



Mathematisch-Naturwissenschaftliche Fakultät



Department of Mathematics

Module Handbook Mathematics Master of Science*

Winter Semester 2025

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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 a 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 the 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's programme, 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. 82) 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 components of the Master's programme are 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 take a well-organised approach to their studies right 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 suitable 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

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

ST	Module Number	Module Title	Type of Course	Type of Module	Course- work	Type of Exam	ECTS- Points	
Section	n 1: Study Fo	cus						
1-3		In addition to the module Seminar Study Focus modules totalling 18 LP in accordance with the more detailed regulations in 3 Module Descriptions		PMW			18	
2-3	MAT-40-01	Seminar: Study Focus	S	PMW	s.M.	Pr	3	
Section	n 2: Advance	d Knowledge in Mathematics						
1-3		Modules amounting to 30-33 LP according to the more detailed regulations in 3 Module Descriptions		PMW			30-33	
Section	n 3: Elective	Specialisation						
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	n 4: Scientific	Work						
3	MAT-40-02	Introduction to Scientific Work	Р	РМ	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, E=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom								
Cours Other		EC=exercise certificate h=hours, o.=or, s.M.=see module descrip	otion. ST=sua	aested term	1			

2.2 Overview by the Course of Studies

First we 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											
2	30	(21 CP)	Advanced Knowledge in Mathematics (30-33 CP)	Elective Specialisation (27-30 CP)									
3	30	Scientific Work	(55 55 51)										
4	30	(39 CP)											
	Explanation of the Abbreviations: FS=semester, 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	ore Area of Mathematic	es	Elective Specialisation
1	30	Study Focus: Advanced Lecture (9 CP)			
2	30	Study Focus: Advanced Lecture (9 CP)	Study Focus: Seminar (3 CP)	Advanced Knowledge in Mathematics: Advanced Lecture (9 CP)	Free Elective Area
3	30	Introduction to Scientific Work (9 CP)	Advanced Knowledge in Mathematics: Advanced Lecture (9 CP)	(27-33 CP)	
4	30		Master T (30 C		

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. 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	ore Area of Mathematic	s	Elective Specialisation
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)	Descriptive Linguistics (M.A. English Linguistics) (12 CP)	
4	30		Master 7 (30 C		

Stud	dy 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)	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)	Numerics of Stochastic Differential Equations (3 CP)	Mathematical Relativity (9 CP)								
4	30		Master 7 (30 C									

Stud	dy Pla	n with the Personal Stu	dy Specialisation Mathe	ematical Physics	
FS	СР	c	ore Area of Mathematic	es	Elective Specialisation
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)	Classical Field Theory (B.Sc. Physics) (9 CP)	
3	30	Introduction to Scientific Work (9 CP)	Selected Chapters from the Theory of Dynamical Systems (3 CP)	Probability Theory (9 CP)	
4	30		Master Thes	is (30 CP)	

Stud	dy Pla	n in the Personal Study	Specialisation Numerio	cal Mathematics and Op	otimisation
FS	СР	c	ore Area of Mathematic	es	Elective Specialisation
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)	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	s	Elective Specialisation
1	30	Stochastic Processes (9 CP)	$SL_2(\mathbb{R})$ (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 Administra- tion) (9 CP)
3	30	Introduction to Scientific Work (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

			T	eachin	g		Semester						
		Exam	Exam		Weight in the final grade	Type of Course			ECTS Points(CP)	nation semes menda locatio course tive na	location s / ECTS sters is o atory nat in of EC es are of ture. Cr ed upon	of exam S points of a record cure. The TS point of an infor edits are comple	to m- e al- es to ma- e only
		Type of Exam	Duration (min)	Grading	Weight	Type of	Status	SWS	ECTS	1. CP	2. CP	3. CP	4. CP
Sec	tion 1: Study Focus						21						
In addition to the module Seminar Study Focus, modules totalling 18 credit points from the selected Personal Study Specialisation in compliance with the in accordance with the requirements on page 12 must be included. Below, a possible schematic distribution of credit points across the academic semesters is provided. First Advanced Module from the Personal Study Specialisation 6 9													
1.	Lecture	Wr.	90–120	Olanoc	20011	L	0	4		6			
'. 2.	Exercise class	o. Or.	o. 20–30	g	9	E	0	2		3			
		the Personal Study Specialisation					<u> </u>	6	9	0			
1.	Lecture	Wr. 90–120	эроон		L	f	4			6			
2.	Exercise class	o. Or.	o. 20–30	g	9		f	2			3		
Sen	ninar Study Focus	01.	20 00					2	3				
1.	Seminar	R	45–90 3	S	0	2			3				
Sec	tion 2: Advanced Knowledg	e in Ma	thematics						30- 33				
	ere, modules amounting to 30	22 050								les offer	ed by the		
of po	Mathematics, taking into accoints across the academic ser	ount th	e guidelines is provided	s on p	age 1			poss	ible so		c distribu	ution of C	credit
of po Mod	pints across the academic ser	ount th	e guidelines is provided	s on p	age 1	4 . Bo					distribu	ution of c	credit
of po Mod	pints across the academic ser	eneral E Wr. o.	e guidelines is provided ducation se 90–120 o.	s on p	age 1		elow, a	poss 6	ible so	chemation	c distribu	ation of c	credit
01 Mod 1.	oints across the academic ser dule from the Mathematical Ge Lecture	eneral E Wr. o. Or.	e guidelines is provided ducation se 90–120 o. 20–30	s on p lectio	n 9	4 . Be	o o	poss 6 4	ible so	chemation 6	c distribu	ution of C	credit
of pool 1. 2.	counts across the academic services the determination of the services across the academic services across	eneral E Wr. o. Or.	e guidelines is provided ducation se 90–120 o. 20–30	s on p lectio	n 9	4 . Be	o o	6 4 2	ible so	chemation 6	c distribu	ution of C	credit
of po	Lecture Exercise class t specialisation module (not free	ount the nesters eneral E Wr. o. Or. om the Or.	e guidelines is provided ducation set 90–120 o. 20–30 Personal St	s on p	n 9 pecia	L E lisatio	o o o n	6 4 2 2	ible so	6 3	c distribu	ution of C	credit
of pool of poo	Lecture Exercise class t specialisation module (not free	wr. Or. Or. Or. t from t Wr.	e guidelines is provided ducation set 90–120 o. 20–30 Personal St	s on p electio g udy S g I Stud	n 9 pecia 3 y Spe	L E lisatio	o o o n	6 4 2 2 2 2	9 3	6 3	distribu	ution of C	credit
of policy of the	Lecture Exercise class t specialisation module (not from the Mathematical Geometric Section 1) Lecture Lecture ond specialisation module (not from the Mathematical Geometric Section 1)	wr. o. Or. om the Or. t from t	e guidelines is provided ducation se 90–120 o. 20–30 Personal St 20–30 he Persona	s on p	n 9 pecia	L E lisatio	o o n o ation)	6 4 2 2 2 6	9 3	6 3		ution of C	credit
of policy of the	Lecture	wr. or. or. or. or. or. or. or. or. or. o	e guidelines is provided ducation set 90–120 o. 20–30 Personal St 20–30 the Personal 90–120 o. 20–30	s on position of the second se	n 9 pecia 3 y Spe	L E lisation L E E E E E E E E E E E E E E E E E E	o o n o ation) o o	6 4 2 2 2 6 4	9 3	6 3	6	ution of C	credit
of po	Lecture Lecture Exercise class t specialisation module (not from the Mathematical General Section 1) Lecture Lecture Lecture Lecture Lecture Exercise class	wr. or. or. or. or. or. or. or. or. or. o	e guidelines is provided ducation set 90–120 o. 20–30 Personal St 20–30 the Personal 90–120 o. 20–30	s on position of the second se	n 9 pecia 3 y Spe	L E lisation L E E E E E E E E E E E E E E E E E E	o o n o ation) o o	6 4 2 2 6 4 2 2	9 3	6 3	6	6	credit

Overview by Course of Study and Examination Requirements													
			Exam				Teaching			Semester			
		Type of Exam Duration (min)		Grading Weight in the final grade	of Course			Points(CP)	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.				
		be c	ırati	Grading	eigh	Type c	Status	SWS	ECTS	1.	2.	3.	4.
		√	۵	্ট	>	≥	Ş	S	Ĕ	CP	СР	СР	СР
Fou	th specialisation module (not	from the	e Personal	Study	Spec	cialisa	tion)	2	3				
1.	Lecture	Or. 20–30 g 3					0	2				3	
Sec	tion 3: Elective Specialisation	on		1					27– 30				

Here you can choose modules totalling 27–30 credit points from the list of modules offered by the Department of Mathematics and other departments in accordance with the restrictive requirements on page 14.

Sec	Section 4: Scientific Work								39			
Intro	Introduction to Scientific Work								9			
1.	Project	Proj.		ng	9		0				9	
Fina	l Module								30			
1.	Master Thesis	MA + Or.		g	30		0					30

Explanation of the Abbreviations:

Marking system : g=graded, ng=non graded

Form of examination: MA=master thesis, Or.=oral exam, Wr.=written exam, Pres=presentation, TP=term paper Form of teaching: L=lecture, SL=Seminar or lecture, E=exercise class, r=revision course, P=practical training,

PS=proseminar, S=seminar

Status : o=obligatory, f=facultative

Other : 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							Type of Module: Compulsory Module with Choice		
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h	Time ii 30 h	n Cla	ss:			Self-Stud	dy:		
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, e	Seminar, talk, presentation, e-learning, blended learning								
Content	Various topics from the chose	Various topics from the chosen Personal Study Specialisation.								
Objectives	Specialisation and prepare the train their presentation technic	Students work independently on in-depth questions from the area of their Personal Study Specialisation and prepare them in a didactically appealing and scientifically sound form. They train their presentation techniques and sharpen their professional discussion style. Depending on the topic chosen, they are introduced to current research questions and prepared for their Master's thesis.								
Requirements for obtaining Credits / Grading (Weighting 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
	participation in the course, discussion or by completing presentation or the preparation	In addition to a successful talk, the acquisition of credit points also requires a 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 of Mathematik.	the mo	dule	is a _l	orere	quisite	for the mod	dule Master	Thesis	M.Sc.

Prerequisites 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				
	graded, ng=not graded IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio				
Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutoria 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			
Workload - Time in Class - Self-Study	Workload: 30 h	Time in Class: 15 h	Self-Study: 15 h	

Duration	1 Semester									
Frequency	not regularly									
Term	3-4									
Language of Instruction	English									
Forms of Teaching and Learning	Presentation, group work, blend	ed le	arnir	ig, p	ractio	cal exe	rcises			
Content	Introduction to vocational Practical training in scien						nication.			
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 the 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 Credits / Grading (Weighting 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 coursewor project is required. There is no e			rm c	of act	tive pa	rticipation a	and a writte	n essay	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 S	Section	on <i>E</i>	lectiv	e Spe	cialisation.			
Prerequisites	There are no prerequisites.									
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, E=essay, P=portfolio $Teaching \ Format \ : L=lecture, \ LE=lecture \ with \ integrated \ exercises, \ SL=seminar \ or \ lecture, \ E=exercise \ class, \ T=tutorial,$

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

: o=obligatory, f=facultative Status

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	·k						f Module: Isory Module)	
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h									
Duration	1 Semester									
Frequency	every Semester									
Term	3									
Language of Instruction	German or English	German or English								
Forms of Teaching and Learning	Individual supervision by a mentor, study of scientific works.									
Content	Definition of an advanced scientific project in coordination with the mentor.									
	Independent search a	ınd stud	y of	the re	eleva	nt scie	ntific literat	ure.		
	Formulation of specifi	c proble	ms a	and n	netho	odical a	pproach to	their solution	on.	
	Written presentation c	of the pr	oject	in co	next	of curi	rent state o	f research o	n 5-10	pages.
	This module serves generall	y as a p	repa	ration	n for	the Ma	ster Thesis	3		
Objectives	Students									
	 develop skills to syste 	matical	ly far	niliar	ise th	nemsel	ves with a ı	new subject	,	
	 learn to work criticall judgement, 	y and to	forr	nas	ubst	antiate	d, professi	onal and int	erdiscip	olinary
	 acquire qualifications problems and approp proposal. 									
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Scientific Project	Р	0	1	9	yes	-	-	ng	-
Transfer	Successful completion of this	module	is a	prere	quisi	ite for p	articipation	in module N	/laster T	hesis.
Prerequisites	Successful completion of mo Advanced Knowledge in Mat			at le	ast 3	0 ECT	S in the Se	ections Spec	ialisatio	n and

Responsible Persons	The dean of studies at the Department of Mathematics
Abbreviations: Grading System : g	=graded, ng=not graded
Examination Type : N	IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom
Status : c	e-obligatory, f=facultative
Other : h	=hours, o.=or, s.M.=see module description, SWS=contact hours per week

Module Number: MAT-40-03	Module Title: Master Thesis M.Sc. Mather	natics					Type of Module: Compulsory Module				
ECTS-Points	30										
Workload - Time in Class - Self-Study	Workload: 900 h	Time 0 h	n Cla	iss:			Self-Stud 900 h	dy:			
Duration	1 Semester										
Frequency	every Semester										
Term	4										
Language of Instruction	German or English										
Forms of Teaching and Learning	Master thesis	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 so										
	the independent search				-						
	the formulation of suitthe independent realis	-									
	results in the context							ion or the pr	ojeci ai	iu tiie	
	The results shall contribute to be worked on, which belongs	scient to the	ific kı math	nowle ema	edge. ical a	In the area of	master thes the chosen	sis, a questi personal sp	on sho pecialis	uld be ation.	
Objectives	The students										
	are capable of familia research topics, till a c									urrent	
	 can use suited scien results in a scientifica 					wing i	ndependen	ce and can	prese	nt the	
	can independently wo methodology knowled		scier	itific 1	opic	and ar	e capable o	f using their	mathe	mtical	
	enhance their problem	solvin	ј ехр	ertise	and	can tra	ansfer their	methodolog	y know	ledge,	
	are able to present the	e result	s of t	ner p	rojec	ts to a	professiona	ıl audience.			
Requirements for obtaining Credits / Grading		Course				work	Exam	Dur. of Exam (min)		Weight for Grade	
(Weighting if applicable)		₽	Status	\S	ECTS	Coursework	₽	r. of l	Grading	ight	
,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	Title	Type	Sta	SWS	EC	රි	Туре	DG	g	We	
	Master Thesis	МТ	0	-	30	no	MT	-	g	100	
Transfer											

