programme, the module cannot be included in the Master of Science in Mathematics programme. The module descriptions indicate which study specialisations the respective module is assigned to; the assignment may depend on taking additional modules.

The module descriptions on the following pages are sorted by module numbers. For clarity, we first provide a list of modules sorted by their title in alphabetical order and then sorted by whether they are offered regularly or irregularly. Subsequently, there are listings of the modules based on their inclusion in the study specialisations.

Modules which are	e offered regularly	(at least once ever	y two years)
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	•	Algorithms of Numerical Mathematics (MAT-70-01, 9 CP)	71
	•	Commutative Algebra (MAT-45-02, 9 CP)	26
	•	Functional Analysis (MAT-55-01, 9 CP)	46
	•	Geometry (MAT-50-01, 9 CP)	32
	•	Geometry in Physics (MAT-65-11, 9 CP)	69
	•	Introduction to Commutative Algebra and Algebraic Geometry (MAT-45-01, 9 CP)	24
	•	Introduction to Partial Differential Equations (MAT-55-21, 9 CP)	50
	•	Non-Linear Optimisation (MAT-70-21, 9 CP)	75
	•	Probability Theory (MAT-75-01, 9 CP)	77
	•	Seminar Mathematical Subjects (MAT-30-30, 3 CP)	23
MC		ules which are not offered regularly	
		Algebraic Topology 1 (MAT-50-21, 9 CP)	
		Calculus of Variations (MAT-55-49, 5 CP)	
		Convex Geometry (MAT-50-02, 9 CP)	
		Elementary Number Theory (MAT-45-25, 6 CP)	
		Foundations of Discrete Mathematics (MAT-75-12, 9 CP)	
		Geometry of Manifolds 1 (MAT-50-10, 9 CP)	
	•	Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP)	44
	•	Introduction to Dynamical Systems (MAT-55-34, 3 CP)	54
	•	Introduction to Geometric Measure Theory (MAT-55-41, 9 CP)	56
	•	Introduction to Geometric Measure Theory – Measure Theoretic Methods (MAT-55-44, 5 CP)	58
	•	Introduction to Geometric Measure Theory – Varifolds (MAT-55-45, 5 CP)	60
	•	Introduction to K-theory (MAT-50-24, 3 CP)	42
	•	Introduction to Mathematical Logic (MAT-55-60, 3 CP)	66
	•	Introduction to Optimisation (MAT-70-20, 6 CP)	73
	•	Introduction to Partial Differential Equations – Part 1 (MAT-55-25, 5 CP)	52
	•	Introduction to set theory (MAT-55-63, 3 CP)	68
	•	Lie Groups (MAT-55-51, 9 CP)	64
	•	Linear Control Theory (MAT-55-07, 6 CP)	48
	•	Number Theory and Cryptography (MAT-45-22, 9 CP)	28
	•	Topology (MAT-50-20, 6 CP)	38

Modules in the Specialisation Algebra and Geometry

The following modules belong to the specialisation Algebra and Geometry. Possible restrictions can be found in the module description.

Algebraic Topology 1 (MAT-50-21, 9 CP)	
	. 40
Commutative Algebra (MAT-45-02, 9 CP)	. 26
Convex Geometry (MAT-50-02, 9 CP)	. 34
Elementary Number Theory (MAT-45-25, 6 CP)	. 30
Foundations of Discrete Mathematics (MAT-75-12, 9 CP)	. 79
Geometry of Manifolds 1 (MAT-50-10, 9 CP)	. 36
Introduction to Commutative Algebra and Algebraic Geometry (MAT-45-01, 9 CP)	. 24
Introduction to K-theory (MAT-50-24, 3 CP)	. 42
• Lie Groups (MAT-55-51, 9 CP)	. 64
Number Theory and Cryptography (MAT-45-22, 9 CP)	. 28
• Topology (MAT-50-20, 6 CP)	. 38
Madulas in the Openialisation Analysis and Differential Openiators	
Modules in the Specialisation Analysis and Differential Geometry	
The following modules belong to the specialisation Analysis and Differential Geometry. Possible restrictions can be fin the module description.	ound
Algebraic Topology 1 (MAT-50-21, 9 CP)	. 40
• Algebraic Topology T (MAT-50-21, 9 GF)	
Calculus of Variations (MAT-55-49, 5 CP)	. 62
Calculus of Variations (MAT-55-49, 5 CP)	46
Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP)	. 46
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) 	. 46 . 32 . 69
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) 	. 46
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) Geometry of Manifolds 1 (MAT-50-10, 9 CP) 	. 46 . 32 . 69 . 36
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) Geometry of Manifolds 1 (MAT-50-10, 9 CP) Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP) 	. 46 . 32 . 69 . 36 . 44
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) Geometry of Manifolds 1 (MAT-50-10, 9 CP) Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP) Introduction to Dynamical Systems (MAT-55-34, 3 CP) 	. 46 . 32 . 69 . 36 . 44 . 54
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) Geometry of Manifolds 1 (MAT-50-10, 9 CP) Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP) Introduction to Dynamical Systems (MAT-55-34, 3 CP) Introduction to Geometric Measure Theory (MAT-55-41, 9 CP) 	. 46 . 32 . 69 . 36 . 44 . 54 . 56
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) Geometry of Manifolds 1 (MAT-50-10, 9 CP) Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP) Introduction to Dynamical Systems (MAT-55-34, 3 CP) Introduction to Geometric Measure Theory (MAT-55-41, 9 CP) Introduction to Geometric Measure Theory – Measure Theoretic Methods (MAT-55-44, 5 CP) 	. 46 . 32 . 69 . 36 . 44 . 54 . 56 . 58
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) Geometry of Manifolds 1 (MAT-50-10, 9 CP) Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP) Introduction to Dynamical Systems (MAT-55-34, 3 CP) Introduction to Geometric Measure Theory (MAT-55-41, 9 CP) Introduction to Geometric Measure Theory – Measure Theoretic Methods (MAT-55-44, 5 CP) Introduction to Geometric Measure Theory – Varifolds (MAT-55-45, 5 CP) 	. 46 . 32 . 69 . 36 . 44 . 54 . 56 . 60
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) Geometry of Manifolds 1 (MAT-50-10, 9 CP) Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP) Introduction to Dynamical Systems (MAT-55-34, 3 CP) Introduction to Geometric Measure Theory (MAT-55-41, 9 CP) Introduction to Geometric Measure Theory – Measure Theoretic Methods (MAT-55-44, 5 CP) Introduction to Geometric Measure Theory – Varifolds (MAT-55-45, 5 CP) Introduction to K-theory (MAT-50-24, 3 CP) 	. 46 . 32 . 69 . 36 . 44 . 54 . 56 . 60 . 42
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) Geometry of Manifolds 1 (MAT-50-10, 9 CP) Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP) Introduction to Dynamical Systems (MAT-55-34, 3 CP) Introduction to Geometric Measure Theory (MAT-55-41, 9 CP) Introduction to Geometric Measure Theory – Measure Theoretic Methods (MAT-55-44, 5 CP) Introduction to Geometric Measure Theory – Varifolds (MAT-55-45, 5 CP) Introduction to K-theory (MAT-50-24, 3 CP) Introduction to Optimisation (MAT-70-20, 6 CP) 	. 466 . 32 . 69 . 36 . 44 . 54 . 56 . 58 . 60 . 42 . 73 . 50
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) Geometry of Manifolds 1 (MAT-50-10, 9 CP) Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP) Introduction to Dynamical Systems (MAT-55-34, 3 CP) Introduction to Geometric Measure Theory (MAT-55-41, 9 CP) Introduction to Geometric Measure Theory – Measure Theoretic Methods (MAT-55-44, 5 CP) Introduction to Geometric Measure Theory – Varifolds (MAT-55-45, 5 CP) Introduction to K-theory (MAT-50-24, 3 CP) Introduction to Optimisation (MAT-70-20, 6 CP) Introduction to Partial Differential Equations (MAT-55-21, 9 CP) 	. 466 . 32 . 69 . 366 . 444 . 566 . 588 . 600 . 422 . 73 . 500
 Calculus of Variations (MAT-55-49, 5 CP) Functional Analysis (MAT-55-01, 9 CP) Geometry (MAT-50-01, 9 CP) Geometry in Physics (MAT-65-11, 9 CP) Geometry of Manifolds 1 (MAT-50-10, 9 CP) Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP) Introduction to Dynamical Systems (MAT-55-34, 3 CP) Introduction to Geometric Measure Theory (MAT-55-41, 9 CP) Introduction to Geometric Measure Theory – Measure Theoretic Methods (MAT-55-44, 5 CP) Introduction to Geometric Measure Theory – Varifolds (MAT-55-45, 5 CP) Introduction to K-theory (MAT-50-24, 3 CP) Introduction to Optimisation (MAT-70-20, 6 CP) Introduction to Partial Differential Equations (MAT-55-21, 9 CP) Introduction to Partial Differential Equations – Part 1 (MAT-55-25, 5 CP) 	. 466 . 32 . 69 . 366 . 444 . 566 . 58 . 600 . 422 . 73 . 500

Modules in the Specialisation Mathematical Physics

The following modules belong to the specialisation Mathematical Physics. Possible restrictions can be found in the module description.

Calculus of Variations (MAT-55-49, 5 CP)	62
Functional Analysis (MAT-55-01, 9 CP)	46
Geometry (MAT-50-01, 9 CP)	32
Geometry in Physics (MAT-65-11, 9 CP)	69
Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP)	44
Introduction to Partial Differential Equations (MAT-55-21, 9 CP)	50
Introduction to Partial Differential Equations – Part 1 (MAT-55-25, 5 CP)	52
Modules in the Specialisation Numerial Mathematics and Optimisation	
The following modules belong to the specialisation Numerial Mathematics and Optimisation. Possible restrictions car found in the module description.	ı be
Algorithms of Numerical Mathematics (MAT-70-01, 9 CP)	71
Functional Analysis (MAT-55-01, 9 CP)	46
Introduction to Optimisation (MAT-70-20, 6 CP)	73
Introduction to Partial Differential Equations (MAT-55-21, 9 CP)	50
Introduction to Partial Differential Equations – Part 1 (MAT-55-25, 5 CP)	52
Non-Linear Optimisation (MAT-70-21, 9 CP)	75
Modules in the Specialisation Stochastics	
The following modules belong to the specialisation Stochastics. Possible restrictions can be found in the module described tion.	rip-
Foundations of Discrete Mathematics (MAT-75-12, 9 CP)	79

Module descriptions (Mathematical General Education)

Module Number:	Module Title: Seminar Mathematical Subjects Type of Module: Compulsory Module										
MAT-30-30		ects					Compi	ulsory Modu	ile		
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time in Class: 30 h					Self-S	Self-Study: 60 h			
Duration	1 Semester										
Frequency	Every semester										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Seminar, exercise classes, talk, practical course, self-study, group work										
Content	Various topics from the advanced fields of mathematics.										
Objectives	The students independently explore a coherent topic in mathematics and prepare it in a didactically appealing manner. They learn how to present their work to a group, respond to factual questions, and conduct a professional discussion. Additionally, they acquire proficiency in a technically sophisticated writing programme and use it to create a digital medium, which can later be utilised for teaching or learning purposes.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Seminar	s	О	2	3	yes	Pr	60-90	g	100	
	ticipation in the course, for ex or by completing assignment the preparation of a handou	In addition to a successful talk, the acquisition of credit points also requires regular active participation in the course, for example in the form of questions and contributions to the discussion or by completing assignments. In addition, a written elaboration of one's own presentation or the preparation of a handout for the participants may be part of the work to be done. This additional work constitutes the coursework for the module.									
Transfer	-										
Prerequisites	There are no further prerequ	isites.									
Responsible Persons	The dean of studies at the de	epartm	nent (of ma	ather	matics					
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 : o=obligatory, f=facultative Other : h=hours, o.=or, s.M.=see module description, SWS=contact hours per week											

Module Number: MAT-45-01	Module Title: Introduction to Commutative Algebra and Algebraic Geometry Type of Module: Compulsory Module 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	German											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SW	S									
Objectives	Integral ring extension Krull's principal ideal Hilbert's Nullstellensa Affine varieties, Zarisl The students have become formula in the students of the stu	Gröbner bases.											
	enables the simultaneous tr students are capable of nar assessing and explaining the In the exercise classes they the terms, statements and m on new problems, to analys team. They are capable of p discourse.	eatme ning a prese have a ethoda e ther	ent all and pented acques of to a an	nd re provir d con ired the le d to	esoluting the nection a correction work work a correction	tion of e esse ons. nfident, e. They c on so	seemingly ntial results precise an have learn lution strate	unrelated q s of the lect d independe ed to transfe egies on the e to argue fo	uestior ure as ent har er the r eir own	ns. The well as adling of nethods or in a			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Introduction to Commutative Algebra and Algebraic Geometry	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 l	have	bee	n acc	uired.	Whether th	e examination					

Literature	Possible References :
	 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 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 '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 : o=obligatory, f=facultative

Module Number: MAT-45-02	Module Title: Commutative Algebra							of Module: ulsory Modu	le with	Choice				
ECTS-Points	9													
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in Cl	lass:			Self-Si 180 h	tudy:						
Duration	1 Semester						<u>'</u>							
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	 Rings and Ideals. 													
	 Localisation and local 	rings.												
	Noetherian and Artinian rings and modules.													
	Integral ring extensions and Cohen-Seidenberg theorems.													
	 Krull's principal ideal t 	Krull's principal ideal theorem and dimension theory.												
	 Primary decomposition 	n.												
	 Normality, regularity a 	nd disc	crete	valu	atior	n rings.								
	Hilbert's Nullstellensa	tz and	Noet	ther	norm	nalisati	on.							
Objectives	The students are familiar wi algebra, which are essential They recognise how adopting the simultaneous treatment a capable of naming and provi explaining the presented con In the exercise classes they the terms, statements and m on new problems, to analys team. They are capable of p discourse.	for study a high nd resolution the ing the nection have a ethods e them	dying ner poolution essens. acquires of the	g the erspon of ential erspon of the ential erspon of the	e field ective seeral res a cor cture work	ds of a e - nan mingly sults of nfident, e. They s on so	gebra, geonely, abstraunrelated quithe lecture precise are have learn lution strat	metry, and r cting the pro uestions. The as well as ad independent and to transfer egies on the	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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade				
	Commutative Algebra	L E	f	4	6	yes	wr. o.	90-180 o. 20-30	g	100				

Literature	Possible References :
	 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 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 '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 : o=obligatory, f=facultative

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	Class	:		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	lass 2	SW	S									
Content	RSA cryptosystem, pr	rimality	/ tes	ts, A	KS al	lgorithr	n.						
	Factorisation methods, number field sieve.												
	Quadratic reciprocity in cryptography.												
	Evaluation of the discrete logarithm.												
	Dynamical systems and Pollard's rho algorithm.												
	Elliptic curve cryptogr	aphy.											
	Lattices and post-qua	ntum (crypt	ogra	phy.								
	Zero-knowledge proof	fs, digi	tal si	ignat	ures	and ha	sh function	S.					
Objectives	The students know the basic cryptography. They have deplines: They encounter methwith elliptic curves over finite colls are working. Through may suprisingly come from noritically. The students are caused well as assessing and explain the exercise classes they the terms, statements and monnew problems, to analysteam. They are capable of prodiscourse.	epenee lods of e fields studyinost di apable ning the have a ethods e then	d and the s. The stince of ne pracques of the analysis of the	d ext theo ney u nany t bra amir esen ired the le	endery of nders open che gand ted correctures work	ed their dynam stand he probles of made proving connections. They are not so the connections on so the connections on so the con so the dynamic descriptions on so the dynamic descriptions of the dynamic descr	knowledge nical system now fundam lems of cry athematics, ng the cent tions. precise an have learn lution strate	about neigles and becomental cryptotography, which is the students aral results of dindependent to transfer on the	nbourir me acc ographi hose s s learn t the le ent har er the r eir own	ng disci- quainted c proto- olutions to think cture as adling of nethods or in a			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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 context examination the coursework oral is decided by the instruction	must l	nave	bee	n acc	uired.	Whether th	e examination					

Literature	Possible References :
	 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 : o=obligatory, f=facultative

Module Number: MAT-45-25	Module Title: Elementary Number Theory							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	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	Divisibility in the integ	ers.						·					
	Prime numbers.												
	Congruences.												
	Quadratic residues.												
	Arithmetic functions.												
	Multiplicative function:	S.											
	Classical Theorems.												
	Applications.												
Objectives	Students deepen their basic mathematical problems of va 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 their	rious A e as we t and o have a ethods them a	kinds ell as critica acqui s of ti and t	. The assally a red a he le o wo	e studes essir analys a cor cture rk on	dents and se the officent, and the se the officent, e. They officent and the second se	are capable explaining to current state precise an have learn on strategies	of naming a he presente e of research d independe ed to transfe s on their ow	ind produced control in the ent har er the ron or in or in the ron 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Elementary Number Theory	L	f	2	3	VAS	wr. o.	90-180	0	100			
	Liementary Number Trieory	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 ł	nave	beer	n acc	uired.	Whether th	e examination					

Literature	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-50-01	Module Title: Geometry							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	s:		Self-Si 180 h	tudy:		
Duration	1 Semester									
Frequency	regularly in Winter Semester	egularly in Winter Semester								
Term	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	Axiomatic foundation of planar geometry.									
	Euclidean and non-Euclidean geometry.									
	Parametrised curves a	Parametrised curves and surfaces.								
Objectives	The students deepen their axiomatic way of thinking and are capable of giving correct proofs. They know the basic principles of geometry, are able to solve concrete problems and know the fundamental links between geometry and topology. 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 to 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Goomatry	L	f	4	6	VOC	wr. o.	90-180	0	100
	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 l	nave	bee	en acc	uired.	Whether th	ie examinatio		
Literature	Possible References :									
	Michele Audin: Geom	etry. S	Spring	ger	2003.					
	Marcel Berger: Geon Springer 2010.	netry F	Reve	alec	d: A J	acob's	Ladder to	Modern Hig	her G	eometry.
	David A. Brannan, Ma sity Press 2012.	atthew	F. E	sple	n, Jei	remy J	. Gray: Geo	ometry. Cam	bridge	Univer-
	• John Stillwell: The fou	ır pillaı	rs of	geo	metry	. Sprin	ger 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	There are no further prerequisites.
Responsible Persons	Christoph Bohle, Carla Cederbaum, Hannah Markwig, 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 $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : o=obligatory, f=facultative

Module Number: MAT-50-02	Module Title: Convex Geometry							of Module: ulsory Modul	le with	Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h		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 Class 2 SWS										
Content	Cones, polytopes, pol	yhedra	a, far	ıs, p	olyec	Iral con	nplexes.				
	Normal fans of polygo	ns.									
	Triangulations, subdivisions, secondary fans, discriminants.										
Objectives	develope a deepened unders example of polytopes and fa sense. The students are cap well as assessing and explai In the exercise classes they the terms, statements and m on new problems, to analys	In the lecture the students learn basic terms, results and methods of convex geometry. They develope a deepened understanding for the concept of duality of mathematical objects on the example of polytopes and fans. Besides they enhance their geometric view and their spatial sense. The students are capable of naming and proving the central 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Convex Geometry	L	f	4	6	yes	wr. o.	90-180	g	100	
	,	E	f	2	3		or.	o. 20-30			
	In this module an exercise context examination the coursework oral is decided by the instruction	must l	have	bee	n acc	quired.	Whether th	e examination			
Literature	Possible References :										
	Günter M. Ziegler: Le	ctures	on F	Polyt	opes	. Spring	ger 1998.				
Transfer	The module belongs to the 3 the chosen personal Study Advanced Knowledge in Ma strictive requirements of the	Specia thema	alisat atics	ion, or <i>E</i>	it ca <i>lectiv</i>	n be ir	cluded in t	he Sections	Study	/ Focus,	
Prerequisites	There are no further prerequ	isites.									
Responsible Persons	Hannah Markwig										

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

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 : o=obligatory, f=facultative

Module Number: MAT-50-10	Module Title: Geometry of Manifolds 1							of Module: ulsory Modu	le with	Choice		
ECTS-Points	9						1					
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	_	lass	:		Self-S 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 C	Lecture 4 SWS + Exercise Class 2 SWS										
Content	Manifolds and subma	nifolds	 3.									
	Vector fields and flows.											
	Metrics, foundations of Riemannian geometry.											
	Complex structures.											
	Theorem of Gauß-Bo	nnet o	n sui	face	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 more to new problems, to analyst team. They are capable of predictions and more problems.	niques ally us of the have ethod e then	s for I egral sed ir lectu acqu s of to	nand calc geo ure a ired he le	ling tulus and the second terms were the second terms to the secon	hem. I and ha ry. The II as as nfident, e. They on so	They have ove exempla a students a sessing an precise are have learn lution strat	leepened the rily experien are capable dexplaining and independened to transfeegies on the eto argue for the record of the recor	eir und ced ho of nam the pr ent har er the r	erstand- w math- ing and esented adling of methods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Geometry of Manifolds 1	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	ertifica must	⊥ te is have	to be	e acc	uired.	Whether th	ne examinati				

Literature	Possible References :										
	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 <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. 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										
	=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 : o=obligatory, f=facultative

Module Number:	Module Title:							f Module:			
MAT-50-20	Topology						Сотри	ılsory 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										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS										
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, sep- 										
	 Spaces of continuous functions: Urysohn's lemma and applications, Stone-Cech compactification, the theorem of Stone-Weierstraß, notions of convergence in functions, compactness in spaces of functions. Baire's spaces and application of Baire's theory: Baire's function classes, existence theorems. Outlook on algebraic topology. 							nctions,			
Objectives	Students have familiarised to theoretical topology and have nomena in different areas of ferent areas of mathematics 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	e under f mathers. The sas assorted have a nethods them a	erstoo emat stud sessi acqu s of t and t	od the tics. ents and an ired in the lead of the lead	at thing the are of th	is theoris way, capable plaining the plainin	ry can be us they link the of naming g the prese precise and have learned on strategies	sed to descr neir knowled and proving nted connec d independe ed to transfe s on their ow	ibe mage of vogether ethous. The enternation of the manner the manner in or in	ny phe- very dif- ssential adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Topology	L E	f	2	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	bee	n acc	uired.	Whether the	e examinatio			

Literature	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-50-21	Module Title: Algebraic Topology 1							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	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	SW	S						
Content	Set theoretical topology.									
	Basic concepts of category theory.									
	The fundamental group of a punctured topological space.									
	Theory of covering sp	aces.								
	Basic concepts of single-	gular h	omo	logy	theo	ry.				
	Applications.									
Objectives	The students learn how to re spaces, into a precise theory how abstract concepts, e.g. ways of speaking that enabstudents are capable of nar assessing and explaining the In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	from collection of the	with categorn form and pented acques of tand tand the categorn formal solution and the categorn formal solution formal solutio	a soperation of the second sec	histine heor n of ng the nection cture rk on	cated t y and lideas e esse ons. nfident, e. They n solution	echnique. Ir homological to be adequintial results precise and have learne on strategies	n particular, in algebra, properties of the lection	they re ovide e emente ure as ent har er the n	cognise effective d. The well as edling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	- Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Algebraic Topology	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	ertifica must h	te is	to be	acq acq	uired.	Whether the	e examination	icipation on is w	n in the ritten or

Literature	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-50-24	Module Title: Introduction to K-theory							• •	f Module: Ilsory Modul	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	l Semester										
Frequency	not regularly	ot regularly										
Term	1-3	-3										
Language of Instruction	German	ierman										
Forms of Teaching and Learning	Lecture 2 SWS											
Content	 Vector bundles. Topological K-theory. Künneth formula and I Characteristic classes Chern character. Algebraic K-theory Plus construction. 		eriod	icity.								
Objectives	The students have learnt an algebra and number theory. different areas. They can ungorical K-groups and apply tare capable of naming and pand explaining the presented	They I dersta hem. proving	nave and a They g the	lear nd u hav ess	nt to se te /e le	recogn erms su arnt to	ise ar Ich as think	nd use vecto in larg	the connector or fibre buge contexts.	tions bundles The s	oetween or cate- students	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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	Max Karoubi: K-theory Emilio Lluis-Puebla, J	Possible References: • Michael Atiyah: K-theory. Addison-Wesley 1989. • Max Karoubi: K-theory. Springer 2008. • Emilio Lluis-Puebla, Jean-Louis Loday, Henri Gillet, Christophe Soule, Victor Snaith: Higher algebraic K-theory: an overview. Springer 1992.										
Transfer	The module belongs to the Differential Geometry. Taking be included in the Sections Specialisation, in accordance	g into <i>Study</i>	acco Foc	ount <i>us</i> , <i>A</i>	the d A <i>dva</i>	chosen <i>nced K</i>	perso nowle	onal S edge ii	tudy Specia n <i>Mathemat</i>	lisation ics or	n, it can <i>Elective</i>	

Prerequisites	There are no further prerequisites.
Responsible Persons	Anton Deitmar
Ahhreviations:	

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 : o=obligatory, f=facultative

Module Number: MAT-50-50	Module Title: Hyperbolic Geometry: Axion Algebraic	natic,	Refle	ectio	n Ge	ometrio		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-S	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	Starting from a system of a incidence and congruence, the introduction of the hypert A Euclidean field is created straight line, with the help algebraically.	he ass oolic a from	ocia kiom the r	ted E this otati	Bachr is co ons a	mann re Intinued around	eflection ge d with reflect an end an	cometry is de ction-geomet ad the transl	evelope tric end ations	ed. After d theory. along a
Objectives	The students have learnt to 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	from c t abou the cu dge of the ma have a tethod them	omplet Backerricule the ain standard standard the ain standard the ain acques of the	etely chma um, inter aten ired he le o wo	differance	erent per group- thus de- ving of the of the nfident, e. They n solution	erspectives theoreticall epen their I geometry a lecture and precise ar have learn on strategie	and to link to yoriented reknowledge of and algebra. It to categorised independent on their own their owne	them to flection f group The se se and ent har er the r	ogether. In geom- os. They students explain adling of methods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic	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	nave	bee	n acc	uired.	Whether th	ie examinatio	icipatio on is w	on in the ritten or
Literature	Possible References: • Friedrich Bachmann: 1959. • Robin Hartshorne: Go • Helmut Karzel, Kay S hoeck und Ruprecht	eometi örense	y: E	uclid	and	beyond	I. Springer	2000.		

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 Geometry is helpful but not required.
Responsible Persons	Hermann Hähl, 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 : o=obligatory, f=facultative

Module Number: MAT-55-01	Module Title: Functional Analysis							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	regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	3						
Content	 Normed spaces, Banach spaces, Dual spaces. Hahn-Banach theorem, uniform boundedness principle. Closed graph theorem, open mapping theorem, Banach-Alaoglu theorem. Compact Operators, normal operators, spectral theorems. 									
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 mon new problems, to analysteam. They are capable of problems.	n apply ms of dents sing an have a lethods e ther	ther spectare of the spectare	n to ctral to capate plain ired a to to detect to the left to the	probitheorole of the correction of the correctio	lems in and finaming the presention of the present	n analysis a can use its ng and prov sented conn precise an have learn plution strate	nd geometry results for ing the esse ections. d independe ed to transfe egies on the	y. They the sole that re ent har er the re eir own	y 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Functional Analysis	L E	f	2	6 3	yes	K o. mP o. H	90-180 o. 20-30	g	100
	In this module an exercise of examination the coursework oral is decided by the instruc	must I	nave	beer	n acc	uired.	Whether the	e examination		

Literature	Possible References :
	 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 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 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 : o=obligatory, f=facultative

Module Number: MAT-55-07	Module Title: Linear Control Theory							f Module: Ilsory 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	not regularly									
Term	1-3	1-3									
Language of Instruction	German	German									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Cl	Lecture 2 SWS + Exercise Class 2 SWS									
Content	and processes. The underlyi but also, in its abstract form, this lecture, finite-dimensiona analysis and linear algebra is resulting criteria for stabilisab	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 ir analysis and their benefits for proving the essential results of connections. Students will be in the subject area. In the exercise classes they if 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Linear Control Theory	L	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	In this module an exercise ce examination the coursework roral is decided by the instruct	rtifica nust l	nave	to be	acc acc	quired.	Whether the	e examination			
Literature	Possible References :										
	Hans Wilhelm Knobloc	h, Hu	ibert	Kwa	akerr	naak: L	ineare Kont	rolltheorie. S	Springe	er 1985.	
	Jerzy Zabczyk: Mather	matic	al Co	ntro	The	ory. Bi	rkhäuser 19	92.			
	Ruth F. Curtain, Hans Springer 1995.	Zwar	t: An	Intr	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 Algbra 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 : o=obligatory, f=facultative

Module Number: MAT-55-21	Module Title: Introduction to Partial Differe	ntial E	quat	ions				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	regularly											
Term	1-3											
Language of Instruction	English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	3								
Content	Harmonic functions.Maximum principles.											
	Sobolev spaces.											
	• L^2 theory.											
	Important examples (I	Laplace	e eq	uatio	n, wa	ave eq	uation, heat	equation).				
	Fundamental solution	s (ellip	tic si	tuati	on).							
	Weak solutions of ellip	otic equ	uatio	ns.								
Objectives	The students got to know a comental for many fields, like a strong connections to geomethese methods in advanced central results of the lecture. In the exercise classes they the terms, statements and mon new problems, to analysteam. They are capable of prodiscourse.	numerion etry, are thods course as well have a ethods e them	cs o re is: of li es. l as a acqui s of the	r storsue of near The stasses ired a he led	chas of the part stude ssing a core cture work	tics. A e lecturial differents ar g and enfident, e. They	Iso evolutione. The stuberential equiver capable of explaining the precise an have learn lution strate.	nary equation dents are actions and a soft naming and e presented d independed to transfergies on the	ons, we cquain are abload processing connections are the reserring constants.	ho have ted with e to use ving the ections. adding of methods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Introduction to Partial	L	f	4	6	yes	wr. o.	90-180	g	100		
	Differential Equations	Е	f	2	3		or.	o. 20-30				
	In this module an exercise context examination the coursework oral is decided by the instruc	must h	nave	beer	n acc	uired.	Whether th	e examination				

Literature	Possible References :
	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

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 : o=obligatory, f=facultative

Module Number: MAT-55-25	Module Title: Introduction to Partial Differe	ntial E	quat	ions	– Pa	rt 1		of Module: ulsory Modul	e 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	not regularly								
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 1	SWS	3						
Content	Harmonic functions.									
	Maximum principles.									
	Sobolev spaces.									
Objectives	analysis, the concepts and as numerics and stochastic: methods of linear partial diff the more advanced courses. results of the lecture as well In the exercise classes they the terms, statements and mon new problems, to analyse	The students have familiarised themselves with the first basic features of a central area of analysis, the concepts and methods of which are fundamental for many other areas, such as numerics and stochastics. Students are familiar with the central concepts, results and methods of linear partial differential equations and can successfully apply these methods in the more advanced 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.								
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Introduction to Partial Differential Equations – Part	П Type of Course	f Status	SMS 2	3 2	Ses	Type of Exam o. o.	Onr. of Exam (min) 90-180 0. 20-30	Grading a	Weight for Grade
	In this module an exercise context examination the coursework oral is decided by the instruction	rtificat must h	te is	to be	e acq	juired.	Whether th	e examinatio		
Literature	Possible References: Lawrence C. Evans: 2010. David Gilbarg, Neil S. Springer 2001. Olga A. Ladyzenskaja ear equations of paral	Trudir , Vsev	nger:	: Elli A. S	ptic p	partial o	differential e	equations of	secon	d order.