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, E=essay, P=portfolio Teaching Format: 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 again. If the courses have already been included in the framework of a module in the Bachelor of Science in Mathematics, the module cannot be included in the Master of Science in Mathematics. 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 the 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 regu	arly (at leas	t once every	two y	years)
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	•	Algorithms of Numerical Mathematics (MAT-70-01, 9 CP)	72
	•	Commutative Algebra (MAT-45-02, 9 CP)	25
	•	Functional Analysis (MAT-55-01, 9 CP)	47
	•	Geometry (MAT-50-01, 9 CP)	33
	•	Geometry in Physics (MAT-65-11, 9 CP)	70
	•	Introduction to Commutative Algebra and Algebraic Geometry (MAT-45-01, 9 CP)	23
	•	Introduction to Partial Differential Equations (MAT-55-21, 9 CP)	51
	•	Non-Linear Optimisation (MAT-70-21, 9 CP)	76
	•	Probability Theory (MAT-75-01, 9 CP)	78
Mc	od	ules which are not offered regularly	
	•	Algebraic Topology 1 (MAT-50-21, 9 CP)	41
	•	Calculus of Variations (MAT-55-49, 5 CP)	63
	•	Convex Geometry (MAT-50-02, 9 CP)	35
	•	Cryptography (MAT-45-23, 5 CP)	29
	•	Elementary Number Theory (MAT-45-25, 6 CP)	31
	•	Foundations of Discrete Mathematics (MAT-75-12, 9 CP)	80
	•	Geometry of Manifolds 1 (MAT-50-10, 9 CP)	37
	•	Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP)	45
	•	Introduction to Dynamical Systems (MAT-55-34, 3 CP)	55
	•	Introduction to Geometric Measure Theory (MAT-55-41, 9 CP)	57
	•	Introduction to Geometric Measure Theory – Measure Theoretic Methods (MAT-55-44, 5 CP)	59
	•	Introduction to Geometric Measure Theory – Varifolds (MAT-55-45, 5 CP)	61
	•	Introduction to K-Theory (MAT-50-24, 3 CP)	43
	•	Introduction to Mathematical Logic (MAT-55-60, 3 CP)	67
	•	Introduction to Optimisation (MAT-70-20, 6 CP)	74
	•	Introduction to Partial Differential Equations – Part 1 (MAT-55-25, 5 CP)	53
	•	Introduction to set theory (MAT-55-63, 3 CP)	69
	•	Lie Groups (MAT-55-51, 9 CP)	65
	•	Linear Control Theory (MAT-55-07, 6 CP)	49
	•	Number Theory and Cryptography (MAT-45-22, 9 CP)	27
	•	Topology (MAT-50-20, 6 CP)	39

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)	41
Commutative Algebra (MAT-45-02, 9 CP)	25
Convex Geometry (MAT-50-02, 9 CP)	35
Cryptography (MAT-45-23, 5 CP)	29
Elementary Number Theory (MAT-45-25, 6 CP)	31
Foundations of Discrete Mathematics (MAT-75-12, 9 CP)	80
Geometry of Manifolds 1 (MAT-50-10, 9 CP)	37
Introduction to Commutative Algebra and Algebraic Geometry (MAT-45-01, 9 CP)	23
Introduction to K-Theory (MAT-50-24, 3 CP)	43
Lie Groups (MAT-55-51, 9 CP)	65
Number Theory and Cryptography (MAT-45-22, 9 CP)	27
• Topology (MAT-50-20, 6 CP)	39
Modules in the Chasielisation Analysis and Differential Coomstry	
Modules in the Specialisation Analysis and Differential Geometry	
The following modules belong to the specialisation Analysis and Differential Geometry. Possible restrictions can be the module description.	found in
Algebraic Topology 1 (MAT-50-21, 9 CP)	41
Calculus of Variations (MAT-55-49, 5 CP)	63
Convex Geometry (MAT-50-02, 9 CP)	35
Functional Analysis (MAT-55-01, 9 CP)	47
Geometry (MAT-50-01, 9 CP)	33
Geometry in Physics (MAT-65-11, 9 CP)	70
Geometry of Manifolds 1 (MAT-50-10, 9 CP)	37
Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP)	45
Introduction to Dynamical Systems (MAT-55-34, 3 CP)	55
Introduction to Geometric Measure Theory (MAT-55-41, 9 CP)	57
Introduction to Geometric Measure Theory – Measure Theoretic Methods (MAT-55-44, 5 CP)	59
Introduction to Geometric Measure Theory – Varifolds (MAT-55-45, 5 CP)	61
Introduction to K-Theory (MAT-50-24, 3 CP)	43
Introduction to Optimisation (MAT-70-20, 6 CP)	74
Introduction to Partial Differential Equations (MAT-55-21, 9 CP)	51
 Introduction to Partial Differential Equations (MAT-55-21, 9 CP) Introduction to Partial Differential Equations – Part 1 (MAT-55-25, 5 CP) 	
	53
Introduction to Partial Differential Equations – Part 1 (MAT-55-25, 5 CP)	53 65

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)	63
Functional Analysis (MAT-55-01, 9 CP)	47
Geometry (MAT-50-01, 9 CP)	33
Geometry in Physics (MAT-65-11, 9 CP)	70
Hyperbolic Geometry: Axiomatic, Reflection Geometric, Algebraic (MAT-50-50, 9 CP)	45
Introduction to Partial Differential Equations (MAT-55-21, 9 CP)	51
Introduction to Partial Differential Equations – Part 1 (MAT-55-25, 5 CP)	53
Modules in the Specialisation Numerial Mathematics and Optimisation	
The following modules belong to the specialisation Numerial Mathematics and Optimisation. Possible restrictions can found in the module description.	be
Algorithms of Numerical Mathematics (MAT-70-01, 9 CP)	72
Functional Analysis (MAT-55-01, 9 CP)	47
Introduction to Optimisation (MAT-70-20, 6 CP)	74
Introduction to Partial Differential Equations (MAT-55-21, 9 CP)	51
Introduction to Partial Differential Equations – Part 1 (MAT-55-25, 5 CP)	53
Non-Linear Optimisation (MAT-70-21, 9 CP)	76
Modules in the Specialisation Stochastics	
The following modules belong to the specialisation Stochastics. Possible restrictions can be found in the module description	ion.
Foundations of Discrete Mathematics (MAT-75-12, 9 CP)	80

Modul descriptions (Mathematical general education)

Module Number: MAT-45-01	Module Title: Introduction to Commutative A	Algebra	and .	Algeb	raic	Geom-	Type of I	Module: ory Module	with C	hoice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time i	in Cla	iss:			Self-Stud	ly:			
Duration	1 Semester	1 Semester									
Frequency	regularly in Winter Semester										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SW	/S									
Content	Rings and ideals.										
	Gröbner bases.										
	Localization.										
	Noetherian rings and i	nodule	s.								
	Integral ring extension	S.									
	Krull's principal ideal t	Krull's principal ideal theorem and dimension theory.									
	Hilbert's Nullstellensat	Hilbert's Nullstellensatz and Noether normalisation.									
	Affine varieties, Zarisk	i topolo	gy, n	norph	isms	3.					
Objectives	The students have become for tative algebra and affine algebra and geome students understand how addenables the simultaneous trustudents are capable of nan assessing and explaining the In the exercise classes they I the terms, statements and monoto new problems, to analy team. They are capable of prediscourse.	ebraic (etry thr opting eatmer ning an preser nave ac ethods se ther	geometought a high a high and properties of the control of the maner and another and another and another and another and another and another a	etry. the her p l reso oving conne ed a c e lect d to v	They example report of the ection confidure.	y have nple of pective on of seessent as. Ident, p They hon solo	experience affine various namely, a eemingly ur ial results or recise and i ave learned	d the profounceties. Furth bstracting the prelated quent of the lecture of the transfer gies on their	und intended into the prolestions we as we thandle the me own of the me own of the me own of the me own of the me own	erplay e, the olem The rell as ing of thods or in a	
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Introduction to Commutative Algebra and Algebraic Geometry	п	t Status	SMS 4	ε g ECTS	Sework	Type of Exam or. o.	90-180 o. 20-30	Grading	Weight for Grade	
	In this module an exercise ce examination the coursework oral is decided by the instruct	rtificate must h	ave b	be a	acqui	ired. W	hether the	examination	is writ		

Other

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 <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the Sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Commutative Algebra' due to the large overlap in content.
Prerequisites	There are no further prerequisites.
Responsible Persons	Jürgen Hausen
Abbreviations: Grading System :	g=graded, ng=not graded
Examination Type:	MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
Teaching Format :	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						Type of Compuls	Module:	with C	hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	regularly in Winter Semester									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	VS								
Content	Rings and Ideals.									
	Localisation and local	rings.								
	Noetherian and Artinia	an rings	and	mod	ules.					
	Integral ring extension	Integral ring extensions and Cohen-Seidenberg theorems.								
	Krull's principal ideal t	Krull's principal ideal theorem and dimension theory.								
	Primary decompositio	Primary decomposition.								
	Normality, regularity a	Normality, regularity and discrete valuation rings.								
	Hilbert's Nullstellensa	tz and N	Noeth	er no	orma	lisation	l.			
Objectives	The students are familiar wi algebra, which are essential They recognise how adopting the simultaneous treatment a capable of naming and prov explaining the presented con In the exercise classes they the terms, statements and m onto new problems, to analy team. They are capable of p discourse.	for study a higher nd resording the nection have acceptable at the second second necessity.	dying er per essences of the mances	the frspectors of some	ields tive eemi resu confi ure. vork	of algorally of algorally urgly urget the of the of the of the of the of the of solution of algorally and algorally algorated algorally algorally algorated	ebra, geom ly, abstraction related que ne lecture a recise and if ave learned ution strates	etry, and nung the problestions. The swell as as independend to transfer gies on their	mber tem - er studentsessin thandlethe me	heory. nables ats are g and ling of ethods or in a
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Commutative Algebra	☐ Type of Course	J. Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	۵ Grading	Weight for Grade
		E	f	2	3		or.	o. 20-30	9	
	In this module an exercise context examination the coursework oral is decided by the instruc	must ha	ave b	een a	acqu	ired. W	hether the	examination	is writ	

Other

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 <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the Sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module cannot be taken together with the module 'Introduction to Commutative Algebra and Algebraic Geometry' due to the large overlap in content.
Prerequisites	There are no further prerequisites.
Responsible Persons	Victor Batyrev, Thomas Markwig
Abbreviations: Grading System :	g=graded, ng=not graded
Examination Type :	MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
Teaching Format :	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:						Type of I	Module:		
MAT-45-22	Number Theory and Cryptog	raphy					Compuls	ory Module	with C	hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud 180 h	ly:		
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 + Ex.cl. 2 SV	VS								
Content	RSA cryptosystem, pr	rimality 1	tests,	AKS	algo	orithm.				
	Factorisation methods	s, numb	er fie	d sie	ve.					
	Quadratic reciprocity	in crypto	ograp	hy.						
	Evaluation of the disc	rete loga	arithn	n.						
	Dynamical systems a	Dynamical systems and Pollard's rho algorithm.								
	Elliptic curve cryptogr	Elliptic curve cryptography.								
	Lattices and post-qua	Lattices and post-quantum cryptography.								
	Zero-knowledge proo	fs, digita	ıl sigr	natur	es ar	nd hasl	n functions.			
Objectives	The students know the basi in cryptography. They have disciplines: They encounter quainted with elliptic curves of protocolls are working. Through any suprisingly come from a critically. The students are causell as assessing and explain the exercise classes they the terms, statements and monto new problems, to analy team. They are capable of prodiscourse.	e deeper method over finiting studies nost distangable of ning the have accepted seethods were then	ned a ds of e field ying the tinct to f nare control c	and enthe ds. The many prance of the entered a centered	exter theo hey ope thes and d cor confidure. work	nded the ry of dounders of mather proving nection they had been to the contraction of the contraction of the contraction on solution of the contraction of the contra	eir knowled ynamical sy tand how ful ems of crytonematics, the the central ns. recise and i ave learned ution strateg	dge about restems and amental contents of the students of the results of the totransfer on their steems on the steems of t	neighbo becon cryptogrose sol- earn to ne lectu t handl the me r own o	ouring ne ac- raphic utions think ure as ing of thods or in a
Requirements for obtaining Credits / Grading (Weighting 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 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 instruc	ertificate must ha	is to	be a	icqui acqu	ired. W	hether the	examination	is writ	

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 programme Bachelor of Science Mathematics are presumed.				
Responsible Persons	Elena Klimenko, Thomas Markwig				
Abbreviations: Grading System : g=graded, ng=not graded Examination Type : MT=master's thesis, or,=oral exam, wr,=written exam, Pr=presentation, E=essay, P=portfolio					

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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-45-23	Module Title: Cryptography						Type of Compuls	Module: ory Module	with C	hoice
ECTS-Points	5									
Workload - Time in Class - Self-Study	Workload: 150 h	Time ii 45 h	n Cla	ss:			Self-Stud 105 h	dy:		
Duration	1 Semester	1 Semester								
Frequency	not regularly	not regularly								
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lectures 2 SWS + Exercise	Classes	2 SV	VS, F	Home	ework A	Assignments	3		
Content	Brief review of key co	ncepts a	and re	esults	s fror	n algel	ora and num	nber theory.		
	 Historical ciphers and schemes. 	d their cr	ypta	nalys	sis (C	Caesar,	Vigenere,	substitution	ı); encr	yption
	Diffie-Hellman protoc	ol and fa	st ex	pone	entiat	ion.				
	Discrete logarithms:	Shanks'	algor	ithm	and	Pollard	l's rho meth	od.		
	RSA: correctness, se	curity, ar	nd att	acks						
	Signature schemes.									
Objectives	Students are familiar with the and algebra, as well as thei covered in Python or Sage Using classical ciphers, they Diffie-Hellman protocol and discrete logarithms in cyclic the recommendations of the scenarios, they can identify By engaging with numerous can, perhaps surprisingly, storitical thinking. The exercise in a practice-oriented way, are capable of naming and pexplaining the presented cor In the exercise classes they the terms, statements and monto new problems, to analyteam. They are capable of pidiscourse.	r applicated in a post of the control of the contro	ation an ex tand liar w liar w liar off esses proble n very entral ly with he ce s. equire of the n and	in cr empl typic ith th ersta ice for of F ems diffe and th CA entral	yptogary r r r r r r r r r r r r r r r r r r	graphy manne rength an-in-th ne RS/ formati when t yptogra areas cort stu ystems ults of t dent, p They h on soli	They can rand know s and weak as cheme, a con Security he requisite aphy — who of mathematical and as She lecture a recise and ave learned attion strateg	implement what to pay nesses; the tack. They and are able (BSI). In very conditions are solution atics – studerking independer as well as a sindepender of to transfer gies on their	the mey attented a transfer own of the media and the media at the medi	ethods tion to. ter the impute erpret attack of met. aches ractise ely and udents ing and ling of ethods or in a
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Cryptography	L	f	2	3	yes	or.	20-30	g	100
		E	f	1	2					
		In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired.								