Transfer	The module belongs to the <i>Study Specialisation 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 Nonstationary Differential Equations', it can be included in the Specialisation <i>Numerical Mathematics and Optimisation</i> . 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 : o=obligatory, f=facultative

Module Number: MAT-55-34	Module Title: Type of Module: Introduction to Dynamical Systems 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	Semester									
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS										
Content	Limit sets. Periodic orbits. Celestial mechanics.	 Equilibrium positions. Stability. Predator-prey model. Poincaré-Bendixson theorem. Limit sets. Periodic orbits. 									
Objectives	The students can ask and exterential equations, like e.g.: states or periodic orbits? The lecture as well as assessing	How le	ong o capa	do ex able	ist m	nathem ıming a	atical solution at the street	ons? Are the the essentia	ere equ	uilibrium	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introducation to Dynamical Systems	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
Literature	Possible References: Morris W. Hirsch, Step algebra. Academic Pr 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 : o=obligatory, f=facultative

Module Number: MAT-55-41	Module Title: Type of Module: Introduction to Geometric Measure Theory Compulsory Module with Choice									Choice	
ECTS-Points	9						<u> </u>				
Workload - Time in Class - Self-Study	Workload: 270 h	1 1111									
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	Measures, Covering densities.	Measures, Covering theorems, differentiation of measures, Hausdorff measures and densities.									
	Isodiametric inequalit	y.									
	Rademacher's theore	m and	l Wh	itney	s em	beddir	ng theorem.				
	Surface- and Cosurfa	ce forr	nula								
	Countable rectifiable	sets, re	ectifi	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 mon new problems, to analyse They are able to present the	whose fame the apable plaining have a nethoden	e coniliaring of records of the acquiside of the acquisite of the acquisit	ncep sed f and namin pres ired ine le to wo	ts are them can are are corrected as correct	nd met selves succes nd prov ed conr nfident, e. They n solution	thods can I with the basefully applying the essinections. precise any have learn on strategie	oe successfasic concepty these methential results d independent of transfess on their owner in critical concepts.	ully ap ts, res nods in s of the ent har er the r or in	pplied to ults and in further e lecture adling of methods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course Status SWS ECTS Coursework Type of Exam Dur. of Exam (min)					Dur. of Exam (min)	Grading	Weight for Grade		
	Introduction to Geometric	L	f	4	6	yes	wr. o.	90-180	g	100	
	Measure Theory	E	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	have	bee	n acc	uired.	Whether th	e examination			

Literature	Possible References :
	 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 : o=obligatory, f=facultative

Module Number: MAT-55-44	Module Title: Introduction to Geometric Measure Theory – Measure Theoretic Methods Type of Module: 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										
Term	1-3										
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	Measures, Covering theorems, differentiation of measures, Hausdorff measures and densities.										
	Isodiametric inequality	/.									
	Rademacher's theore	m and	Whi	tney'	s em	beddin	g theorem.				
Objectives	Students have familiarised tanalysis and geometry and various problems. They have methods of geometric meas courses. The students are cas well as assessing and explinithe exercise classes they the terms, statements and mon new problems, to analyse They are able to present the	whos ye famure the apable blaining have a ethods	e co illiaris eory e of n g the acqui s of t and t	ncepsed tand amir preserved to the left to	ts ar can ng ar sente a cor cture rk on	nd met selves succes nd provi ed conn nfident, e. They n solution	hods can be with the basefully applying the essections. precise an have learn an strategie	oe successfasic concepty these methential results dindependential results on their own	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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Geometric Measure Theory – Measure	L	f	2	3	yes	wr. o.	90-180	g	100	
	Theoretic Methods	Е	f	1	2	ycs	or.	o. 20-30	9	100	
	In this module an exercise context examination the coursework oral is decided by the instruc	must l	nave	beei	n acc	uired.	Whether th	e examination			
Literature	Possible References: • Lawrence C. Evans, tions. CRC Press 199 • Herbert Federer: Geo • Leon Simon: Lecture 1984.	2. metric	mea	asure	the	ory. Sp	ringer 1969).			

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 : o=obligatory, f=facultative

Module Number: MAT-55-45	Module Title: Introduction to Geometric Me	asure	The	ory -	- Var	ifolds		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	Self-Study: 105 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 2 SWS + Exercise Cl	ecture 2 SWS + Exercise Class 1 SWS									
Content		 Surface- and Cosurface formula. 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 mon 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.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Introduction to Geometric Measure Theory – Varifolds	п Туре of Course	t Status	SMS 2	S ECTS	Coursework	Type of Exam o. o.	Dur. of Exam (min) 90-180 o. 20-30	Grading	Weight for Grade	
	In this module an exercise ce examination the coursework oral is decided by the instruct	rtificat must h	e is	to be	acc acc	quired.	Whether th	e examinatio	icipation on is w	on in the ritten or	
Literature	Possible References: • Lawrence C. Evans, Fitions. CRC Press 1999 • Herbert Federer: Geo. • Leon Simon: Lecture: 1984.	2. metric	mea	ısure	the	ory. Sp	ringer 1969				

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 : o=obligatory, f=facultative

Module Number: MAT-55-49	Module Title: Calculus of Variations		of Module: ulsory Modu	le with	Choice						
ECTS-Points	5										
Workload - Time in Class - Self-Study							Self-Si 105 h	Self-Study: 105 h			
Duration	1 Semester	1 Semester									
Frequency	not regularly										
Term	1-3	1-3									
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	ecture 2 SWS + Exercise Class 1 SWS									
Content	Direct method of calc	Direct method of calculus of variations.									
	Euler-Lagrange equa	tions.									
	Palais-Smale condition	n.									
	Mountain-Pass Lemma according to Ambrosetti-Rabinowitz.										
Objectives	In the first part of the course which is primarily used to probut also has applications in ebasics from functional analy different context, e.g. geom about a so-called mountain in 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. diff sis and etric ar-pass I sof pass I have a nethods them a	exist feren d par nalys lemm artial resul acqui s of th	ence tial of tial of sis. I na. of diffe ts of red a he le o wo	e of water of white of the continuation of the corrections of the corr	reak so letry. The ential electore its heleal equilecture infident, e. They in solution	lutions of paney have all quations and part of to p, they can ations. The as well as precise and have learn strategie	artial differer so acquired and can also he course, so analyse not assessing a dindependent to transfers on their ownem in critical	ntial equithe neuse the student on-unice the real and exert har er the real and or in or in	uations, cessary ese in a ts learnt queness pable of plaining adding of methods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Calculus of Variations	L	f	2	3	yes	wr. o.	90-180	g	100	
		E	f	1	2		or.	o. 20-30			
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	nave	beer	acc	uired.	Whether th	e examination	icipation on is w	on in the rritten or	

Literature	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-55-51	Module Title: Lie Groups		f 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	udy:		
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 4 SWS + Exercise C	ecture 4 SWS + Exercise Class 2 SWS								
Content	Manifolds and Lie gro	Manifolds and Lie groups,								
	Lie algebras and expo	Lie algebras and exponential map,								
	Covering spaces and	classif	icatio	on of	Lie	groups	by their Lie	algebras,		
	Classical Lie groups,									
	Operations of Lie groups and homogeneous spaces.									
Objectives	describing the symmetries of differential equations, in par learn from a prominent examathematics can work toge developed that can precisely capable of naming and provexplaining the presented cor in the exercise classes they the terms, statements and mon new problems, to analyse	Lie groups lie at the interface between geometry, algebra and analysis. They are suitable for describing the symmetries of geometric objects, but also algebraic equations or solutions of differential equations, in particular if these symmetries form a continuous set. The students learn from a prominent example how different disciplines of mathematics can disciplines of mathematics can work together extremely successfully and how a convincing formalism is developed that can precisely describe a variety of symmetry phenomena. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Lie Groups	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
		E	f	2	3					
	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 examination		

Literature	Possible References :								
	Joachim Hilgert, Karl-Hermann Neeb: Liegruppen und Lie-Algebren. Vieweg 199								
	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	here 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 : o=obligatory, f=facultative

Module Number: MAT-55-60	Module Title: Introduction to Mathematical Logic							f Module: Ilsory Modu	le with	Choice
ECTS-Points	3	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	ot regularly								
Term	1-3	-3								
Language of Instruction	German	German								
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS								
Content	 Completeness a Theory of computation Register machin Gödelisation. Incompleteness of arin First and second Set theory: Ordinal- and can 	 Languages of the first order: Completeness and compactness. Theory of computations: Register machines; Gödelisation. Incompleteness of arithmetic: First and second incompleteness theorem. 								
Objectives	Students are able to underst ematical logic. They unders the difference between truth mathematical content. The sof the lecture as well as asse	tand and p tuden	the li roval ts ar	imits cility e cap	of p and pable	ossible can ap of nar	mathemati ply basic the ming and pr	cal knowled eoretical mo oving the es	dge, re odel thi	cognise nking to
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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	Possible References : • Rautenberg, Wolfgan 2008. • Ziegler, Martin: Mathe							Logik. Vid	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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom$

Status : o=obligatory, f=facultative

Module Number: MAT-55-63	Module Title: Introduction to set theory							f Module: Ilsory Modul	le with	Choice	
ECTS-Points	3	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										
Content	Content:	content:									
Objectives	- The students are able to view mathematical theorems and theories in the context of mathematical logic. They understand the boundaries of the mathematically knowable, the difference between truth and provability, and are able to apply model-theoretic considerations to mathematical problems. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to set theory	L	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
Literature	Possible References :		1	ı	ı		I	I			
Transfer											
Prerequisites	There are no further prerequi	sites.									
Responsible Persons	Frank Loose										
Examination Type : M Teaching Format : L T Status : 0	=graded, ng=not graded IT=master's thesis, or.=oral exa =lecture, LE=lecture with inte =tutorial, P=project, S=seminal =obligatory, f=facultative =hours, o.=or, s.M.=see module	egrate , IC=i	d ex nvert	ercis ed c	ses, lassr	SL=se	eminar or l	ecture, E=e	•		

Module Number: MAT-65-11	Module Title: Geometry in Physics							of Module: ulsory Modu	le with	Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h					Self-St 180 h	Self-Study: 180 h		
Duration	1 Semester						·			
Frequency	regularly in Winter Semester	egularly in Winter Semester								
Term	1-3	J-3								
Language of Instruction	English									
Forms of Teaching and Learning	ectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements									
Content	relevance for physics. Partici and associated notions of cu	he module provides an introduction to fundamental methods of differential geometry and their elevance for physics. Particular topics are manifolds, differential forms, Riemannian metrics and associated notions of curvature, Riemannian geometry of submanifolds, real vector bunles, and connections. Applications of these concepts in Physics are discussed.								
Objectives	tions of differential geometry ential and integral calculus a are naturally applied within placquaintance with the use of ticular, a deeper understand examples how the mathematidents are able to name and pwell as to explain the context Through homework assignment and independent acquaintan lectures. They learn how to to develop solution strategies	Students obtain knowledge, understanding, and acquaintance with the use of the listed notions of differential geometry. They develop, in particular, a deeper understanding of differential and integral calculus and experience through examples how the mathematical notions are naturally applied within physical theories. Students obtain knowledge, understanding, and acquaintance with the use of the listed notions of differential geometry. They develop, in particular, a deeper understanding of differential and integral calculus and experience through examples how the mathematical notions are naturally applied within physical theories. 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.								
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Geometry in Physics	L	0	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	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.						nitted to			
Literature	Possible References: • John Lee: Introduction • John Lee: Riemanniar • Chris Isham: Modern e • Mikio Nakahara: Geor	n man differe	ifolds ential	s: An geor	intro	oductio y for ph	n. Springer lysicists. Wo	orld Scientifi).

Transfer	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	There are no further prerequisites.
Responsible Persons	Christoph Bohle, Carla Cederbaum, 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 $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : o=obligatory, f=facultative

Module Number: MAT-70-01	Module Title: Algorithms of Numerical Mat		of Module: ulsory Modul	e with	Choice						
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										
Frequency	regularly	egularly									
Term	1-3	-3									
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ecture 4 SWS + Exercise Class 2 SWS									
Content	 Fast Fourier transform QR algorithms for the Method of conjugated methods in numeric line 	 Advanced, important 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	Coursework	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. Possible References: 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 Taking into account the chos tions Study Focus, Advanced dance with the restrictive req	en pe <i>l Kno</i> v	rson vled	al St ge in	udy S Matl	Special nematio	isation, it ca s or <i>Electi</i> v	an be includ	ed in t	he Sec-	

Prerequisites	There are no further prerequisites.
Responsible Persons	Christian Lubich, 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 : o=obligatory, f=facultative

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	_	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 3 SWS + Exercise Class 1 SWS									
Content	 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 understand methods and algorithms for solving convex and linear optimisation problems. They have learnt to apply the methods to simple problems related to economics, technology or physics. They will be able to critically assess the possibilities and limitations of using the methods. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Optimisation	Introduction to Optimisation								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	e examinati		
Literature	Possible References :					· ·			· ·	
	Methoden. Springer 2	 Florian Jarre, Joseph Stoer: Optimierung: Einführung in mathematische Theorie und Methoden. Springer 2019. Jorge Nocedal, Stephen J. Wright: Numerical optimization. Springer 2006. 								

Transfer	The module belongs to the Study Specialisation 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	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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom \\$

Status : o=obligatory, f=facultative

Module Number: MAT-70-21	Module Title: Non-Linear Optimisation							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	regularly											
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 4 SWS											
Content	 Finite-dimensional optimisation, gradient method with Armijo's rule, globalised Newton method. Restricted optimisation, Farkas' lemma, tangent cone. Abadie CQ, KKT conditions, Slater conditions. Linear programme, duality, simplex method. Penalty and barrier methods, interior point method. Nonlinear programs, SQP methods, non-smooth optimisation. 							Newton				
Objectives	optimisation problems. The softhe lecture as well as asselin the exercise classes they the terms, statements and mon new problems, to analyse	Students master the basic principles and techniques of analysis and numerics of constrained optimisation problems. 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.							I results adling of methods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Non-Linear Optimisation	L	f	4	6	yes	or.	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												
Transfer	The module belongs to the Taking into account the chos tions Study Focus, Advanced dance with the restrictive requirements.	en pe d <i>Kno</i> i	rson vled	al St ge in	udy S <i>Mati</i>	Special hematic	isation, it c s or <i>Electi</i>	an be includ	led in t	he Sec-		

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 : o=obligatory, f=facultative

Module Number: MAT-75-01	Module Title: Probability Theory						of Module: ulsory Modul	le 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	1 Semester								
Frequency	regularly in Winter Semeste									
Term	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	 Characteristic functions and additions to the central limit theorem. Conditional expectations and further measure-theoretic foundations. Markov chains and martingales in discrete time, classification, asymptotic behaviour, stopping times, stationarity, ergodicity. Introduction to processes in contiuous time like Poisson processes and Brownian motion. 									
Objectives	The students got to know the central terms results and methods of probability theory. They can model, analyse and interprete stochastic dependency structures of random quantities in a measure theoretically founded manner. The students are capable of naming and proving the central results of the lecture as well as assessing and explaining the presented connections. The students are capable of naming and proving the central 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Probability Theory	L	f	4	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	Possible References :				
	 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 : o=obligatory, f=facultative

Module Number:	Module Title:						of Module:				
MAT-75-12	Foundations of Discrete Mathematics						Comp	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	1 Semester									
Frequency	not regularly										
Term	1-3										
Language of Instruction	German	German									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS										
Content	• Logic.										
	Sets, relations, functi	ons.									
	Partial orders.										
	Combinatorics.										
	Number theory.										
	Graph theory.										
	Algorithms and forma	ıl langı	ages	S.							
	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	Coursework	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	Е	f	2	3	703	or.	o. 20-30	9		
	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	Possible References :							
	 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 Möhle, 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 : o=obligatory, f=facultative

Modules of Type Specialisation Modules

The Specialisation Modules listed here are modules that generally build on one or more of the modules for Mathematical General Education and deepen the knowledge and competencies acquired there. If there are content dependencies on such modules or between each other, these are indicated in the respective module descriptions. There is no requirement to complete specific modules successfully to prevent any delays in the study programme due to missing individual examination components. The courses underlying the modules may have been included, in justified cases, in the modules of the third year of the Bachelor of Science in Mathematics programme. If the courses have already been included in the framework of a module in the Bachelor of Science in Mathematics programme, the module cannot be included in the Master of Science in Mathematics programme again. The module descriptions indicate which study specialisations the respective module is assigned to; the assignment may depend on taking additional modules.

The module descriptions on the following pages are sorted by module numbers. For clarity, we first provide a list of modules sorted by their title in alphabetical order and then sorted by whether they are offered regularly or irregularly. Subsequently, there are listings of the modules based on their inclusion in the study specialisations.

Modules which are offered regularly (at least once every two years)

95
97
281
275
277
335
303
301
299
92
337
249
217
283
285
101
173
105
115
161
163
99
167
165
221
231

•	Bayesian Networks and Causality (MAT-75-21, 5 CP)	355
•	Cohomology and Sheaves (MAT-55-61, 9 CP)	233
•	Combinatorics (MAT-75-02, 9 CP)	333
•	Computer Algebra (MAT-45-03, 9 CP)	. 93
•	Consistency Proofs (MAT-55-62, 6 CP)	235
•	Control Theory (MAT-55-06, 9 CP)	187
•	Cox Rings (MAT-45-18, 9 CP)	109
•	Elastic Curves (MAT-55-46, 3 CP)	223
•	Elliptic Curves and Cryptography (MAT-45-27, 9 CP)	121
•	Elliptic Curves and Taniyama-Shimura (MAT-45-28, 9 CP)	123
•	Elliptic Functions and Elliptic Curves (MAT-45-24, 9 CP)	117
•	Ergodic Theory (MAT-55-05, 9 CP)	185
•	Explicit Mathematics (MAT-55-65, 6 CP)	239
•	Financial Mathematics and Numerics (MAT-70-51, 6 CP)	331
•	Fully Non-Linear Elliptic Equations (MAT-55-27, 5 CP)	211
•	Fully Non-Linear Elliptic and Parabolic Partial Differential Equations (MAT-60-36, 3 CP)	271
•	Game Theory (MAT-70-40, 3 CP)	330
•	Geometric Evolution Equations (MAT-60-01, 3 CP)	245
•	Geometric Group Theory (MAT-50-30, 9 CP)	175
•	Geometric Measure Theory (MAT-55-42, 9 CP)	219
•	Geometric Measure Theory – Flows (MAT-55-48, 5 CP)	227
•	Geometric Measure Theory – Varifolds (MAT-55-47, 5 CP)	225
•	Geometric Variation Problems (MAT-60-02, 3 CP)	247
•	Geometry of Manifolds 2 (MAT-50-11, 9 CP)	143
•	Graph Theory (MAT-75-10, 9 CP)	349
•	Gravitational Collapse and Singularities in General Relativity (MAT-60-30, 3 CP)	267
•	Gromov-Witten Theory (MAT-50-40, 6 CP)	177
•	Groups and Representations (MAT-65-05, 9 CP)	273
•	Hamiltonian Systems (MAT-65-38, 9 CP)	297
•	Harmonic Analysis in Euclidean Space (MAT-55-12, 9 CP)	197
•	Harmonic Analysis on Abelian Groups (MAT-55-13, 9 CP)	199
•	Harmonic Analysis on General Groups (MAT-55-14, 9 CP)	201
•	Information Geometry (MAT-50-12, 3 CP)	145
•	Information Geometry and Neural Data Processing 2 (MAT-50-13, 3 CP)	147
•	Information Theory (MAT-75-07, 9 CP)	343
•	Integrable Systems (and Infinite Dimensional Lie Algebras) (MAT-50-18, 9 CP)	157
•	Introduction to Analytic Number Theory (MAT-45-26, 3 CP)	119
	Introduction to Berkovich Geometry (MAT-45-20, 3 CP)	113

•	Introduction to Combinatorial Birational Geometry (MAT-45-40, 9 CP)	131
•	Introduction to Combinatorial Mirror Symmetry (MAT-45-41, 6 CP)	133
•	Introduction to Harmonic Analysis (MAT-55-11, 9 CP)	195
•	Introduction to Integrable Systems (Classical Mechanics, Riemann Surfaces, and Spectral Theory) (MAT-50-CP)	
•	Introduction to Modular Forms (MAT-45-29, 3 CP)	125
•	Introduction to Riemann Surfaces (MAT-50-15, 5 CP)	151
•	Introduction to Stochastic Differential Equations - Part 1 (MAT-70-12, 5 CP)	313
•	Introduction to Tropical Enumerative Geometry (MAT-50-05, 5 CP)	139
•	Limits of Spaces (MAT-60-05, 6 CP)	253
•	Markov Chains and Applications (MAT-75-11, 9 CP)	351
•	Mathematical Aspects of Neuronal Information Processing 1 (MAT-50-14, 3 CP)	149
•	Mathematical Aspects of Neuronal Information Processing 2 (MAT-50-19, 3 CP)	159
•	Mathematical Aspects of the Quantum Hall Effect (MAT-65-32, 6 CP)	289
•	Mathematical Methods for Condensed Matter Physics (MAT-65-31, 6 CP)	287
•	Mathematical Population Genetics (MAT-75-08, 6 CP)	345
•	Mathematical Statistical Physics (MAT-65-14, 9 CP)	279
•	Matrix Analysis and Applications (MAT-65-37, 6 CP)	295
•	Morse Theory (MAT-55-28, 3 CP)	213
•	Non-Commutative Ergodic Theory (MAT-55-09, 9 CP)	191
•	Non-Linear Elliptic and Parabolic Partial Differential Equations (MAT-60-35, 6 CP)	269
•	Non-Linear Functional Analysis (MAT-55-02, 9 CP)	179
•	Nonlinear Elliptic Partial Differential Equations in Minimal Surface Theory (MAT-55-24, 9 CP)	207
•	Null Geometry in General Relativity (MAT-60-08, 5 CP)	259
•	Numerical Optimisation (MAT-70-25, 5 CP)	320
•	Numerics of Differential Equations of Surfaces (MAT-70-06, 6 CP)	309
•	Numerics of Stochastic Differential Equations (MAT-70-15, 3 CP)	315
•	Operator Algebras (MAT-55-04, 9 CP)	183
•	Operator Algebras and their Applications to Statistical Mechanics (MAT-55-71, 6 CP)	243
•	Operator Theory (MAT-55-03, 9 CP)	181
•	Optimal Control Theory with Ordinary Differential Equations (MAT-70-05, 5 CP)	307
•	Optimisation with Differential Equations (MAT-70-22, 9 CP)	318
•	Ordinary Differential Equations - Analysis and Numerics (MAT-70-04, 9 CP)	305
•	Partial Differential Equations (MAT-55-22, 9 CP)	205
•	Partial Differential Equations in Conformal Geometry: the Yamabe Problem (MAT-55-26, 3 CP)	209
•	Percolation Theory (MAT-75-05, 3 CP)	339
	Point Processes (MAT-75-09, 6 CP)	347

	• Primes of the form $\mathbf{x}^2 + ny^2$ and $ClassFieldTheory(MAT-45-30, 3CP)$ 127 $ProbabilityDistances for DataSet 75-20, 6CP)$	
•	Pseudo Differential Operators (MAT-55-10, 3 CP)	193
•	Quantum Information Theory (MAT-65-36, 9 CP)	293
•	Real Algebraic Geometry (MAT-45-19, 6 CP)	111
•	Representation Theory of Finite Groups (MAT-45-31, 6 CP)	129
•	Riemannian Geometry (MAT-50-16, 6 CP)	153
•	SL2(R) (MAT-55-52, 3 CP)	229
•	Selected Chapters from Dynamical Systems Theory (MAT-55-32, 3 CP)	215
•	Selected Chapters from Functional Analysis (MAT-55-70, 6 CP)	241
•	Selected Chapters from Operator Theory (MAT-55-15, 9 CP)	203
•	Space-Like Hypersurfaces in Lorentzian Manifolds (MAT-60-04, 6 CP)	251
•	Special Relativity (MAT-60-07, 3 CP)	257
•	Special Topics in Evolution Equations for Submanifolds (with Exercise Class) (MAT-60-10, 6 CP)	263
•	Special Topics in Evolution Equations for Submanifolds (without Exercise Classes) (MAT-60-11, 3 CP)	265
•	Spectral Theory of Positive Operators (MAT-55-08, 6 CP)	189
•	Statistical Learning Theory for Nonparametric Regression 1 (MAT-70-31, 9 CP)	324
•	Statistical Learning Theory for Nonparametric Regression 2 (MAT-70-32, 9 CP)	326
•	Stochastic Analysis (MAT-75-06, 9 CP)	341
•	Stochastic Differential Equations (MAT-70-11, 9 CP)	311
•	Stochastic Optimal Control in Infinite Dimensions (MAT-70-16, 3 CP)	317
•	The Einstein Constraint Equations (MAT-60-09, 6 CP)	261
•	The Ricci Flow of Riemannian Metrics (MAT-60-06, 6 CP)	255
•	Theoretical Aspects of Machine Learning (MAT-70-30, 6 CP)	322
•	Theory and Numerics for Constrained Optimisation Problems (MAT-70-33, 9 CP)	328
•	Theory of Mathematical Proofs (MAT-55-64, 6 CP)	237
•	Topological Vector Spaces and Distributions (MAT-50-27, 6 CP)	169
•	Toric Geometry (MAT-45-17, 9 CP)	107
•	Toric Varieties and Mori Dream Spaces (MAT-45-15, 9 CP)	103
•	Tropical Enumerative Geometry (MAT-50-04, 9 CP)	137
•	Tropical Enumerative Geometry - Part 2 (MAT-50-06, 5 CP)	141
•	Tropical Geometry (MAT-50-03, 9 CP)	135
•	Uniformisation of Riemann Surfaces (MAT-50-28, 5 CP)	171
	Wave Equations of Belativistic Quantum Mechanics (MAT-65-33, 6 CP)	291

Modules in the Specialisation Algebra and Geometry

The following modules belong to the specialisation Algebra and Geometry. Possible restrictions can be found in the module description.

•	Algebraic Curves (MAT-45-14, 9 CP)	101
•	Algebraic Curves and Riemann Surfaces (MAT-50-29, 9 CP)	173
•	Algebraic Geometry (MAT-45-11, 9 CP)	. 95
•	Algebraic Geometry and Toric Varieties (MAT-45-12, 9 CP)	. 97
•	Algebraic Groups (MAT-45-16, 9 CP)	105
•	Algebraic Number Theory (MAT-45-21, 9 CP)	115
•	Algebraic Topology 2 (MAT-50-22, 9 CP)	161
•	Algebraic Topology 3 (MAT-50-23, 3 CP)	163
•	Algebraic Transformation Groups (MAT-45-13, 9 CP)	. 99
•	Applied Topology 2 (MAT-50-26, 3 CP)	167
•	Applied topology 1 (MAT-50-25, 3 CP)	165
•	Automorphic Forms (MAT-55-53, 5 CP)	231
•	Cohomology and Sheaves (MAT-55-61, 9 CP)	233
•	Combinatorics (MAT-75-02, 9 CP)	333
•	Computer Algebra (MAT-45-03, 9 CP)	. 93
•	Consistency Proofs (MAT-55-62, 6 CP)	235
•	Cox Rings (MAT-45-18, 9 CP)	109
•	Elliptic Curves and Cryptography (MAT-45-27, 9 CP)	121
•	Elliptic Curves and Taniyama-Shimura (MAT-45-28, 9 CP)	123
•	Elliptic Functions and Elliptic Curves (MAT-45-24, 9 CP)	117
•	Explicit Mathematics (MAT-55-65, 6 CP)	239
•	Geometric Group Theory (MAT-50-30, 9 CP)	175
•	Geometry of Manifolds 2 (MAT-50-11, 9 CP)	143
•	Graph Theory (MAT-75-10, 9 CP)	349
•	Gromov-Witten Theory (MAT-50-40, 6 CP)	177
•	Groups and Representations (MAT-65-05, 9 CP)	273
•	Information Geometry (MAT-50-12, 3 CP)	145
•	Information Geometry and Neural Data Processing 2 (MAT-50-13, 3 CP)	147
•	Integrable Systems (and Infinite Dimensional Lie Algebras) (MAT-50-18, 9 CP)	157
•	Introduction to Analytic Number Theory (MAT-45-26, 3 CP)	119
•	Introduction to Berkovich Geometry (MAT-45-20, 3 CP)	113
•	Introduction to Combinatorial Birational Geometry (MAT-45-40, 9 CP)	131
•	Introduction to Combinatorial Mirror Symmetry (MAT-45-41, 6 CP)	133
•	Introduction to Integrable Systems (Classical Mechanics, Riemann Surfaces, and Spectral Theory) (MAT-50-CP)	

	Introduction to Modular Forms (MAT-45-29, 3 CP)	125
	Introduction to Riemann Surfaces (MAT-50-15, 5 CP)	151
	Introduction to Tropical Enumerative Geometry (MAT-50-05, 5 CP)	139
	Mathematical Aspects of Neuronal Information Processing 1 (MAT-50-14, 3 CP)	149
	Mathematical Aspects of Neuronal Information Processing 2 (MAT-50-19, 3 CP)	159
	Morse Theory (MAT-55-28, 3 CP)	213
	Percolation Theory (MAT-75-05, 3 CP)	339
	• Primes of the form $\mathbf{x}^2 + ny^2$ and $ClassFieldTheory(MAT-45-30,3CP)$ 127 $RealAlgebraicGeometry(MAT-45-19,6CP)$	
•	Representation Theory of Finite Groups (MAT-45-31, 6 CP)	129
•	Riemannian Geometry (MAT-50-16, 6 CP)	153
•	SL2(R) (MAT-55-52, 3 CP)	229
•	Seminar Advanced Knowledge in Mathematics (MAT-40-11, 3 CP)	92
•	Theory of Mathematical Proofs (MAT-55-64, 6 CP)	237
•	Toric Geometry (MAT-45-17, 9 CP)	107
•	Toric Varieties and Mori Dream Spaces (MAT-45-15, 9 CP)	103
•	Tropical Enumerative Geometry (MAT-50-04, 9 CP)	137
•	Tropical Enumerative Geometry - Part 2 (MAT-50-06, 5 CP)	141
•	Tropical Geometry (MAT-50-03, 9 CP)	135
,	Uniformisation of Riemann Surfaces (MAT-50-28, 5 CP)	171
	Madulas in the Considiration Analysis and Differential Connector	
	Modules in the Specialisation Analysis and Differential Geometry The following modules belong to the specialisation Analysis and Differential Geometry. Possible restrictions can be formally and Differential Geometry.	found
	in the module description.	iouria
	Abstract Dynamical Systems (MAT-55-33, 9 CP)	217
	Algebraic Curves (MAT-45-14, 9 CP)	101
	Algebraic Curves and Riemann Surfaces (MAT-50-29, 9 CP)	173
	Algebraic Topology 2 (MAT-50-22, 9 CP)	161
	Algebraic Topology 3 (MAT-50-23, 3 CP)	163
	Applied Topology 2 (MAT-50-26, 3 CP)	167
	Applied topology 1 (MAT-50-25, 3 CP)	165
	Area Minimising Flows (MAT-55-43, 5 CP)	221
	Automorphic Forms (MAT-55-53, 5 CP)	231
	Cohomology and Sheaves (MAT-55-61, 9 CP)	233
	Consistency Proofs (MAT-55-62, 6 CP)	235
	Control Theory (MAT-55-06, 9 CP)	187
	Elastic Curves (MAT-55-46, 3 CP)	223
	Elliptic Company and Taniscome Chinasura (MAAT 45 00, 0 CD)	123
	Elliptic Curves and Taniyama-Shimura (MAT-45-28, 9 CP)	120

•	Explicit Mathematics (MAT-55-65, 6 CP)	239
•	Fully Non-Linear Elliptic Equations (MAT-55-27, 5 CP)	211
•	Fully Non-Linear Elliptic and Parabolic Partial Differential Equations (MAT-60-36, 3 CP)	271
•	Geometric Evolution Equations (MAT-60-01, 3 CP)	245
•	Geometric Group Theory (MAT-50-30, 9 CP)	175
•	Geometric Measure Theory (MAT-55-42, 9 CP)	219
•	Geometric Measure Theory – Flows (MAT-55-48, 5 CP)	227
•	Geometric Measure Theory – Varifolds (MAT-55-47, 5 CP)	225
•	Geometric Variation Problems (MAT-60-02, 3 CP)	247
•	Geometry of Manifolds 2 (MAT-50-11, 9 CP)	143
•	Gravitational Collapse and Singularities in General Relativity (MAT-60-30, 3 CP)	267
•	Hamiltonian Systems (MAT-65-38, 9 CP)	297
•	Harmonic Analysis in Euclidean Space (MAT-55-12, 9 CP)	197
•	Harmonic Analysis on Abelian Groups (MAT-55-13, 9 CP)	199
•	Harmonic Analysis on General Groups (MAT-55-14, 9 CP)	201
•	Information Geometry (MAT-50-12, 3 CP)	145
•	Information Geometry and Neural Data Processing 2 (MAT-50-13, 3 CP)	147
•	Integrable Systems (and Infinite Dimensional Lie Algebras) (MAT-50-18, 9 CP)	157
•	Introduction to Analytic Number Theory (MAT-45-26, 3 CP)	119
•	Introduction to Berkovich Geometry (MAT-45-20, 3 CP)	113
•	Introduction to Harmonic Analysis (MAT-55-11, 9 CP)	195
•	Introduction to Integrable Systems (Classical Mechanics, Riemann Surfaces, and Spectral Theory) (MAT-50-CP)	
•	Introduction to Riemann Surfaces (MAT-50-15, 5 CP)	151
•	Limits of Spaces (MAT-60-05, 6 CP)	253
•	Mathematical Aspects of Neuronal Information Processing 1 (MAT-50-14, 3 CP)	149
•	Mathematical Aspects of Neuronal Information Processing 2 (MAT-50-19, 3 CP)	159
•	Mathematical Aspects of the Quantum Hall Effect (MAT-65-32, 6 CP)	289
•	Mathematical Methods for Condensed Matter Physics (MAT-65-31, 6 CP)	287
•	Mathematical Relativity (MAT-65-13, 9 CP)	277
•	Matrix Analysis and Applications (MAT-65-37, 6 CP)	295
•	Morse Theory (MAT-55-28, 3 CP)	213
•	Non-Commutative Ergodic Theory (MAT-55-09, 9 CP)	191
•	Non-Linear Elliptic and Parabolic Partial Differential Equations (MAT-60-35, 6 CP)	269
•	Non-Linear Functional Analysis (MAT-55-02, 9 CP)	179
•	Nonlinear Elliptic Partial Differential Equations in Minimal Surface Theory (MAT-55-24, 9 CP)	207
•	Null Geometry in General Relativity (MAT-60-08, 5 CP)	259
	Operator Algebras (MAT-55-04, 9 CP)	183

Operator Algebras and their Applications to Statistical Mechanics (MAT-55-71, 6 CP)	243
Operator Theory (MAT-55-03, 9 CP)	181
Optimal Control Theory with Ordinary Differential Equations (MAT-70-05, 5 CP)	307
Optimisation with Differential Equations (MAT-70-22, 9 CP)	318
Ordinary Differential Equations - Analysis and Numerics (MAT-70-04, 9 CP)	305
Partial Differential Equations (MAT-55-22, 9 CP)	205
Partial Differential Equations in Conformal Geometry: the Yamabe Problem (MAT-55-26, 3 CP)	209
Pseudo Differential Operators (MAT-55-10, 3 CP)	193
Riemannian Geometry (MAT-50-16, 6 CP)	153
• SL2(R) (MAT-55-52, 3 CP)	229
Selected Chapters from Dynamical Systems Theory (MAT-55-32, 3 CP)	215
Selected Chapters from Functional Analysis (MAT-55-70, 6 CP)	241
Selected Chapters from Operator Theory (MAT-55-15, 9 CP)	203
Seminar Advanced Knowledge in Mathematics (MAT-40-11, 3 CP)	92
Special Relativity (MAT-60-07, 3 CP)	257
• Special Topics in Evolution Equations for Submanifolds (with Exercise Class) (MAT-60-10, 6 CP)	263
• Special Topics in Evolution Equations for Submanifolds (without Exercise Classes) (MAT-60-11, 3 CP)	265
Spectral Theory of Positive Operators (MAT-55-08, 6 CP)	189
The Einstein Constraint Equations (MAT-60-09, 6 CP)	261
The Ricci Flow of Riemannian Metrics (MAT-60-06, 6 CP)	255
Theory of Mathematical Proofs (MAT-55-64, 6 CP)	237
Topics in Mathematical Relativity (MAT-60-03, 3 CP)	249
Topological Vector Spaces and Distributions (MAT-50-27, 6 CP)	169
Uniformisation of Riemann Surfaces (MAT-50-28, 5 CP)	171
Modulos in the Specialisation Mathematical Physics	
Modules in the Specialisation Mathematical Physics The following modules belong to the specialisation Mathematical Physics. Possible restrictions can be found in the	modula
description.	module
Advanced Topics in Mathematical Quantum Theory (MAT-65-21, 9 CP)	283
Advanced Topics in Mathematical Relativity (short version) (MAT-65-24, 6 CP)	285
Ergodic Theory (MAT-55-05, 9 CP)	185
Foundations of Quantum Mechanics (MAT-65-15, 9 CP)	281
Fully Non-Linear Elliptic and Parabolic Partial Differential Equations (MAT-60-36, 3 CP)	271
Gravitational Collapse and Singularities in General Relativity (MAT-60-30, 3 CP)	267
Gromov-Witten Theory (MAT-50-40, 6 CP)	177
Groups and Representations (MAT-65-05, 9 CP)	273
Hamiltonian Systems (MAT-65-38, 9 CP)	297
Limits of Spaces (MAT-60-05, 6 CP)	253

•	Mathematical Aspects of the Quantum Hall Effect (MAT-65-32, 6 CP)	289
•	Mathematical Methods for Condensed Matter Physics (MAT-65-31, 6 CP)	287
•	Mathematical Quantum Theory (MAT-65-12, 9 CP)	275
•	Mathematical Relativity (MAT-65-13, 9 CP)	277
•	Mathematical Statistical Physics (MAT-65-14, 9 CP)	279
•	Matrix Analysis and Applications (MAT-65-37, 6 CP)	295
•	Non-Commutative Ergodic Theory (MAT-55-09, 9 CP)	191
•	Non-Linear Elliptic and Parabolic Partial Differential Equations (MAT-60-35, 6 CP)	269
•	Nonlinear Elliptic Partial Differential Equations in Minimal Surface Theory (MAT-55-24, 9 CP)	207
•	Null Geometry in General Relativity (MAT-60-08, 5 CP)	259
•	Operator Algebras (MAT-55-04, 9 CP)	183
•	Operator Algebras and their Applications to Statistical Mechanics (MAT-55-71, 6 CP)	243
•	Operator Theory (MAT-55-03, 9 CP)	181
•	Partial Differential Equations (MAT-55-22, 9 CP)	205
•	Partial Differential Equations in Conformal Geometry: the Yamabe Problem (MAT-55-26, 3 CP)	209
•	Percolation Theory (MAT-75-05, 3 CP)	339
•	Propagation of Chaos (MAT-65-39, 9 CP)	299
•	Quantum Information Theory (MAT-65-36, 9 CP)	293
•	Riemannian Geometry (MAT-50-16, 6 CP)	153
•	Selected Chapters from Functional Analysis (MAT-55-70, 6 CP)	241
•	Selected Chapters from Operator Theory (MAT-55-15, 9 CP)	203
•	Seminar Advanced Knowledge in Mathematics (MAT-40-11, 3 CP)	. 92
•	Space-Like Hypersurfaces in Lorentzian Manifolds (MAT-60-04, 6 CP)	251
•	Special Relativity (MAT-60-07, 3 CP)	257
•	Special Topics in Evolution Equations for Submanifolds (with Exercise Class) (MAT-60-10, 6 CP)	263
•	Special Topics in Evolution Equations for Submanifolds (without Exercise Classes) (MAT-60-11, 3 CP)	265
•	Spectral Theory of Positive Operators (MAT-55-08, 6 CP)	189
•	The Einstein Constraint Equations (MAT-60-09, 6 CP)	261
•	The Ricci Flow of Riemannian Metrics (MAT-60-06, 6 CP)	255
•	Topological Vector Spaces and Distributions (MAT-50-27, 6 CP)	169
	Wave Equations of Relativistic Quantum Mechanics (MAT-65-33, 6 CP)	291

Modules in the Specialisation Numerial Mathematics and Optimisation

The following modules belong to the specialisation Numerial Mathematics and Optimisation. Possible restrictions can be found in the module description.

•	Bayesian Networks and Causality (MAT-75-21, 5 CP)	355
•	Financial Mathematics and Numerics (MAT-70-51, 6 CP)	331
•	Game Theory (MAT-70-40, 3 CP)	330
•	Geometric Evolution Equations (MAT-60-01, 3 CP)	245
•	Hamiltonian Systems (MAT-65-38, 9 CP)	297
•	Integrable Systems (and Infinite Dimensional Lie Algebras) (MAT-50-18, 9 CP)	157
	Introduction to Integrable Systems (Classical Mechanics, Riemann Surfaces, and Spectral Theory) (MAT-50-1 CP)	
•	Introduction to Stochastic Differential Equations - Part 1 (MAT-70-12, 5 CP)	313
•	Numerical Optimisation (MAT-70-25, 5 CP)	320
•	Numerics of Differential Equations of Surfaces (MAT-70-06, 6 CP)	309
•	Numerics of Instationary Differential Equations (MAT-70-03, 9 CP)	303
•	Numerics of Stationary Differential Equations (MAT-70-02, 9 CP)	301
•	Numerics of Stochastic Differential Equations (MAT-70-15, 3 CP)	315
•	Optimal Control Theory with Ordinary Differential Equations (MAT-70-05, 5 CP)	307
•	Optimisation with Differential Equations (MAT-70-22, 9 CP)	318
•	Ordinary Differential Equations - Analysis and Numerics (MAT-70-04, 9 CP)	305
•	Partial Differential Equations (MAT-55-22, 9 CP)	205
•	Probability Distances for Data Science (MAT-75-20, 6 CP)	353
•	Seminar Advanced Knowledge in Mathematics (MAT-40-11, 3 CP)	. 92
•	Statistical Learning Theory for Nonparametric Regression 1 (MAT-70-31, 9 CP)	324
•	Statistical Learning Theory for Nonparametric Regression 2 (MAT-70-32, 9 CP)	326
•	Stochastic Differential Equations (MAT-70-11, 9 CP)	311
•	Stochastic Optimal Control in Infinite Dimensions (MAT-70-16, 3 CP)	317
•	Theoretical Aspects of Machine Learning (MAT-70-30, 6 CP)	322
•	Theory and Numerics for Constrained Optimisation Problems (MAT-70-33, 9 CP)	328
Mod	ules in the Specialisation Stochastics	
	llowing modules belong to the specialisation Stochastics. Possible restrictions can be found in the module des	crin-
tion.	nowing modulos scieng to the openialisation etcomatics. I coolisis restrictions can be loand in the module dec	onp
•	Applied Topology 2 (MAT-50-26, 3 CP)	167
•	Applied topology 1 (MAT-50-25, 3 CP)	165
•	Bayesian Networks and Causality (MAT-75-21, 5 CP)	355
•	Combinatorics (MAT-75-02, 9 CP)	333
•	Financial Mathematics and Numerics (MAT-70-51, 6 CP)	331
•	Graph Theory (MAT-75-10, 9 CP)	349

•	Information Geometry (MAT-50-12, 3 CP)	145
•	Information Geometry and Neural Data Processing 2 (MAT-50-13, 3 CP)	147
•	Information Theory (MAT-75-07, 9 CP)	343
•	Introduction to Stochastic Differential Equations - Part 1 (MAT-70-12, 5 CP)	313
•	Markov Chains and Applications (MAT-75-11, 9 CP)	351
•	Mathematical Population Genetics (MAT-75-08, 6 CP)	345
•	Mathematical Statistical Physics (MAT-65-14, 9 CP)	279
•	Mathematical Statistics (MAT-75-03, 9 CP)	335
•	Numerics of Stochastic Differential Equations (MAT-70-15, 3 CP)	315
•	Operator Algebras and their Applications to Statistical Mechanics (MAT-55-71, 6 CP)	243
•	Percolation Theory (MAT-75-05, 3 CP)	339
•	Point Processes (MAT-75-09, 6 CP)	347
•	Probability Distances for Data Science (MAT-75-20, 6 CP)	353
•	Propagation of Chaos (MAT-65-39, 9 CP)	299
•	Seminar Advanced Knowledge in Mathematics (MAT-40-11, 3 CP)	. 92
•	Statistical Learning Theory for Nonparametric Regression 1 (MAT-70-31, 9 CP)	324
•	Statistical Learning Theory for Nonparametric Regression 2 (MAT-70-32, 9 CP)	326
•	Stochastic Analysis (MAT-75-06, 9 CP)	341
•	Stochastic Differential Equations (MAT-70-11, 9 CP)	311
•	Stochastic Optimal Control in Infinite Dimensions (MAT-70-16, 3 CP)	317
•	Stochastic Processes (MAT-75-04, 9 CP)	337
•	Theoretical Aspects of Machine Learning (MAT-70-30, 6 CP)	322

Module descriptions (Specialisation Modules)

Module Number: MAT-40-11	Module Title: Seminar Advanced Knowledge in Mathematics 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	Every semester									
Term	2-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Seminar, talk, presentation, e	e-learr	ning,	blen	ded I	earning				
Content	Various topics from the Stud	/ Spec	cialis	ation	s of	the stu	dy programi	me.		
Objectives	Students work independently on in-depth questions from the area of their Study Specialisation and prepare them in a didactically appealing and scientifically sound form. They train their presentation techniques and sharpen their professional discussion style.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Seminar	s	0	2	3	yes	Pr	60-90	g	100
	In addition to a successful talk, the acquisition of credit points also requires regular active participation in the course, for example in the form of questions and contributions to the discussion or by completing assignments. In addition, a written elaboration of one's own presentation or the preparation of a handout for the participants may be part of the work to be done. This additional work constitutes the coursework for the module.									
Transfer	-									
Prerequisites	There are no further prerequ	isites.								
Responsible Persons	The dean of studies at the department of mathematics									
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 : o=obligatory, f=facultative Other : h=hours, o.=or, s.M.=see module description, SWS=contact hours per week										

Module Number: MAT-45-03	Module Title: Computer Algebra						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	 Canonical forms and standard bases for ideals and modules. Computation of important operations for ideals and modules. Syzygies, free resolutions and the proof of the Buchberger criterion. Calculation of the primary decomposition of ideals. Hilbert functions. 									
Objectives	Students are familiar with important problems in the interplay of commutative algebra and algebraic geometry as well as algorithmic approaches to solving them. In particular, they are familiar with the theory of standard bases and their diverse applications. They are also familiar with important software packages in the field of symbolic computing and have implemented algorithms in these. 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. They also learnt about important software packages in the field of symbolic computing and have implemented algorithms in them themselves									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Computer Algebra	L E	f f	4	6 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	Possible References :
	 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 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 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

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 : o=obligatory, f=facultative

Module Number: MAT-45-11	Module Title: Type of Module: Algebraic Geometry Compulsory Modu						le with	Choice		
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h									
Duration	1 Semester									
Frequency	regularly in Summer Semes	ter								
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	Prevarieties and varieties.	eties.								
	Projektive varieties at	nd hom	noge	neou	s spe	ectrum				
	Finite and proper mo	rphism	s.							
	Blow-up and Grassm	annian	S.							
	Rational maps.									
	Divisors and line bun	dles, c	lass	grou	o and	l Picar	d group.			
Objectives	The students learn central terms, results and methods of modern Algebraic Geometry and they develop a deeper 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Algebraic Geometry	L	f	4	6	yes	wr. o.	90-180	g	100
	- Inguitable Goombily	Е	f	2	3	,55	or.	o. 20-30	9	
	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	Possible References :						
	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 : o=obligatory, f=facultative

Module Number: MAT-45-12	Module Title: Algebraic Geometry and Toric Varieties Type of Module: Compulsory Module with Choic							Choice		
ECTS-Points	9							,	<u> </u>	
Workload - Time in Class - Self-Study	Workload: 270 h	1 1111								
Duration	1 Semester	1 Semester								
Frequency	regularly in Summer Semes	regularly in Summer Semester								
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ecture 4 SWS + Exercise Class 2 SWS								
Content	Projective space.	Projective space.								
	Prevarieties, morphis	ms, tan	ngent	spa	ce a	nd sing	ularities.			
	Products and separate	Products and separation.								
	Projective varieties as	Projective varieties and Grassmannians.								
	Divisors and line bundles, class group and Picard group.									
	Toric varieties.									
Objectives	Students learn the central country develop an advanced upon the commerce of th	ndersta lass of nvestig Algebra ing the nnection have a nethods them a	Indination ation ation a and e essens. Indicate the according at the according according to the according according to the according according to the according according according to the according to the according according to the according according to the	g of to various of a discontinuity of a discontinuity of the less	the retrietie in im omet al reservation corrections the reservation in the retrieval in the retrievation i	elations s, they portan ry by a sults of nfident, e. They solution	ships between also learn texample confurther conthe lecture precise and have learn on strategies	en Geometr how methodelass of Algelenponent. The as well as and independent ed to transfess on their owner in critical and independent ed to transfess on their owner in critical ed.	y and / ods of braic v e stude assess ent har er the r	Algebra. Convex arieties, ents are ing and adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Algebraic Geometry and Toric Varieties	L E	f f	2	6 3	yes	wr. o. or.	90-180 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	Possible References :
	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
Alabaaaiatiaaaa	

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 : o=obligatory, f=facultative

Module Number: MAT-45-13	Module Title: Algebraic Transformation Gr		of Module: ulsory Modul	le with	Choice					
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time in	n Cla	ss:	Self-St 180 h	udy:				
Duration	1 Semester	1 Semester								
Frequency	not regularly	not regularly								
Term	1-3	1-3								
Language of Instruction	German or English	German or English								
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2 S	SWS							
Chiectives	Elements of the struction Elements of the represent of the representation of the	Additionally certain aspects of topics from the following list are covered:								
Objectives	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. They are able to present their solutions and, if necessary, defend them in critical discourse.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title			ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Algebraic Transformation Groups			4 6 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	Possible References :
	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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom \\$

Status : o=obligatory, f=facultative

Module Number: MAT-45-14	Module Title: Algebraic Curves							of Module: ulsory Modu	le with	Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3	i-3								
Language of Instruction	German or English	German or English								
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Cl	ecture 4 SWS + Exercise Class 2 SWS								
Content	 Ramified coverings, TI Linear systems, embe Singularities of plane of 	 Projective curves, divisors, Theorem of Riemann-Roch. Ramified coverings, Theorem of Hurwitz. Linear systems, embeddings, Castelnuovo inequality. Singularities of plane curves, Puiseux expansions. Classification and moduli spaces, Jacobi variety. 								
Objectives	selected sub-area of algebra oped an in-depth understand capable of naming and provi explaining the presented con In the exercise classes they I the terms, statements and me	Students have familiarised themselves with the central concepts, results and methods in a selected sub-area of algebraic geometry. familiarised themselves with it. They have developed an in-depth understanding of algebraic curves and their classification. 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 Algebraic Curves	Type of Course	t Status	SMS 4	9 ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	In this module an exercise ce	E rtifica	f te is	2 to be	3 acc		or. us coursewo	o. 20-30 ork. For part	g icipatio	
	examination the coursework oral is decided by the instruct	must l	nave	beer	n acc	quired.	Whether th	e examination		
Literature	Possible References :									
	Robin Hartshorne: Alg	ebrai	c ged	omet	ry. S	pringer	2006.			
	Gerd Fischer: Ebene a	algebr	aiscl	ne Kı	ırveı	n. View	eg 1994.			
	Rick Miranda: Algebra	ic Cu	rves	and I	Riem	nann Sı	urfaces. 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 $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : o=obligatory, f=facultative

Module Number: MAT-45-15	Module Title: Type of Module: Toric Varieties and Mori Dream Spaces 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	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	In the lecture Mori Dream Sp	oaces a	are c	onsi	dered	d as ge	neralisation	s of toric va	rieties:	
	Geometry and combine	natorial	l the	ory fo	or tor	ic varie	eties and Mo	ori Dream S	paces.	
	Divisors on toric varie	ties an	d Mo	ori D	ream	Space	es.			
	Quotient representation	on and	Cox	ring	for t	oric va	rieties and N	Mori Dream	Space	S.
	Sheaves of divisorial algebras.									
	Cox sheaves and cha	racteris	stic s	space	Э.					
	Quotients of H-factori	Quotients of H-factorial affine varieties.								
	Shaded rings.									
	Varieties with torus or	oeration	ns.							
Objectives	and methods of modern alg With the class of Mori dream 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Toric Varieties and Mori Dream Spaces	L E	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	Possible References :
	 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 : o=obligatory, f=facultative

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								
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS							
Content	Definition and examp	les of algebraic groups.							
	Hopf algebras.								
	Operations of algebra	Operations of algebraic groups on varieties.							
	Linearisation of algebraic groups.								
	Group closure.								
	Resolvable and nilport	tent groups.							
	The Lie algebra of an	algebraic group.							
	Examples of Lie alge	bras.							
	Convolutions and cor	nmutators.							
	The adjoint represent	ation and its differential.							
	The Jordan decompo	sition in affine algebraic group	S.						
	Characters of an alge	ebraic group.							
	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 classifi	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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Algebraic Groups	L E	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	Possible References : • James E. Humphreys: 1981. • Armand Borel: Linear a					·	, -	1975. 21, S	pringe	r-Verlag
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 Transformation Groups' due to the large overlap in content.									
Prerequisites	Knowledge of the modules Co a prerequisite for participation							ometry are I	nelpful	, but not
Responsible Persons	Victor Batyrev, 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 : o=obligatory, f=facultative

Module Number: MAT-45-17	Module Title: Type of Module: Compulsory Module with Choi									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	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	Lattice and algebraic	tori.								
	Monoids, monoidal al	gebras	S.							
	Affine toric varieties, i	normal	ity.							
	Fundamentals of convex geometry cones, polytopes, fans.									
	Affine, complete and projective toric varieties.									
	Orbital layout of a toric variety.									
	Smoothness and singular points.									
	Singularity resolution.									
	Divisor class group as	nd Pica	ard g	roup						
	Intersection sheaves	and ho	mog	enec	ous c	oordin	ates.			
Objectives	and methods of modern alge combinatorics. With the class of combining algebraic geomenother important methodolor. The students are capable of assessing and explaining the lin 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. With the class of toric varieties and their investigation, they have learnt a way of combining algebraic geometry with methods of combinatorics. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Toric Geometry	L E	f	2	6	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	must h	nave	beei	n acc	uired.	Whether th	e examination		

Literature	Possible References :
	David Cox, John Little, Hal Schenk: Toric varieties. AMS 2011.
	William Fulton: Introduction to toric varieties. PUP 1993.
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 of commutative algebra and algebraic geometry algebraic geometry to the extent of the module Introduction to Commutative Algebra and Algebraic Geometry is assumed.
Responsible Persons	Jürgen Hausen, 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 : o=obligatory, f=facultative

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	Semester											
Frequency	not regularly												
Term	1-3												
Language of Instruction	English												
Forms of Teaching and Learning	ecture 4 SWS + Exercise Class 2 SWS												
Content	Divisorial algebras.	•											
	Cox rings.												
	Charakteristic spaces	i.											
	Good quotients.												
	Geometric invariant the Gold display.	neory.											
	Gale-duality.Connections to toric g	noomatry											
		peometry. eties with finitely generated Co	ny ring										
	Singularities.	siles with limitery generated oc	ing.										
	Picard group.												
	Basis locus.												
	Ampleness.												
	Kanonical class.												
	Intrinsic quadrics.												
	• k*-surfaces.												
	Varieties with torus ac	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	braic geometry in its interplay miliarised themselves with the of geometric spaces. In doin with another important metho proving the essential results of connections. have acquired a confident, protethods of the lecture. They have and to work on solutions.	ling of the central concepts, results between geometry and algebra and Cox ring as an algebraic object for g so, they expand the interplay bedological component. The students of the lecture as well as assessing recise and independent handling of ave learned to transfer the methods strategies on their own or in a team. defend them in critical discourse.										

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	J Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Cox Rings	Е	f	2	3	yes	or.	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	Possible References : • Ivan Arzhantsev, Ulrich 2014.	n Der	entha	al, Ji	irger	n Haus	en, Antonio	Laface: Co	x Ring	s. CUP
Transfer	The module belongs to the S the chosen personal Study S Advanced Knowledge in Mat strictive requirements of the re	Specia hema	alisat <i>tics</i> (ion, or <i>El</i>	it ca <i>ectiv</i>	n be in	icluded in th	ne Šections	Study	Focus,
Prerequisites	Knowledge of commutative al duction to commutative algeb								modu	le Intro-
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 : o=obligatory, f=facultative

Module Number: MAT-45-19	Module Title: Real Algebraic Geometry							of Module:	le with	Choice	
ECTS-Points	6										
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in C	lass	3 :		Self-St 120 h	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	English	English									
Forms of Teaching and Learning	Lecture 3 SWS	ecture 3 SWS									
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	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. 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	Coursework	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	
		must h	nave	bee	n acq	uired.	Whether th	e examinatio			
Literature	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. Possible References: • Frederice Mangolte: Real Algebraic Varieties. Springer 2020. • Robert Silhol: Real Algebraic Surfaces. Springer 1989. • Riccardo Benedetti, Jean-Jacques Risler: Real Algebraic and Semi-algebraic Sets. Editions Herrmann 1990. • Alex Degtyarev, Viatcheslav Kharlamov: Topological properties of real algebraic varieties: du côté de chez Rokhlin. arXiv:math/0004134.										

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 : o=obligatory, f=facultative

	3						Compu	Ilsory Modu	ie with	Choice	
Workload	3										
Ti i Ol	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 3 SWS										
Content	 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 fields and their induced topo challenges in developing a table. Berkovich's approach to additine in Berkovich's frameworthey have encountered a type encountered in their studies familiar with the connections students are capable of name assessing and explaining the lin the exercise classes they the terms, statements and m to new problems, to analyse team. They are capable of p discourse.	ology. cheory ressing k in de of ge (such to alg ning a prese have a ethods to them	The of a g the etail, ome as v gebra acquires of t	y had naly se is both tric sectoratic growing loon in the left to be a	ve gastic gessues a set- pace r space r space gestie the correction of the correctio	ained a cometr. The stheore fundarices, very three esse ons. If ident, a. They on so	an understa y over thes students have tically and to mentally diff arieties, or loo ough the a ntial results precise and have learned ution strate	e fields and the efields and the examined topologically erent from comanifolds). Inalytification of the lecture of the lecture dindependent transferigies on the	e fund I have I the pr I the pr I in d I there They I funct ure as ent har er the r	amental studied rojective roing so, camples are also or. The well as adding of nethods or in a	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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.	writter	n or	oral	s de	cided I	by the instru	uctor with a	pprova	l by the	
Literature	Possible References :										
	Annette Werner: Nich	tarchir	nedi	sche	Geo	metrie.	Vorlesungs	sskript.			

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 : o=obligatory, f=facultative

Module Number: MAT-45-21	Module Title: Algebraic Number 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-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	ass 2	SW	S								
Content		 Class numbers. Dirichlet's unit theorem. Extension of Dedekind rings. Valuation theory. Local fields. 										
Objectives	The students have learned the 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	namin prese have a ethoda thema	g and entectacques of t and t	d pro I con ired a he le o wo	oving necti a cor ecture rk or	the essions. Infident, They I solution	precise an have learn on strategie	Its of the lec d independe ed to transfe s on their ow	ture as ent har er the r n or in	well as adding of nethods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Algebraic Number Theory	L E	f	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 examination				
Literature	Possible References: • Jürgen Neukirch: Alge • Alexander Schmidt: E • Andre Weil: Basic nur	inführ	ung i	n die	alge	ebraisc	he Zahlenth		iger 20	07.		