Literature	Possible References :				
	 Jeffrey Hoffstein, Jill Pipher, Joseph H. Silverman: An introduction to mathematical cryptography. Springer 2008. 				
	 Christian Karpfinger, Hubert Kiechle: Kryptologie, Algebraische Methoden und Algorithmen, Vieweg 2010. 				
	 Dan Boneh, Victor Shoup: A Graduate Course in Applied Cryptography. 2023 (online Version: https://toc.cryptobook.us/). 				
	Jonathan Katz, Yehuda Lindell: Introduction to Modern Cryptography. Chapman and Hall/CRC 2020.				
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 'Number Theory and Cryptography' due to the large overlap in content.				
Prerequisites	Knowlegde from the modules Algebraic Structures and Algebra are assumed.				
Responsible Persons	Thomas Markwig				
Abbreviations: Grading System : g=graded, ng=not graded					

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format : 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: Type of Module						Module:			
MAT-45-25	Elementary Number Theory						Compuls	ory Module	with C	hoice
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	German									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SV	VS								
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 varies essential results of the lectur Students will be able to reflect area. In the exercise classes they be terms, statements and method new problems, to analyse the They are able to present the	erious kil e as we et and cr ave acq ods of th em and	nds. II as a riticall uired e lect	The sasses y and a cocure.	stude ssing alyse nfide They on so	ents are and ex the cu nt, pred have l	e capable of xplaining the rrent state of cise and ind earned to tr strategies o	naming and e presented of research i ependent has ansfer the non their own	d provir connect the standling nethods or in a	of the sonto team.
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Elementary Number Theory		f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	Le aleie erre I. I.	E	f	2	3					
	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 head of the examination board.								

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, E=essay, P=portfolio Teaching Format: 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						Type of Compuls	Module: ory Module	with C	hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h									
Duration	1 Semester									
Frequency	regularly in Winter Semester									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SW	/S								
Content	Axiomatic foundation of	of plana	r ged	metr	ry.					
	Euclidean and non-Eu	clidean	geo	metry	/ .					
	Parametrised curves a	Parametrised curves and surfaces.								
Objectives	They know the basic principle fundamental links between g proving the essential results connections. In the exercise classes they the terms, statements and more to new problems, to analyse the statements.	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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Geometry	L	f	4	6	yes	wr. o.	90-180	g	100
		E	f	2	3	,,,,	or.	o. 20-30	9	100
	In this module an exercise ce examination the coursework oral is decided by the instruct	must ha	ıve b	een a	acqu	ired. W	hether the	examination	is wri	
Literature	Possible References :									
	Marcel Berger: Geom Springer 2010.	 Michele Audin: Geometry. Springer 2003. Marcel Berger: Geometry Revealed: A Jacob's Ladder to Modern Higher Geometry. Springer 2010. David A. Brannan, Matthew F. Esplen, Jeremy J. Gray: Geometry. Cambridge University 								
	John Stillwell: The fou	r pillars	of ge	eome	etry. S	Springe	er 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, E=essay, P=portfolio Teaching Format: 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-50-02	Module Title: Convex Geometry						Type of Module: Compulsory Module with Choice			
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time 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 + Ex.cl. 2 SWS									
Content	Cones, polytopes, polyhedra, fans, polyedral complexes.									
	 Normal fans of polygons. Triangulations, subdivisions, secondary fans, discriminants. 									
Objectives	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. Furthermore 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 onto 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 necessary to argue for it in a critical discourse.									
Requirements for obtaining Credits / Grading (Weighting 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	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 head of the examination board.									
Literature	Possible References: • Günter M. Ziegler: Lectures on Polytopes. Springer 1998.									
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, E=essay, P=portfolio Teaching Format: 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: Geometry of Manifolds 1						Type of I		with C	haiaa
ECTS-Points	-	Geometry of Manifolds 1 Compulsory Module with Choice 9							noice	
Workload - Time in Class - Self-Study	Workload: 270 h	Workload: Time in Class: Self-Study:								
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	V S								
Content	Manifolds and subman	nifolds.								
	Vector fields and flows	Vector fields and flows.								
	Metrics, foundations or	Metrics, foundations of Riemannian geometry.								
	Complex structures.	Complex structures.								
	Theorem of Gauß-Bor	Theorem of Gauß-Bonnet on surfaces.								
Objectives	geometry and the basic tech understanding of differential mathematical concepts are a naming and proving the esse presented connections. In the exercise classes they the terms, statements and m to new problems, to analyse	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 transfer the methods to new problems, to analyse them and to work on solution strategies on their own or in a transfer the methods.								
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	г Type of Course	J Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Geometry of Manifolds 1	E	f	2	3	yes	wr. o. or.	o. 20-30	g	100
	In this module an exercise ce examination the coursework oral is decided by the instruc	ertificate must h	e is to ave b	be a	acqui acqui	ired. W	hether the	examination	is writ	

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 Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the Sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section. Due to a significant overlap in contents the module cannot be taken together with either of the modules 'Geometry in Physics' and 'Introduction to Differential Geometry'.
Prerequisites	There are no further prerequisites.
Responsible Persons	Christoph Bohle, Frank Loose
Abbroviotionou	

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:						Type of	Module:		
MAT-50-20	Topology						Compuls	ory Module	with C	hoice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: 180 h	Time i 60 h	n Cla	ss:			Self-Stud	ly:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SV	WS								
Content		Review of metric spaces: closed sets, environment, continuity, complete metric spaces, compactness in metric spaces metric spaces.								
	Set-theoretic topology ration axioms.	: topolo	gical	spac	es, c	ontinui	ty converge	nce, compa	ctness,	sepa-
	 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.						tence			
	Outlook on algebraic	topology	/.							
Objectives	set-theoretical topology and phenomena in different area different areas of mathematic results of the lecture as well In the exercise classes they be terms, statements and method new problems, to analyse the	Students have familiarised themselves with the central concepts, results and methods of set-theoretical topology and have understood that this theory can be used to describe many phenomena in different areas of mathematics. In this way, they link their knowledge of very different areas of mathematics. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods onto 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Title								9	>
	Topology	E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	examination the coursework									

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, E=essay, P=portfolio Teaching Format: 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						Type of I	Module: ory Module	with C	noice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	VS								
Content	Set theoretical topological topologic	gy.								
	Basic concepts of cat	egory th	neory.							
	The fundamental groups	ıp of a p	ouncti	ured	topol	ogical	space.			
	Theory of covering sp	aces.								
	Basic concepts of singular homology theory.									
	Applications.									
Objectives	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 be terms, statements and method new problems, to analyse the	The students learn how to realise ideas in topology, e.g. the detection of holes in topological spaces, into a precise theory, even with a sophisticated technique. In particular, they recognise how abstract concepts, e.g. from category theory and homological algebra, provide effective ways of speaking that enable the formation of ideas to be adequately implemented. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods onto 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 Credits / Grading (Weighting if applicable)	Title Algebraic Topology	г Type of Course	J Status	SMS 4	e ECTS	s S Coursework	Type of Exam	Dur. of Exam (min)	ت Grading	Weight for Grade
		E	f	2	3	,	or.	o. 20-30	3	
	In this module an exercise continuous examination the coursework oral is decided by the instruc	must h	ave b	een a	acqui	ired. W	hether the	examination	is writ	

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, E=essay, P=portfolio Teaching Format: 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	7.						with C	hoice	
ECTS-Points	3	3								
Workload - Time in Class - Self-Study	Workload: 90 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS									
Content		 Topological K-theory. Künneth formula and Bott periodicity. Characteristic classes. Chern character. Algebraic K-theory 								
Objectives	The students have learnt an algebra and number theory. different areas. They can ucategorical K-groups and appare capable of naming and prexplaining the presented con	They haunderstanderstanderstanderstanding them oving them	ive leand and and and and and and and and and	arnt and i y ha	to re use i ve le	cognis terms arnt to	e and use the such as vec think in large	ne connection otor or fibre e contexts.	ons be bund The stu	tween les or idents
Requirements for obtaining Credits / Grading (Weighting 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									
Transfer	The module belongs to the Differential Geometry. Takin be included in the Sections Specialisation, in accordance	g into a <i>Study F</i>	ccou ocus	nt th	e cho <i>vanc</i>	osen p ed Kno	ersonal Stu owledge in I	dy Specialis Mathematic	sation, s or <i>E</i>	it can <i>lective</i>

Prerequisites There are no further prerequisites.						
Responsible Persons	Anton Deitmar					
Abbreviations: Grading System : g=graded, ng=not graded						
Examination Type : I	MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio					
	=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom					
Status : d	p=obligatory, f=facultative					
Other : h	n=hours, o.=or, s.M.=see module description, SWS=contact hours per week					

Module Number: MAT-50-50	Module Title: Hyperbolic Geometry: Axion Algebraic	natic, F	eflec	tion	Geo	metric,	Type of Compuls	Module: ory Module	with C	hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	VS								
Content	incidence and congruence, the introduction of the hyperb A Euclidean field is created	Starting from a system of axioms for plane absolute geometry with the basic concepts of neidence and congruence, the associated Bachmann reflection geometry is developed. After the introduction of the hyperbolic axiom, this is continued with reflection-geometric end theory. A Euclidean field is created from the rotations around an end and the translations along a straight line, with the help of which the hyperbolic plane under consideration is described algebraically.								
Objectives	and hyperbolic planes) from particular, they have learnt at which rarely appears in the codeepened their knowledge at able to name and prove the relationships presented. In the exercise classes they have the particular transport of the particular transpo	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 onto new problems, to analyse them and to work on solution strategies on their own or in a team.								
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Hyperbolic Geometry: Axiomatic, Reflection Geometr Algebraic	E	t Status	SMS 4 2	6 3	Sework	wr. o. or.	Onr. of Exam (min) 90-180 o. 20-30	Grading	00 Weight for Grade
	In this module an exercise context examination the coursework oral is decided by the instruc	must ha	ave b	een a	acqu	ired. W	hether the	examination	is wri	
Literature	Possible References: Friedrich Bachmann: 1959. Robin Hartshorne: Ge Helmut Karzel, Kay So hoeck und Ruprecht 1	eometry örensen	: Euc	lid a	nd be	eyond.	Springer 20	000.		_

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, E=essay, P=portfolio Teaching Format : 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						Type of I	Module: ory Module	with C	hoice
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	regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	ecture 4 SWS + Ex.cl. 2 SWS								
Content	Hahn-Banach theoren Closed graph theoren	 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	dimensional spaces and can a the complexity of problems of problems. The students are of as well as assessing and exp In the exercise classes they the terms, statements and m onto new problems, to analy	The students are aquainted with the basic principles and techniques of the theory of infinte dimensional spaces and can apply them to problems in analysis and geometry. They understand the complexity of problems of spectral theory and can use its results for the solution of analytical 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 onto 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 necessary to argue for it in a critical								
Requirements for obtaining Credits / Grading (Weighting 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	4 2	6	yes	K o. mP o. H	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 head of the examination board.								

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
Abbreviations: Grading System : g	=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio $Teaching \ Format \ : L=lecture, \ LE=lecture \ with \ integrated \ exercises, \ SL=seminar \ or \ lecture, \ E=exercise \ class, \ T=tutorial,$

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

Status : o=obligatory, f=facultative

Module Number: MAT-55-07	Module Title: Linear Control Theory						Type of I	Module: ory Module	with C	hoice
ECTS-Points	6	6								
Workload - Time in Class - Self-Study	Workload: 180 h	,								
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SW	/S								
Content	and processes. The underlyi but also, in its abstract form, of lecture, finite-dimensional system and linear algebra is sufficient criteria for stabilisability. If the	lathematical 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, at also, in its abstract form, due to the clarity and elegance of its methods and results. In this cture, 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 riteria 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	experienced and understood and analysis and their benefits proving the essential results connections. Students will be in the subject area. In the exercise classes they hat terms, statements and method	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 onto new problems, to analyse them and to work on solution strategies on their own or in a team.								
Requirements for obtaining Credits / Grading (Weighting 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.	90-180	a	100
		Е	f	2	3	yes	or.	o. 20-30	g	100
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the head of the examination board.								
Literature	Possible References :									
	Hans Wilhelm Knobloo	h, Huib	ert k	wak	erna	ak: Lin	eare Kontro	lltheorie. Sp	ringer	1985.
	Jerzy Zabczyk: Mathe	matical	Con	trol T	heor	y. Birkl	näuser 1992	2.		
	Ruth F. Curtain, Hans Springer 1995.	Zwart:	An I	ntrod	luctic	n to In	finite-Dimer	nsional Syst	ems T	heory.

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, E=essay, P=portfolio Teaching Format : 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	ential Ed	guatic	ns			Type of Compuls	Module:	with C	hoice
ECTS-Points	9		<u>'</u>				'	<u>, </u>		
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	regularly									
Term	1-3									
Language of Instruction	English	nglish								
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	ecture 4 SWS + Ex.cl. 2 SWS								
Content	Harmonic functions.		_							
	Maximum principles.									
	Sobolev spaces.	Sobolev spaces.								
	• L^2 theory.	• L^2 theory.								
	Important examples (Important examples (Laplace equation, wave equation, heat equation).								
	Fundamental solution	ıs (ellipt	tic situ	atior	1).					
	Weak solutions of ellip	ptic equ	ıation	S.						
Objectives	mental for many fields, like strong connections to geom central terms, results and m these methods in advanced central results of the lecture In the exercise classes they the terms, statements and m onto new problems, to analy	The students got to know a central branch of analysis, whose terms and methods are fundamental for many fields, like numerics or stochastics. Also evolutionary equations, who have strong connections to geometry, are issue of the lecture. The students are acquainted with central terms, results and methods of linear partial differential equations and are able to use these methods in advanced courses. 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 onto 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 necessary to argue for it in a critical								
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Introduction to Partial Differential Equations		f	SMS 4 2	e θ ECTS	Coursework	Type of Exam o. o.	Our. of Exam (min) 08-020	ص Grading	Weight for Grade
	examination the coursework									

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:				_		Type of			
MAT-55-25		Introduction to Partial Differential Equations – Part 1 Compulsory Module with Choice								
ECTS-Points	5	5								
Workload - Time in Class - Self-Study	1101111001011									
Duration	1 Semester									
Frequency	not regularly	ot regularly								
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 1 SW	3								
Content	Harmonic functions.	Harmonic functions.								
	Maximum principles.									
	Sobolev spaces.	Sobolev spaces.								
Objectives	analysis, the concepts and me numerics and stochastics. Student of linear partial differential equadvanced courses. The studenthe lecture as well as assessing in the exercise classes they has terms, statements and method new problems, to analyse the	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 onto 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Partial Differ-	L	f	2	3	yes	wr. o.	90-180	g	100
	In this module an exercise cer examination the coursework n	ential Equations – Part 1 E f 1 2 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 head of the examination board.								
Literature	Possible References :									
	Lawrence C. Evans: Pa	rtial di	ferer	ıtial e	equat	ions. A	merican Ma	thematical S	Society	2010.
	• David Gilbarg, Neil S. Springer 2001.	David Gilbarg, Neil S. Trudinger: Elliptic partial differential equations of second order.								
	Olga A. Ladyzenskaja, very equations of parabolic to the second sec					ov, Nina	a N. Uralcev	a: Linear an	d quas	ilinear

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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: Introduction to Dynamical Syst	ems					Type of I	Module: ory Module	with C	hoice
ECTS-Points	3	3								
Workload - Time in Class - Self-Study										
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	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 ex- differential equations, like e.g.: states or periodic orbits? Wh proving the essential results of connections.	How lo	ong d e tra	o ma ecto	then	natical : stable?	solutions exi They are	st? Are ther capable of	e equil namin	ibrium g and
Requirements for obtaining Credits / Grading (Weighting 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, Stephealgebra. Academic Preserved. Vladimir I. Arnold: Mathematical Carl Ludwig Siegel, Jürg	s 197 emati	'4. cal m	etho	ds of	f classi	cal mechani	ics. Springe	r 2010	

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 : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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: Introduction to Geometric Me	easure	Theo	'v			Type of	Module:	with C	hoice
ECTS-Points	9			,			Обтраю	iory modulo		
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English	German or English								
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	ecture 4 SWS + Ex.cl. 2 SWS								
Content Objectives	densities. Isodiametric inequalit Rademacher's theore Surface- and cosurface Countable rectifiable	 Measures, covering theorems, differentiation of measures, Hausdorff measures and densities. Isodiametric inequality. Rademacher's theorem and Whitney's embedding theorem. Surface- and cosurface formula. Countable rectifiable sets, rectifiable varifolds. 								
Objectives	analysis and geometry and various problems. They have methods of geometric meast courses. The students are cas well as assessing and explinithe exercise classes they be terms, statements and method new problems, to analyse the	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 the 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 onto 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 Credits / Grading (Weighting 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	L	f	4 2	6	yes wr. o. 90-180 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 head of the examination board.								

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 <i>Study Specialisation Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the Sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Reiner Schätzle

Grading System : g=graded, ng=not graded

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

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							Module: ory Module	with C	hoice
ECTS-Points	5									
Workload - Time in Class - Self-Study	Workload: 150 h									
Duration	1 Semester	I Semester								
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 1 SW	ecture 2 SWS + Ex.cl. 1 SWS								
Content	 Measures, covering the densities. 	Measures, covering theorems, differentiation of measures, Hausdorff measures and densities.								
	 Isodiametric inequality 									
	Rademacher's theorem and Whitney's embedding theorem.									
Objectives	analysis and geometry and various problems. They have methods of geometric measus courses. The students are can as well as assessing and explinithe exercise classes they have terms, statements and method new problems, to analyse the	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 the 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 onto 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 Credits / Grading (Weighting 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 Theoretic Methods	L E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise ce examination the coursework oral is decided by the instruct	nust ha	ave b	een a	acqu	ired. W	hether the	examination	is writ	
Literature	Possible References: • Lawrence C. Evans, Roc CRC Press 1992. • Herbert Federer: Geor Leon Simon: Lectures 1984.	metric r	neas	ure t	heor	y. Sprir	nger 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 : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:		Γh	\	/- v:f-	lala	Type of I		ماند	haina			
	Introduction to Geometric Me	asure	neoi	y – \	/ariio	olas	Compuis	ory Module	with C	noice			
ECTS-Points	5						1						
Workload - Time in Class - Self-Study	Workload: 150 h	Time i 45 h	n Cla	ss:			Self-Study: 105 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 + Ex.cl. 1 SWS												
Content	Surface- and cosurface	e formu	ıla.										
	Countable rectifiable sets, rectifiable varifolds.												
Objectives	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 onto 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 Credits / Grading (Weighting if applicable)	Title Introduction to Geometric Measure Theory – Varifolds	г Туре of Course	J Status	SMS 2	ε ECTS	Sework	Type of Exam	Dur. of Exam (min) 081-09 0-20-30	ے Grading	Weight for Grade			
	weasure rneory – variioids	E	f	1	2		or.	0. 20-30					
	In this module an exercise ce examination the coursework oral is decided by the instruc	must ha	ave b	een a	acqu	ired. W	hether the	examination	is writ				
Literature	Possible References :		_		_								
	 Lawrence C. Evans, R CRC Press 1992. Herbert Federer: Geo Leon Simon: Lecture 1984. 	metric r	neas	ure t	heor	y. Sprir	nger 1969.						

Transfer	The module belongs to the <i>Study Specialisation Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the Sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section. The module is part of the 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

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

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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						Type of Compuls	Module: ory Module	with C	hoice			
ECTS-Points	5												
Workload - Time in Class - Self-Study	Workload: 150 h	Time ii 45 h	n Cla	ss:			Self-Stud	dy:					
Duration	1 Semester												
Frequency	not regularly	not regularly											
Term	1-3	1-3											
Language of Instruction	German or English												
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 1 SW	/S											
Content	Direct method of calcu	Direct method of calculus of variations.											
	Euler-Lagrange equations.												
	Palais-Smale condition.												
	Mountain-Pass Lemma according to Ambrosetti-Rabinowitz.												
Objectives	which is primarily used to probut also has applications in e basics from functional analys different context, e.g. geome about a so-called mountain-particular existence of solutions of particular proving the essential results connections. In the exercise classes they have terms, statements and method new problems, to analyse the	In the first part of the course, students have learnt the direct method of calculus of variations, which is primarily used to prove the existence of weak solutions of partial differential equations, but also has applications in e.g. differential geometry. They have also acquired the necessary basics from functional analysis and partial differential equations and can also use these in a different context, e.g. geometric analysis. In the second part of the course, students learnt about a so-called mountain-pass lemma. With its help, they can analyse non-uniqueness in the existence of solutions 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 onto 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 Credits / Grading (Weighting if applicable)	Title Calculus of Variations	ш г Type of Course	t Status	SMS 2	S ECTS	Coursework	wr. o.	Onr. of Exam (min) 90-180 0. 20-30	Grading	Weight for Grade			
	In this module an exercise ce examination the coursework oral is decided by the instruct	must ha	ave b	een a	acqu	ired. W	hether the	examination	is writ	in the ten or			
Literature	Possible References :												
	 Michael Struwe: Varia David Gilbarg, Neil S. Springer 1998. Walter Rudin: Function 	Truding	er: E	Iliptio	c Par	tial Diff	erential Equ		econd	Order,			
	112.10.		, 5.0,										

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, E=essay, P=portfolio Teaching Format: 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						Type of Compuls	Module: ory Module	with C	hoice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time ii 90 h	n Cla	SS:			Self-Stud	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SWS										
Content	 Manifolds and Lie groups, Lie algebras and exponential map, Covering spaces and classification of Lie groups by their Lie algebras, Classical Lie groups, Operations of Lie groups and homogeneous spaces. 										
Objectives	Lie groups lie at the interface describing the symmetries of differential equations, in part learn from a prominent examiner very successfully and how a variety of symmetry phenome results of the lecture as well as In the exercise classes they have terms, statements and method new problems, to analyse the They are able to present their	geome icular if iple how convince na. The as asse ave acq ds of the em and	etric of these we differ sing for stude ssing uired to we	objected systems of the control of t	ets, b mme t disc lism are c expl expl nfide They on so	etries for ciplines is dever capable aining ent, pred lution s	algebraic e orm a contir of mathem eloped that e of naming a the present cise and ind learned to tr strategies o	equations or nuous set. Thatics can we can precisel and proving ed connective ependent hat ansfer the non their own	solution students or second the estimate of th	ons of idents gether cribe a sential of the s onto team.	
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Lie Groups In this module an exercise ce examination the coursework oral is decided by the instruct	must ha	ve b	een a	acqui	ired. W	hether the	examination	is writ		
Literature	Possible References: • Joachim Hilgert, Karl-H • Gerhard P. Hochschild • Frank W. Warner: For 1983.	: The s	tructi	ıre o	f Lie	groups	s. Holden-D	ay 1965.			

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching 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-55-60	Module Title: Introduction to Mathematical L	ogic					Type of I	Module: ory Module	with C	hoice		
ECTS-Points	3						'					
Workload - Time in Class - Self-Study		Time ii 30 h	n Cla	ISS:			Self-Stud	dy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS										
Content	Propositional logic.											
	 Languages of the first order: Completeness and compactness. 											
	 Theory of computations: Register machines; Gödelisation. Incompleteness of arithmetic: First and second incompleteness theorem. Set theory: Ordinal- and cardinal numbers; 											
	 Incompleteness of 	of set t	heor	у.								
Objectives	Students are able to understa ematical logic. They understa the difference between truth a mathematical content. The stuthe lecture as well as assessing	and the nd pro dents a	e lim vabil are c	its of ity ar apab	f pos nd ca le of	sible n ın appl namin	nathematica y basic theo g and provin	al knowledge retical mode g the essen	e, reco el thinl	ognise king to		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Introduction to the Mathemati cal Logic	· L	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100		
Literature		Possible References: Rautenberg, Wolfgang: Einführung in die Mathematische Logik. Vieweg+Teubner 2008. Ziegler, Martin: Mathematische Logik. Birkhäuser 2016.										
Transfer	The module is not assigned to Knowledge in Mathematics or ments of the respective section	Electiv										

Prerequisites There are no further prerequisites.							
Responsible Anton Deitmar Persons							
Abbreviations: Grading System : g=graded, ng=not graded Fromination Time + MT master's thesis are explayed with written even By presentation Fragery By partfelling							
Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutol P=project, S=seminar, IC=inverted classroom							
Status : c	p=obligatory, f=facultative						
Other : I	n=hours, o.=or, s.M.=see module description, SWS=contact hours per week						

Status

Other

: o=obligatory, f=facultative

Module Number: MAT-55-63	Module Title: Introduction to set theory						Type of I	Module: ory Module	with C	:hoice	
ECTS-Points	3						Compais	ory woodale	With	110100	
Workload - Time in Class - Self-Study	Workload: Time in Class: 30 h							ly:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 2 SWS										
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 Credits / Grading (Weighting 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		1						
Transfer	Mathematische Breitenbildun	g									
Prerequisites	There are no further prerequi-	sites.									
Responsible Persons	Frank Loose										
Examination Type: M Teaching Format: L P	=graded, ng=not graded IT=master's thesis, or.=oral exa =lecture, LE=lecture with integra =project, S=seminar, IC=inverte	ted exe	rcise	s, SL							