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 : o=obligatory, f=facultative

Module Number: MAT-45-24	Module Title: Elliptic Functions and Elliptic	Curves	3				of Module: ulsory Modul	le with	Choice				
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	in Cla	iss:		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	Lecture 4 SWS + Exercise Class 2 SWS											
Content	Elliptic functions, Wei	erstrass	s-P-fu	nction,	Riema	nn surfaces	, complex to	ri.					
	Plane projective curves, Theorem of Bezout, elliptic curves.												
	Curves over finite fields, rational points.												
	 Applications in crypto 	graphy.											
	 Additionally a selection Modular forms; 	n of the	follo	wing:									
	- Classification o	f elliptic	curv	es;									
	 Moduli spaces. 												
Objectives	The students have expanded have learnt about elliptic cursive relevance in a wide sprotions, methods and result Number Theory, Topology ar understand their mutual interessential results of the lecture. 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 d Crypt rrelation e as we have ac nethods lyse the	a cla of m the c tographs. T ell as a cquire s of the	ass of rathemadiscipling the students of the s	nathem atical arenes Corrich are dents and ing and infident, are. The ork on s	atical objecteas. The samplex Calcorelevant in the capable of explaining the precise and ey have leasolution stra	ts, which has tudents have ulus, Algebrathe given conformating as the presented independerned to trantegies on the	es come ve stude raic Ge ntext, a nd pro d conn ent har esfer th eir owl	prehendied the ecometry, and they ving the ections. Indiing of e methon or in a				
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Elliptic Functions and Elliptic		J Status	SWS 4 6 ECTS	Coursework Type of Exam Type of Exam Our. of Exam (min) Grading Weight for Grade								
	In this module an exercise or examination the coursework oral is decided by the instruc	must ha	ave b	een ac	quired a	Whether th	e examinatio						

Literature	Possible References :
	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 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 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 : o=obligatory, f=facultative

Module Number: MAT-45-26	Module Title: Introduction to Analytic Numb	er Th	eory	,				of Module: ulsory Modul	e with	Choice	
ECTS-Points	3						'				
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	Clas	s:		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	Lecture 2 SWS									
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. 										
Objectives	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 the specific area.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ecTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Analytic Number Theory	L	f	2	3	no	wr. o. or.	o. 20-30	g	100	
	Whether the examination is Board of Examiners.	writte	n or	ora	l is de	ecided	by the instr	uctor with a	pprova	ll by the	
Literature	Possible References : • Komaravolu Chandras 1968.	sekha	ran:	Int	roduc	tion to	Analytic N	umber The	ory. S	Springer	
Transfer	The module belongs to the of Differential Geometry. Taking be included in the Sections Specialisation, in accordance	g into <i>Study</i>	Foc	oun eus,	t the o	chosen nced K	personal S <i>nowledge il</i>	tudy Specia n <i>Mathemat</i>	lisation ics or	n, it can <i>Elective</i>	
Prerequisites	There are no further prerequi	sites									
Responsible Persons	Anton Deitmar										

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

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 : o=obligatory, f=facultative

Module Number: MAT-45-27	Module Title: Elliptic Curves and Cryptogra	aphy						of Module: ulsory Modul	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 C	lass 2	SWS	3								
Content	Basic concepts of cry	Basic concepts of cryptography.										
	Symmetric cryptosystems, public key systems, discrete logarithm, RSA.											
	Factorisation into prin	nes, att	acks	on o	crypt	osyste	ms.					
	Basic concepts of pla	ne proj	ectiv	⁄e ge	ome	try.						
	Elliptic curves as Abe	lian gro	oups									
	Curves over finite field	ds, Frol	benii	us m	orph	ism, er	ndomorphis	m ring.				
	Counting points, Hass	se bour	nd, V	Veil o	onje	ctures,	Schoof's a	lgorithm.				
	Cryptosystems on elli	ptic cu	rves	, algo	orithr	ns and	attacks.					
Objectives	Students are familiar with the cryptographically motivated advanced algebraic and geo lenges of algorithmic implem are 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	questicemetricementation proving deconnection have a dethods them a	ons retechnion are the ection are th	relation rel	ng to es for e fan entia a cor cture rk on	elliption r answer niliar word resultion fident, e. They r solution	c curves an ering them. ith standards of the led precise an have learn on strategies	d have an interpretation of the desired to transfer on their own t	nsight stand to the self as as ent har er the render in or in	into the he chal- students esessing adling of methods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Elliptic Curves and	L	f	4	6	yes	wr. o.	90-180	g	100		
	Cryptography	Е	f	2	3	_	or.	o. 20-30				
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	ave	beer	acc	uired.	Whether th	e examinatio				

Literature	Possible References :
	 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

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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom \\$

Status : o=obligatory, f=facultative

Module Number: MAT-45-28	Module Title: Elliptic Curves and Taniyama-Shimura Type of Module: Compulsory Module 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 or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ass 2	SWS	3								
Content	 Group-law, arithmetic Modular curves and for Riemann surfaces, abe Geometric version of a plained. Connection to Fermat L-series. 	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 proviexplaining the presented con current state of research in the In the exercise classes they the terms, statements and mon new problems, to analyse They are able to present their	ound rappling the nection substitution the substitution to the nection substitution in the nection in the necti	mathe catio e ess ns. S pject acqu s of t and t	emat n to sentia Stude area ired he le o wo	ical c the p al res ents v a cor ecture rk or	question proof of sults of will be a nfident, e. They n solution	ns using the Fermat's t the lecture able to reflect precise and have learn on strategie	e example of heorem. The as well as ct and critical d independent ed to transfers on their ow	the cone stude assessully ana ent har er the r	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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Elliptic Curves and Taniyama-Shimura L f 4 6 E f 2 3 yes wr. o. 90-180 o. 20-30 g 100								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	Possible References : • Joseph H. Silverman:											

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 $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : o=obligatory, f=facultative

Module Number: MAT-45-29	Module Title: Introduction to Modular Forms							of Module: ulsory Modu	le with	Choice		
ECTS-Points	3	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	Gauss, Eisenstein and Ram have many surprising application square theorem and the course aims to give an introduce of Modular forms for the Examples: Eisenstein Arithmetic application	The study of modular forms traces back its roots to the late 19th and early 20th century with Gauss, Eisenstein and Ramanujan, and is a fascinating blend of analysis and algebra. They have many surprising applications to number theory, including a beautiful proof of Lagrange's four square theorem and the ground-breaking proof of Fermat's last theorem in 1995. This course aims to give an introductory understanding of this broad topic. • Modular forms for the Modular group and congruence subgroups. • Examples: Eisenstein series, the Ramanujan Delta function, Theta series. • Arithmetic applications and conjectures. • Hecke operators and eigenforms.										
Objectives	Students have learnt the bas lar forms. They are familiar v The students are capable of as assessing and explaining critically analyse the current	ith an nami the p	alytic ng a rese	al, a nd p nted	lgebr rovin conr	raic and g the e nections	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	re of Course ws ws coursework re of Exam wr. of Exam (min)							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.	Whether the examination is written or oral is decided by the instructor with approval by the										

Literature	Possible References :
	 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 <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 '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:	aradad na nataradad

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 : o=obligatory, f=facultative

Module Number: MAT-45-30	Module Title:Type of Module:Primes of the form $x^2 + ny^2 and Class Field Theory$ Compulsory Module with Choice											
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 90 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	Just as Gauss once described number theory as the queen of mathematics, Class Field Theory can be described as her Crown Jewel. Class field theory brings together the Galois theoretic structure of of a number field, and links it to the arithmetic structure of its the ring of integers, through a deep understanding of reciprocity laws. This course aims to introduce the central notions and concepts of Class Field theory naturally through solving the elementary motivating problem of what primes can be expressed as the form $x^2 + ny^2$, and bridge elementary number theory to modern number theory. • The theory of Quadratic forms and Genus theory.											
	• Generalisations of the Hilbert Class field. • A statement of Artin Reciproof $\mathbf{x}^2 + ny^2$.	law c	f qua	adrat	ic red	ciprocit	y. Arithmeti					
Objectives	Students have learned the form of class field theory in the confunction understanding of where the students are capable of narrassessing and explaining the critically analyse the current	ase on the second and	f qua conce nd p sente	dratepts rovired co	ic fie come ng the onne	eld exte e from e esse ctions.	nsions of C through an ntial results Students v	Q, and have elementary of the lect	a very examp ure as	hands le. The well as		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Primes of the form $x^2 + ny^2 and Class Field Theory$	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 I	by the instru	uctor with a	pprova	l by the		
Literature	Possible References: • David Cox: Primes of the form $x^2 + ny^2.Wiley2013, JamesMilne : Classfieldtheory.OnlineNotes2020.$ Jürgen Neukirch: Algebraic number theory. Springer 1999.											

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	An understanding of Galois theory and other basic algebraic structures (groups and rings) is essential. Deep results taught in any first course in algebraic number theory will be clearly stated and introduced, but not proven, and will be treated as a black box.
Responsible Persons	Anton Deitmar

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

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 : o=obligatory, f=facultative

Module Number: MAT-45-31	Module Title: Representation Theory of Fi		of Module: ulsory Modul	le with	Choice							
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: 180 h	Self-Study: 120 h										
Duration	1 Semester											
Frequency	not regularly	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	 Groups and group actions. Representations, irreducibility, Schursch's lemma. Semisimplicity, Maschke's theorem. Characters, orthogonality relations. Isotypical decomposition, character tables. Representations of the symmetric group. Semi-simple Artinian algebras. 											
Objectives	In the lecture, students learn understanding for the interact are capable of naming and and explaining the presenter In the exercise classes they the terms, statements and non new problems, to analyse They are able to present the	ction of proving d conne have a nethods them a	georgeonection geometric g	metri e ess ns. ired a he le o wo	c and entia a corecture rk on	d alget I result ofident, e. They or solution	oraic method ts of the lec precise and have learn on strategies	ds. methods sture as well d independe ed to transfe s on their ow	. The solution as	students sessing adling of nethods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Representation Theory of Finite Groups	ш Гуре of Course	t Status	SMS 2	s s ECTS	Coursework	Type of Exam or.	Onr. of Exam (min) 90-180 o. 20-30	ص Grading	Weight for Grade		
	In this module an exercise c examination the coursework oral is decided by the instruc	must h	nave	beer	n acc	uired.	Whether the	e examination				

Literature	Possible References :						
	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 Study Specialisation Algebra and 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. 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						

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 : o=obligatory, f=facultative

Module Number: MAT-45-40	Module Title: Introduction to Combinatorial Birational Geometry Type of Module: Compulsory Module with Cho						
ECTS-Points	9	,	,				
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h				
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	Class 2 SWS					
Content	 map for surfaces X or divisors. The divisor of divisors. The divisor of the variety. Ample and veriety. The cone of curves of formations. Desingularization of racombinatorial construction. Cyclic quotient surfaction. Finite subgroups of Salarization. Birational classification the Fine interior F(Δ). The Kodaira dimensionels of nondegenerate. 	over the complex numbers. The class group $Cl(X)$ and the bilist bundles, invertible sheaves. But ample divisors. Oraic curves in toric surfaces. Every ample divisors. Oraic curves in toric surfaces. Every and blow ups and blow dow of a surface. The Zariski decomposition of pairs are singularities and their combinations of pairs are singularities and their combination of nondegenerate surfaces of their Newton polytopes Δ . On of algebraic varieties. Combined and the complex of the composition of algebraic varieties.	position. Birational Cremona trans- mooth toric surfaces X via blow ups. (X,D) for normal toric surfaces X . inatorial minimal desingularization. ularities and their minimal desingu- in 3-dimensional toric varieties via binatorial constructing minimal mod-				
Objectives	In the lecture, students learn how to apply concepts, results and methods of convex geometry in order to analyse important classes of algebraic surfaces. They learn to recognise and calculate complex algebro-geometric constructions. They are familiarised with an interesting and deep classification problem, the minimal models for algebraic surfaces. 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 Birational	П Type of Course	b Status	SMS 4	9 ECTS	Sework	Type of Exam o. o.	Dur. of Exam (min) 081-06	ص Grading	Weight for Grade
	In this module an exercise cer examination the coursework n oral is decided by the instructor	nust h	nave	beer	n acc	uired.	Whether the	rk. For part e examinatio		
Literature	 Possible References: Laurent Buse, Fabrizio History of Shapes. Spr Klaus Hulek: Elementa Tadao Oda: Convex Bo Toric Varieties. Springe Robin Hartshorne: Algo 	inger re Alq odies er 198	2023 gebra and 38.	3. aisch Alge	ne Ge braic	eometri Geom	e. Springer netry: An Int	2012.		
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 of commutative algebra and algebraic geometry are assumed: some of the essential concepts from these areas are briefly repeated at the beginning of the course.									
Responsible Persons	Victor Batyrev									

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 : o=obligatory, f=facultative

Module Number: MAT-45-41	Module Title: Type of Module: Introduction to Combinatorial Mirror Symmetry Compulsory Module with									
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 C	Class 2 SWS								
Content	Quintic 3-folds in proj	ective 4-space and their mirror	rs.							
	Toric varieties associated with lattice polyh		nedral cones. Toric varieties associ-							
	Resolution of singular	rities. Cohomology rings of sm	nooth 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	alabi-Yau 3-folds. Monomial-divisor							
	Combinatorial mirror calabi-Yau varieties.	construction for Calabi-Yau cor	mplete intersections. Mirrors of rigid							
	Computation of period functions.	ds of Calabi-Yau hypersurface:	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	nov-Witten invariants of Calabi	-Yau complete intersections.							
	A combinatorial appro	oach to Berglund-Hübsch mirr	or symmetry.							
	based on polar duality in the the most famous examples dodecahedron. In combination considered reflexive polyhedra Δ^* below lattice of characters of an anone-parameter subgroups in is the theory of toric varieties symmetry discovered by phyto N and from Δ to Δ^* . The aim of the module is to	odule is to explain the connection between reflexive polyhedra and Calabine most understandable way possible and 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	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Combinatorial Mirror Symmetry	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	examination the coursework n	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	Possible References :	· · · · · · · · · · · · · · · · · · ·								
		 Victor Batyrev: Dual Polyhedra and Mirror Symmetry for Calabi-Yau Hypersurfaces in Toric Varieties. J. Alg. Geom. 3 (1994), no. 3, 493–535. 								
		 Victor Batyrev, Duco van Straten: Generalized hypergeometric functions and rational curves on Calabi-Yau complete intersections in toric varieties. Comm. Math. Phys., 								
	 Victor Batyrev and Lev Calabi-Yau manifolds. Soc., Providence, RI (1 	Mirro	r Sy	mme						
	David Cox, Sheldon K Surveys and Monograp						d Algebraic	Geometry.	Mathe	ematical
	Israil Gelfand, Mikhail k tidimensional Determin							nants, Resul	tants a	nd Mul-
	Masao Jinzenji: Classi Band 29, 2018.	tidimensional Determinants. Springer-Birkhäuser 1994. • Masao Jinzenji: Classical Mirror Symmetry. SpringerBriefs in Mathematical Physics, Band 29, 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	Knowledge of the modules Co	mmı	ıtativ	e Alg	jebra	and A	lgebraic Ge	ometry are	assum	ed.
Responsible Persons	Victor Batyrev									

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 : o=obligatory, f=facultative

Module Number: MAT-50-03	Module Title: Tropical Geometry							of Module:	le with	Choice
ECTS-Points	9						Compt	JISOTY WIOGU	ic with	0110100
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 or English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SWS	3						
Content	Tropical numbers and	polyno	omia	ls.						
	Tropical hypersurface	s and \	varie ⁶	ties.						
	Tropical toric varieties	3.								
	Matroid fans and trop	Matroid fans and tropical abstract varieties.								
	Tropical modifications	, stable	e inte	ersec	tions	and ra	ational equi	valence.		
	Tropical curves and linear systems.									
	• Tropical (p,q) -homolo	gy.								
	Correspondence thec	rems.								
Objectives	mental techniques for working geometry and they have lea fully in algebraic geometry. Tand they can explain their in In the exercise classes they the terms, statements and more to new problems, to analys	The students know and understand the subjects studied from tropical geometry and the fundamental techniques for working them. They have reached a deepend understanding of convex geometry and they have learned, how concepts from combinatorics can be applied successfully in algebraic geometry. 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	Type of Course	Status	SWS	b ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Tropical Geometry	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	ertificat must h	te is nave	to be	acq acq	uired.	Whether th	e examination		

Literature	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-50-04	Module Title:Type of Module:Tropical Enumerative GeometryCompulsory Module with Cho									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 C	lass 2	SWS	S						
Content	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 lattice 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	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 me to new problems, to analys	The students know basic terms, results and methods of enumerative geometry in the context of tropical geometry methods. They develop a deeper understanding of the possibilities and limitations of the tropical access in connection with more complex issues. Furthermore, they deepen their knowledge in the field of algebraic geometry towards modular spaces and Gromov-Witten theory. 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	Type of Course	Status	SWS	ECTS	Coursework	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	nave	bee	n acc	uired.	Whether th	e examinati		

Literature	Possible References :
	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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, } \mbox{LE=lecture with integrated exercises, } \mbox{SL=seminar or lecture, } \mbox{E=exercise class, } \mbox{T=tutorial, P=project, S=seminar, IC=inverted classroom}$

Status : o=obligatory, f=facultative

Module Number: MAT-50-05	Module Title: Introduction to Tropical Enumerative Geometry Type of Module: 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									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 1	SWS	3						
Content	Tropical enumerative Combinatorial method Correspondence thed	 Enumerative geometry of algebraic curves, in particular in the plane. Tropical enumerative problems and multiplicities. Combinatorial methods, floor diagrams and lattice paths. Correspondence theorems for curves in the plane through given points. Real counts, Welschinger invariants and polynomial invariants. 								
Objectives	text of tropical geometry me and limitations of the tropical they deepen their knowledge students are capable of nar assessing and explaining the In the exercise classes they the terms, statements and me to new problems, to analyse	The students know basic terms, results and methods of enumerative geometry in the context of tropical geometry methods. They develop a deeper understanding of the possibilities and limitations of the tropical access in connection with more complex issues. Furthermore, they deepen their knowledge in the field of algebraic geometry towards moduli 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 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	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Tropical Enumerative Geometry	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 l	have	beei	n acc	uired.	Whether th	e examination	icipatic on is w	on in the ritten or
Literature	Possible References : Grigory Mikhalkin, Jo	nanne	s Ra	u: Tro	opica	al geom	netry. 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 : o=obligatory, f=facultative

Module Number: MAT-50-06	Module Title: Type of Module: Compulsory Module with Choice								Choice	
ECTS-Points	5	5								
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									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	ecture 2 SWS + Exercise Class 1 SWS								
Content	 Multiplicities. Welschinger invariants Lattice paths. Floor diagrams. Hurwitz numbers. 	Welschinger invariants.Lattice paths.Floor diagrams.								
Objectives	The students deepen their kr acquainted with various met merative problems which can name and prove the central tions. In the exercise classes they the terms, statements and m to new problems, to analyse team. They are capable of p discourse.	nods to be seemed	co en colvects of the acquision of the	ume d with he le ired a he le	rate h the cture a cor cture work	tropica e aid of e and the offident, e. They on so	I curves, as tropical ge ney can exp precise an have learn lution strate	s well as wit ometry. The blain their in d independe ed to transfe egies on the	h varion student student har the return 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	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Tropical Enumerative Geometry - Part 2	E	f	1	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	beei	n acc	uired.	Whether th	e examination		
Literature	Possible References :									
	Diane Maclagan, Berr Grigory Mikhalkin, Joh							-	1 S 201	5.

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 : o=obligatory, f=facultative

Module Number: MAT-50-11	Module Title: Geometry of Manifolds 2						of Module: ulsory Modu	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	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	Cohomology of manif Analysis of differentia	 Global aspects of Riemannian geometry Cohomology of manifolds. Analysis of differential operators on manifolds. Applications on Riemann surfaces (and complex manifolds). 											
Objectives	geometry. They have deeped they have exemplarily expensive students are capable of nanassessing and explaining the In the exercise classes they the terms, statements and more to new problems, to analys	The students are familiar with the fundamental concepts of global real and complex differential geometry. They have deepened their understanding of methods in differential geometry, and they have exemplarily experienced how local and global aspects in geometry interact. 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 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	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Geometry of Manifolds 2	L E	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100			
	examination the coursework	must	have	bee	n acc	uired.	Whether th	e examination	h 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	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-50-12	Module Title: Information Geometry							f Module: Ilsory Modul	le with	Choice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in C	lass			Self-Sti 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	tionships for parametrent).	Application to neural data processing (in particular supervised learning in artificial neu-									
Objectives	Students have an elementary understanding of how to apply concepts of differential geometry to problems in information theory and statistics. 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	Coursework	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	cided	by the instru	uctor with a	pprova	l by the	
Literature	 Anthony C. C. Cooler Processing Systems. Shun-Ichi Amari: Nati 1998. Yann Ollivier: Rieman 	 Possible References: 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 									
Transfer	The module belongs to the ferential Geometry and Stock sation, it can be included in to r Elective Specialisation, in section.	<i>hastic</i> he Se	s. Ta	king s <i>Sti</i>	into i udy I	accour <i>Focus</i> ,	it the chose Advanced k	n personal S Knowledge i	Study S n Math	Speciali- ematics	

Prerequisites	Basic knowledge from differential geometry (Riemannian metrics, connections and curvature, geodesics) and from stochastics is assumed.
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 : o=obligatory, f=facultative

Module Number: MAT-50-13	Module Title: Information Geometry and Ne	eural [Data	Proc	essi	ng 2		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	not regularly									
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS									
Content	 Further basics of information geometry (e.g. dual flat structures for exponential families, Pythagoras' theorem and information projections, em algorithm). Application to neural data processing (in particular <i>Unsupervised Learning</i> in artificial neural networks, e.g. Boltzmann and Helmholtz machines). 										
Objectives	Students have an elementary understanding of how to apply concepts of differential geometry to problems in information theory and statistics. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Information Geometry and Neural Data Processing 2	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is a Board of Examiners.	writter	or or	oral i	s de	cided	oy the instru	uctor with a	pprova	l by the	
Literature	 Anthony C. C. Cooler Processing Systems. (Shun-Ichi Amari: Natu 1998. Yann Ollivier: Rieman 	 Possible References: 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 									
Transfer	The module belongs to the Signature Differential Geometry. Taking be included in the Sections Specialisation, in accordance	g into Study	Foc	ount us, A	the d Idva	chosen nced K	personal S <i>nowledge ii</i>	tudy Specia n <i>Mathemat</i>	lisation ics or	n, it can <i>Elective</i>	
Prerequisites	The module Information Geor	netry	and	Neui	al D	ata Pro	cessing 1 is	s a prerequi	site.		

Responsible Persons

Christoph Bohle

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 : o=obligatory, f=facultative

Module Number: MAT-50-14	Module Title: Mathematical Aspects of Neing 1	urona	l Info	orma	tion I	Proces		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	not regularly									
Term	1-3	-3									
Language of Instruction	German	ierman									
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS									
Content	 Artificial neural networmethods. Dynamic interpretation ics) and the change of the	n as the f weight model in the leaders in the leade	ne flo hts o els fo ical f	w of luring r the ounc	data g trai dyna latior	/activat ning (sl amics o	ions through ow dynamic of neural net eep learning	n the networes). tworks. I and biolog	rk (fast	dynam- olausible	
Objectives	The students have learned ral networks and biologically systems as a possible framdents can name and prove the connections.	/ more ework	e pla for t	usibl heor	e alt etica	ernativ I and r	es. They a nathematica	re familiar v al investigati	with dy ions.	namical The stu-	
Requirements for Obtaining Credit, Grading, Weight if applicable Title Title Title Title Title Title Title								90-180	Grading	Weight for Grade	
	Mathematical Aspects of Neuronal Information Processing 1		f	2	3	no	wr. o. or.	o. 20-30	g		
	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	Possible References :
	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
Alabaraniakiana	

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 : o=obligatory, f=facultative

Module Number: MAT-50-15	Module Title: Introduction to Riemann Sur	faces						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-S 105 h	tudy:			
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	Coverings and fundations	Coverings and fundamental groups.									
	Topological classifica	Topological classification of the surfaces.									
	Theorem of Riemann	-Hurwi	tz.								
	Differential forms and	integr	ation								
	Sheaves and cohomo	ology.									
	Theorem of Riemann	-Roch.									
	Serre duality.										
	Kobayashi metric.										
	Theorem of Picard.										
Objectives	Students develop an approad based on local-to-global rearigidity resulting from analyt damental questions naturally can ultimately be used to a terrelated and in many case proving the essential results connections. Students will be in the subject area.	soning ical proy lead nswer of the of the	. In the propert to industrial to industrial to the propert to the	he co creas tions depe ure a	once Usin singly s. The ender s we	pt of hong the standard the sta	olomorphy, sheaf concept concept the students as students as seessing ar	they grasp the ept, students tualisations a metry and a are capable and explaining	ne prin s see h and ho nalysis of nam the pr	ciples of now fun- w these s are in- ning and esented	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Riemann Surfaces	L	f	2	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 instructionally be offered by the awarded for the module in the	must lotor with the lect	nave th ap urer	beer prove with	n acc al by	quired. the Bo	as coursew Whether thoard of Exa	ork. For part ne examination miners. – Th	on is w	ritten or lule may	

Literature	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-50-16	Module Title: Riemannian Geometry							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	not regularly										
Term	1-3	1-3										
Language of Instruction	English	∃nglish										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	ecture 2 SWS + Exercise Class 2 SWS										
Content	Riemannian manifolds	Riemannian manifolds.										
	Geodesics.	Geodesics.										
	Curvature.											
	Geometry of submanifolds.											
Objectives	manifolds from a classical p cussed. The students were e are sufficient to study their ronotions of curvature was deferential geometry was achie the essential statements and veloped in the lecture and to critically challenge the curren Through homework assignment and independent acquaintan 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	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Riemannian Geometry	L	f	2	3	yes	wr. o.	90-180	<u> </u>	100		
	Themailian deometry	Е	f	2	3	yes	or.	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				
Literature	Possible References :											
	John M. Lee: Riemani	nian m	nanif	olds:	An i	ntrodu	ction to curv	ature. Sprin	ger 19	97.		
	Barret O'Neill: Semi-F Press 1983.	Riema	nnia	n ge	omet	try. Wi	th application	ons to relativ	rity. Ad	cademic		

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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom \\$

Status : o=obligatory, f=facultative

Module Number: MAT-50-17	Module Title: Introduction to Integrable Sy Riemann Surfaces, and Spe	stems (Classical Mechanics, ctral Theory)	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	English	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 deformation case symmetric matrices. We study an important class 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 geomet 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 solutions can be systems interpretation of the document of the system on the space of paratry of Lie algebras and Lie group the geometry of Riemann surfacts planed to explain how infinitival and spectral to explain how infinitival and spectral to explain how infinitival and spectral to the space of paratry of Lie algebras and Lie group the geometry of Riemann surfacts planed to explain how infinitival and spectral to the space of paratry of Lie algebras and Lie group the geometry of Riemann surfacts and the space of paratry of Lie algebras and Lie group the geometry of Riemann surfacts and the space of paratry of Lie algebras and Lie group the space of paratry of Lie algebras and Lie al	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 mechan-caplained 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	faces, mechanics, and spec were discovered mainly in the a branch of mathematics so dents can name and prove the connections. In the exercise classes they the terms, statements and me to new problems, to analys	ctral theory – as well as other second half of the twentiet metimes called soliton theory he central results of the lecture have acquired a confident, protethods of the lecture. They have them and to work on soluti	n classical topics like Riemann sur- er branches of mathematics – that the century during the emergence of or integrable mathematics. The stu- e and they can explain their intrinsic recise and independent handling of ave learned to transfer the methods on strategies on their own or in a applicable to argue for it in a critical								

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Integrable Systems	L E	f	4	6	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 instructe	nust ł	nave	beer	n acc	uired.	Whether the	e examination		
Literature	Olivier Babelon, Denis tems. CUP 2004. Leonid A. Dickey: Solit Alan C. Newell: Soliton Sergei P. Novikov, Sergof Solitons - The Inverse	on ed s in r gei V.	luation nathe Man	ons a emat	ind Hics a	lamilto nd phy / P. Pita	nian system sics. SIAM aevskii, Vlad	is. World Sc 1985. dimir E. Zak	ientific	2003.
Transfer	The module belongs to the St ential Geometry and Mathem Specialisation, it can be include ematics or Elective Specialisa spective section.	<i>atica</i> led in	<i>Phy</i> the	<i>sics.</i> Sect	Tak ions	ing into Study	o account th <i>Focus</i> , <i>Adva</i>	ne chosen p anced Know	ersona ledge i	al Study in Math-
Prerequisites	The module Introduction to Co Basic knowledge of differenti necessary.									
Responsible Persons	Christoph Bohle, Frank Loose									
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 $\begin{array}{lll} \text{Teaching Format} & : \text{L=lecture, } & \text{LE=lecture with integrated exercises, } & \text{SL=seminar or lecture, } & \text{E=exercise class, } \\ & & \text{T=tutorial, P=project, S=seminar, IC=inverted classroom} \\ \end{array}$

Status : o=obligatory, f=facultative

Module Number: MAT-50-18	Module Title: Integrable Systems (and Inbras)	finite [Dime	nsio	nal L	ie Alge		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	udy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	English	English										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ecture 4 SWS + Exercise 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 deformation case symmetric matrices. This lecture is the continuation sical Mechanics, Riemann Sintegrable equations using s	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	The students have aquired a 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 analyst team. They are capable of p discourse.	nts cai nectic have a ethods e them	n nar ons. acqu s of t	ne alired in the le	nd pr a cor cture work	ove the ofident, e. They on so	precise an have learn lution strate	ults of the le d independe ed to transfe egies on the	ecture a ent har er the r eir own	and they adling of nethods or in a		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Integrable Systems (and Infinite Dimensional Lie	п Гуре of Course	t d Status	SMS 4	e e ECTS	Coursework	Type of Exam (min) o. o. o. Dur. of Exam (min) decorption of Exam (min)					
	Algebras) In this module an exercise of examination the coursework oral is decided by the instruc	must I	nave	bee	n acc	uired.	s coursewo Whether th	rk. For part e examinatio				

Literature	Possible References :
	 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 $\begin{array}{lll} \text{Teaching Format} & : \text{L=lecture, } & \text{LE=lecture with integrated exercises, } & \text{SL=seminar or lecture, } & \text{E=exercise class, } \\ & & \text{T=tutorial, } & \text{P=project, } & \text{S=seminar, } & \text{IC=inverted classroom} \\ \end{array}$

Status : o=obligatory, f=facultative

Module Number: MAT-50-19	Module Title: Mathematical Aspects of Neing 2	urona	l Info	rma	tion I	Proces		f Module: Ilsory Modu	le with	Choice		
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 90 h	Self-St 60 h	Self-Study: 60 h									
Duration	1 Semester						·					
Frequency	not regularly	not regularly										
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS										
Content	data. • Dynamic interpretation through the network namics). • Simple neuroscientification	 Dynamic interpretation of neural data processing methods as flow of data/activations through the network (fast dynamics) and change of weights during training (slow dy- 										
Objectives	Students have learnt the bas biologically more plausible a framework for theoretical and ing and proving the essential presented connections.	lternat d math	ives. nema	The tical	y are	e familia stigatio	ar with dyna ns. The stu	mic systems dents are ca	s as a apable	possible of nam-		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Mathematical Aspects of Neuronal Information Processing 2 Whether the examination is		f n or	2 oral	3 is de	no	wr. o. or.	90-180 o. 20-30 uctor with a	g pprova	100		
	Board of Examiners.											
Literature	Ian Goodfellow, Yoshi Anthony C. C. Cooler cessing Systems. OL	 Possible References: 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. Simon Haykin: Neural Networks: A Comprehensive Foundation. Pearson 1998. 										
Transfer	The module belongs to the Differential Geometry. Takin be included in the Sections Specialisation, in accordance	g into Study	acco Foc	ount us, <i>i</i>	the o	chosen nced k	personal S <i>(nowledge ii</i>	tudy Specia n <i>Mathemat</i>	ilisatio <i>ics</i> or	n, it can <i>Elective</i>		

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 : o=obligatory, f=facultative

Module Number:	Module Title: Algebraic Topology 2							of Module:	e with	Choice			
ECTS-Points	9						Оотпро	noory wooda	- With				
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 Class 2 SWS												
Content	Further development of singular homology theory.												
	Simplicial complexes	Simplicial complexes and their simplicial homology.											
	CW spaces and their	cellula	r hor	nolo	gy.								
	Axiomatic homology.												
	Homological algebra.												
	Cohomology.												
	 Homology and Cohor 	nology	with	coe	fficie	nts.							
	Product structures in	homolo	ogy a	and c	ohor	nology							
	The Poincaré duality to	theorer	n for	topo	ologic	cal mar	nifolds.						
Objectives	The students extend their at structions. They deepen the even technically very challer 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	eir knownging taging tage as we have a lethods them a	wledgasks. ell as acqui s of the	ge in The s ass ired a he le o wo	absi essir essir a cor cture rk on	tract madents and	athematica re capable explaining to precise an have learn on strategies	I disciplines of naming a he presente d independe ed to transfes on their ow	to acc nd pro d conn ent har er the r n or in	omplish ving the ections. Idling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Algebraic Topology 2	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	beer	n acc	uired.	Whether th	e examination					