	Module Title: Geometry in Physics										
9											
l:	Time ir 90 h	ı Cla	ss:			Self-Stud	ly:				
ter											
regularly in Winter Semester											
1-3											
English											
Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignments											
The module provides an introduction to fundamental methods of differential geometry and their relevance for physics. Particular topics are manifolds, differential forms, Riemannian metrics and associated notions of curvature, Riemannian geometry of submanifolds, real vector bundles, and connections. Applications of these concepts in Physics are discussed.											
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. In particular, they develop 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											
	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
ry in Physics	L	0	4	6	VAS	wr. o.	90-180	a	100		
y III I IIy3iC3	Е	0	2	3	yes	or.	o. 20-30	9	100		
							n order to be	admit	ted to		
References :											
hn Lee: Introduction	n to smo	oth n	nanif	olds.	Spring	ger 2012.					
hn Lee: Riemannia	n manifo	lds:	An in	ıtrodı	uction.	Springer 19	997.				
nris Isham: Modern	different	ial ge	eome	etry f	or phys	sicists. Worl	d Scientific	1999.			
kio Nakahara: Geoi	metry, To	polo	gy a	nd P	hysics.	IOP Publis	hing 2003.				
	dule provides an intivance for physics. Indivance for physical notions. A obtain knowledge, untial geometry. They alculus and experiential stee of the listed notions are not the essential state eveloped in the lect homework assignment acquaintare. They learn how to produce to stand for the estimation of the es	ter in Winter Semester 4 SWS + Exercise Classes ule provides an introduction vance for physics. Particul and associated notions of currand connections. Application obtain knowledge, understantial geometry. They develop alculus and experience throusithin physical theories. Studiuse of the listed notions of dending of differential and intentical notions are naturally appet the essential statements eveloped in the lecture and shomework assignments and pendent acquaintance with They learn how to transfer proposed in strategies on their and to stand for them in a composition strategies on their and to stand for them in a composition of the students need to succeed the succeed to the students of the succeed to the students of the succeed to the succ	ter in Winter Semester 4 SWS + Exercise Classes 2 SW ule provides an introduction to vance for physics. Particular to not associated notions of curvatur and connections. Applications of obtain knowledge, understanding notial geometry. They develop, in palculus and experience through exithin physical theories. Students use of the listed notions of differential and integral of tical notions are naturally applied eveloped in the lecture and to pure homework assignments and exercite pendent acquaintance with the property of the students and to stand for them in a critical and to stand for them in a critical policy of the students need to successful. The type of examination is set to the second of the students need to successfue the second of the	ter in Winter Semester 4 SWS + Exercise Classes 2 SWS, Full provides an introduction to fund vance for physics. Particular topics and associated notions of curvature, Riand connections. Applications of these obtain knowledge, understanding, and it all geometry. They develop, in particular and experience through examplify the physical theories. Students obtains and experience through examplify applied with the essential statements and conceiveloped in the lecture and to put it in thomework assignments and exercise pendent acquaintance with the notion. They learn how to transfer these may poslution strategies on their own and and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and to stand for them in a critical discontinuous and the standard for them in a critical discontinuous and the standard for them in a critical discontinuous and the standard for them in a critical discontinuous and the standard for them in a critical discontinuous and the standard for them in a critical discontinuous and the standard for them in a critical discontinuous and the standard for them in a critical discontinuous and the standard for them in a critical discontinuous and the standard for them in a	ter in Winter Semester 4 SWS + Exercise Classes 2 SWS, Home vance for physics. Particular topics are not associated notions of curvature, Rieman and connections. Applications of these containts of these containts and experience through examples within physical theories. Students obtain knuse of the listed notions of differential geometry. They develop, in particular, alculus and experience through examples within physical theories. Students obtain knuse of the listed notions of differential geometry and integral calculus a stical notions are naturally applied within physical theories. Students obtain knuse of the listed notions of differential geometry and integral calculus a stical notions are naturally applied within physical to the essential statements and concepts eveloped in the lecture and to put it into a homework assignments and exercise class pendent acquaintance with the notions, so they learn how to transfer these methor posolution strategies on their own and with and to stand for them in a critical discours and to stand for them in a critical discours. They learn how to transfer these methor posolution strategies on their own and with and to stand for them in a critical discours. They learn how to transfer these methor posolution strategies on their own and with and to stand for them in a critical discours. They learn how to transfer these methor posolution strategies on their own and with and to stand for them in a critical discours. They learn how to transfer these methor posolution strategies on their own and with and to stand for them in a critical discours. They learn how to transfer these methor posolution strategies on their own and with and to stand for them in a critical discours. They learn how to transfer these methor posolutions are naturally applied within posolutions. They learn how to transfer these methor posolutions are naturally applied within posolutions. They learn how to transfer these methor posolutions are naturally applied within posolutions.	ter in Winter Semester 4 SWS + Exercise Classes 2 SWS, Homework And the surface for physics. Particular topics are maniformed associated notions of curvature, Riemannian grand connections. Applications of these concepts obtain knowledge, understanding, and acquaintaintial geometry. They develop, in particular, a deep alculus and experience through examples how the hithin physical theories. Students obtain knowledge alculus and experience through examples how the hithin physical theories. Students obtain knowledge alculus and experience through examples how the hithin physical theories. Students obtain knowledge alculus and experience through examples how the hithin physical the essential statements and concepts from the eveloped in the lecture and to put it into a larger homework assignments and exercise classes streamed to acquaintance with the notions, statements. They learn how to transfer these methods to not posolution strategies on their own and within a grand to stand for them in a critical discourse if new and to	ter in Winter Semester 4 SWS + Exercise Classes 2 SWS, Homework Assignments will be provided an introduction to fundamental methods of divance for physics. Particular topics are manifolds, different associated notions of curvature, Riemannian geometry of and connections. Applications of these concepts in Physics obtain knowledge, understanding, and acquaintance with the tital geometry. They develop, in particular, a deeper understalculus and experience through examples how the mathemat in the listed notions of differential geometry. In particular notions are naturally applied within physical theories. Students obtain knowledge, understause of the listed notions of differential geometry. In particular notions are naturally applied within physical theories. Stee the essential statements and concepts from the lecture are eveloped in the lecture and to put it into a larger framework. homework assignments and exercise classes students developed in the lecture and to put it into a larger framework. homework assignments and exercise classes students developed in the lecture and to put it into a larger framework. homework assignments and exercise classes students developed in the lecture and to put it into a larger framework. homework assignments and exercise classes students developed in the lecture and to put it into a larger framework. homework assignments and exercise classes students developed in the lecture and to put it into a larger framework. homework assignments and exercise classes students developed in the lecture and to put it into a larger framework. homework assignments and exercise classes students developed in the lecture and to put it into a larger framework. homework assignments and exercise classes students developed in the lecture and to put it into a larger framework. homework assignments and exercise classes students developed in the lecture and to put it into a larger framework. homework assignments in the lecture and to put it into a larger framework. homework assignments in the lecture and t	ter in Winter Semester 4 SWS + Exercise Classes 2 SWS, Homework Assignments ulle provides an introduction to fundamental methods of differential gevance for physics. Particular topics are manifolds, differential forms, and associated notions of curvature, Riemannian geometry of submanifolds and connections. Applications of these concepts in Physics are discussed obtain knowledge, understanding, and acquaintance with the use of the lintial geometry. They develop, in particular, a deeper understanding, and alculus and experience through examples how the mathematical notions of the listed notions of differential geometry. In particular, they develoding of differential and integral calculus and experience through examples the histed notions of differential geometry. In particular, they develoding of differential and integral calculus and experience through examples the histed notions are naturally applied within physical theories. Students are at the essential statements and concepts from the lecture as well as to eveloped in the lecture and to put it into a larger framework. Homework assignments and exercise classes students develop a confidence of the lecture and to put it into a larger framework. Homework assignments and exercise classes students develop a confidence of the lecture and to put it into a larger framework. They learn how to transfer these methods to new problems, to analyst position strategies on their own and within a group. They are able to part of the properties of their own and within a group. They are able to part of the properties of the properties of the properties of the properties. They are able to part of the properties of the properties of the properties of the properties. They are able to part of the properties of the	ter in Winter Semester 4 SWS + Exercise Classes 2 SWS, Homework Assignments ule provides an introduction to fundamental methods of differential geometry vance for physics. Particular topics are manifolds, differential forms, Riemand associated notions of curvature, Riemannian geometry of submanifolds, real and connections. Applications of these concepts in Physics are discussed. obtain knowledge, understanding, and acquaintance with the use of the listed in thial geometry. They develop, in particular, a deeper understanding of differential accounts and experience through examples how the mathematical notions are natiful applied within physical theories. Students obtain knowledge, understanding, and acquaintse of the listed notions of differential geometry. In particular, they develop a dinding of differential and integral calculus and experience through examples how the mathematical notions are naturally applied within physical theories. Students are able to be the essential statements and concepts from the lecture as well as to explain eveloped in the lecture and to put it into a larger framework. homework assignments and exercise classes students develop a confident, propendent acquaintance with the notions, statements, and methods explained. They learn how to transfer these methods to new problems, to analyse ther position strategies on their own and within a group. They are able to present and to stand for them in a critical discourse if necessary. They learn how to transfer these methods to new problems, to analyse the position strategies on their own and within a group. They are able to present and to stand for them in a critical discourse if necessary. They learn how to transfer these methods to new problems, to analyse the position strategies on their own and within a group. They are able to present and to stand for them in a critical discourse if necessary. They learn how to transfer these methods to new problems, to analyse there is a supplementary of the problems, to analyse the problems, to a		

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, E=essay, P=portfolio Teaching Format: 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-70-01	Module Title: Algorithms of Numerical Mathe	ematic	s				Type of I	Module: ory Module	with C	hoice			
ECTS-Points	9												
Workload - Time in Class - Self-Study		Time ii 90 h	n Cla	ss:			Self-Stud	Self-Study: 180 h					
Duration	1 Semester												
Frequency	regularly												
Term	1-3												
Language of Instruction	German												
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SWS												
Content	 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 th mathematics. The students a lecture as well as assessing a In the exercise classes they ha terms, statements and method new problems, to analyse the They are able to present their	re cap nd exp ve acq s of the m and	able lainii uired e lec to w	of nagether a conture.	amin e pre nfide They on so	g and sented on the sented on	proving the I connection cise and indi learned to tr strategies o	essential ross. ependent have ansfer the man their own	esults andling nethod or in a	of the of the s onto team.			
Requirements for obtaining Credits / Grading (Weighting 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	g	100			
	In this module an exercise cer examination the coursework n oral is decided by the instructor	nust ha	ive b	een a	acqu	red as ired. W	hether the	examination	pation is writ				
Literature	Possible References :												
	Peter Deuflhard, Andre Martin Hanke-Bourged senschaftlichen Rechne	is: Gı	rundl	ager	ı der			_					
Transfer	The module belongs to the S Taking into account the chosen Study Focus, Advanced Know with the restrictive requiremen	perso ledge	nal S in Ma	tudy a <i>ther</i>	Spec natio	cialisati s or <i>El</i>	on, it can be <i>ective Spec</i>	included in	the Se	ctions			

Prerequisites There are no further prerequisites.					
Responsible Persons Christian Lubich, Andreas Prohl					
Abbreviations: Grading System : g=graded, ng=not graded					
Examination Type : I	MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio				
Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutor P=project, S=seminar, IC=inverted classroom					
Status : c	p=obligatory, f=facultative				
Other : h	n=hours, o.=or, s.M.=see module description, SWS=contact hours per week				

Module Number: MAT-70-20	Module Title: Introduction to Optimisation					Type of Compuls	Module:	with C	hoice	
ECTS-Points	6	6								
Workload - Time in Class - Self-Study	Workload: 180 h	Time ii 60 h	n Cla	ss:			Self-Stud	dy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 3 SWS + Ex.cl. 1 SW	Lecture 3 SWS + Ex.cl. 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 onto 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Optimisation	L E	f	3	4,5 1,5	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise ce examination the coursework oral is decided by the instruct	must ha	ive b	een a	acqui	ired. W	hether the	examination	is writ	
Literature	Possible References :									
	 Florian Jarre, Joseph Methoden. Springer 20 Jorge Nocedal, Stepho 	019.					-			e und

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, E=essay, P=portfolio Teaching Format: 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 Compuls	Module: ory Module	with C	hoice	
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud	dy:		
Duration	1 Semester									
Frequency	regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS									
Content Objectives	 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. Students master the basic principles and techniques of analysis and numerics of constrained									
	optimisation problems. The st the lecture as well as assess In the exercise classes they have terms, statements and metho new problems, to analyse the They are able to present their	ng and ave acq ds of th em and	expl uired e lec to w	ainin a co ture. ork c	g the nfide They on so	prese nt, pred have lution s	nted connective and ind learned to the strategies o	ctions. ependent har ansfer the r n their own	andling nethod or in a	of the s onto team.
Requirements for obtaining Credits / Grading (Weighting 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 ce examination the coursework oral is decided by the instruct	must ha	ave b	be a	L cqui acqu	ired. W	hether the	examinatior	i is writ	
Literature		Possible References: Carl Geiger, Christian Kanzow: Theorie und Numerik restringierter Optimierungsaufgaben. Springer 2002.								
Transfer	The module belongs to the Taking into account the chose Study Focus, Advanced Knowith the restrictive requirements	n perso <i>vledge</i>	nal S in Ma	tudy a <i>ther</i>	Spec natio	cialisati s or <i>El</i>	on, it can be <i>ective Spec</i>	included in	the Se	ctions

Prerequisites There are no further prerequisites.					
Responsible Persons	Andreas Prohl				
Abbreviations: Grading System : g=graded, ng=not graded					
Examination Type : I	MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio				
Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutori P=project, S=seminar, IC=inverted classroom					
Status : c	p=obligatory, f=facultative				
Other : h	n=hours, o.=or, s.M.=see module description, SWS=contact hours per week				

Module Number: MAT-75-01	Module Title: Probability Theory				Type of Compuls	Module: ory Module	with C	hoice		
ECTS-Points	9	9								
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud	dy:		
Duration	1 Semester									
Frequency	regularly in Winter Semester									
Term	1-3									
Language of Instruction	German	German								
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	Lecture 4 SWS + Ex.cl. 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	can model, analyse and inter measure theoretically founder central results of the lecture. The students are capable of assessing and explaining the In the exercise classes they the terms, statements and monto new problems, to analy	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 onto 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 necessary to argue for it in a critical								
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Probability 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	ertificate must ha	is to	be a	icqui acqui	ired. W	hether the	examination	is writ	

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				
Abbreviations: Grading System : g=graded, ng=not graded Examination Type : MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio					

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

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

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

: o=obligatory, f=facultative

Status

Other

Module Number:	Module Title:						Type of I	Module:		
MAT-75-12	Foundations of Discrete Mat	hematic	s				Compuls	ory Module	with C	hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	in Cla	ss:			Self-Stud	dy:		
Duration	1 Semester	'								
Frequency	not regularly									
Term	1-3									
Language of Instruction	German	German								
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SN	Lecture 4 SWS + Ex.cl. 2 SWS								
Content	• Logic.									
	Sets, relations, functi	ons.								
	Partial orders.									
	Combinatorics.									
	Number theory.									
	Graph theory.									
	Algorithms and forma	ıl langua	iges.							
	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 onto 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 Credits / Grading (Weighting if applicable)	Title Foundations of Discrete	г Туре of Course	J Status	SMS 4	e ECTS	Sework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Mathematics	Е	f	2	3	700	or.	o. 20-30	9	100
	In this module an exercise c examination the coursework oral is decided by the instruc	must ha	ave b	een a	acqui	ired. W	hether the	examination	is writ	

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 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	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, E=essay, P=portfolio Teaching Format: 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. If the courses have already been included in the framework of a module in the Bachelor of Science in Mathematics, the module cannot be included in the Master of Science in Mathematics 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 the 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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Algebraic Geometry (MAT-45-11, 9 CP)	. 95
Algebraic Geometry and Toric Varieties (MAT-45-12, 9 CP)	. 97
Foundations of Quantum Mechanics (MAT-65-15, 9 CP)	281
Mathematical Quantum Theory (MAT-65-12, 9 CP)	275
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•	Control Theory (MAT-55-06, 9 CP)	187
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•	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)	289

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)	. 357
	Financial Mathematics and Numerics (MAT-70-51, 6 CP)	333
	Game Theory (MAT-70-40, 3 CP)	332
	Geometric Evolution Equations (MAT-60-01, 3 CP)	245
	Hamiltonian Systems (MAT-65-38, 9 CP)	295
	Information Theory, Pattern Recognition, and Neural Networks (MAT-75-22, 3 CP)	359
	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-CP)	
	Introduction to Stochastic Differential Equations - Part 1 (MAT-70-12, 5 CP)	313
	Mathematical Introduction to Data Science (MAT-70-34, 5 CP)	330
	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)	355
	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
Мо	odules in the Specialisation Stochastics	
The	following modules belong to the specialisation Stochastics. Possible restrictions can be found in the module description	iption
	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)	357
	Combinatorics (MAT-75-02, 9 CP)	335
	Financial Mathematics and Numerics (MAT-70-51, 6 CP)	333
	• Graph Theory (MAT-75-10, 9 CP)	351

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)	345
Information Theory, Pattern Recognition, and Neural Networks (MAT-75-22, 3 CP)	359
Introduction to Stochastic Differential Equations - Part 1 (MAT-70-12, 5 CP)	313
Markov Chains and Applications (MAT-75-11, 9 CP)	353
Mathematical Aspects of Deep Learning 1 (MAT-50-14, 3 CP)	149
Mathematical Aspects of Deep Learning 2 (MAT-50-19, 3 CP)	159
Mathematical Introduction to Data Science (MAT-70-34, 5 CP)	330
Mathematical Population Genetics (MAT-75-08, 6 CP)	347
Mathematical Statistical Physics (MAT-65-14, 9 CP)	279
Mathematical Statistics (MAT-75-03, 9 CP)	337
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)	341
Point Processes (MAT-75-09, 6 CP)	349
Probability Distances for Data Science (MAT-75-20, 6 CP)	355
Propagation of Chaos (MAT-65-39, 9 CP)	297
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)	343
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)	339
Theoretical Aspects of Machine Learning (MAT-70-30, 6 CP)	322

Modul descriptions (Specialisation modules)

Module Number:	Module Title:						Type of		:46 0	hainn
MAT-45-03	Computer Algebra Compulsory Module with Cho							noice		
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	in Cla	ss:			Self-Stud	ly:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	VS								
Content	Canonical forms and	standar	d bas	es fo	r ide	als and	d modules.			
	Computation of impor	tant ope	eratio	ns fo	r ide	als and	l modules.			
	Syzygies, free resolut	ions an	d the	proo	f of t	he Buc	hberger crit	erion.		
	Calculation of the prin	nary de	comp	ositic	on 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 onto 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Computer Algebra	L	f	4	6	V00	wr. o.	90-180	~	100
	Computer Algebra	Е	f	2	3	yes	or.	o. 20-30	g	100
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the head of the examination board.								

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 <i>Study Specialisation Algebra and Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the Sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	Knowledge from the modules Commutative Algebra and Algebraic Geometry are helpful however not absolutely necessary for participation in the module Computer Algebra
Responsible Persons	Hannah Markwig, Thomas Markwig

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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: Algebraic Geometry						Type of Module: Compulsory Module with Choice			
ECTS-Points	9 Workload: Time in Class: Self-Study: 180 h 1 Semester									
Workload - Time in Class - Self-Study										
Duration										
Frequency	regularly in Summer Semester									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SW	IS								
Content	Prevarieties and variet	ies.								
	Projektive varieties and	d homo	ogen	eous	spec	trum.				
	Finite and proper morphisms.									
	Blow-up and Grassma	Blow-up and Grassmannians.								
	Rational maps.									
	Divisors and line bundles, class group and Picard 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 a 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 ont 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.							gebra. vell as of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting 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	Vec	wr. o.	90-180	~	100
	Algebraic Geometry	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 instruct	must ha	ave b	een a	acqu	ired. W	hether the	examination	i is writ	

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 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 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					
Abbreviations: Grading System : g=graded, ng=not graded Examination Type : MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio						

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

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

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

: o=obligatory, f=facultative

Status

Other

Module Number: MAT-45-12	Module Title: Algebraic Geometry and Tori	c Variet	ies				Type of I	Module: ory Module	with Cl	hoice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud	ly:			
Duration	1 Semester	Semester									
Frequency	regularly in Summer Semester										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	VS									
Content	Projective space.	Projective space.									
	Prevarieties, morphism	ns, tang	gent s	расе	and	singul	arities.				
	Products and separati	on.									
	Projective varieties ar	d Grass	sman	nians	S.						
	Divisors and line bund	lles, cla	ss gr	oup a	and F	Picard (group.				
	Toric varieties.										
Objectives	Students learn the central country develop an advanced ur Using the example of the conference of Geometry can facilitate the in and expand the interplay of Acapable of naming and provexplaining the presented confiniting the presented confinition of the exercise classes they have problems, to analyse the They are able to present their	nderstar lass of nvestiga Algebra ing the nection ave acq ids of the em and	nding toric ation (and (esser s. uired e lect	of the varied of an Geometrial of a continue.	e relations, imported in the control of the control	ationsh they a ortant e by a fu ts of th nt, pred have l	ips betweer also learn hexample clauther comple lecture as cise and independent to trategies of	of Geometry ow method ss of Algebronent. The swell as as ependent has ansfer the non their own min critical	and Alg s of Co raic var studen sessing andling nethods or in a	gebra. convex ieties, ts are g and of the s onto team.	
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Algebraic Geometry and Tor Varieties	i ⊃i	t Status	SMS 4	e θ ECTS	Ses	Type of Exam o. o.	Our. of Exam (min) 0. 20-30	ص Grading	Weight for Grade	
	In this module an exercise ce examination the coursework oral is decided by the instruc	ertificate must ha	is to	be a	L cqui acqui	red. W	hether the d	examination	is writ		

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 <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' due to the large overlap in content.						
Prerequisites	Essential knowledge from the module Introduction to Commutative Algebra and Algebraic Geometry is assumed.						
Responsible Persons	Jürgen Hausen						
Abbreviations: Grading System : g=graded, ng=not graded Examination Type : MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format : 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 Transformation Gro	าแทร					Type of I	Module:	with C	hoice	
ECTS-Points	9	<u> </u>					Compaid	ory Wioddio	With O	110100	
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud	ły:			
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 + Ex.cl. 2 SV	Lecture 4 SWS + Ex.cl. 2 SWS									
Content	 Elements of the struct Elements of the repre Quotients in algebraic Classical invariant the Geometrical invariant Additionally certain as Toric varieties; 	 Operations of algebraic groups on algebraic varieties, homogeneous spaces. Elements of the structure theory of affine-algebraic groups and their Lie algebras. Elements of the representation theory of affine-algebraic groups and their Lie algebras. Quotients in algebraic geometry. Classical invariant theory: Hilbert's finiteness theorem, calculation of invariants. Geometrical invariant theory: Mumford's construction of quotients, variation of quotients. Additionally certain aspects of topics from the following list are covered: Toric varieties; Spheric varieties. 									
Objectives	The students learn basic in structures. At the same time for example from group and naming and proving the esse presented connections. In the exercise classes they be terms, statements and method new problems, to analyse the They are able to present their	e, they e ring the ential res ave acq ods of th em and	eory, is cults of uired e lect	ence in alg of the a co ture. ork o	the lectunfide They	interaction intera	etion of differmetry. The well as assectise and independent to the strategies o	rent algebra students ar essing and e ependent ha ansfer the n n their own	aic con e capa xplainin andling nethods or in a	cepts, ble of ng the of the s onto team.	
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Algebraic Transformation Groups	п Type of Course	t Status	SMS 4	e θ ECTS	Coursework	Type of Exam o. o. or.	On: of Exam (min) 0. 20-30	a Grading	Weight for Grade	
	In this module an exercise or examination the coursework oral is decided by the instruc	ertificate must ha	is to	be a	L cqui acqui	ired. W	hether the	examination	is writ		

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, E=essay, P=portfolio Teaching Format: 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:						Type of		0			
MAT-45-14	Algebraic Curves						Compuls	ory Module	with C	hoice		
ECTS-Points	9						_					
Workload - Time in Class - Self-Study	Workload: 270 h	Time in 90 h	n Cla	ss:			Self-Stud	Self-Study: 180 h				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SW	/S										
Content	Projective curves, divis	sors, Th	eore	m of	Rien	nann-F	Roch.					
	Ramified coverings, Ti	neorem	of H	urwit	Z.							
	Linear systems, embe	ddings,	Cas	telnu	ovo i	nequal	ity.					
	Singularities of plane of	curves,	Puis	eux e	expar	nsions.						
	Classification and mod	duli spa	ces,	Jaco	bi va	riety.						
Objectives	selected sub-area of algebrai an in-depth understanding of of naming and proving the es the presented connections. In the exercise classes they have terms, statements and metho new problems, to analyse the	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 onto 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Algebraic Curves	L	f	4	6	yes	wr. o.	90-180	g	100		
		E	f	2	3	,00	or.	o. 20-30	9			
	In this module an exercise ce examination the coursework oral is decided by the instruct	must ha	ive b	een a	acqui	ired. W	hether the	examination	is writ			
Literature	Possible References :											
	Robin Hartshorne: Alg	ebraic	geon	netry.	Spr	inger 2	006.					
	Gerd Fischer: Ebene a	algebra	sche	Kur	ven.	Viewe	j 1994.					
	Rick Miranda: Algebra	ic Curv	es ar	nd Ri	emaı	nn Surf	aces. AMS	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, E=essay, P=portfolio Teaching Format: 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:						Type of	Module:			
MAT-45-15	Toric Varieties and Mori Drea	am Spac	ces				Compuls	ory Module	with C	hoice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	-3									
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SN	WS									
Content	In the lecture Mori Dream Sp	oaces ar	e cor	nside	red a	as gene	eralisations	of toric varie	eties:		
	Geometry and combi	natorial	theor	y for	toric	varieti	es and Mori	i Dream Spa	aces.		
	Divisors on toric varie	ties and	l Mor	i Drea	am S	Spaces	-				
	Quotient representati	on and (Cox r	ing fo	r tor	ic varie	ties and Mo	ori Dream S _l	oaces.		
	Sheaves of divisorial	algebras	3.								
	Cox sheaves and cha	racteris	tic sp	ace.							
	Quotients of H-factori	al affine	varie	eties.							
	Shaded rings.										
	Varieties with torus op	peration	S.								
Objectives	Students have deepened the and methods of modern alg With the class of Mori dream varieties and their investiga added another important m geometry. The students are as well as assessing and ex In the exercise classes they be terms, statements and method new problems, to analyse the They are able to present the	ebraic of spaces tion using ethodolocapable plaining nave acquods of the mand	geomes, they no me of na the puired e lectory	etry i y hav ethoc I con aming reser a co ture. ork o	in its re be ds of npon and nted nfide Theyon so	interp come in convenient to I proving connection, pre- int, pre- int, pre- lution s	lay betweer familiar with a geometry. the interplate the esser ctions. Cise and indicate the trategies of the estimate of the strategies o	a geometry a generalis In doing s ay between Itial results of ependent ha ransfer the n n their own m in critical	and algation of the least of th	gebra. If toric have a and ecture of the s onto team.	
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Toric Varieties and Mori Dream Spaces	П Type of Course	t Status	SMS 4	α 9 ECTS	Coursework	Type of Exam or. o.	Onr. of Exam (min) 90-180 0. 20-30	ص Grading	Weight for Grade	
	In this module an exercise c examination the coursework oral is decided by the instruc	ertificate must ha	is to	be a	L cqui acqui	ired. W	hether the	examination	is writ		

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, E=essay, P=portfolio Teaching Format: 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 Groups		Type of Module: Compulsory Module with Choice								
ECTS-Points	9		Compaisory Module with Choice								
		Time in Class:	Calf Ctudy								
Workload - Time in Class - Self-Study	Workload: 270 h	90 h	Self-Study: 180 h								
Duration	1 Semester	Semester									
Frequency	not regularly	regularly									
Term	1-3										
Language of Instruction	German or English	erman or English									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	ecture 4 SWS + Ex.cl. 2 SWS									
Content	Definition and examp	les of algebraic groups.									
	Hopf algebras.										
	Operations of algebra	aic groups on varieties.									
	Linearisation of algeb	oraic groups.									
	Group closure.										
	Resolvable and nilpo	tent groups.									
	The Lie algebra of an	algebraic group.									
	Examples of Lie alge	bras.									
	Convolutions and cor	mmutators.									
	The adjoint represent	tation and its differential.									
		sition in affine algebraic grou	ups.								
	Characters of an alge										
	Semi-invariants of a r	·									
		uction of quotients with appli	cations.								
	Diagonalisable group										
	Rigidity of diagonalisa										
	Theorem of Lie-Kolch Chrysture of affine year										
	Structure of affine res		arouna								
		imple elements of algebraic	groups.								
	Borel subgroups and Structure and classifications		uio arouno								
	- Structure and Classiff	cation of semisimple algebra	iic groups.								