Literature	Possible References :
	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

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 : o=obligatory, f=facultative

Module Number: MAT-50-23	Module Title: Algebraic Topology 3							of Module: ulsory Modu	le with	Choice	
ECTS-Points	3										
Workload - Time in Class - Self-Study		Time 30 h	in C	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	Lecture 2 SWS									
Content	A selection of the following top	A selection of the following topics will be covered:									
	Basic concepts of hom	Basic concepts of homotopy theory;									
	Homotopy group of spheres;										
	Spectral sequences;										
	K-theory;										
	Characteristic classes.	Characteristic classes.									
Objectives	With the in-depth knowledge introduced to current areas of which can lead to a Master's possible doctorate in algebraic essential results of the lecture	rese thes topo	arch sis, fo ology	and or ex . The	they amp	tackle le. The dents a	a small res ey will also re capable	search proje lay the fou of naming a	ct ther indatio	nselves, ns for a ving the	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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 t	oe exp	olain	ed b	y the	examii	ner at the b	eginning of	the co	urse.	
Literature	Possible References :										
	Allen Hatcher: Algebra	ic top	olog	y. Ca	ambr	idge Ur	niversity Pre	ess 2009.			
	Allen Hatcher: Vector to	oundle	es ar	ıd K-	theo	ry. Mar	uskript 200	9.			
	John W. Milnor, James 1974.	D. Si	tashe	eff: C	Chara	ıcteristi	c classes. I	Princeton U	niversi	ty Press	
	John W. Milnor: Lectu 1965.	ires c	n th	e h-	cobo	rdism t	heorem. F	Princeton U	niversi	ty Press	

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 $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : o=obligatory, f=facultative

Module Number: MAT-50-25	Module Title: Applied topology 1							f Module: Ilsory Modul	e 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	German											
Forms of Teaching and Learning	Lecture 2 SWS											
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	Coursework	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	or	oral	is de	cided	by the instru	uctor with a	pprova	I by the		
Literature	Possible References :											
	Herbert Edelsbrunner	, John	L. H	arer	Cor	nputati	onal Topolo	gy. AMS 20	10.			
	Robert Ghrist: Elemei	ntary A	Applie	ed To	polo	gy. Cre	eate Space	2014.				
	Sergey V. Matveev: Le	ecture	s on	Alge	braic	Topolo	ogy. EMS 20	006.				
Transfer	The module belongs to the a Geometry and Stochastics. tions into account, the modu Knowledge Mathematics or B	Taking Ie can	the be a	perso assig	onal Ined	special to the	isation and	the restriction	ons of	the sec-		
Prerequisites	There are no further prerequ	isites.										
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 : o=obligatory, f=facultative

Module Number: MAT-50-26	Module Title: Applied Topology 2							of Module: ulsory Modul	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	German										
Forms of Teaching and Learning	Lecture 2 SWS										
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	Coursework	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.	writter	n or	oral	is de	ecided	by the instri	uctor with a	pprova	l by the	
Literature	Possible References :										
	Herbert Edelsbrunner	, John	L. H	arer	: Coi	mputati	onal Topolo	gy. AMS 20	10.		
	Robert Ghrist: Elemei	ntary A	Appli	ed To	polo	ogy. Cre	eate Space	2014.			
	Sergey V. Matveev: Le	ecture	s on	Alge	braid	c Topolo	ogy. EMS 20	006.			
Transfer	The module belongs to the State chosen personal Study Advanced Knowledge in Mastrictive requirements of the	Specia thema	alisat <i>tics</i>	ion, or <i>E</i>	it ca <i>lecti</i> v	ın be ir	ncluded in t	he Sections	Study	/ Focus,	
Prerequisites	The contents of the module from differential geometry is			opolo	ogy 1	l' are a	ssumed. N	loreover, ba	sic kno	owledge	
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 : o=obligatory, f=facultative

Module Number: MAT-50-27	Module Title: Topological Vector Spaces a	nd Dis	tribu	tions				of Module:	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 or English												
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS												
Content	 Locally convex topolo Duality: Hahn-Banaci Generalised functions Properties of distributions 	 A selection of the following topics will be covered: Locally convex topological vector spaces, Frechet spaces, LF spaces and LB spaces. Duality: Hahn-Banach theorem, dual space, topologies on the dual space. Generalised functions, Radon measures and distributions. Properties of distributions and operations on the space of distributions. Applications and examples. 											
Objectives	Students master the basic prand understand how to ap Schwartz. Students are also which classical questions or capable of naming and provexplaining the presented coruln the exercise classes they the terms, statements and non new problems, to analyse They are able to present the	oly this o able mathe ing the inectio have a them a	s to e to emate essons. acquis of tand t	the name ical period ical peri	theore the ohysical research	ry of g main cs can sults of nfident, e. They solution	eneralised applications be treated the lecture precise and have learne on strategies	functions as s of the the with it. The as well as a d independe ed to transfe s on their ow	ccordir ory and stude assess ent har er the n	ng to L. id show ents are ing and idling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Topological Vector Spaces and Distributions	Type of Course	b Status	SMS 2	s ECTS	Sework	Type of Exam or. o.	Dur. of Exam (min) 081-09 0-20-30	ت Grading	Weight for Grade			
	In this module an exercise c examination the coursework oral is decided by the instruc	must l	nave	beei	n acc	uired.	s coursewo Whether the	rk. For parti e examinatio	icipatio				

Literature	Possible References :
	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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom \\$

Status : o=obligatory, f=facultative

Module Number: MAT-50-28	Module Title: Uniformisation of Riemann S	urface	s					of Module: ulsory Modul	e 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	not regularly										
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 1 SWS											
Content	Uniformisation of Riemann 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Uniformisation of Riemann Surfaces	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 exceptionally be offered by t points will be awarded for the	must I tor wit he led	nave h ap ture	beer prova with	n acc al by nout	quired. the Bo exercis	Whether the ard of Exar	e examination niners. – Th	on is w e mod	ritten or ule may		
Literature	Possible References :											
	Hershel M. Farkas, Irv	vin Kra	a: Rie	emar	ın Sı	urfaces	. Springer 1	992.				
Transfer	The module belongs to the Differential Geometry. Taking be included in the Sections Specialisation, in accordance	g into <i>Study</i>	Foc	ount o us, A	the c I <i>dvai</i>	chosen nced K	personal S nowledge i	tudy Specia n <i>Mathemat</i>	lisation <i>ics</i> or	n, it can <i>Elective</i>		
Prerequisites	The module Introduction to Bachelor of Science Mathem								odule	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 : o=obligatory, f=facultative

Module Number: MAT-50-29	Module Title: Algebraic Curves and Riemann Surfaces Type of Module: Compulsory Module with Choice								
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								
Frequency	not regularly								
Term	1-3								
Language of Instruction	German or English								
Forms of Teaching and Learning	Lecture 4 SWS								
Content	Compact Riemann su	urfaces.							
	Normalisation of plan	e curves.							
	Topological genus.								
	Coverings.								
	Forms and integration	Forms and integration.							
	Sheaves and cohomo	ology.							
	Hodge theory.								
	Arithmetic and geome	etric genus.							
	Abel's theorem.								
	Riemann-Roch theore	em.							
	Serre duality.								
	 Jacobian and Abelian 								
	Riemann bilinear rela								
	Jacobi inverse proble								
	Elliptic curves and fur	nctions.							
	• j-Invariant.								
	Uniformisation.	naat Diamann aurfaan							
	Topology of non-comp	pact Riemann sunaces.							
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. By example of the concept of sheaves, 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.								

Other

Requirements for Obtaining Credit, Grading, Weight if applicable	Title Algebraic Curves and Riemann Surfaces	с: Г Туре of Course	t Status	SMS 4	S D ECTS	Coursework	Type of Exam o. o.	Dur. of Exam (min) 0. 20-30	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. – 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.							ritten or ule may		
Literature	Robert Silhol: Real Alg Riccardo Benedetti, Je Editions Herrmann 199 Alex Degtyarev, Viatch	 Possible References: Frederice Mangolte: Real Algebraic Varieties. Springer 2020. Robert Silhol: Real Algebraic Surfaces. Springer 1989. Riccardo Benedetti, Jean-Jacques Risler: Real Algebraic and Semi-algebraic Sets. Editions Herrmann 1990. Alex Degtyarev, Viatcheslav Kharlamov: Topological properties of real algebraic varieties: du côté de chez Rokhlin. arXiv:math/0004134. 								
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. The module cannot be taken together with the module Introduction to Riemann Surfaces due to the large overlap in content.									
Prerequisites	In terms of content, the courses on integration and measure theory as well as the introduction to function theory of ordinary differential equations are assumed.									
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, T=tutorial, P=project, S=seminar, IC=inverted classroom Status : o=obligatory, f=facultative										

Module Number: MAT-50-30	Module Title: Geometric Group 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									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SW	S						
Content	Group actions on graph	ohs, fre	ee gr	oups	S.					
	Quasi isometries.									
	Growth types.									
	Hyperbolic groups.									
	• Ends.									
Objectives	Students learn to explore properties of finitely generated groups using geometric tools, starting from the Cayley graph of the group. They are able to investigate the geometric properties of the Cayley graphs with the help of analytical methods and to work out their connections to the underlying group. Students understand how algebra and analysis can work together to develop a new theory at the interface of algebra and geometry that leads to interesting statements about groups. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Geometric Group Theory	L E	f 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	Clara Löh: Geometric Thorsten Camps, Volk binatorische und die g	mar G	iroße	e Reb	oel, G	Gerhard	l Rosenberg	ger: Einführu		lie kom-

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 : o=obligatory, f=facultative

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: 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 C	lass 1	SWS	3						
Content	 Enumerative geometr Moduli spaces of stabe Moduli spaces of stabe Universal families, Forgetful maps, Gluing maps, Gromov-Witten invariance Computation of Grome Divisor equations, Kontsevich's formula. 	ole curvo ole map ants, ov-Witt	s,	nvari	ants,					
Objectives	Students are based on their research field of Gromov-Wi understand important example them as cut products on more Gromov-Witten invariants. In the exercise classes they the terms, statements and more on new problems, to analyse They are able to present the	itten the ple class duli spa The stuas asse have a nethods them a	eory sses aces uden essin cqui of th	and of each of	enui enum ident re ca nd ex a con cture rk on	merative erative s mast upable plainin officent, solution solution meratives.	re geometry invariants er the basic of naming g the prese precise an have learn on strategies	y. The stude and know he algorithms and proving nted connect d independent ed to transfers on their ow	ents krow to for cal the etions. ent har the ron or in	ow and present culating ssential adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Gromov-Witten Theory	L	f	3	4,5 1,5	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise or tion is written or oral is decide									

Literature	Possible References :
	 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 : o=obligatory, f=facultative

Module Number:	Module Title: Non-Linear Functional Analysis							of Module:		01
MAT-55-02	, , ,									
ECTS-Points	9									
Workload - Time in Class	Workload: 270 h	Time 90 h	in C	lass			Self-St 180 h	udy:		
- Self-Study	27011	90 11					16011			
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS	Lecture 4 SWS								
Content	Differentiation and int	Differentiation and integration in Banach spaces.								
	Compact, coercive, p	roper r	napp	ings	and	gradie	nt mappings	S.		
	Fredholm mappings.									
	Continuity method.									
	Degree of mapping.									
	Fixed point theorems									
	Variational inequalitie	S.								
	Monotone operators.									
Objectives	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	Type of Course	b Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Analysis	ü	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	ertifica must	te is	to be	acq acq	uired.	Whether the	e examination		

Literature	Possible References :
	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 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 : o=obligatory, f=facultative

Module Number: MAT-55-03	Module Title: Operator Theory		of Module: ulsory Modu	le with	Choice						
ECTS-Points	9						·				
Workload - Time in Class - Self-Study	Workload: 270 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										
Objectives	Operator semigroups Theorem of Hille-Yosic Applications of concre Spectral theory of ser Asymptotic of semigroups Applications: Semigroups of of the Semigroups of the	ete evolution e control e	y an ort protection of the control o	d pa d pa of th d pa of th d pro l con ired a he le o wo	e opos in the control of the control	ns. enerator- nis absiscuss the estons. nfident, e. They	valued exportant form. The qualitate sential resurbace an have learn on strategies	onential func They are able ive behavior Its of the lec d independe ed to transfe s on their ow	e to prour of some ture as ent had er the into t	ove well- olutions. s well as adling of methods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Operator Theory	c: Type of Course	t Status	SMS 4	SECTS 6 3	Coursework	Type of Exam o. o. or.	Onr. of Exam (min) 90-180 o. 20-30	ص Grading	Weight for Grade	
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	ave	beei	n acc	uired.	Whether th	e examination			

Literature	Possible References :
	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 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 : o=obligatory, f=facultative

Module Number: MAT-55-04	Module Title:Type of Module:Operator AlgebrasCompulsory 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	 Spectral theory in Ba Commutative Banac Gelfand-Naimark. The spectral theorem Operator topologies a Kaplansky's density t Von Neumann algebr struction of examples The axiomatics of C* 	spaces and their spectral nach algebras. h algebras and the reference for normal operators of and von Neumann's bicor heorem. as and their classification is - and W^* -algebras, the tand the representation the	presentation theorem of Gelfand and a Hilbert space.					
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.							

Status

Other

: o=obligatory, f=facultative

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	- Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Operator Algebras	ü	f	2	3	yes	wr. o. or.	o. 20-30	g	100
	In this module an exercise cer examination the coursework n oral is decided by the instructo	tifica nust h	te is	to be	e acc	uired.	Whether the	e examinatio		
Literature	Possible References :									
	Bruce Blackadar: Oper	ator	algeb	oras.	Spri	nger 2	006.			
	Ola Bratelli, Derek Robi	Ola Bratelli, Derek Robinson: Operator Algebras and Quantum Physics. Springer 1997.								
	 Richard Kadison, John IV. AMS 1997. 	Ring	rose	: Fur	ndam	nentals	of the Theo	ry of Operat	or Alge	ebras I -
	Gert Pedersen: Analys	is no	w. Sp	oring	er 19	995.				
	• Shoichiro Sakai: C^st - a	nd W	*-Al	gebra	as. S	pringe	r 1998.			
	Masamichi Takesaki: T	heory	y of (Oper	ator i	Algebra	as I - II. Spri	nger 2002.		
Transfer	ematical Physics. Taking into included in the Sections Study	The module belongs to the <i>Study Specialisation 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.								
Prerequisites	The content of the Functional	Anal	ysis ı	modı	ule is	prerec	quisite for pa	articipation i	n this n	nodule.
Responsible Persons	Ulrich Groh, 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										

Module Number: MAT-55-05	Module Title: Ergodic Theory							of Module:	le with	Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 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 C	ecture 4 SWS + Exercise Class 2 SWS								
Content	Topological and meas	Topological and measure-theoretical dynamical systems.								
	Recurrence and mixir	Recurrence and mixing properties.								
	Ergodic theorems of v	Ergodic theorems of von Neumann and Birkhoff.								
	Spectral theory of the	Koopr	man	oper	ator.					
	Operators with discre	Operators with discrete spectrum (Halmos-von Neumann)								
	Applications in stocha	stics a	and r	umb	er th	eory.				
Objectives	The students have familiaris of ergodic theory. They have and topology using the example analytical perspective make ously. 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	re exposed point of exp	erier dyn ssibl nam ne pr acqu s of t	nced amic e to ning a esen ired a he le o wo	the paystage of the system of	profour ems a with a proving connec offident, e. They a solution	nd interplay nd their class nd solve va the essentitions. precise and have learn on strategies	between messification. It is proble it is proble it is a results of the independent of the independent is on their ow	reasure The fur The sin The le The le The har The r The r The r	e theory nctional- nultane- cture as adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Ergodic Theory	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	examination the coursework									

Literature	Possible References :
	 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

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 : o=obligatory, f=facultative

Module Number: MAT-55-06	Module Title: Type of Module: Control Theory Compulsory Module with Choic									Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 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 C	lass 2	SWS	3							
Content	- Controllability, o - Kalman criterio - Stabilisability th - Examples. • Introduction to infinite	 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 importate They are able to use the that are capable of naming and and explaining the presented in the exercise classes they the terms, statements and non new problems, to analyse They are able to present the	eory i provin d conn have a nethod them	n are g the ectio acqu s of t and t	eas c ess ns. ired a he le o wo	of appendication of app	plication I result Infident, Infident, Infidention	on such as ts of the led precise and have learn on strategie	mechanics. cture as wel d independe ed to transfe s on their ow	The solution The sent har er the roll or in	students sessing adling of methods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Control Theory	L	f	4 2	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
	examination the coursework										

Literature	Possible References :
	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 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	Rainer Nagel
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 : o=obligatory, f=facultative

Module Number: MAT-55-08	Module Title: Spectral Theory of Positive O	perato	ors					f Module: Ilsory Modu	le with	Choice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: Time in Class: 60 h					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 Cl	ass 2	SWS	3						
Content	matrices, positive linear map properties are analysed. The powers and means, can ther	starting from the classical theorems of Perron and Frobenius on the spectrum of positive natrices, positive linear mappings to C^* - and W^* -algebras and their spectral and algebraic roperties are analysed. The ergodic properties of these operators, i.e. the convergence of owers and means, can then be derived from these. We then discuss the generalisation to perator semigroups. Applications of the theory can be found in mathematical physics, among thers.								
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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Spectral Theory of Positive Operators	L E	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100
	Whether the examination is a Board of Examiners. – The recise classes; in this case, 5.	writter modul	n or e	oral i	is de	ionally	be offered	by the lectu	rer witl	nout ex-
Literature	Possible References :									
	Tanja Eisner, Markus Theory. Springer 2015		e, Ra	ainer	Nag	gel : O	perator The	oretic Aspe	ects of	Ergodic
	Ulrich Groh: Spectral Preprint.	Theo	ry of	Con	nplete	ely Pos	sitive Maps	on C^st - and	W^* -A	lgebras.
Transfer	The module belongs to the St ematical Physics. Taking int included in the Sections Studicialisation, in accordance with	o acci ly Foc	ount us, A	the A <i>dva</i>	chos nced	en per Knowl	sonal Study <i>edge in Ma</i>	/ Specialisa thematics o	tion, it r <i>Electi</i>	can be
Prerequisites	Knowledge from functional ar	nalysis	anc	l ope	rator	algeb	ras is assun	ned.		

Responsible Persons	Ulrich Groh, Rainer Nagel
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 : o=obligatory, f=facultative

Module Number: MAT-55-09	Module Title: Type of Mo Non-Commutative Ergodic Theory Compulsory								e with	Choice
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						•			
Frequency	not regularly	ot regularly								
Term	1-3	3								
Language of Instruction	German or English	erman or English								
Forms of Teaching and Learning	Lecture 4 SWS									
Content	discussed. Then, based on c fined. With the help of the so- dynamical systems can be c	stly, the essential basic concepts and properties of C* and W* algebras are introduced and coussed. Then, based on commutative theory, non-commutative dynamical systems are deed. With the help of the so-called cross products it is then shown how such non-commutative namical systems can be characterised with the help of the group representation. The signance in mathematical physics is always emphasised.								
Objectives	godic theory, i.e. of dynamic fascinating interplay between spectral-theoretical) behaviou axiomatic and structural point simultaneously. The students lecture as well as assessing a lin the exercise classes they the terms, statements and more on new problems, to analyse	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.							nced the otic and how an roblems its of the indling of methods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Non-Commutative Ergodic Theory	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 h	ave	bee	n acc	uired.	Whether th	ie examinatio		
Literature	Possible References :									
	 Tanja Eisner, Balint Farkas, Markus Haase, Rainer Nagel: Operator Theoretic Aspects of Ergodic Theory. Springer 2015. Bruce Blackadar: Operator Algebras. Springer 2006. Alai Guichardet: Systèmes dynamiques non commutatifs. Astérisque 13-14 1974. Dirk Werner: Funktionalanalysis. Springer 1995. Volker Runde: A Taste of Topology. Springer 2005. 									

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 $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : o=obligatory, f=facultative

Module Number:	Module Title:							f Module:		
MAT-55-10	Pseudo Differential Operator	S					Compu	llsory Modu	le with	Choice
ECTS-Points	3									
Workload	Workload:	Time	in C	lass	:		Self-St	udy:		
- Time in Class - Self-Study	90 h	30 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	ecture 2 SWS								
Content	Fourier transform and	Sobo	lev s	pace	s.					
	Pseudodifferential operation	erators	on i	mani	folds					
	Finite propagation vel	Finite propagation velocity.								
	Fredholm operators and elliptic complexes .									
	The heat conduction kernel and the local index theorem.									
	The Atiyah-Bott-Pator	di theo	rem.							
	Von Neumann algebra	as and	repr	eser	ntatio	ns.				
	The L2 index theorem	1.								
Objectives	geometry. They will understated how both merge into the most transition from one to the other will be able to use theoretical will learn to use modern apport The students are capable of as assessing and explaining	Students learn basic techniques in the theory of elliptic differential operators and spectral geometry. They will understand the connection between differential and integral operators and how both merge into the more general calculus of pseudo-differential operators and how the transition from one to the other results in solution techniques for differential equations. They will be able to use theoretical approaches to solve specific problems in concrete cases. They will learn to use modern approaches of L2 theory to prove deep group theoretical statements. 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	Coursework	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 instru	uctor with a	pprova	I by the

Literature	Possible References :
	 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
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 : o=obligatory, f=facultative

Module Number: MAT-55-11	Module Title: Introduction to Harmonic An		of Module: ulsory Modu	le with	Choice					
ECTS-Points	9							<u> </u>		
Workload - Time in Class - Self-Study	Workload: Time in Class: 90 h							udy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise 0	ecture 4 SWS + Exercise Class 2 SWS								
Content	Fourier series and Fourier	urier tr	ansf	orma	ition.					
	Plancherel theorem a	ınd inve	erse	theo	rems	S.				
	Poisson summation for	ormula								
	tempered distribution	tempered distributions.								
	Additionally a selection of the following topics will be covered:									
	· ·	- LCA groups;								
	general Fourier transformation;non-abelian groups and representations;									
	- Sobolev-space			•		,				
	 Singular integral 									
	 Poisson integra 	ıls.								
Objectives	They recognise the interplay and can apply the knowledge theory. They understand the into various function spaces results of the lecture as well in the exercise classes they the terms, statements and non new problems, to analyse	Students can combine algebraic and analytical methods and apply them to solve problems. They recognise the interplay between the properties of functions and their Fourier transforms and can apply the knowledge gained from this to questions in physics, analysis and number theory. They understand the interaction of group theory and analysis and gain deep insights into various function 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 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Harmonic Analysis	L	f	2	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	examination the coursework									

Literature	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-55-12	Module Title: Harmonic Analysis in Euclidean Space						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						·			
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ecture 4 SWS + Exercise Class 2 SWS								
Content	 Covering-, decomposi Singular integrals, Poi Hardy- and BMO-space 	 Fourier transformation. Covering-, decomposition- and interpolation theorems. Singular integrals, Poisson integrals. Hardy- and BMO-spaces, multiplier theorems, Littlewood-Paley theory. 								
Objectives	euclidean space. The studer lecture as well as assessing In the exercise classes they the terms, statements and m on new problems, to analyse	The students got to know the central terms, results and methods of harmonic analysis in euclidean space. 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	Coursework	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	Е	f	2	3	, , , ,	or.	o. 20-30	9	
	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	Possible References :
	• Charles L. Feffermann, Elias M. Stein: 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 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 $\begin{array}{lll} \text{Teaching Format} & : \text{L=lecture, } & \text{LE=lecture with integrated exercises, } & \text{SL=seminar or lecture, } & \text{E=exercise class, } \\ & & \text{T=tutorial, P=project, S=seminar, IC=inverted classroom} \end{array}$

Status : o=obligatory, f=facultative

Module Number:	Module Title: Harmonic Analysis on Abelia	n Gro	uns					of Module:	le with	Choice
ECTS-Points	-	9								
Workload - Time in Class - Self-Study	Workload: 270 h					Self-St	Self-Study: 180 h			
Duration	1 Semester						'			
Frequency	not regularly									
Term	1-3									
Language of Instruction	German	German								
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	ecture 4 SWS + Exercise Class 2 SWS								
Content	Locally compact group	Locally compact groups, existence and uniqueness of Haar measures.								
	Convolution algebras,	Convolution algebras, Banach algebras, the Gelfand-Neumark theorem.								
	LCA groups, Pontryag	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^* -ories. The students are capa well as assessing and explain the exercise classes they the terms, statements and mon new problems, to analyse	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. They are able to present their solutions and, if necessary, defend them in critical discourse.					between in alge- her the- cture as adding of methods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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	Possible References :									
	Anton Deitmar: A first	cours	e in l	Harn	nonic	: Analy:	sis. Springe	er 2005.		
	Anton Deitmar, Siegfri	ed Ec	hterh	off:	Princ	ciples o	f Harmonic	Analysis. S	pringe	2008.
	Edwin Hewitt, Kenneth	Ross	s: Ab	strad	t hai	rmonic	analysis. V	ol. I. Springe	er 1979	9.
	Walter Rudin: Fourier	analy	sis o	n gro	ups.	John \	Viley 1990.			

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 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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom \\$

Status : o=obligatory, f=facultative

Module Number: MAT-55-14	Module Title: Harmonic Analysis on Gener	al Gro	ups					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	1 Semester								
Frequency	not regularly	not regularly								
Term	1-3	-3								
Language of Instruction	German	German								
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	lass 2	SW	S						
Content	Representation theory	of co	mpa	ct g	roups	, Peter	Weyl theore	em.		
	Representation theory	of ge	nera	l gr	oups.					
	trace formula and app	- trace formula and applications to the Heisenberg group and $SL_2(\mathbb{R}).$								
Objectives	The students have familiarised themselves with the deeper concepts and methods of abstract harmonic analysis and know how to use them. They have mastered the trace formula and understand its far-reaching implications, also for other 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.				aula and students sessing adling of nethods a team.					
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Harmonic Analysis on General Groups	L E	f	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	must	nave	be	en acc	uired.	Whether th	e examination		
Literature	Possible References :									
	Anton Deitmar, Siegfr	ied Ed	hterh	noff	: Princ	ciples c	f Harmonic	Analysis. S	pringe	2008.
	Gerald B. Folland: A cematics. Boca Raton		in a	bstı	ract ha	ırmonio	analysis. S	Studies in Ad	dvance	d Math-
	Michael E. Taylor: No.		nuta	tive	Harm	onic A	nalysis. AM	S 1986.		
Transfer	The module belongs to the sinto account the chosen per Study Focus, Advanced Knowith the restrictive requirements	rsonal <i>wledg</i>	Stu e in l	dy <i>Ma</i> i	Specia thema	alisation tics or	n, it can be <i>Elective Sp</i> e	included in	the S	Sections

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 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 : o=obligatory, f=facultative

Module Number: MAT-55-15	Module Title: Selected Chapters from Ope	rator T	heo	ry				of Module: ulsory Modul	e with	Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h Self-Study: 180 h						udy:	ıdy:	
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	SWS	3						
Content	culus. • Spectral theory of pos	 Spectral theory of restricted and unrestricted linear operators, especially spectral calculus. Spectral theory of positive operators – Perron-Frobenius theory. Spectral theory for operators of ergodic theory. 								
Objectives	Students master the concepts of spectral theory and in particular the abstract functional calculus. They can then apply this to concrete operators and discuss properties such as asymptotic behaviour. They are also able to recognise cross-connections to other mathematical fields such as stochastics, ergodic theory or number theory. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Selected Chapters from	L	f	4	6	yes	wr. o.	90-180	g	100
	Operator Theory	Е	f	2	3	yes	or.	o. 20-30	9	100
	In this module an exercise context examination the coursework oral is decided by the instruction	must ł	nave	bee	n acc	uired.	Whether th	e examinatio		
Literature	Possible References :									
	equations. Springer 2	 Possible References: Klaus Jochen Engel, Rainer Nagel: One-parameter semigroups for linear evolution equations. Springer 2000. Markus Haase: The Functional Calculus for Sectorial Operators. Birkhäuser 2006. 								
Transfer	The module belongs to the Mathematical Physics. Takir be included in the Sections Specialisation, in accordance	ig into <i>Study</i>	Foc	ount <i>us</i> , <i>i</i>	the d Adva	chosen nced K	personal S nowledge i	tudy Specia n <i>Mathemat</i>	llisatio <i>ics</i> or	n, it can <i>Elective</i>

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 : o=obligatory, f=facultative

Module Number: MAT-55-22	Module Title: Partial Differential Equations							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									
Forms of Teaching and Learning	Lecture 4 SWS									
Content	 Schauder estimates. Calderon-Zygmund estimates. Harnack's inequality. Hölder regularity. Viscosity solutions. Existence of solutions according to Perron. Evans-Krylov theorem. 									
Objectives	After the students have lear ferential Equations, this kno 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 o stuc essi acqu s of t and t	deepolents Ing ar Ired a Ing le Ing wo	ened are nd ex a cor cture rk on	I. Stud capabl cplainin nfident, e. They n solution	lents are prove of naming ag the presse and have learned 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 r	roduced essential adling of nethods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Partial Differential Equations	г Type of Course	4 Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	In this module an exercise or examination the coursework oral is decided by the instruc	ü ertifica must h	nave	beei	n acc	uired a	Whether the	e examination	icipatic	n in the

Literature	Possible References :
	 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 Schätzle
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 : o=obligatory, f=facultative

Module Number: MAT-55-24	Module Title: Nonlinear Elliptic Partial Differential Equations in Minimal Surface Theory							of Module: ulsory Modul	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	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	for minimal graphs with pres Nash estimate, which is one foundational in the study of connections between minim equation arising in the theory entire solutions (namely the	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 advaunderstanding of connection will acquire an array of new on objects governed by nonlapplications of Sobolev theo Moser iteration, and the us and when these techniques prove the essential statemer developed in the lecture and critically challenge the currer In the exercise classes they the terms, statements and mon new problems, to analyst team. They are capable of processing the discourse.	s between techninear of the control	veen nique differ caling nono pplic t it ir e of racques of t	this es for ential estable cepts ito a lessed ired in to	theory estated the continuity for the continuity fo	ry and ablishir uations uations upactnoormulae given put the leer framon the shifted and the shifted and the shifted and so	profound pring quantitate. These tectors argume. Students problem. The ecture as we sework. The pecific area precise an have learn lution strate.	oblems in grive and quate hniques includes includes will be able to a stock and a stock an	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	п Туре of Course	t Status	SMS 4	6 g	Coursework	Type of Exam o. o.	Dur. of Exam (min) 90-180 o. 20-30	ت Grading	Weight for Grade	
	In this module an exercise of examination the coursework oral is decided by the instruc	ertifica must	te is	to be	e acc	uired.	Whether th	e examinatio			