Other

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 onto 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Algebraic Groups	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise certificate is to be acquired as coursework. For participation i examination the coursework must have been acquired. Whether the examination is writt oral is decided by the instructor with approval by the head of the examination board.									
Literature	Possible References : • James E. Humphreys: L 1981. • Armand Borel: Linear alg					·		75. 21, Spr	inger-\	/erlag
Transfer	The module belongs to the Studenth the chosen personal Study Spectral vanced Knowledge in Mathemat requirements of the respective so The module cannot be taken too to the large overlap in content.	cialisa ics or sectio	ation <i>Ele</i> on.	, it ca ctive	an be <i>Spec</i>	includ cialisati	ed in the Se on, in accord	ections <i>Stud</i> dance with t	<i>y Focu</i> ne rest	s, Ad- rictive
Prerequisites	Knowledge of the modules Com a prerequisite for participation in							netry are he	lpful, b	ut not
Responsible Persons	Victor Batyrev, Jürgen Hausen									
Examination Type: M Teaching Format: La	Abbreviations: Grading System : g=graded, ng=not graded Examination Type : MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial,									
	=project, S=seminar, IC=inverted =obligatory, f=facultative	3.400		•						

Module Number: MAT-45-17	Module Title: Toric Geometry						Type of I	Module: ory Module	with Cl	hoice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud	ly:			
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 + Ex.cl. 2 SV	VS									
Content	 Affine toric varieties, r Fundamentals of conv Affine, complete and r Orbital layout of a tori Smoothness and sing Singularity resolution. Divisor class group ar 	 Lattice and algebraic tori. Monoids, monoidal algebras. Affine toric varieties, normality. 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 and Picard group. Intersection sheaves and homogeneous coordinates. 									
Objectives	Students have deepened the and methods of modern alge combinatorics. With the class combining algebraic geometric another important methodolor. The students are capable of assessing and explaining the lin the exercise classes they be terms, statements and method new problems, to analyse the They are able to present their	braic ge of toric try with ogical co naming or presen ave acq ods of th em and	omet varie meth ompo and pated of uired e lect to w	ry in atties a code or connection at code or c	its in and to foot to the ection of the ecti	terplay heir inv mbinat e inter e esse ss. nt, pred have lution s	between gevestigation, torics. In do play between tial results cise and independent to the trategies o	eometry and they have le ing so, they n algebra a of the lectu ependent ha ansfer the r n their own	algebrarnt a vand geo re as wandling nethods	a and vay of added metry. vell as of the sonto team.	
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Toric Geometry	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 ha	ave b	een a	acqui	ired. W	hether the	examination	is writ		

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, E=essay, P=portfolio Teaching Format: 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:		Type of Module:								
MAT-45-18	Cox Rings		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	3									
Language of Instruction	English	nglish									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	WS									
Content	Divisorial algebras.										
	Cox rings.										
	Charakteristic spaces	5.									
	Good quotients.										
	Geometric invariant the second content of the second content	neory.									
	Gale-duality.										
	Connections to toric	geometry.									
	Defining data for variegations	eties with finitely generated Co	ox ring.								
	Singularities.										
	Picard group.										
	Basis locus.										
	Ampleness.										
	Kanonical class.										
	Intrinsic quadrics.										
	 k*-surfaces. 										
	Varieties with torus ac	ction.									
Objectives	and methods of modern alg and combinatorics. They h object for investigating speci interplay between algebra a The students are capable of assessing and explaining the In the exercise classes they h terms, statements and methon new problems, to analyse the	pebraic geometry in its interplated familiarised themselves cial classes of geometric spand geometry with another implications and proving the essert presented connections. In average acquired a confident, precode of the lecture. They have learn and to work on solution s	ling of the central concepts, results ay between geometry and algebra with the Cox ring as an algebraic ces. In doing so, they expand the cortant methodological component. In the cortant methodological component as well as ise and independent handling of the cearned to transfer the methods onto trategies on their own or in a team. In defend them in critical discourse.								

Other

Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Cox Rings	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 head of the examination board.									
Literature	Possible References: • Ivan Arzhantsev, Ulrich Derenthal, Jürgen Hausen, Antonio Laface: Cox Rings. CUP 2014.									
Transfer	The module belongs to the Stud the chosen personal Study Spec vanced Knowledge in Mathemat requirements of the respective s	cialisa <i>ics</i> or	ation Elec	, it ca	an be	includ	ed in the Se	ections Stud	y Focu	s, Ad-
Prerequisites	Knowledge of commutative algebra							tent of the r	nodule	Intro-
Responsible Persons	Jürgen Hausen									
Abbreviations: Grading System : g	g=graded, ng=not graded									
Examination Type : N	MT=master's thesis, or.=oral exam	, wr.=	writte	en ex	kam,	Pr=pre	sentation, E	=essay, P=	portfoli	0
	electure, LE=lecture with integrated P=project, S=seminar, IC=inverted				.=sen	ninar oı	r lecture, E=	exercise clas	ss, T=tı	utorial,
Status : c	eobligatory, f=facultative									

Module Number:	Module Title:						Type of I		0		
MAT-45-19	Real Algebraic Geometry						Compuls	ory Module	with C	hoice	
ECTS-Points	6										
Workload - Time in Class - Self-Study	1101111001011	Time ii 60 h	n Cla	ss:			Self-Stud 120 h	ly:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	1-3									
Language of Instruction	English	English									
Forms of Teaching and Learning	Lecture 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 onto 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 Credits / Grading (Weighting 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	
	In this module an exercise cer examination the coursework m oral is decided by the instructo	iust ha	ıve b	een a	acqu	ired. W	hether the	examination	is writ		
Literature	Possible References :										
	Frederice Mangolte: Re	al Alg	ebra	c Va	rietie	s. Spri	nger 2020.				
	Robert Silhol: Real Alge	ebraic	Surf	aces	. Spr	inger 1	989.				
	Riccardo Benedetti, Je Editions Herrmann 199	an-Ja				_		nd Semi-alg	gebraic	Sets.	
	Alex Degtyarev, Viatches du côté de chez Rokhlir						properties of	of real algeb	raic vai	rieties:	

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, E=essay, P=portfolio Teaching Format : 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-45-20	Module Title: Introduction to Berkovich Geo	metry					Type of Compuls	Module:	with C	hoice	
ECTS-Points	3							•			
Workload - Time in Class - Self-Study	Workload: 180 h	Time i 60 h	n Cla	ss:			Self-Stud	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	English										
Forms of Teaching and Learning	Lecture 2 SWS										
Objectives	Non-Archimedean field Ultrametric triangle ine Affinoid domains. Berkovich affine and p Analytification of algeb The students have become fields and their induced topo challenges in developing a tl Berkovich's approach to addrline in Berkovich's framework they have encountered a type encountered in their studies familiar with the connections students are capable of name assessing and explaining the In the exercise classes they be the terms, statements and me to new problems, to analyse team. They are capable of prince the statements and me to new problems, to analyse team. They are capable of prince the statements and me to new problems, to analyse team. They are capable of prince triangle in the statements and me to new problems, to analyse team. They are capable of prince triangle in the statements and me to new problems, to analyse team. They are capable of prince triangle in the statements and me to new problems, to analyse team.	quality rojectiv raic va amiliar logy. Theory clessing condition and to algorithms are acceptable without them	and e line with They f and these tail, k metri as ve ebbraid d pro tted c equire of the and	the restaurant the re	most gain geometric the confiners confiners.	imporned anometry The stundam es, var thro essentins. dent, p They han solu	tant example understand over these udents have cally and to entally differ ieties, or mugh the analial results of the carecise and the example to example the example of th	les of non-Ading of the fields and the examined the pologically. The rent from other anifolds). The lectural independent to transferies on their	fundan nave si he proj In doi ner exa hey are functor e as w t hand the me own o	nental audied ective ng so, mples e also . The rell as ling of ethods or in a	
Requirements for obtaining Credits / Grading (Weighting if applicable)	discourse. 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	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is wr of the examination board.	itten or	oral	is de	cideo	d by the	e instructor v	vith approva	l by the	head	
Literature	Possible References : • Annette Werner: Nicht	archim	edisc	he G	ieom	etrie. \	/orlesungss	kript.			

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, E=essay, P=portfolio Teaching 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-45-21	Module Title: Algebraic Number Theory						Type of Compuls	Module: ory Module	with C	hoice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time ii 90 h	n Cla	.ss:			Self-Stud 180 h	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German	German									
Forms of Teaching and Learning	_ecture 4 SWS + Ex.cl. 2 SWS										
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 reassessing and explaining the In the exercise classes they have terms, statements and method new problems, to analyse the They are able to present their	naming presen ave acq ds of the em and	and ted c uired e lec to w	provi conne a co ture. ork c	ng thection ofide They on so	e essens. ent, pred have lution s	ntial results cise and ind learned to to strategies o	of the lectu ependent ha ransfer the n n their own	re as wandling nethods or in a	of the s onto team.	
Requirements for obtaining Credits / Grading (Weighting 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 instruct	nust ha	ive b	een a	acqu	ired. W	hether the	examination	is writ		
Literature	Possible References :										
	Jürgen Neukirch: Alge	braisch	e Za	hlent	heor	ie. Spr	inger 2007.				
	Alexander Schmidt: Ei	nführur	ng in	die a	lgeb	raische	Zahlenthe	orie. Springe	er 2007	7.	
	Andre Weil: Basic num	ber the	ory.	Sprir	nger	1995.					

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format : 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: Elliptic Functions and Elliptic	Curves					Type of	Module:	with Cl	hoice			
ECTS-Points	9						Обтраю	iony modulo					
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud	dy:					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3	1-3											
Language of Instruction	German or English												
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SWS												
Content	Elliptic functions, Weight	Elliptic functions, Weierstrass-P-function, Riemann surfaces, complex tori.											
	Plane projective curve	Plane projective curves, Theorem of Bezout, elliptic curves.											
	Curves over finite field	ds, ratio	nal po	oints.									
	Applications in crypto	graphy.											
	Additionally a selection	n of the	follov	ving:									
	- Modular forms;												
	Classification ofModuli spaces.	elliptic	curve	es;									
	Woddii spassis.												
Objectives	The students have expanded have learnt about elliptic curvicely relevance in a wide spectrum methods and results from the Theory, Topology and Cryptostand their mutual interrelation results of the lecture as well exercise classes they have act statements and methods of problems, to analyse them a are capable of presenting the	ves as a not mained discipography ns. The as assequired a the lectured to we	class them plines , whice stude essin a confiture. ork or	s of natical section of the content	nather mather ma	ematica as. The x Calc evant in apable olaining cise an re lean strateg	al objects, we students he ulus, Algebon the given of naming a the present independed to transgies on their	thich has contained studied and proving and proving the connection than the met rown or in a	mpreher the noting they uthe essentions. of the thods to	ensive otions, amber under- sential In the terms, o new They			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Elliptic Functions and Ellipti	л Type of Course	Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Curves	E	f	2	3	yes	or.	o. 20-30	g	100			
	In this module an exercise of examination the coursework oral is decided by the instruc	ertificate must ha	ave b	be a	ıcqui acqui	red. W	hether the	examination	is writ				

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, E=essay, P=portfolio Teaching Format: 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 Number	er The	ory				Type of I	Module: ory Module	with C	hoice	
ECTS-Points	3										
Workload - Time in Class - Self-Study		Time ii 30 h	n Cla	ss:			Self-Stud	ly:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	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 Credits / Grading (Weighting if applicable)	Title Introduction to Analytic Num	т Type of Course	ъ Status	SMS 2	ω ECTS	o Coursework	Type of Exam o. o. or.	Dur. of Exam (min)	ص Grading	Weight for Grade	
	ber Theory Whether the examination is wri of the examination board.	tten or	oral	is de	cideo	d by the	instructor w	o. 20-30 vith approva	l by the	e head	
Literature	Possible References : • Komaravolu Chandrase	kharar	n: Int	rodu	ction	to Ana	lytic Numbe	r Theory. S	pringe	r 1968.	
Transfer	The module belongs to the <i>S</i> Differential Geometry. Taking be included in the Sections <i>S</i> Specialisation, in accordance	into a tudy F	ccou ocus	nt th	e cho vanc	osen p ed Kno	ersonal Stu owledge in I	dy Specialis Mathematic	sation, s or E	it can <i>lective</i>	
Prerequisites	There are no further prerequis	ites									
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, E=essay, P=portfolio Teaching Format: 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: Elliptic Curves and Cryptogr	anhy					Type of	Module:	with C	hoico			
ECTS-Points	9	арпу					Compuis	ory wodule	Willi	HOICE			
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in Cla	ISS:			Self-Stud	dy:					
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 + Ex.cl. 2 SWS												
Content	Symmetric cryptosyst	 Basic concepts of cryptography. Symmetric cryptosystems, public key systems, discrete logarithm, RSA. Factorisation into primes, attacks on cryptosystems. 											
	Factorisation into primes, attacks on cryptosystems.												
	Basic concepts of pla			geor	netry	/ .							
	Elliptic curves as Abe												
	Curves over finite field						•	J					
	Counting points, Hass Cryptopystoms on all				-		_	oritrim.					
	Cryptosystems on ell	iptic cui	ves, a	aigori	ums	a a lu a	llacks.						
Objectives	Students are familiar with the cryptographically motivathe advanced algebraic and the challenges of algorithmistudents are capable of natassessing and explaining the In the exercise classes they be terms, statements and methonew problems, to analyse the They are able to present the	ated que d geom c imple ming ar e presen nave acc ods of the nem and	estion etric menta nd pro nted o quired ne lec d to w	s relation ation oving connection a content to the	ating and the ection nfide They	to ellipes for a are far essentes. ent, predution s	otic curves answering to miliar with strict with strict and industrial results consisted and industrial to the strategies of the strategie	and have and hem. They tandard algorithm lecture ependent har ansfer the non their own	n insight under orithms e as wandling nethods or in a	of the sonto team.			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Elliptic Curves and	☐ Type of Course	J Status	SMS 4	e ECTS	Sework	Type of Exam	Dur. of Exam (min)	Grading a	Weight for Grade			
	Cryptography	Е	f	2	3	, 500	or.	o. 20-30	9	.00			
	In this module an exercise c examination the coursework oral is decided by the instruc	must h	ave b	een a	acqu	ired. W	hether the	examination	i is writ				