Literature	Possible References :
	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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom$

Status : o=obligatory, f=facultative

Module Number: MAT-55-26	Module Title: Partial Differential Equations in Conformal Geometry: the Yamabe Problem							of Module: ulsory Modu	le with	Choice	
ECTS-Points	3										
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										
Content	dimensible amination the potent This is the so-called Yamabe were fixed only in 1984, by control of the transfer of the transf	conformally equivalent to one with constant sectional curvature. The appropriate higher-differential equations are sectional curvature. The appropriate higher-differential equations in the complete proof of the section of the se									
Objectives	The students can state the dents are familiar with basic (sub-critical) Yamabe energy can study the conformal Grelem. The students are also frenowned Positive Mass The can provide the main ideas of ter elements of the minimal statements and concepts frolecture and to put it into a lar the current state of research Through homework assignmand independent acquaintar lectures. They learn how to to develop solution strategie solutions and to stand for the	methor function from the particle from the particle from the particle from the ents ance with transis on the function on the function from the ents ance with transis on the function function from the function function from the function function from the function f	ods of ional unction with still proof e the lecture special and e the their of the lecture special and e the their of the lecture special and e the	of the ls an on a the linki of the eory. Ure a vork. Exercise no nese own a	e calcount the calcount of the	culus of a associate it on of m to the estitive N are a asses asses, statements to the roots to the culture of	f variation, priated elliptic to the solvants in math solution of the solution	particularly of contents of the semi-linear strain of the the Yamabe and, in page and prove context defibe and critical velop a contents of methods exems, to ana	concer or PDE Yamak lativity proble articul e the e evelope cally ch fident, xplaine lyse th	ning the s. They be proband the em; they ar, massessential ed in the nallenge precise, d in the em and	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Partial Differential Equations in Conformal Geometry: the Yamabe Problem		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	l by the	

Literature	Possible References :
	• John M. Lee, Thomas H. Parker: The Yamabe problem. Bull. Am. Math. Soc., New Ser. 17, 37–91, 1987.
	Richard Schoen, Shing-Tung Yau: Lectures on differential geometry. International Press 1994.
	Thierry Aubin: Some nonlinear problems in Riemannian geometry. Springer 1998.
	Michael Struwe: Variational methods. Applications to nonlinear partial differential equations and Hamiltonian systems. Springer 2008.
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 modules Geometry in Physics and Introduction to Partial Differential Equations 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

 $\begin{array}{lll} \text{Teaching Format} & : \text{L=lecture, } & \text{LE=lecture with integrated exercises, } & \text{SL=seminar or lecture, } & \text{E=exercise class, } \\ & & \text{T=tutorial, } & \text{P=project, } & \text{S=seminar, } & \text{IC=inverted classroom} \\ \end{array}$

Status : o=obligatory, f=facultative

Module Number: MAT-55-27	Module Title: Fully Non-Linear Elliptic Equa	ations						of Module: ulsory Modu	le with	Choice
ECTS-Points	5									
Workload - Time in Class - Self-Study	Workload: 150 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 C	ass 1	SW	3						
Content	Solution of general ful	y non	-line	ar ec	uatio	ons witl	n elliptic equ	uations.		
	Solution of the Monge	-Ampe	ere e	quat	ion.					
Objectives	the second derivatives of a glearn how the modulus of content of Evans-Krylov theorem and I solution. In particular, they are and to the special, non-unifor of naming and proving the estimate the presented connections.	The students learn the techniques to successively estimate the supremum, the gradient and the second derivatives of a given solution of a fully non-linear elliptic equation. The students learn how the modulus of continuity of the second derivatives is then estimated using the Evans-Krylov theorem and learn the continuity method, which leads to the existence of a solution. In particular, they are able to apply the methods to general uniformly elliptic equations and to the special, non-uniformly elliptic Monge-Ampere equation. 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.					students sing the nce of a quations capable plaining			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Fully Non-Linear Elliptic Equations	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 exceptionally be offered by t points will be awarded for the	must l tor wit he led	nave h ap cture	beei prova r with	n acc al by nout	quired. the Bo exercis	Whether the ard of Exar	e examination miners. – Th	on is w ie mod	ritten or ule may
Literature	Possible References :									
	 Luis A. Caffarelli, Jose second-order elliptic e Pure and Applied Mati Luis A. Caffarelli, Jose nonlinear second-order elliptic, equations. In 209-252. David Gilbarg, Neil S. Springer 1998. 	equation nemate ph Ko er ellip : Con	ons. ics 3 ohn, l otic e nmur	I. M 7,3 p Luis quat nicati	onge op. 3 Nirer ions. ons	e-Ampe 69-402 nberg, II. Co on Pur	re equation Joel Spruck mplex Mon e and Appl	n. In: Comr :: The Dirich ge-Ampere, lied Mathem	nunica let pro and u natics (blem for niformly 38,2 pp.

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

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 : o=obligatory, f=facultative

Module Number: MAT-55-28	Module Title: Morse Theory							f Module: Isory Modul	e with	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 or English									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	Riemannian metrics o Dynamic systems on o Homotopy type of diffe Main approaches of M	 Topology of differentiable manifolds. Riemannian metrics on differentiable manifolds. Dynamic systems on differentiable manifolds. Homotopy type of differentiable manifolds. Main approaches of Morse theory. Outlook on Morse homology. 								
Objectives	Students learn how to analys using the tools of analysis, ir learn how the level surfaces used to obtain statements al to algebraic topology, which The students are capable of assessing and explaining the	n parti of nor bout t analy namin	cula n-deq he h ses g an	r the gene omot the t d pro	theorate topy opoloving	ory of d function type of ogy (of the ess	ynamical syns, so-called manifolds. manifolds)	rstems. In p d Morse fun They also using algeb	oarticul ctions, build a oraic m	lar, they can be a bridge nethods.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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.	writter	n or	oral	is de	ecided k	by the instru	uctor with a	oprova	I by the
Literature	Possible References: • John Milnor: Morse Theorems 1961. • Morris W. Hirsch: Differences 1988.									

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 $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : o=obligatory, f=facultative

Module Number: MAT-55-32	Module Title: Selected Chapters from Dyna	mica	Sys	tems	: The	eory		Type of Module: 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										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS										
Content	dynamical systems as isomorphic invariants o linear skew-product flo	 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. 						ns;			
Objectives	Students are familiar with quitial equations and the metho functional analysis, operator applicability of abstract math proving the essential results connections.	ds us theor emat	ed to y an ical o	o an d er conc	alyse godic epts.	e them. theor The	On the bay, they have students ar	asis of solid e experience e capable o	know ed the of nam	ledge of diverse ing and	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Selected Chapters from Dy- namical Systems Theory	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is a Board of Examiners.	vrittei	n or	oral	is de	cided	by the instru	uctor with a	pprova	Il by the	
Literature	Possible References: Tanja Eisner, Balint Fa of ergodic theory. Spriner: Manfred Einsiedler, Tr ory. Springer 2011. David Kerr, Hanfeng 1 2016.	nger 2 Iomas	2015 s Wa	rd: E	rgod	lic thec	ory: with a v	iew towards	s Numl	per 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 $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : o=obligatory, f=facultative

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 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 + Exercise Cl	ass 2	SWS	3						
Content	(topological) ergodicity are r plied to category theoretical deLeeuw-Glicksberg decomp Furstenberg-Zimmer structur research topics are addresse	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 esearch 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 de theoretical or ergodic-theoret ples of the usefulness of abstract and proving the essential ressented connections. In the exercise classes they the terms, statements and metals and metals are sented.	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	Coursework	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	bee	n acc	uired.	Whether th	e examination		
Literature	Possible References: • Tanja Eisner et al.: Op • Jan de Vries: Topolog tinuous mappings. De • Saunders Mac Lane: 0 • Helmut H. Schaefer: E	ical dy Gruy Categ	/nam ter 20 ories	iical 014. for t	syste	ems. A	n introduction	on to the dy	namics er 199	of con-

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 : o=obligatory, f=facultative

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-S 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	lass 2	SWS	3						
Content	First and second varia	ition fo	r var	ifold	S.					
	Monotonicity formula.									
	Allard's integral comp	actnes	s the	eorer	n.					
	Lipschitz approximation	n.								
	tilt-excess descent.									
	Allard's regularity thed	Allard's regularity theorem.								
	General and rectifible	General and rectifible flows.								
	Deformation theorem.									
	Surface minimizing flo	WS.								
Objectives	After having learned the basis 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 analysteam. They are capable of p discourse.	The ts are of and ex have a ethods ethem	stud capa cplain cqui of the	lents ble on ing i red a he le d to	will of na the p a cor cture work	be preming a present of the premium	epared for a and proving ed connect precise ar have learr dution strat	and guided the essential ions. Indicate to transfer egies on the	to prob I resultent har er the reir own	olems of the ndling of methods or in a
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Geometric Measure Theory	L	f	4	6	yes	wr. o.	90-180 o. 20-30	g	100

Literature	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-55-43	Module Title: Area Minimising Flows							Type of Module: Compulsory Module with Choice			
ECTS-Points	5										
Workload - Time in Class - Self-Study	Workload: 150 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 C	ass 1	SW	S							
Content	Compactness theoren Regularity of area min		_		ws.						
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.						of recent e lecture adling of methods a team.				
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Area Minimising Flows	L	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	Possible References: 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 sinto account the chosen per Study Focus, Advanced Kno with the restrictive requireme	sonal wledg	Štud e in i	dy S _l <i>Math</i>	pecia <i>ema</i>	alisation <i>tics</i> or	n, it can be Elective Sp	included in	n the S	Sections	
Prerequisites	Knowledge from the modules sure Theory is expected.	Introd	ductio	on to	Geo	metric	Measure TI	neory and G	eomet	ric Mea-	

Responsible Persons	Reiner Schätzle
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 : o=obligatory, f=facultative

Module Number: MAT-55-46	Module Title: Elastic Curves							f Module: Ilsory Modul	e with	Choice	
ECTS-Points	3	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										
Content	 Classification of elastic curves according to Langer and Singer. Order reduction of the Euler-Lagrange equation of the elastic energy of a curve. Qualitative behaviour of an elastic curve. 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	Coursework	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	ora	l is de	ecided	by the instru	uctor with a	oprova	l by the	
Literature	Possible References :										
	Filippo Gazzola, Han Value Problems, Sprin			h (Gruna	u, Gui	do Sweers:	Polyharmo	nic B	oundary	
	David Gilbarg, Neil S. Springer 1998.	Trudi	nger	: El	liptic p	oartial	differential e	quations of	secon	d order.	
	Joel Langer, David A. ential Geom. Band 20							of closed cu	rves, c	J. Differ-	
	John M. Lee: Introduc	tion to	smo	oth	n mani	ifolds.	Springer 20	13.			
	Michael Struwe: Varia	tional	Meth	nod	s. 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 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 $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : o=obligatory, f=facultative

Module Number: MAT-55-47	Module Title: Geometric Measure Theory – Varifolds Type of Module: Compulsory Module with Choice									Choice
ECTS-Points	5	5								
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									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Cl	ass 1	SW	S						
Content	First and second varia	tion fo	or va	rifold	S.					
	Monotonicity formula.									
	Allard's integral compa	actnes	s the	eorer	n.					
	Lipschitz approximatio	n.								
	tilt-excess descent.									
	Allard's regularity theo	rem.								
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 leave the terms, statements and meaning on new problems, to analyse they are able to present their	edge i o curr I resu nave a ethods them a	rent rent related of the control of	eperesea f the ired a he le	ned varch (lection control) a control cture rk or	with a valuestion ure as only of the state o	view to vari ns. The stu well as ass precise an have learn on strategie	iabilities. Standents are casessing and dindependent to transfess on their ow	explaid explaid ent hare er the r	s will be of nam- ning the adling of methods a team.
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Geometric Measure Theory	L	f	2	3	yes	wr. o.	90-180	g	100
	- Varifolds	E	f	1	2	,	or.	o. 20-30		
	In this module an exercise ce examination the coursework oral is decided by the instruct	must l	nave	beer	n acc	quired.	Whether th	e examination		
Literature	Possible References :									
	Herbert Federer: Georgian	metric	mea	asure	the	ory. Sp	ringer 1969).		
	Enrico Giusti: Minimal	surfa	ces a	and f	uncti	ions of	bounded va	ariation. Birk	häuse	r 1984.
	• Leon Simon: Lecture: 1984.	s on (geom	netric	: me	asure t	heory. Aus	stralian Natio	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 Geometric Measure Theory 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 : o=obligatory, f=facultative

Module Number: MAT-55-48	Module Title: Geometric Measure Theory -	- Flow	'S					of Module: ulsory Modul	le with	Choice
ECTS-Points	5	5								
Workload - Time in Class - Self-Study	Workload: 150 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	ass 1	SWS	3						
Content	General and rectifiable	flows	6.			· ·				
	Deformation theorem.									
	Surface minimizing flows.									
Objectives	Measure Theory, this knowled prepared for and introduced to the ing and proving the essential presented connections. In the exercise classes they the terms, statements and more on new problems, to analyse.	After the students have learnt the basic concepts and methods in Introduction to Geometric Measure Theory, this knowledge is deepened with a view to variabilities. Students will be prepared for and introduced to current research questions. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Geometric Measure Theory – Flows	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		
Literature	Possible References :									
	Herbert Federer: Geo	metric	mea	asure	the	ory. Sp	ringer 1969).		
	Enrico Giusti: Minimal	surfa	ces a	and f	uncti	ons of	bounded va	ariation. Birk	häuse	r 1984.
	Leon Simon: Lecture: 1984.	s on (geon	etric	mea	asure t	heory. Aus	stralian Natio	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 Geometric Measure Theory 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 : o=obligatory, f=facultative

Module Number: MAT-55-52	Module Title: SL2(R)							f Module: Ilsory Modul	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	Peutsch und Englisch									
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS									
Content	Introduction to the rep Computation of the ur	 Structure theory of the Lie group SL₂(R). Introduction to the representation theory of SL₂(R). Computation of the unitary dual. Proof of the explicit Plancherel formula. 									
Objectives	With the $SL_2(\mathbb{R})$ the students have studied an important Lie group in detail. That way they have become familiar with the basics of the representation theory of Lie groups as well as with the basics of hyperbolic geometry. The students have learned to construct, to split and to classify representations. Moreover, they are able to transfer their knowledge to analyse other Lie groups, and they have gathered a deeper understanding of the theory of Lie groups. They understand the analysis lying underneath the Theorem of Plancherel and apply it successfully. The students are capable of naming and proving the central 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	Coursework	Type of Exam	081-06 Dur. of Exam (min)	Grading	Weight for Grade	
	$SL_2(\mathbb{R})$	L	f	2	3	no	wr. o. or.	o. 20-30	g	100	
Literature	Possible References :				ory of	· semis	imple group	s. PUP 200	1.		
Transfer	The module belongs to the Differential Geometry. Takin be included in the Sections Specialisation, in accordance	g into Study	Foc	ount <i>us</i> , <i>i</i>	the d A <i>dva</i>	chosen nced K	personal S <i>(nowledge ii</i>	tudy Specia n <i>Mathemat</i>	lisatio <i>ics</i> or	n, it can <i>Elective</i>	
Prerequisites	There are no further prerequ	isites.									
Responsible Persons	Anton Deitmar										

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

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 : o=obligatory, f=facultative

Module Number: MAT-55-53	Module Title: Automorphic Forms							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	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	lass 1	SWS	3							
Content	Modular forms for the	modu	le gr	oup a	and it	ts cong	ruence sub	groups.			
	Examples: Eisenstein	series	s, Ra	man	ujan	delta fı	unction, the	ta series.			
	Modular curves.										
	Arithmetic application:	s and	conje	ectur	es.						
	Hecke operators.										
	The L-function of a mo	odular	form	and	its c	connect	ions with el	liptic curves	•		
Objectives	Students have familiarised the of automorphic forms in exaconnection between modular 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	amples r, real proving conn have a ethods them	e and representation acquired to the second	d are sent essent ns. ired a he le o wo	e abl ation entia a cor cture rk or	e to us n theory al result nfident, e. They n solution	se them. To and adelices of the lector precise and have learn on strategies.	They have under the L-functions between as well as well independent to transfers on their own.	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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Automorphic Forms	L	f	2	3	yes	K o. mP	90-180	g	100	
	- Tatemerpine i emie	Е	f	1	2	,00	o. H	o. 20-30	9		
	In this module an exercise context examination the coursework oral is decided by the instruc	must l	nave	beer	n acc	quired.	Whether the	e examination			
Literature	Possible References :										
	Deitmar, Anton: Autor	norphi	c Fo	rms.	Spri	nger 20)12.				
	Goldfeld, Dorian: Auto University Press 2015		nic fo	rms	and I	L-functi	ons for the (group GL(n,	R). Caı	mbridge	
	Serre, Jean-Pierre: A	cours	e in a	arithn	netic	. Sprin	ger 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

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

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 : o=obligatory, f=facultative

Module Number: MAT-55-61	Module Title: Cohomology and Sheaves							of Module: ulsory Modu	le with	Choice	
ECTS-Points	9										
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 or English										
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Cl	ass 2	SW	8							
Content	as derivatives of the section frexpansion) can be shown ver Introduction to categor Presentation of the cur Sheaves, derived func	t is shown how different cohomology theories (singular, de Rham, Cech) can all be understood as derivatives of the section 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.									
Objectives	The students see and unders ries. They understand mecha They have learned to abstract preciate cohomology theory as generalisations of function naming and proving the essente presented connections. State of research in the subjections.	inisms as a g spacential Stude	s tha itrary ener ces fo resul	t con matal ob or top ts of	nbine hem stac oolog the	e algeb latical tale le theo gical que lecture	raic, geome heories usi ry in applic lestions. The as well as	etric and ana ng category ations and to ne students assessing	alytic not theory of use a care care and example and e	nethods. y, to ap- sheaves pable of plaining	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Cohomology and Sheaves	L	f	4	6	yes	wr. o.	90-180	g	100	
		E	f	2	3	,,,,	or.	o. 20-30	9	100	
	Whether the examination is a Board of Examiners. – The m cises; in this case, only 6 cred	odule	ma	exc	eptic	onally b	e offered b	y the lecture	r witho		
Literature	Possible References :										
	Saunders Mac Lane: 0	Catego	ories	for th	ne w	orking ı	mathematic	ian. Springe	er-Verla	ng 1971.	
	Allen Hatcher: Algebra	ic top	olog	y. Ca	ambr	idge U	niversity Pr	ess 2002.			
	Glen Bredon: Sheaf th	eory.	Spri	nger-	Verl	ag 199	7.				
	Joseph Rotman: An in	trodu	ction	to h	omol	ogical	algebra. Sp	ringer-Verla	g 2008	3.	
	2000					- 9.041		95. 75.10		· ·	

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.	
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 : o=obligatory, f=facultative

Module Number: MAT-55-62	Module Title: Consistency Proofs 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	German											
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SWS	3								
Content	 Historical examples o paradoxes). 	f the qu	uesti	on o	f cor	sisten	cy (limits; pa	arallel axiom	ı; set-t	heoretic		
	Philosophical foundational programs (logicism; formalism; intuitionism).											
	The Hilbert program and Gödel's theorems.											
	Gentzen's transfinite (consist	ency	pro	of for	numb	er theory.					
	Alternative approache	es to co	nsis	tenc	y (ind	cluding	Gödel's T).					
	Current situation of co	onsistei	ncy p	oroof	s.							
Objectives	Students learn about the hist formal mathematical theories ing this question mathematic in mathematics both historica 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 arose ally. The ally and compression of the have a sethods them a	e, as ney a phile hen but the lecture is of the	well are all losor demonstrated and the memoral are are less to the less to th	as the ble to blicate corselves well a corecture rk on	ne releved categorally. In a categoral categor	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 acquate of non-con re capable of d explaining d independe ed to transfe s on their ow	for invalue of the formal of the property of the property of the property of the representation of the property of the representation of the property of the p	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	Coursework	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 context examination the coursework oral is decided by the instruction	must h	ave	beer	n acc	uired.	Whether the	e examinatio				

Literature	Possible References :
	 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 $\begin{array}{lll} \text{Teaching Format} & : \text{L=lecture, } & \text{LE=lecture with integrated exercises, } & \text{SL=seminar or lecture, } & \text{E=exercise class, } \\ & & \text{T=tutorial, } & \text{P=project, } & \text{S=seminar, } & \text{IC=inverted classroom} \\ \end{array}$

Status : o=obligatory, f=facultative

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	udy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	ecture 2 SWS + Exercise Class 2 SWS									
Content	 Gentzen's proof of col Ordinal number analysis Provable recursive fur Predicative analysis. 	 Axiomatic theories, incompleteness. Gentzen's proof of consistency for arithmetic. Ordinal number analysis. Provable recursive functions. Predicative analysis. Theories of inductive definitions. 									
Objectives	Students are familiar with the calculations for mathematica are capable of naming and prexplaining the presented con current state of research in the In 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 oject acqu s of t and t	and tesser Stude area ired a he le o wo	their ntial r ents v a cor ecture rk or	metam results of will be a nfident, e. They n solution	athematica of the lecturable to reflect precise an have learn on strategies	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 ron or in	students sing and lyse the adling of methods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Theory of Mathematical Proofs	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	must l	nave	beei	n acc	quired.	s coursewo Whether th	rk. For part e examinatio			
Literature	Possible References : • Wolfram Pohlers. Prod	of The	ory.	Sprir	nger	2009.					
Transfer	The module belongs to the Differential Geometry. Takin be included in the Sections Specialisation, in accordance	g into <i>Study</i>	acco Foc	ount <i>us</i> , <i>A</i>	the d Adva	chosen nced K	personal S <i>nowledge i</i>	tudy Specia n Mathemat	lisation ics or	n, it can <i>Elective</i>	

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 : o=obligatory, f=facultative

Module Number: MAT-55-65	Module Title: Explicit Mathematics							of Module: ulsory Modul	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										
Language of Instruction	German	àerman									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	ecture 2 SWS + Exercise Class 2 SWS									
Content	 Applicative theories. Explicit mathematics. Universes in explicit mathematics. Applications in proof theory. 										
Objectives	Students are familiar with an systems of analysis and are students are capable of nam sessing and explaining the pranalyse the current state of r In the exercise classes they the terms, statements and m on new problems, to analyse They are able to present their	familia ing an esente eseare have a ethoda thema	ar with and property of the contract of the co	h the oving onne of the street at the street at the le o wo	eir fur the ctions subje a cor cture rk or	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 strategie	oretical investif the lecture able to reflect independent of transfers on their ow	stigatio as we ct and ent har er the r on or in	ns. The ll as ascritically adling of nethods a team.	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Explicit Mathematics	L E	f	2	3	yes	or.	90-180 o. 20-30	g	100	
	In this module an exercise ce examination the coursework offered by the lecturer withou the module instead of 6.	must	have	bee	n ac	quired	- The mo	dule may ex	ceptio	nally be	

Literature	Possible References :
	 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 : o=obligatory, f=facultative

Module Number: MAT-55-70	Module Title: Selected Chapters from Fun	ctional	Ana	lysis				of Module:	le with	Choice		
ECTS-Points	6						<u>'</u>	•				
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 C	lass 2	SWS	S								
Content	A selection of the following to	opics v	vill be	e cov	ered	:						
	Topological vector spa	aces a	nd dı	uality	thec	ory.						
	(LB) and (LF) spaces	(LB) and (LF) spaces and distributions.										
	Compactness concepts (Eberlein's theorem, Banach-Alaoglu, Krein-Milman, Smulian).											
	Theorems from topolo tional analysis.	gy (Ti	etze,	, Ury	sohn	, Stone	e-Cech) and	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	esults utions mather oving nection he sub have a thods	to co . The emati the e ns. S iject a acqui s of t	oncreed had been concredulated as the second	ete exave resuch a such a stial rents vents v ents vents vents vents ecture rk on	ecognias mea esults vill be a nfident, solution	s from the issed and unasure theory of the lecturable to reflect precise and have learn on strategies.	field of funct derstood the or topology e as well as ct and critical d independe ed to transfe s on their ow nem in critical	ional are many and the many assess ally ana ent hare refer the refer to or in	analysis, y cross- 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Selected Chapters from Functional Analysis	L E	f	2	3	no	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 ł	nave	beei	n acc	uired.	Whether th	e examination	icipatic on is w	on in the ritten or		

Literature	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-55-71	Module Title: Operator Algebras and the Mechanics		of Module: ulsory Modul	le with	Choice					
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	English									
Forms of Teaching and Learning	Lecture 3 SWS + Exercise C	lass 1	SWS	3						
Content	Basics on operator all	gebras	(C*-	alge	bras,	algeb	raic states,	inductive lim	iits);	
	 Introduction to algebra amples); 	aic defo	orma	ation	quar	ntizatio	n (general s	set-up, coher	ent sta	ates, ex-
	 Applications to the classical limit of quantum mechanics and statistical mechanics in- cluding asymptotic emergence (phase transitions, large deviations (entropy), sponta- neous symmetry breaking). 									
Objectives	The students have obtained deepend knowledge in selections questions in algebraic quantum theory with an emphasis on algebraic deformation quantisation and their applications to the classical limit of quantum mechanics and statistical mechanics. They have learned algebraic techniques in order to develop abstract structures encoding the features of a physical theory. They are familiar with techniques to prove existence results of limits of sequences/nets encoded by algebraic states, examine these, and put them into a general perspective. Moreover, they understand the physical relevance of the results and are able to relate them to features of equilibrium thermodynamics, such as phase transitions and spontaneous symmetry breaking. They are able to describe the current state of research in the specific area. 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 Operator Algebras and their Applications to Statistical Mechanics	п Туре of Course	t Status	SMS 3	SLO3 4,5	yes	wr. o. or.	o. of Exam (min) 08-02 09-30	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	Possible References :
	Klaas Landsman: Foundations of Quantum Theory, From Classical Concepts to Operator Algebras. Springer 2017.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry, Mathematical Physics 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 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 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 : o=obligatory, f=facultative

Module Number: MAT-60-01	Module Title: Geometric Evolution Equations							f Module: Isory Modu	le with	Choice		
ECTS-Points	3						1					
Workload - Time in Class - Self-Study	Workload: 90 h	-	Time in Class: 30 h				Self-Sti 60 h	Self-Study: 60 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	Lecture 2 SWS										
Content	 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. 						cci flow,					
Objectives	Students learn to combine their knowledge of differential geometry and partial differential equations and apply it to specific problems in selected geometric evolution equations. They learn techniques for checking solutions of non-linear evolution equations, which enables 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.							s. They es them h a view				
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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.	writte	n or	oral	is de	cided	by the instru	uctor with a	pprova	al by the		
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. In combination with one of the modules Numerics of Nonstationary Differential Equations or Numerics of Differential Equations on Surfaces, it can be included in the subject specialisation <i>Numerical Mathematics and Optimisation</i> .											
Prerequisites	Knowledge from the module of differential geometry are re			n to	Partia	al Differ	ential Equat	tions and ba	ısic kn	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 : o=obligatory, f=facultative

Module Number: MAT-60-02	Module Title: Geometric Variation Problems							Type of Module: Compulsory Module 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	not regularly									
Term	1-3	1-3									
Language of Instruction	German or English	German or English									
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS									
Content	 harmonic mappings ar Direct methods of calc Regularity theory for some 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 their knowledge of differential geometry and analysis and apply it to specific problems in selected geometric variational problems. They learn techniques for proving solutions to various variational problems and for analysing the properties of solutions, which provide a basis for independent scientific work, for example in 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.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Geometric Variation Problems	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is National Board of Examiners.	vritter	n or	oral	is de	ecided	by the instri	uctor with a	pprova	I by the	
Transfer	into account the chosen per Study Focus, Advanced Know	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 from the module lof differential geometry are re			n to F	Partia	al Differ	ential Equa	tions and ba	sic kn	owledge	
Responsible Persons	Carla Cederbaum, Gerhard F	luiske	n	_	_						

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

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 : o=obligatory, f=facultative

Module Number: MAT-60-03	Module Title: Topics in Mathematical Relati	vity						Type of Module: Compulsory Module with Choice			
ECTS-Points	3	3									
Workload - Time in Class - Self-Study	Workload: 90 h							udy:	dy:		
Duration	1 Semester										
Frequency	regularly										
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS									
Content	 A 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 knowledge of selected issues in the mathematical theory of relativity. They learn analytical and geometric techniques for proving and investigating solutions to Einstein's equations and are able to categorise the physical relevance of the mathematical results. The lecture introduces students to their first independent scientific work, for example in 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.										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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 a Board of Examiners.	writte	n or	oral	is de	ecided	by the instru	uctor with a	pprova	I by the	
Transfer	ematical Physics. Taking int included in the Sections Stud	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	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								

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

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 : o=obligatory, f=facultative

Module Number: MAT-60-04	Module Title: Space-Like Hypersurfaces in Lorentzian Manifolds							of Module: ulsory Modul	le with	Choice
ECTS-Points	6	6								
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h		Class	•		Self-St 120 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 2 SWS + Exercise C	Lecture 2 SWS + Exercise Class 2 SWS								
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 deepend knowledge on selected questions in mathematical relativity. They learn analytic and geometric techniques in order to prove existence of solutions of Einstein equations and to examine these. Moreover, they do understand the physical relevance of the mathematical solutions. 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. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Space-Like Hypersurfaces	L	f	2	3	yes	wr. o.	90-180	n	100
	in Lorentzian Manifolds	Е	f	2	3	763	or.	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	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-60-05	Module Title: Limits of Spaces							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 3 SWS + Exercise C	ass 1	SWS	3								
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. 											
Objectives	ular problems in metric geometric which properties are stable in synthetic and concrete curvated differential geometry and ger the essential results of the lettions. In the exercise classes they the terms, statements and mon new problems, to analyse	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										
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Limits of Spaces	ш Г Туре of Course	t Status	SMS 3	SL 4,5 1,5	yes	Type of Exam or.	Dur. of Exam (min) 90-180 o. 20-30	ص Grading	Weight for Grade		
	In this module an exercise ce tion is written or oral is decide											
Literature	Possible References: • Jeff Cheeger, David 1975. • Dimitri Burago, Yuri Bute Mikhail Gromov: Messpringer 2007.	ırago,	Serç	jei Iv	/ano:	A Cou	ırse in Metri	c Geometry	. AMS	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	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 : o=obligatory, f=facultative

Module Number: MAT-60-06	Module Title: The Ricci Flow of Riemannia	n Meti	rics					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 2 SWS									
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.									
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	The Ricci Flow of	L	f	2	3	no	wr. o.	90-180	g	100
	Riemannian Metrics	ü	0	2	3	110	or.	o. 20-30	9	100
	Whether the examination is Board of Examiners. – The ercise classess; in this case 6.	modul	e ma	ау ех	cept	ionally	be offered	by the lectu	rer with	nout ex-
Literature	Possible References :									
	Simon Brendle: Ricci-	flow a	nd th	e sp	here	theore	m. AMS 20	10.		
	Peter Topping: Lecture	es on t	the F	Ricci-	Flow	. Lectu	re Notes 20	006.		
	Richard Hamilton: Rie 17, 1982.	manni	an 3	-mar	nifold	s with p	oositive Rice	ci curvature.	J. Diff.	Geom.
Transfer	The module belongs to the Si ematical Physics. Taking int included in the Sections Stuccialisation, in accordance wit	o acc	ount us, A	the A <i>dva</i>	chos nced	en per Knowi	sonal Studgedge in Ma	y Specialisa thematics o	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 : o=obligatory, f=facultative

Module Number: MAT-60-07	Module Title: Special Relativity							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	English											
Forms of Teaching and Learning	Lecture 2 SWS											
Content		 Derivation of the Minkowski metric from basic physical assumptions. Physical consequences of relativity such as length contraction, time dilation and some popular paradoxes. 										
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.											
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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 Board of Examiners.	writte	n or	oral i	s de	cided I	by the instru	uctor with a	pprova	ll by the		
Literature	Possible References :											
	Albert Einstein: Relati	vity: tł	ne sp	ecia	and	l gener	al theory. Po	ublic domair	า 1920			
	Thomas A. Moore: Six	idea	s tha	t sha	ped	physics	s: unit R. Mo	Graw-Hill 2	003.			
	Robert Resnick: Introd	ductio	n to S	Spec	ial R	elativity	. Wiley 200	7.				
	Bernard Schutz: A F 2009.	irst C	ourse	e in (Gene	eral Re	elativity. Ca	mbridge Ur	niversit	y Press		
Transfer	The module belongs to the Si ematical Physics. Taking int included in the Sections Studies cialisation, in accordance with	o acc	ount <i>us</i> , A	the A <i>dvai</i>	chos nced	en per Knowl	sonal Study <i>edge in Ma</i> i	/ Specialisa thematics o	tion, it r <i>Elect</i>	can be		
Prerequisites	Knowledge from the module of differential geometry are re			n to F	Partia	al Differ	ential Equa	tions and ba	ısic kn	owledge		

Responsible Persons	Carla Cederbaum, Gerhard Huisken
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

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

Status : o=obligatory, f=facultative

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-60-08	Module Title: Null Geometry in General Re	Module Title: Null Geometry in General Relativity Type of Module: Compulsory Module 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						·					
Frequency	not regularly											
Term	1-3											
Language of Instruction	English											
Forms of Teaching and Learning	Lecture 2 SWS											
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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Null Geometry in General Relativity	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 the points will be awarded for the	must l tor wit he led	nave h ap ture	beei prova with	n acc al by hout	quired. the Bo exercis	Whether th ard of Exar	e examination miners. – Th	on is w e mod	ritten or ule may		
Literature	Possible References: • Barrett O'Neill: Semi-lemonth of the semi-	iations	of N	lull h	ıyper	surface	s and the F	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 : o=obligatory, f=facultative

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										
Term	1-3										
Language of Instruction	English	English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	ecture 2 SWS + Exercise Class 2 SWS									
Content	- The Einstein ed - The Cauchy pro • The constraint equati - The conformal - Overview of the - Classification o • Asymptotically Euclid - AE manifolds a	e elliptic theory on closed man f constant mean curvature on	ifolds;								
Objectives	liptic partial differential equal equations and analyse propers nections between the theory problem and the Yambe propers nian 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 monnew problems, to analyse	tions and thus describe parts parties of the associated solute and questions of geometric applies and are familiar with the nalysis and physics for answer for naming and proving the essented connections, state of research in the subject have acquired a confident, put them and to work on solution	in's constraints into a system of el- of the solution spaces of Einstein's tions. They have learnt about con- nalysis such as the scalar curvature e interplay of methods of Rieman- ering questions of general relativity. tential results of the lecture as well Students will be able to reflect and ct area. The cise and independent handling of ave learned to transfer the methods strategies on their own or in a team. defend them in critical discourse.								

Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	The Einstein Constraint	L	f	2	3	yes	wr. o.	90-180	g	100	
	Equations	Е	f	2	3	yes	or.	o. 20-30	9		
	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 seminative of the seminative of the semination of the sections of the semination of the semina	into Study	Foci	ount us, A	the d I <i>dvai</i>	chosen nced K	personal S nowledge ii	tudy Specia n <i>Mathemat</i>	llisatior <i>ics</i> or	n, it can <i>Elective</i>	
Prerequisites	Basic knowledge of differential geometry and Riemannian geometry is assumed. Previous knowledge of partial differential equations is an advantage, but not essential. Previous knowledge of general relativity is also useful, but the necessary concepts are also covered in the lecture.										
Responsible Persons	Carla Cederbaum										
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

: o=obligatory, f=facultative Status

Module Number: MAT-60-10	Module Title: Special Topics in Evolution (with Exercise Class)	Special Topics in Evolution Equations for Submanifold										
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 C	lass 2	SWS	3								
Content	deform curves, hypersurface											
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. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Special Topics in Evolution	L	f	2	3	V00	wr. o.	90-180		100		
	Equations for Submanifolds	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 l	nave	beer	n acc	quired.	Whether th	e examination	icipation on is w	on in the rritten or		
Literature	Possible References :											
	Klaus Ecker: Regulari	ty the	ory fo	or me	ean c	urvatu	re flow. Birk	häuser 2004	4.			
Transfer	The module belongs to the <i>S</i> ematical Physics. Taking in included in the Sections Stuccialisation, in accordance with	to acc	ount <i>us</i> , A	the A <i>dva</i>	chos nced	en per Knowl	sonal Stud ledge in Ma	y Specialisa <i>thematics</i> o	tion, it r <i>Elect</i>	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			_								

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

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 : o=obligatory, f=facultative

Module Number: MAT-60-11	Module Title: Special Topics in Evolution (without Exercise Classes)		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	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	Coursework	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	Possible References :											
	Klaus Ecker: Regulari	ty the	ory fo	or me	ean c	curvatu	re flow. Birk	häuser 2004	4.			
Transfer	The module belongs to the Si ematical Physics. Taking int included in the Sections Stuccialisation, in accordance with	o acc	ount <i>us</i> , A	the A <i>dva</i>	chos ncea	sen pei Know	sonal Study ledge in Ma	y Specialisa <i>thematics</i> o	tion, it	can be		
Prerequisites	Knowledge from the module of differential geometry is rec			n to F	Partia	al Diffe	ential 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 : o=obligatory, f=facultative

Module Number: MAT-60-30	Module Title: Gravitational Collapse and Stivity		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										
Content	in general relativity, the cau we will study singularities ar And finally we will study Perholes, the phenomenon of singularities, and some exar cosmic censorship conjectur • Causality theory: — Time orientation • Singularities: — Raychoudhuri's • Black holes:	 Time orientation, causal hierarchy, global hyperbolicity. Singularities: Raychoudhuri's equations, conjugate points, singularity theorems. 									
Objectives	Students have acquired in-c general relativity. They will le ing singularity theorems. The 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 relati	ly to get ame onsi	polog an ov and nips p	gical moverview prove present	ethods in ca of cosmic the main st ed. Student	nusality theo censorship of atements of its will be abl	ry and conject the le e to re	in prov- ture and cture as	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Gravitational Collapse and		J Status	SWS 2	S ECTS	Coursework	Type of Exam o. o. or.	o. 20-30	ص Grading	Weight for Grade	
	Singularities in General Relativity Whether the examination is Board of Examiners.		n or	oral	is de	ecided	by the instr		pprova	I by the	

Possible References :
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.
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.
Basic knowledge of relativity is required to follow the course.
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 : o=obligatory, f=facultative

Module Number: MAT-60-35	Module Title: Non-Linear Elliptic and Parent Equations	araboli	ic P	artia	l Dif	fferenti		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	English											
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SWS	3								
Content	 Minimum surface oper Parabolic geometric e Hölder continuity accordinates 	 Semilinear and quasilinear elliptic and parabolic partial differential equations; Minimum surface operator and surfaces of prescribed mean curvature; Parabolic geometric equations, e.g. flow along the mean curvature; Hölder continuity according to De Giorgi and Nash; Inner regularity and boundary regularity of solutions. 										
Objectives	Students have learnt analytic differential equations of sect amples of partial differential techniques were learnt to pr The students are capable of assessing and explaining the In the exercise classes, studenth of the studenth of the problem solution of the problem solution in the problem sol	ond or equat ove th namin prese lents I	der dions e exi g and ented nave apply	of the from isten d pro l con acqu ther	e ellip mat ce a eving necti uired m ind	ptic an hematind registher the essential cons. It confide the pendicular to the essential confideration and the essential esse	d parabolic cal physics ularity of so sential resu ence in the ently to other	type. Using and different solutions to solutions to solutions to solutions to solutions the lecter technical her problems.	g cond ntial ge uch eq ture as nandlin They	erete ex- eometry, uations. s well as g of the are able		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Non-Linear Elliptic and Parabolic Partial Differential Equations	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	rtifica must l	nave	to be beer	acq acq	uired.	Whether th	e examination				

Literature	Possible References :
	 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

 $\label{thm:master} \textbf{Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, H=essay, P=portfolious exam, Pr=presentation, Pr=presen$ 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 : o=obligatory, f=facultative

Module Number: MAT-60-36	Module Title: Fully Non-Linear Elliptic and Equations		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-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									
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 them	of the niquest to g and entection of the acquest of	e elli les v ass othe d pro l con lired he le o wo	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 and have learn on strategies	Using conce existence problems. I equations lts of the lec d independent on their own their own	erete exand read and read stude indepe ture as ent hare read ar or in	amples egularity nts can ndently. well as adding of nethods a team.
They are able to present their solutions and, if necessary, defe						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								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	Possible References :
	 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

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 $\begin{array}{lll} \text{Teaching Format} & : \text{L=lecture, } & \text{LE=lecture with integrated exercises, } & \text{SL=seminar or lecture, } & \text{E=exercise class, } \\ & & \text{T=tutorial, P=project, S=seminar, IC=inverted classroom} \end{array}$

Status : o=obligatory, f=facultative

Module Number: MAT-65-05	Module Title: Groups and Representations	S	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	not regularly									
Term	1-3	1-3									
Language of Instruction	English	English									
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS										
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: symmet	tries and degeneracies in qua	ntum mechanics, selection rules.								
	Representations of fill potents.	nite groups: group algebra, re	egular representation, ideals, idem-								
	Symmetric groups: You	oung tableaux, Young operato	rs, dimensions and characters.								
	Applications: identica	l particles in quantum theories	S								
	Lie groups: Haar mea	asure, representations, Lie alg	ebras.								
	Tensor representation	ns of classical groups: symme	try classes, Young tableaux.								
	Applications: SU(2) a	and SU(3) in particle physics (s	spin, isospin, flavour)								
	Moreover a selection	of the following:									
		esentations of the Lorentz and	- '								
		otion of particles in quantum the otion of particles in quantum the	neories. on of semi-simple Lie algebras								
	Troote and worg	Tho, raining Ourtain oldcomodia	on or some simple are digostate								
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, thu 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 representation 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 tear. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Groups and Representations	L E	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	Possible References :									
	Mechanics. NEO Pres • Barry Simon: Represe	 Irene Verona Schensted: A course on the Application of Group Theory to Quantum Mechanics. NEO Press 1976. Barry Simon: Representations of Finite and Compact Groups. AMS 1996. Wu-Ki Tung: Group Theory and Physics. World Scientific 1985. 								
Transfer	The module belongs to the S Physics. Taking into account the Sections Study Focus, An accordance with the restrictive. The module cannot be take Groups' due to the large over	the c <i>vance</i> e requ n tog	hose ed Kr uirem ethe	n pe nowle nents r wit	rson edge of th	al Stud in Mat ne resp	ly Specialisa hematics or pective section	ation, it can Elective Sp on.	be inc ecialis	luded in ation, in
Prerequisites	There are no further prerequis	sites.								
Responsible Persons	Stefan Keppeler									
Abbreviations: Grading System : g	=graded, ng=not graded									

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

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

Status : o=obligatory, f=facultative

Module Number: MAT-65-12	Module Title: Mathematical Quantum Theo	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-Study: 180 h					
Duration	1 Semester						·				
Frequency	regularly in Winter Semester										
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements										
Content	The module provides an introduction to mathematical quantum theory. Particular topics are the stationary and time-dependent Schrödinger equation, fundamental approximation methods as Rayleigh-Schrödinger perturbation theory and Hartree- resp. Hartree-Fock theory, the Fock space formalism, and elements of scattering theory. Optionally, other topics such as adiabatic theory and semiclassical approximations can be discussed.										
Objectives	Students obtain knowledge at them to analyse known and physical problems in atom, sepectral and interference the the mathematical model and amples how the mathematical they enhance their knowledge derstanding of the listed notion problems from quantum theostate and particle pysics and retical methods and to quest of the results derived from it notions are naturally applied on methods and subjects. Stoncepts from the lecture as it into a larger framework. Through homework assignmand independent acquaintar lectures. They learn how to to develop solution strategies solutions and to stand for the	new polid storetics of the of the landing e on roons and their ion the within udents well a ents a ce wittenst on the contranst on the landing ents a contranst contranst e on the landing ents a contranst e on the landing ents a lan	roble ate a capacitation and capacitatio	ems f frame	rom particle s an deriv atura atura atura des a	quantucle pysid to quantucle pysid to quantucle defended from ally appeared in the care of the care and adequate through asses a state of the care of	m theory. The students are them to be students are them to be students are them to be students are the students are the students are the students are the students dements, and a new problem of the students are the students are the students are the students are the students. The group. The students are the students are the students are the students are the students.	They are ablar mathematic relevance and the experience obtain known to analyse known the emathematic relevance the essential sed in the lector welop a continuation of the experience of the exp	e to intect to intect to intect to intect to intect to intect to intert to i	errelate dels via puacy of ugh ex- hereby, and un- and new m, solid te theo- del and ematical by ledge ents and d to put precise, d in the em and	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Mathematical Quantum	L	0	4	6	yes	wr. o.	90-180	g	100	
	In this module students need the exam. The type of exami					nplete a		o. 20-30 s in order to			
Transfer								a a prorosult	ito for	the per	
iransier	Successful completion of mo ticipation in the module Adva pletion of one of the modules prerequisite for the participat	nced Math	Topic emat	cs in tical	Math Quar	nemation ntum T	al Quantur heory and N	n Theory. Sเ	iccessi	ul com-	

Prerequisites	-
Responsible Persons	Christian Hainzl, 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 : o=obligatory, f=facultative

Module Number: MAT-65-13	Module Title: Mathematical Relativity							of Module: ulsory Modu	le with	Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	_	lass	:		Self-Si 180 h	tudy:		
Duration	1 Semester									
Frequency	regularly in Summer Semest	er								
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lectures 4 SWS + Exercise (Classe	es 2 \$	SWS	, Hoi	mework	Assignem	ents		
Content	The module provides an introduction to the mathematical theory of relativity. Particular topics are Newton's theory of gravity, special theory of relativity, relativistic effects, Einstein's equations, the Schwarzschild spacetime. Optionally, other topics such as cosmological models, matter models, black holes, Cauchy problem and ADM decomposition, singularity theorems or 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 not in contial gresultined the contents and transfer on the contents and the contents and transfer on the contents and transfer	ew posterior of the context of the c	roble logy etry a rivec ghou prove xt de xerci e no nese own a	ems f and to and to d from it the e the evelo se cl tions meth and v	rom the astroph o quest m it. The first seesen ped in lasses and asses to within a	e theory of nysics and ion the rele nereby, they emester, in tial statementhe lecture students dements, and new probligroup. The	relativity. The their mather wance and a renhance the particular intents and contant to put evelop a contant to a contant	ney are matical dequa- neir kno- n modu cepts it into fident, kplaine lyse th	e able to models by of the bwledge ale MAT- from the a larger precise, d in the em and
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Mathematical Relativity	т Туре of Course	o o Status	SMS 4	e a	Soursework	Type of Exam or. o.	Onr. 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 adr	nitted to
Transfer	Successful completion of mo in the module Advanced Top the modules Mathematical F the participation in the modules	ics in Relativ	Mat ity o	hema r Ma	atica them	l Relati natical (vity. Succe	ssful comple	etion o	f one of
Prerequisites	Participation in the module G	ieome	try ir	Phy	sics	is a pre	erequisite.			
Responsible Persons	Carla Cederbaum, Gerhard I	Huiske	en, Fr	ank	Loos	se				

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

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 : o=obligatory, f=facultative

Module Number:	Module Title:							f Module:			
MAT-65-14	Mathematical Statistical Phys	sics					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	not regularly, in Summer Sen	nester									
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements										
Content	The module provides an introduction to mathematical statistical physics. Particular topics are concepts of probability theory, classical statistical mechanics of gases (equivalence of ensembles, thermal equilibrium, Boltzmann equation, entropy), Brownian motion (stochastic processes, Wiener process), lattice models (Ising model, Gibbs measure, thermodynamic limit, phase transitions), statistical quantum mechanics (quantum mechanical ensembles, transition to thermal equilibrium, Bose-Einstein condensate). Optionally, other topics such as open quantum systems, transport phenomena, renormalization group theory and the fluctuation-dissipation theorem can be discussed.										
Objectives	Students obtain knowledge at them to analyse known and rundamental physical concepematical models via probabili mathematical model and of the on methods and subjects gaiory. Students are able to na lecture as well as to explain framework. Through homework assignment independent acquaintant lectures. They learn how to to develop solution strategies solutions and to stand for the	ew protes, such stic mane resident the contract and the c	obler ch as ethoults or roug nd pronte: and ethous the the ethous	ms fr equ ds allerive hout rove xt de xerci e not lese lese	om sillibriumd to ed from the fither evelopes e claim methand v	tatisticum, irre questi om it. T first ser essenti ped in asses , state nods to vithin a	al physics. To eversibility and on the relevance on the relevance of the reby, they mester, in partial statement the lecture of the students dements, and onew problements. The representation of the results of the res	They are abled and entropy, a vance and act of enhance the articular on particular on and to put the velop a content of ens, to ana	e to intended the to intended the the dequace one in the corobab cepts fit into fident, eplaine the type the total t	errelate ir math- ey of the owledge ility the- rom the a larger precise, d in the em and	
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Mathematical Statistical Physics	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	com			in order to	be adr	nitted to	
Transfer	Successful completion of more Topics in Mathematical Statis				uisite	for the	e participatio	on in the mo	dule Ad	dvanced	
Prerequisites	-										
Responsible Persons	Marcello Porta, Roderich Tur	nulka									

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

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 : o=obligatory, f=facultative

Module Number: MAT-65-15	Module Title: Foundations of Quantum Mechanics							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	tudy:			
Duration	1 Semester										
Frequency	regularly every two years										
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignements									
Content	The module provides an introduction to fundamental questions of quantum mechanics, including its mathematical and philosophical aspects. Various interpretations such as Copenhagen, Bohmian mechanics, many worlds and spontaneous collapse of the wave function are presented and analysed mathematically and physically. Other topics include Born's rule, Heisenberg's uncertainty principle, the quantum measurement problem, Bell's non-locality theorem, identical particles and no-hidden-variable theorems.										
Objectives	Students know and can apply the rules of quantum mechanics in different environments and understand several important theories of how the quantum world works. They acquire mathematical knowledge relevant to the application of these rules and theories and can connect the mathematical treatment with the physical meaning. They will familiarise themselves with the surprising phenomena and paradoxes of quantum mechanics. They will appreciate what is controversial about the orthodox interpretation and why, and will be able to follow the current debate on fundamental issues. 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	Coursework	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 so	et by tl	ne in	struc	tor.						
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 Analy	The basic modules on Analysis and Linear Algebra are required.									
Responsible Persons	Roderich Tumulka										

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

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 : o=obligatory, f=facultative

Module Number: MAT-65-21	Module Title: Advanced Topics in Mathematical Quantum Theory							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	English	English									
Forms of Teaching and Learning	Lectures 4 SWS + Exercise	Classe	s 2 S	SWS	, Hoi	meworl	k Assignem	ents			
Content	The module provides an introduction to an advanced topic of mathematical quantum theory, 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 open problems.										
Objectives	Students obtain knowledge and understanding of the acquired notions and methods and are able to apply them in the analysis of known and new problems from the specific area of Mathematical Quantum 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. 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	Coursework	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	
	Theory E o 2 3 or. o. 20-30 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.						nitted to				
Transfer	The module may be a prerequisite for the master thesis.										
Prerequisites	Knowledge from the module Mathematical Quantum Theory is assumed.										
Responsible Persons	Stefan Teufel										

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

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 : o=obligatory, f=facultative

Module Number: MAT-65-24	Module Title: Advanced Topics in Mathematical Relativity (short version)							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, in Winter Semester									
Term	1-3									
Language of Instruction	English	English								
Forms of Teaching and Learning	Lectures 2 SWS + Exercise (Lectures 2 SWS + Exercise Classes 2 SWS, Homework Assignements								
Content	The module provides a short introduction to an advanced topic of mathematical theory of relativity. 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 open problems.									
Objectives	Students obtain deepend knowledge on selected questions in mathematical relativity. They learn analytic and geometric techniques in order to prove existence of solutions of Einstein equations and to examine these. Moreover, they do understand the physical relevance of the mathematical solutions. 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. They are able to describe and in parts also 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 Advanced Topics in Mathematical Relativity	т Туре of Course	o Status	SMS 2	s ECTS	Coursework	wr. o. or.	Dur. of Exam (min) 90-180 o. 20-30	ص Grading	Weight for Grade
	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. — In exceptional cases the module can be offered by the lecturer without exercises, in this case, only 3 credit points are awarded for the module instead of 6.					module				
Transfer	The module may be a prerequisite for the master thesis.									
Prerequisites	Knowledge from the module	Mathe	emati	cal F	Relati	ivity is	assumed.			
Responsible Persons	Carla Cederbaum, Gerhard Huisken, 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 : o=obligatory, f=facultative

Module Number: MAT-65-31	Module Title: Mathematical Methods for Co		Type of Module: Compulsory Module 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	English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS									
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, understand and are familiar with the concepts of the lecture. In particular, they have developed a deeper understanding of how mathematical concepts are applied in a natural way in solid state 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Mathematical Methods for Condensed Matter Physics	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 l	have	bee	n acc	quired.	Whether th	e examination		
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.									
Prerequisites	In terms of content, only kno Mathematik are required.	In terms of content, only knowledge from the basic courses of the first two years in the B.Sc. Mathematik are required.								

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=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,

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

Status : o=obligatory, f=facultative

Module Number: MAT-65-32	Module Title: Mathematical Aspects of the Quantum Hall Effect Type of Module: Compulsory Module with Choice								Choice	
ECTS-Points	6	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	English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	ass 2	SWS	3						
Objectives	Review of the classica Analysis of the Landar Linear response theor Wannier functions and Magnetic perturbation The students have learned, the lectures. In particular, the	The course is focused on the description of mathematical models for the quantum Hall 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. The 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 speci. 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 transf	vell aney ane ea. and each the cer the	xerciae not esse	explode to se classions methode	ain the descri asses s stater nods to vithin a	context de be and critic students de nents, and new proble group. The	veloped in to cally challer velop a conto methods exems, to ana	he lect nge the fident, kplaine lyse th	ure and current orecise, d in the em and
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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 instruc	must l	nave	beer	n acc	uired.	Whether the	e examination		
Transfer	The module belongs to the matical Physics. Taking the account, the module can be a Mathematics or Elective Spe	perso Issign	nal s ed to	peci the	alisa	tion an	d the restri	ctions of the	e section	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 : o=obligatory, f=facultative

Module Number: MAT-65-33	Module Title: Wave Equations of Relativistic Quantum Mechanics							of Module: ulsory Modu	le with	Choice
ECTS-Points	6	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 or English									
Forms of Teaching and Learning	Lecture 2 SWS + Exercise C	lass 2	SW	S						
Content	Klein-Gordon equatio	n.				· ·			· ·	
	Dirac equation.									
	Representation Theo	ry of th	ie Lo	rent	z Gro	oup.				
	Relativistic Many-Particle Systems (Multi-Time Formalism).									
Objectives	mechanics. They learn and solutions of the Klein-Gordo their properties. The studen results. They are able to no lecture as well as to explain framework. They are able to the specific area. Through homework assignment and independent acquaintal lectures. They learn how to	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	Coursework	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	Possible References :
	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

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 : o=obligatory, f=facultative

Module Number:	Module Title:						Туре о	of Module:		
MAT-65-36	Quantum Information Theory	/					Compu	ulsory Modu	e 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									
Content	Basic notions on the universality and meas			Juant	um c	omput	er: Quantur	n gates, qua	antum	circuits,
	Quantum algorithms:	Deuts	ch-J	ozsa	, Sho	or and (Grover.			
	Quantum communica coding. Quantum key				thed	orem, c	uantum tele	eportation ar	nd supe	erdense
	Physical realizations:	DiVino	enzo	o crit	eria,	Cirac 2	Zoller quantı	um compute	r, Circı	uit QED.
	Decoherence and operations	en qua	ntun	ı sys	tems	S.				
	Quantum error correct	tion. F	ault	toler	ant q	uantun	n computing	J.		
	Alternative quantum of	comput	ting r	mode	els: A	diabat	ic quantum	computation	۱.	
	Introduction to the the entanglement, multiple					nt: De	finition, crit	eria and me	easure	ment 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Quantum Information Theory	ü	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 the	e examination		

Literature	Possible References :
	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
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	There are no prerequisites.
Responsible Persons	Angela Capel Cuevas
	egraded, 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

Status : o=obligatory, f=facultative

Module Number: MAT-65-37	Module Title: Matrix Analysis and Applications						Type of Module: Compulsory Module with Choice				
ECTS-Points	6						<u> </u>				
Workload - Time in Class - Self-Study	Workload: 180 h	Time in 60 h	Class:			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 C	lass 1 SV	WS								
Objectives	Mappings and algebra Positive matrices. Functional calculus ar Matrix monotone func Matrix means and ine Applications in quantu Students have acquired in-ditional analysis. They have be 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 their	as. and derivations and qualities. am inform the pecome for the pecome for the pecome in the pecom	tions. d converted a converte	e of m with e mat ney a cion thure a a con cture	natrix a some rix fun re also heory. s well fident, . They solution	analysis froi aspects of ctions, matio familiar wi The studer as assession precise and have learn on strategies	m the persp analysis in rix averages ith several to nts are capa ng and expla d independe ed to transfe s on their ow	ective the co, majo ypical able of aining ent harer the ren or in	ntext of risation, applicanaming the prediction of nethods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Marix Analysis and Applications	Type of Course	3	SLO3 4,5 1,5	S Coursework	Type of Exam or. o.	On: 06 Exam (min) 0. 20-30	Grading	Weight for Grade		

Literature	Possible References :
	 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	

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 : o=obligatory, f=facultative

Module Number: MAT-65-38	Module Title: Hamiltonian 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 C	lass 2	SWS	3						
Content	mechanics. This builds a bi	The module provides an introduction to the theory of Hamiltonian systems as used in classical mechanics. This builds a bridge between the fields of differential geometry, symplectic geometry and dynamical systems as well as theoretical physics. The main points of the lecture are:								
	Symplectic manifolds	and th	e ca	noni	cal 1	-form o	f the cotan	gent bundle.		
	Darboux-Moser theorem	em.								
	Lagrangian and Hami	Itonian	syst	tems						
	Integrable systems ar	d Arno	old-L	iouvi	lle th	eorem	•			
	Moment mappings.									
	Symplectic reduction.									
	Symplectic manifolds	and to	ric e	ffects	S .					
Objectives	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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Hamiltonian Systems	L E	f f	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	ertificat must h	te is	to be	acq acc	uired.	Whether th	e examination		

Literature	Possible References :
	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 : o=obligatory, f=facultative

Module Number: MAT-65-39	Module Title: Propagation of Chaos						of Module: ulsory Modul	e with	Choice	
ECTS-Points	9	9								
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h			Self-St 180 h	Self-Study: 180 h				
Duration	1 Semester									
Frequency	regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS									
Content	Mean-field situations (Explicit treatment of co	 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Propagation of Chaos	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	bee	n acc	uired.	Whether the	e examination		
Literature	Possible References: 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 Sing into account the chosen particle Study Focus, Advanced Knowith the restrictive requireme	persor wledg	nal S e in l	tudy <i>Math</i>	Spec emai	cialisati tics or i	on, it can b Elective Sp	e included i	n the S	Sections

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 : o=obligatory, f=facultative

Module Number: MAT-70-02	Module Title: Numerics of Stationary Differ	ential	Equa	ation	s			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	regularly	regularly											
Term	1-3												
Language of Instruction	German or English												
Forms of Teaching and Learning	Lecture 4 SWS												
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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Numerics of Stationary 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	beer	n acc	uired.	Whether th	e examination	icipation on is w	on in the rritten or			
Literature	Possible References : • Dietrich Braess: Finite • Wolfgang Hackbusch: ner 1986.			•	Ū	•		erentialgleicl	nunger	n. Teub-			
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> ı	rsona vledo	al Stu ge in	udy S <i>Matl</i>	Special hematic	isation, it ca es or <i>Electi</i> v	an be includ	ed in t	he Sec-			
Prerequisites	Knowledge of the numerical	algorit	hms	mod	ule is	s helpfı	ul, but not m	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 : o=obligatory, f=facultative

Module Number: MAT-70-03	Module Title: Numerics of Instationary Diffe	erentia	al Eq	uatio	ns			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-Si 180 h	tudy:				
Duration	1 Semester											
Frequency	regularly											
Term	1-3	-3										
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS	Lecture 4 SWS										
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	Coursework	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 instruct	must l	nave	beer	n acc	uired.	Whether th	e examination				
Literature	Possible References: • Ernst Hairer, Gerhard lems. Springer 1996. • Vidar Thomee: Galer 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	rsona vledo	al Sti ge in	udy S <i>Mati</i>	Specia hemati	lisation, it c cs or <i>Electi</i>	an be includ	ed in t	the Sec-		
Prerequisites	Knowledge from the module helpful, but not absolutely ne			l Ma	then	natics	of Stationar	y Differentia	ıl Equa	ations is		
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 : o=obligatory, f=facultative

Module Number: MAT-70-04	Module Title: Ordinary Differential Equation		of Module: ulsory Modu	le with	Choice							
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	not regularly											
Term	1-3	-3										
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS											
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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Ordinary Differential Equations - Analysis and Numerics	L E	f	4	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 l	nave	bee	n acc	uired.	Whether th	e examinati				
Literature		 Lawrence Perko: Differential equations and dynamical systems. Springer 1993. David Griffiths, Desmond J. Higham: Numerical methods for ordinary differential equa- 										
Transfer	The module belongs to the S merical Mathematics and Opcialisation, it can be included ics or Elective Specialisation section.	otimisa in the	<i>tion.</i> Sect	Tak ions:	ing in Stuc	nto acc <i>ly Focu</i>	ount the ch s, <i>Advance</i>	osen persor d Knowledg	nal Stu e in Ma	dy Spe- athemat-		

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 : o=obligatory, f=facultative

Module Number: MAT-70-05	Module Title: Optimal Control Theory with tions	Ordii	nary	Diffe	rentia	al Equa		f Module: Ilsory Modu	le with	Choice			
ECTS-Points	5												
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	e in C	Class	:		Self-St 180 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	Brief overview of existence and uniqueness theory for ODEs.												
	Numerical solutions to	ODE	s.										
	Introduction to optima	l cont	rol pr	oble	ns w	ith OD	Es.						
	 Existence and uniqueness theory for linear quadratic optimal control problems (LQ problems). 												
	Pontryagin's maximur	n prin	ciple.										
	Numerical approxima	tion 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 assired in the letter the second in the letter the let	e pro estudessir a cor ecture rk or	blem. dents a ng and nfident, e. They n solution	They are all re capable explaining to precise and have learned strategies	so familiar vof naming and the presente dindepended to transfes on their ow	with quand proder on the connection of the conne	alitative ving the ections. Idling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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 continuous examination the coursework oral is decided by the instructions.	must	have	bee	n acc	uired.	Whether the	e examination					
Literature	Possible References :												
	Matthias Gerdts: Opti	mal C	ontro	ol of (DDE	s and D	AEs. De Gi	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 : o=obligatory, f=facultative

Module Number: MAT-70-06	Module Title: Numerics of Differential Equa	ations	of Sı	urfac	es			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	tudy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3	-3										
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 2 SWS											
Content	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	ing) surfaces. In particular, to very strong, general and rick The students are capable of assessing and explaining the In the exercise classes they the terms, statements and mon new problems, to analyse	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	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Numerics of Differential Equations of Surfaces	L	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	nave	bee	n acc	uired.	Whether th	e examinati				
Literature		Possible References: 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 <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	dule i	s helpfı	ul, but not m	nandatory.		_		

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

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

Status : o=obligatory, f=facultative

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-70-11	Module Title: Stochastic Differential Equat	ions						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	tudy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3	3										
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 4 SWS											
Content	Stochastic processes, filtrations, martingales.											
	Wiener process, random walk, Donsker's theorem.											
	Diffusion semigroup,	Diffusion semigroup, Ito's integral.										
	Solution of a stochast	Solution of a stochastic differential equation.										
	Markov property, Malliavin calculus, rough path theory.											
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.									ndling of methods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Stochastic Differential	L	f	4	6	yes	wr. o.	90-180	g	100		
	Equations	ü	f	2	3	ycs	or.	o. 20-30	9	100		
	In this module an exercise of examination the coursework oral is decided by the instruc	must l	nave	bee	n acc	quired.	Whether th	ne examination	icipation on is w	on in the rritten or		
Literature	Possible References :											
	Bernt Oksendal: Stoc	hastic	diffe	rtial	equa	itions. \$	Springer 20	00.				
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 modules S ory from the Bachelor of Sci							ion and Mea	surem	ent The-		

Responsible Persons	Andreas Prohl
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 : o=obligatory, f=facultative

Module Number: MAT-70-12	Module Title: Introduction to Stochastic Dif	ferent	ial E	quati	ons -	- Part 1		of Module: ulsory Modul	e with	Choice	
ECTS-Points	5						'				
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 2 SWS + Exercise Class 1 SWS										
Content	 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Stochastic 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 instruc	must l	nave	bee	n acc	quired.	Whether th	e examination			
Literature	Possible References :										
	Bernt Oksendal: Stock	nastic	diffe	renti	al eq	uations	s. Springer	2000.			
Transfer	The module belongs to the and Stochastics. Taking intincluded in the Sections Stuccialisation, in accordance with	o acco	ount cus, A	the A <i>dva</i>	chos <i>ncea</i>	en per <i>Knowi</i>	sonal Study <i>ledge in Ma</i>	y Specialisa thematics o	tion, it <i>Electi</i>	can be	
Prerequisites	Knowledge from the modules from the Bachelor of Science						on to Integr	ation and M	easure	Theory	
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 : o=obligatory, f=facultative

Module Number: MAT-70-15	Module Title: Numerics of Stochastic Differ	ential	Equ	atior	าร			of Module: ulsory Modul	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	3										
Language of Instruction	German	German										
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS										
Content	Random number gene	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 principles and techniques for the numerical approximation of 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.									ving the		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	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	al by the		
Literature	Possible References :											
	Peter E. Kloeden, Ecl tions. Springer 1999.	khard	Plate	en: l	Nume	erical s	olution of st	ochastic dif	ferenti	al equa-		
Transfer	The module belongs to the S Stochastics. Taking into account the Sections Study Focus, in accordance with the restrict	unt th	e ch	oser <i>Knc</i>	pers	sonal S <i>lge in N</i>	Study Specia Mathematics	llisation, it ca or <i>Elective</i>	an be i	included		
Prerequisites	Knowledge from the Stochas	tics m	odul	e in	the B	Bachelo	or 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 : o=obligatory, f=facultative

Module Number: MAT-70-16	Module Title: Stochastic Optimal Control in		of Module: ulsory Modul	e 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	German or English	German or English									
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS									
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	Coursework	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 Board of Examiners.	writte	n or	oral	is de	cided	by the instru	uctor with a	pprova	l by the	
Transfer	The module belongs to the and Stochastics. Taking into included in the Sections Stuccialisation, in accordance with	acco	ount aus, 7	the d Adva	chos ncea	en per <i>Knowi</i>	sonal Study <i>ledge in Ma</i>	Specialisa thematics o	tion, it <i>Electi</i>	can be	
Prerequisites	The contents of the module N	lumer	ical I	Math	ema	tics are	assumed.				
Responsible Persons	Andreas Prohl										
	graded, ng=not graded	ım. wı	:=wr	itten	exar	n, Pr=r	presentation	, H=essav. F	P=portf	folio	

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 : o=obligatory, f=facultative

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: 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	 Direct method in the calculus of variations, Euler-Lagrange equation. Brouwer-Minty theorem, non-linear evolution equations. Gateaux and Frechet differentiability. Proof of existence of optimal controls, necessary optimality conditions. Adjoint, convergent optimisation methods in Banach spaces. Variational discretisation concepts. 										
Objectives	Students master the basic principles and techniques for deriving optimality conditions for prototypical control problems with constraints in the form of partial 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.										
Requirements for Obtaining Credit, Grading, Weight if applicable	They are able to present their solutions and, if necessary, defend them in critical discourse. SMS SMS Conrsework Our. of Exam Weight for Grading Title Title										
	Optimisation with Differential Equations	L ü	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 ł	nave	bee	n acc	uired.	Whether th	e examinatio			
Literature	Possible References : • Michael Hinze, Rene constraints. Springer 2		u, M	icha	el Ull	brich, §	Stefan Ullric	h: Optimiza	ition 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 $\label{eq:lecture} \mbox{Teaching Format} \quad : L=\mbox{lecture, } \mbox{ L=lecture with integrated exercises, } \mbox{ SL=seminar or lecture, } \mbox{ E=exercise class, } \mbox{ T=tutorial, } \mbox{ P=project, } \mbox{ S=seminar, } \mbox{ IC=inverted classroom.}$

Status : o=obligatory, f=facultative

Module Number: MAT-70-25								Type of Module: Compulsory Module 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	An introduction to numerical methods for solving optimisation problems in science and technology with a focus on continuous optimisation and non-linear programming.												
	Basic concepts of optimization.												
	Unconstrained optimization and Newton-type algorithms.												
	Optimization with equations as constraints.												
	Optimization with inequalities as constraints.												
	Applications:												
	Economy: resource allocation in logistics, investments, etc.												
	 Science: model estimation and adaptation to measurement data, experimental design. 												
	 Engineering: design and operation of technical systems such as bridges, cars, airplanes, digital devices, etc. 												
Objectives	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	Requirements for Obtaining Credit, Grading, Weight if												
	Numerical Optimisation	L	f	2	3	yes	wr. o.	90-180	g	100			
	- Isinonda Optimidation	ü	f	1	2	700	or.	o. 20-30	9				
	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	Possible References: • 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 : o=obligatory, f=facultative

Module Number: MAT-70-30	Module Title: Theoretical Aspects of Machine Learning 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-S 120 h	tudy:				
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											
Objectives	The lecture covers some rec The theory of Reprod Applications of RKHS mean embeddings. Approximation capabit Dynamics of neural nets Recent advances in high generalisation. The students learn the math 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.	theory lities of etwork nigh difference a earningeded for essented in the challed ents a	Kerner v succession v succession for the call for the call sine leepinge end expenses of the cal	el Hill h as ural r d the bund serne d with e discaten cture the exerci-	sylvania state of the state of	Space Is, kerr orks. ral tang tistics, is of subthods. bir thecion and color as and color as asses.	gent kernel. in particular in	earning theo familiar wit is, mathema on of algorithm the lecturarger framework in the specyclop a con	cA, and the case when the case	ural net- amental pproach hey are rell as to hey are rea. precise,		
	and independent acquaintar lectures. They learn how to to develop solution strategies solutions and to stand for the	nce wit transf s on th	th the er the	e not lese wn a	ions meth ind w	, stater nods to vithin a	nents, and new probl group. The	methods exems, to ana	kplaine lyse th	d in the em and		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Theoretical Aspects of Machine Learning	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 exceptional cases, be offer only 3 credit points are award	must h tor wit red wit	nave h ap _l hout	beer prova exer	n acc al by cises	quired. the Bo	Whether th ard of Exar	ne examination miners. – Th	on is w e mod	ritten or ule may,		

Literature	Possible References :
	 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 <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	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 : o=obligatory, f=facultative

Module Number: MAT-70-31	Module Title: Statistical Learning Theory for Nonparametric Regression 1 Type of Module: Compulsory Module 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										
Content	Non-parametric regression, regression estimator.										
	(Universal) consistency.										
	Rate convergence.										
	Stone's theorem.										
	Kernel estimator, k-N	N estin	nator								
	Slow rate convergence, minimax convergence rates.										
Objectives	Students are familiar with basic non-parametric regression estimators, in particular with their universal consistency and rate convergence. They are familiar with the basic principles and methods of stochastic learning 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. 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	Coursework	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	,55	or.	o. 20-30	9		
	In this module an exercise c examination the coursework oral is decided by the instruc	must I	nave	bee	n acc	uired.	Whether th	e examination			
Literature	Possible References :										
	 Laslo Györfi, Michael nonparametric regres 						rro Walk: A	distribution	-free th	neory of	

Transfer	The module belongs to the Study Specialisation 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	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 : o=obligatory, f=facultative

Module Number: MAT-70-32	Module Title: Statistical Learning Theory sion 2	for N	onpa	rame	etric	Regres		of Module: ulsory Modul	le with	Choice			
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 90 h 180 h						tudy:						
Duration	1 Semester	1 Semester											
Frequency	not regularly												
Term	1-3												
Language of Instruction	German	German											
Forms of Teaching and Learning	Lecture 4 SWS												
Content	 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	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. They are able to present their solutions and, if necessary, defend them in critical discourse.												
Requirements for Obtaining Credit, Grading, Weight if applicable	Title Statistical Learning Theory	Type of Course	+ Status	SWS	n ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	for Nonparametric Regression 2 L f 4 6 ves 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 oral is decided by the instructor with approval by the Board of Examiners.												
Literature	Possible References : • Laslo Györfi, Michael nonparametric regres:	Kohle	r, Ad	am I	Krzyz	ak, Ha			-free tl	neory of			
Transfer	The module belongs to the S Stochastics. Taking into accoin the Sections Study Focus, in accordance with the restrict	unt th <i>Advai</i>	e ch nced	osen <i>Kno</i>	pers wled	sonal S ge in M	tudy Specia <i>athematics</i>	alisation, it can	an be i	ncluded			
Prerequisites	Knowledge from the module	Statis	tical	Lear	ning	1 is as	sumed.						

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	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class,							

Status : o=obligatory, f=facultative

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-70-33	Module Title: Theory and Numerics for Co lems	Theory and Numerics for Constrained Optimisation Prob-							le with	Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 180 h							tudy:		
Duration	1 Semester	1 Semester								
Frequency	not regularly									
Term	1-3									
Language of Instruction	English	English								
Forms of Teaching and Learning	Lecture 4 SWS	_ecture 4 SWS								
Content	We start with the unconstrained convex minimisation problem (on spaces), and the gradient method with step size control according to Armeijo for the approximate calculation of a minimum, as well as its variants. The simplex method solves linear programmes on polyhedra. Central 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, Abadie condition, Karush-Kuhn-Tucker conditions). In addition, numerical solution methods based on these theoretical concepts (interior points method, penalty methods, SQP method) are presented and analysed.									
Objectives	constrained optimisation pro simplex method, interior point be able to analyse the algor naming and proving the ess the presented connections. In the exercise classes they the terms, statements and m	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	Coursework	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
	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	Possible References : • Carl Geiger, Christian gaben. Springer 2002		ow:	The	orie	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 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 : o=obligatory, f=facultative

Module Number: MAT-70-40	Module Title: Game Theory							of Module: ulsory Modu	le with	Choice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: Time in Class: 30 h						Self-St 60 h	Self-Study: 60 h			
Duration	1 Semester	1 Semester									
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS										
Content	The focus is on Nash and ger	neralis	ed N	ash	equil	librium	problems ar	nd their num	erical	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	Coursework	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 instr	uctor with a	pprova	l by the	
Literature	Possible References :	xandr	a Sc	hwar	tz: S	Spielthe	orie. Birkha	euser 2018.			
Transfer	The module belongs to the Taking into account the chos tions Study Focus, Advanced dance with the restrictive requirements.	en pe d <i>Kno</i> ı	rson vled	al St ge in	udy <i>Mat</i>	Specia <i>hemati</i>	lisation, it ca cs or <i>Electi</i> v	an be includ	led in t	he Sec-	
Prerequisites	Basic knowledge of analysis dents of related fields with ba							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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, } \mbox{LE=lecture with integrated exercises, } \mbox{SL=seminar or lecture, } \mbox{E=exercise class, } \mbox{T=tutorial, P=project, S=seminar, IC=inverted classroom}$

Status : o=obligatory, f=facultative

Module Number: MAT-70-51	Module Title: Financial Mathematics and Numerics							of Module:	le with	Choice	
ECTS-Points	6										
Workload - Time in Class - Self-Study							Self-St 120 h	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 Cl	-		-							
Content	els and numerical techniques that are essential for understanding and solving problems in mosecourse designed is convidence and the numerical methods necessary for approximating solutions to complex financial equations. Key topics include the mathematics behind derivative pricing models, such as the Black-Scholes framework, and the use of stochastic calculus (SDE theory) in risk management and portfolio optimisation. By integrating theory with numerical practice, this course bridges the gap between financial mathematics and real-world applications, equipping students with the quantitative skills required for careers in quantitative finance, risk analysis, and financial engineering.										
Objectives	The students know important mathematical models for the description of problems in financial mathematics and can apply numerical approaches to their solutions in a targeted manner. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Financial Mathematics and Numerics	L E	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 course examination the coursework must have been acquired. Whethe oral is decided by the instructor with approval by the Board of E in exceptional cases, be offered without exercises at the discretic only 3 credit points are awarded instead of 6.						Whether th ard of Exan	ther the examination is written or f Examiners. – The module may,				
Literature	Possible References: • Steven Shreve: Stochastic Calculus for Finance. Springer 2005.										

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	Knowledge of calculus, linear algebra, basic programming, ordinary differential equations theory and introductory probability is recommended.
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 : o=obligatory, f=facultative

Module Number: MAT-75-02	Module Title: Combinatorics							Type of Module: Compulsory Module 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	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	Basic combinatorial o Generating functions.	Basic combinatorial objects. Generating functions.								
	 Partial orders, Möbius 	invers	sion.							
	Method of Polya and	Redfiel	ld.							
	Symbolic combinatori	cs.								
	Transfer matrix methor	d.								
	Euler-Maclaurin sumr	nation	form	ula.						
	Asymptotic methods.									
Objectives	The students have learned the application of basic combinatoric methods. They can analyse discrete structures and counting problems. Furthermore they are familiar with applying common identities and handling counting coefficients. 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Combinatorics	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	Possible References :
	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 actions), function theory (Cauchy's integral formula) and the foundations of discrete mathematics are expected.
Responsible Persons	Martin Möhle, 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 : o=obligatory, f=facultative

Module Number: MAT-75-03	Module Title: Mathematical Statistics						of Module:	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	regularly									
Term	1-3									
Language of Instruction	German	German								
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS								
Objectives	 Statistical models, exponential families, sufficient statistics. Rao-Blackwell theorem, Lehmann-Scheffe theorem, Cramer-Rao theorem. Estimation methods, UMVU estimator, quality criteria, asymptotic behaviour of estimators. Hypothesis testing, confidence interval, Neyman-Pearson lemma. Testing methods, UMPU tests, 1- and 2-sample tests. Models with growing density quotients, non parametric models. Introduction in regression and variance analysis. Students can model statistical relationships mathematically. They can mathematically construct, analyse, compare and apply statistical estimation and test methods and interpret their									
results. The students are capable of naming and proving the essential reas well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent the terms, statements and methods of the lecture. They have learned to train on new problems, to analyse them and to work on solution strategies on the They are able to present their solutions and, if necessary, defend them in contents to the state of the s					ed to transfe s on their ow nem in critica	er the n n or in	nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Mathematical Statistics	L E	f	4 2	6 3	yes	wr. o. or.	90-180 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	Possible References :						
	 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 Martin Möhle, Martin Zerner Persons							
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

: o=obligatory, f=facultative Status

Module Number: MAT-75-04	Module Title: Stochastic Processes							of Module: ulsory Modul	le 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	regularly											
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 4 SWS											
Content	Stochastic processes in continuous time, such as											
	Markov processes;	Markov processes;										
	Martingale;	Martingale;										
	Brownian motion, Pol	sson p	roce	sses	and	genera	al Levy proc	esses;				
	Gaussian processes.	Gaussian processes.										
	Among other things, existe these processes are analyse		nd co	nver	genc	e state	ements as v	well as path	n prope	erties of		
Objectives	The students have learnt the stochastic processes in con are capable of naming and and explaining the presente In the exercise classes they the terms, statements and n on new problems, to analyse They are able to present the	tinuou: provin d conn have nethod them	s tim g the ectio acqu s of t and t	e and e ess ns. ired he le	d car entia a cor cture rk on	n hand Il resul nfident, e. They n solution	e them mat ts of the lec precise an have learn on strategies	thematically. Sture as well d independe ed to transfe s on their ow	The solution The s	students sessing adling of nethods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Stochastic Processes	L	f	4	6	yes	wr. o.	90-180	g	100		
	0.001105110 1 10003303	ü	f	2	3	y 63	or.	o. 20-30	9	100		
	In this module an exercise of examination the coursework oral is decided by the instruc	must	have	bee	n acc	uired.	Whether the	e examination				

Literature	Possible References :
	 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 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 : o=obligatory, f=facultative

Module Number: MAT-75-05	Module Title: Percolation Theory							f Module: Ilsory Modul	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	German									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	 Edge percolation on graphs, especially on multidimensional grids. 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	Coursework	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	Possible References : • Béla Bollobás, Oliver • Geoffrey Grimmett: Pe						bridge Unive	ersity Press	2006.	
Transfer	The module belongs to the <i>Physics</i> and <i>Stochastics</i> . To can be included in the Section tive Specialisation, in accordance	aking ons <i>St</i>	into i	acco Focu	unt t is, A	the cho dvance	sen person d Knowledg	al Study Sp e in Mather	ecialis natics	sation, it or <i>Elec</i> -
Prerequisites	Knowledge of the module Pro	babil	ty Tł	neor	y 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 : o=obligatory, f=facultative

Module Number: MAT-75-06	Module Title: Stochastic Analysis							of Module:	le 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	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	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 particu	lar for	proc	esse	s witl	h jump	s).							
	Stochastic differential	equat	ions	•										
Objectives	The students know the main and they know how to handl the lecture and they can exp In the exercise classes they the terms, statements and m to new problems, to analys team. They are capable of p discourse.	e then lain th have a ethod e then	n. Their in acques of to acques of the acques of the anconstructure of the acques of t	ne stu trinsi ired a he le d to	udent c cor a cor cture work	ts can nnection fident, e. They on so	name and poins. precise and have learn lution strate	orove the ce d independe ed to transfe egies on the	ntral re ent har er the r eir own	esults of adling of nethods or in a				
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade				
	Stochastic Analysis	L	f	4	6	yes	wr. o.	90-180	g	100				
	Ciochadao / maryoto	Е	f	2	3	703	or.	o. 20-30	9					
	In this module an exercise or examination the coursework oral is decided by the instruc	must	have	beer	n acc	uired.	Whether th	e examination						

Literature	Possible References :
	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 $\label{eq:lecture} \mbox{Teaching Format} \ : \mbox{L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom \\$

: o=obligatory, f=facultative Status

Module Number:	Module Title: Information Theory							of Module:	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	not regularly											
Term	1-3												
Language of Instruction	German												
Forms of Teaching and Learning	Lecture 4 SWS + Exercise Class 2 SWS												
Content	Entropy and entropy rates in the discrete case.												
	Theorem of Shannon-McMillan-Breiman.												
	Entropy rates of Markov chains.												
	Kolmogorov complexi	ty.											
	Data compression.												
	Chanel capacity.												
	Differential entropy.												
Objectives	Students learn to describe in the basic theory to concrete also apply the theoretical concapable of naming and provexplaining the presented corning the exercise classes they the terms, statements and monnew problems, to analyse They are able to present the	e rando oncepts ing the nnection have a tethods them a	om e s to s e ess ns. acqui s of t and t	xper speci sentia ired a he le o wo	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 and have learned on strategies	processes. theory. The as well as a d independe ed to transfe s on their ow	Stude stude assessent har er the nor in	ents can ents are ing and adling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Information Theory	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	beer	n acc	uired.	Whether the	e examinatio					

Literature	Possible References :
	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 Möhle, Martin Zerner, Elmar Teufl
Abbrasiations	

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 : o=obligatory, f=facultative

Module Number: MAT-75-08	Module Title: Mathematical Population Ge	notice						of Module:	lo with	Choico			
ECTS-Points	6	Helics					Compt	iisoi y iviodu	ie with	Choice			
Workload	Workload:	Time	in C	lacc			Self-St	udv:					
- Time in Class - Self-Study	180 h	60 h	: III C	iiass.	•		120 h	uuy.					
Duration	1 Semester	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	Exchangeable population models.												
	Probability of extinction.												
	Descendants and ancestors.												
	Duality of Markoff pro	cesses	3.										
	Coalescent processe	s and a	asso	ciate	d cor	nverge	nce rates.						
	Simple mutation mod	els, Ew	vens	sam	pling	formu	la.						
	Statistical application	s, e.g.	estin	natin	g the	mutat	ion rate.						
Objectives	In the lecture, students lea an understanding for the int capable of naming and prov- explaining the presented cor 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	eractio ing the inectio he sub have a ethods them a	n of e ess ns. S ject a acqui s of t and t	geor sentia Stude area ired a he le o wo	metri al res ents v a cor ecture rk on	c and sults of will be a fident, e. They a solution	algebraic m the lecture able to reflect precise and have learned on strategies	ethods. The as well as a trand critical dindependent to transfers on their ow	e stude assess ally 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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Mathematical Population Genetics	L E	f	2	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	beer	n acc	uired.	Whether the	e examination					

Literature	Possible References :
	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 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 : o=obligatory, f=facultative

Module Number:	Module Title:							f Module:		O		
MAT-75-09	Point Processes						Compi	Ilsory Modu	le with	Choice		
ECTS-Points	6											
Workload - Time in Class	Workload:	Time	in C	lass			Self-St 120 h	udy:				
- Self-Study	180 h	180 h 60 h 120 h										
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 2 SWS											
Content	Random measures, point processes, Poisson processes.											
	Factorial measure, Mecke equation.											
	Transformation, labelling, thinning.											
	Characterisation of po	Characterisation of point processes.										
	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 pro- roving nectione sub have a ethoda them a	cess the e ns. S ject acqu s of t and t	es aresser Stude area ired a he le o wo	nd cantial rents was core controls with the core core core core core core core cor	in hand esults vill be a nfident, e. They n solution	dle them ma of the lectur able to reflect precise and have learn on strategies	thematically e as well as and critica d independe ed to transfe s on their ow	The sassessally ana ent har er the ron or in	students sing and alyse the adling of methods a team.		
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Point Processes	L	f	2	3	yes	wr. o.	90-180	g	100		
		ü	f	2	3		or.	o. 20-30				
	In this module an exercise context examination the coursework oral is decided by the instruction	must I	nave	beei	n acc	uired.	Whether the	e examination				

Literature	Possible References :
	 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 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 : o=obligatory, f=facultative

Module Number: MAT-75-10	Module Title: Graph Theory							of Module: ulsory Modul	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	German											
Forms of Teaching and Learning	Lecture 4 SWS + Exercise C	Lecture 4 SWS + Exercise Class 2 SWS											
Content		 Basic concepts in graph theory, Basic graph theory algorithms, 											
	 Basic graph theory algorithms, Flows, cuts, connectedness, matchings, 												
	 Plows, cuts, connectedness, matchings, Cycle and cut space (cohomology theory), 												
	 Spectral graph theory, matrix tree theorem, 												
	Planar graphs, theore	m of Kı	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 benef 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	praction to the practic from the properties of the practical process. The practical process is the practical process. The practical process is the practical process. The practical practical process is the practical process. The practical practica	ce. Themell as cqui of the control o	They a. The ass red he le o wo	will a e stu essir a cor cture rk on	also re dents a ag and afident, e. They solution	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	geome and prod d conn ent han er the n	etry and ving the ections. dling of nethods a team.			
Requirements for Obtaining Credit, Grading, Weight if applicable	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Graph Theory	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	ave	beer	n acc	uired.	Whether th	e examination	icipatio on is w	n in the ritten or			

Literature	Possible References :						
	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						
Abbreviations: Grading System : g=graded, ng=not graded							

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Status : o=obligatory, f=facultative

Module Number: MAT-75-11	Module Title: Markov Chains and Applications						Type of Module: Compulsory Module with Choice				
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: Time in Class: 90 h						Self-St 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 C	lass 2	SWS	3							
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	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Markov Chains and Applications	L E	f	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 examination			
Literature	 Possible References: 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 <i>ctive</i>	n be	inclu	uded in	the Section	ns <i>Study Fo</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

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Module Number: MAT-75-20	Module Title: Probability Distances for Data Science						of Module: ulsory Modul	e 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	1-3									
Language of Instruction	English										
Forms of Teaching and Learning	Lecture 2 SWS + Exercise Class 2 SWS										
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	Type of Course Status SWS ECTS Coursework Type of Exam Type of Exam Grading									Weight for Grade	
	Probability Distances for Data Science L f 2 3 yes wr. o. 90-180 o. 20-30 g 100								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	Possible References :						
	 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, 200						
	 Imre Csiszar, Paul C. Shields: Information theory and statistics: a tutorial. Foundat and Trends in Communications and Information Theory 1.4 (2004). 417-528. 						
	 Ily Tolstikhin et al.: Wasserstein auto-encoders. 6th International Conference on Lea ing 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

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Module Number: MAT-75-21	Module Title: Bayesian Networks and Causality Type of Module: Compulsory Module with Cho										
ECTS-Points	5	5									
Workload - Time in Class - Self-Study	Workload: 150 h	Time in Class: 45 h	Self-Study: 115 h								
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	1-3									
Language of Instruction	English	English									
Forms of Teaching and Learning		Lecture 2 SWS + Exercise Class 1 SWS									
Content	to deal with it. Therefore, the corporate probabilities was human understanding goes ever the sprinkler is on, to postul the plants will be wet, but if In this course, Bayesian ne probability distributions. In pudiscussed. Moreover, it will be distributions, but are also ab of Bayesian networks will be data. • Part I: Bayesian Networks will be data. • Part II: Bayesian Networks will be data.	 Part I: Bayesian Networks as an Efficient Representation of Probability Distributions: Computing probabilities using Bayesian networks. d-Separation: A graphical criterion for probabilistic independence. Parameter and structure learning in Bayesian networks. Part II: Bayesian Networks as a Representation for Causal Knowledge: Functional causal models: A representation of causal knowledge. Pearl's causal ladder: Predicting the effects of external interventions and reasoning with counterfactuals. Causal Bayesian networks. Causal structure discovery: Learning causal relationships from data. Counterfactual identifiability: Answering counterfactual. questions using causal 									
Objectives	In the first part of the course, students have learned how Bayesian networks represent probability distributions and how this representation can be used to efficiently compute probabilities or determine whether two random variables are independent. In the second part, students have learned to distinguish inference tasks in artificial intelligence according to Pearl's causal ladder: probabilistic, interventional, and counterfactual reasoning, which generally require increasingly detailed knowledge. They are familiar with identifiability results, which provide assumptions under which certain queries on the causal ladder can be answered using only knowledge from lower levels. For instance, they know how to answer queries about the effects of external interventions using only knowledge of the correct probability distribution, which can often be estimated from observational data. 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 Bayesian Networks and	Type of Course	- Status	SWS 2	ω ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Causality	E	f	1	2	yes	or.	o. 20-30	g	100
	Whether the examination is written or oral is decided by the instructor with approval by the Board of Examiners.									
Literature	Possible References: • Judea Pearl: Causality: Models, Reasoning and Inference. Cambridge University Press 2009.									
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 module Stochastics is assumed.									
Responsible Persons	Stephan Eckstein									

Grading System : g=graded, ng=not graded

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4 Exchange Programmes

4.1 Exchange Programme with the Università degli Studi di Trento

As part of the M.Sc. Mathematics programme, students can participate in the exchange programme with the Università degli Studi di Trento. After successful completion of the programme, students will receive the M.Sc. Mathematics degree from the University of Tübingen and the Laurea Magistrale in Mathematica degree from the Università degli Studi di Trento. The basis for this is the agreement on the exchange programme between the two universities, which can be downloaded from the websites of the department for the M.Sc. Mathematics programme.

The courses at the Università degli Studi di Trento are offered in English, while the courses at the University of Tübingen are offered in German or English. Therefore, students of the Università degli Studi di Trento must provide proof of German language skills (DSH-2 or DSH-3), and students of the University of Tübingen must provide proof of English language skills (GER B2). Students are only required to pay tuition fees, if applicable, at their home university.

Students of the University of Tübingen study the first academic year at the University of Tübingen and the second year at the Università degli Studi di Trento; for students of the Università degli Studi di Trento, it is the opposite. At both universities, students earn 60 credit points each; the thesis is to be written in the second academic year.

The achievements obtained during studies at both locations will be credited to both programmes, provided they are essentially equivalent to the achievements they are supposed to replace. The creditability of the intended achievements is ensured for students from Tübingen by the study and examination plan, which must be discussed with the personal mentor and approved by a joint commission responsible for the programme at both universities. Students of the University of Tübingen may replace the module *Introduction to Scientific Work* with other achievements that they complete at the Università degli Studi di Trento according to the requirements there in the second year of study. The conversion of grades for recognition purposes is carried out in accordance with the conversion table in the annex of the agreement on the exchange programme.

All modules listed in this module handbook can be included in the exchange programme at both locations. Information about the modules currently part of the study programme at the Università degli Studi di Trento can be found at:

http://offertaformativa.unitn.it/en/lm/mathematics/course-content

Current semester course offerings and module descriptions can be viewed in the course catalog at:

https://www.esse3.unitn.it/Guide/PaginaRicercaInse.do?cod_lingua=eng

A list of modules that were part of the regular offerings at the Università degli Studi di Trento at the time of signing the agreement is also included in the agreement on the exchange programme.