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, E=essay, P=portfolio Teaching Format: 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:Type of Module:Elliptic Curves and Taniyama-ShimuraCompulsory Module with Choice											
ECTS-Points	9											
Workload - Time in Class - Self-Study		ime i	n Cla	ISS:			Self-Stud	dy:				
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 + Ex.cl. 2 SWS											
Content	A selection of the following top	cs wil	l be	cove	red:							
	Group-law, arithmetic of	ellipti	c cu	ves.								
	Modular curves and forr	ns.										
	Riemann surfaces, abel	an dif	ferer	ntials	, Jac	obian.						
	 Geometric version of T explained. 	aniyaı	ma-S	Shimu	ıra-c	onjectu	ure (i.e. Wil	es' modular	ity the	orem)		
	Connection to Fermat's	last th	neore	m.								
	• L-series.											
Objectives	The students have learnt and using and geometry to answer profour of Taniyama-Shimura and its a capable of naming and proving explaining the presented connecurrent state of research in the In the exercise classes they have terms, statements and methods new problems, to analyse them.	nd mapplications the constitutions the constitution that constitutions the constitutions the constitution that constitutions the constitutions the constitution that constitut	athen ation esse s. Stu ect ar uired e lec to w	natica to th ntial udent ea. a co ture. ork c	al que e pro resu s wil nfide They on so	estions oof of F Its of th I be able ent, pred I have	using the effermat's the ne lecture a le to reflect cise and ind learned to trattagies o	xample of the corem. The swell as as and critically ependent har ansfer the non their own	ne conjustudent sessint analy andling nethod or in a	ecture ts are g and se the of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting 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-	L	f	4	6	yes	wr. o.	90-180	а	100		
	In this module an exercise cert examination the coursework m	Shimura E 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 head of the examination board.										
Literature	Possible References :											
	Joseph H. Silverman: T	ne Ari	thme	etic of	f Ellip	otic Cui	rves. Spring	jer 2009.				

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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-45-29	Module Title: Introduction to Modular Forms							Module: ory Module	with C	hoice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h										
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS										
Content	Gauss, Eisenstein and Rama have many surprising applicat four square theorem and the course aims to give an introdu • Modular forms for the N • Examples: Eisenstein s • Arithmetic applications	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 basic forms. They are familiar with The students are capable of as assessing and explaining toritically analyse the current so	analyt naming he pre	ical, g and sent	algel I prov ed co	oraic /ing onne	and g the es ctions.	eometric as sential resul Students w	pects of mo	dular cture a	forms. s well	
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Modular Forms Whether the examination is wri		f oral	2 is de	3 cideo	no d by the	wr. o. or.	90-180 o. 20-30 vith approva	g I by the	100 head	

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: Grading System : g=graded, ng=not graded Examination Type: MT=master's thesis or =oral exam wr =written exam Pr=presentation F=essay P=portfolio					

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format : 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 TheoryCompulsory Module with Choice											
ECTS-Points	3											
Workload - Time in Class - Self-Study		Time i 30 h	ime in Class: 0 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											
Content	can be described as her Crow structure of of a number field, through a deep understandin notions and concepts of Class problem of what primes can be theory to modern number them. • The theory of Quadratic. • Generalisations of the structure o	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 law of quadratic reciprocity. • Arithmetic in number fields and the Hilbert Class field. • A statement of Artin Reciprocity, and a solution to the problem of describing primes of the form $x^2 + ny^2$.										
Objectives	Students have learned the four of class field theory in the car on understanding of where the students are capable of name assessing and explaining the critically analyse the current s	se of ese coing an	quad ncep d pro ented	ratic its co ving con	field me f the nect	exten from the essentions.	sions of Q, rough an ele tial results of Students wil	and have a ementary ex of the lectur	very xample e as w	hands e. The vell as		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Primes of the form $x^2 + ny^2$	г Type of Course	4 Status	SMS 2	ω ECTS	o Coursework	Type of Exam o. o. or.	Onr. of Exam (min) 90-180 o. 20-30	ص Grading	0 Weight for Grade		
	and Class Field Theory Whether the examination is wr of the examination board.	tten or	oral	is de	cided	by the	instructor v		l by the	head		
Literature	Possible References : • David Cox: Primes of the form $x^2 + ny^2$. Wiley 2013, • James Milne: Class field theory. Online Notes 2020. • 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 : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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	Type of I	Module: ory Module	with C	hoice							
ECTS-Points	6	6										
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h											
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SV	VS										
Content	Groups and group ac	tions.										
	Representations, irred	ducibilit	ty, Scl	nursc	h's le	emma.						
	Semisimplicity, Masch	nke's th	eorer	n.								
	Characters, orthogon	ality rel	ation	S.								
	 Isotypical decomposit 	ion, ch	aracte	er tab	les.							
	Representations of th	e symn	netric	grou	p.							
	Semi-simple Artinian	algebra	as.									
Objectives	In the lecture, students learn understanding for the interact are capable of naming and p explaining the presented cor In the exercise classes they he terms, statements and method new problems, to analyse the They are able to present the	etion of roving to the control of th	geom the es ns. quired he led d to v	etric sentia d a co cture.	and a al res nfide They on so	algebra sults of ent, pred have l	tic methods. the lecture a cise and indicarned to trategies o	methods. as well as as well as as ependent has ansfer the non their own	The stu ssessing andling nethods or in a	of the sonto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Representation Theory of	L	f	2	3	yes	wr. o.	90-180	g	100		
	Finite Groups	E	f	2	3	, 50	or.	o. 20-30	9			
	In this module an exercise context examination the coursework oral is decided by the instruc	must h	nave b	een a	acqu	ired. W	hether the	examination	i is writ			

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:		Type of Module:					
MAT-45-40	Introduction to Combinatoria	al Birational Geometry	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 + Ex.cl. 2 S	WS						
Content	 map for surfaces <i>X</i> or divisors. The divisors. Cartier divisors, line variety. Ample and veriety. Ample and veriety. Nondegenerate algebrate modification of surface. The cone of curves transformations. Desingularization of a Combinatorial construction. Cyclic quotient surface. Finite subgroups of <i>S</i> ization. Birational classification the Fine interior <i>F</i>(Δ). The Kodaira dimension models of nondegeneral. 	over the complex numbers. The class group $Cl(X)$ and the bilist bundles, invertible sheaves. But ample divisors. Oraic curves in toric surfaces. Ease via blow ups and blow down of a surface. The Zariski demondegenerate curves D on structing minimal models of pairs the singularities and their combes $U(2)$ and surface Du Val singularities of their Newton polytopes Δ sion of algebraic varieties. Consider the bilines of the complex considerable of the considerabl	ecomposition. Birational Cremona mooth toric surfaces X via blow ups. $S(X,D)$ for normal toric surfaces X inatorial minimal desingularization. Iarities and their minimal desingularies in 3-dimensional toric varieties via combinatorial constructing minimal					
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 onto 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.							

Other

Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Combinatorial Birational Geometry	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100
	——————————————————————————————————————	E	f	2	3		OI.	0. 20-30		
	In this module an exercise certif examination the coursework mu oral is decided by the instructor	st ha	ve b	een a	acqu	ired. W	hether the	examination	is writ	
Literature	Possible References :									
	 Laurent Buse, Fabrizio C History of Shapes. Spring 			Elisa	Pos	tinghel	: Algebraic	Curves and	Surfac	es: A
	Klaus Hulek: Elementare	Alge	brais	sche	Geo	metrie.	Springer 20	012.		
	 Tadao Oda: Convex Bodi Toric Varieties. Springer Robin Hartshorne: Algeb 	1988	•				•	duction to th	ne The	ory of
Transfer	The module belongs to the Stude the chosen personal Study Spectral Vanced Knowledge in Mathematic requirements of the respective states.	cialisa ics or	ation Elec	, it ca	ın be	includ	ed in the Se	ections Stud	y Focu	s, Ad-
Prerequisites	Knowledge of commutative algebrancepts from these areas are be								the ess	ential
Responsible Persons	Victor Batyrev									
Abbreviations: Grading System : g=graded, ng=not graded										
1	IT=master's thesis, or.=oral exam,							-		
P	=lecture, LE=lecture with integrated =project, S=seminar, IC=inverted				=ser	ninar o	r lecture, E=	exercise clas	ss, T=ti	utorial,
Status : o	obligatory, f=facultative									

Module Number: MAT-45-41	Module Title: Introduction to Combinatoria	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	German or English						
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SV	NS					
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 Calaborellexive polyhedra. 	oi-Yau varieties as hypersurfac	es in toric varieties associated with				
	 A combinatorial form correspondence. 	ula for Hodge numbers of Ca	labi-Yau 3-folds. Monomial-divisor				
	Combinatorial mirror of Calabi-Yau varieties.	construction for Calabi-Yau cor	mplete intersections. Mirrors of rigid				
	Computation of period functions.	ds of Calabi-Yau hypersurfaces	s using generalized hypergeometric				
	Stringy Hodge number	ers of singular Calabi-Yau varie	eties.				
	 Moduli spaces. Bour secondary polytopes. 		s of Calabi-Yau hypersurfaces and				
	Computation of Grom	nov-Witten invariants of Calabi	-Yau complete intersections.				
	A combinatorial appro	oach to Berglund-Hübsch mirro	or symmetry.				
	based on polar duality in the the most famous examples dodecahedron. In combinat considered reflexive polyhereflexive polyhedra Δ^* belo lattice of characters of an a one-parameter subgroups in the theory of toric varieties. symmetry discovered by phy N and from Δ to Δ^* . The aim of the module is to example of the subgroup	module is to explain the connection between reflexive polyhedra and Calabi-Yau ne most understandable way possible and to inform students about further results					

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 onto 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. (min) Weight for Grade Type of Course Requirements Dur. of Exam Type of Exam Coursework for obtaining Credits / Grading Grading Status (Weighting if ECTS SWS applicable) Title f 2 3 L Introduction to Combinatorial 90-180 wr. o. yes 100 g Mirror Symmetry o. 20-30 or. 2 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 head of the examination board. 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., 168:3 (1995), 493-533. Victor Batyrev and Lev A. Borisov: Dual cones and mirror symmetry for generalized Calabi-Yau manifolds. Mirror Symmetry II, AMS/IP Stud. Adv. Math. 1, Amer. Math. Soc., Providence, RI (1997), 71-86. David Cox, Sheldon Katz: Mirror Symmetry and Algebraic Geometry. Mathematical Surveys and Monographs, Vol. 68, AMS, 1999. · Israil Gelfand, Mikhail Kapranov, Andrei Zelevinsky: Discriminants, Resultants and Multidimensional Determinants. Springer-Birkhäuser 1994. Masao Jinzenji: Classical Mirror Symmetry. SpringerBriefs in Mathematical Physics, Band 29, 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. **Prerequisites** Knowledge of the modules Commutative Algebra and Algebraic Geometry are assumed. Responsible Victor Batyrev **Persons**

Abbreviations:

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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: Tropical Geometry							Module:	with C	hoice	
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	1-3									
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	Lecture 4 SWS + Ex.cl. 2 SWS									
Content	Tropical numbers and	polyno	mials								
	Tropical hypersurface	s and v	arietie	es.							
	Tropical toric varieties										
	Matroid fans and trop	ical abs	stract	varie	ties.						
	Tropical modifications	, stable	inter	section	ns a	ınd rati	onal equiva	lence.			
	Tropical curves and lii	near sy	stems	S.							
	• Tropical (p,q) -homolo	gy.									
	Correspondence thec	rems.									
Objectives	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 discourse.										
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Tronical Geometry	Type of Course	L/A	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	00 Weight for Grade	
	Tropical Geometry	Е	f	2	3	yes	or.	o. 20-30	g	100	
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	ave b	een a	acqu	ired. W	hether the	examination	is writ		

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, E=essay, P=portfolio Teaching Format: 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:						Type of				
MAT-50-04	Tropical Enumerative Geome	Tropical Enumerative Geometry Compulsory Module with Choice									
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	iss:			Self-Stud 180 h	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	1-3									
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	WS									
Content	Enumerative geometr	y of alg	ebrai	c cur	ves,	in parti	cular in the	plane.			
	Tropical enumerative	problem	ıs and	d mul	tiplic	ities.					
	Combinatorial method	ds, floor	diag	rams	and	lattice	paths.				
	Correspondence thec	rems fo	r cur	ves ir	the	plane	through give	en points.			
	Tropical and classic G	Gromov-	Witte	n the	ory i	n genu	s 0.				
	Real counts, Welschi	nger inv	arian	ts an	d pol	ynomia	al invariants				
	Hurwitz numbers.										
	Tropical corresponder	nces for	Hurv	vitz n	umbe	ers.					
	Real Hurwitz numbers	s and Zi	gzag	num	bers.						
Objectives	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 discourse.										
Requirements for obtaining Credits / Grading (Weighting 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 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 ha	ave b	een a	acqui	ired. W	hether the	examination	is writ		

Literature	Possible References: • Grigory Mikhalkin, Johannes Rau: Tropical geometry. Manuscript 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.
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, E=essay, P=portfolio Teaching Format: 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-50-05	Module Title: Introduction to Tropical Enum	Type of Module: Compulsory Module with 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 + Ex.cl. 1 SW	Lecture 2 SWS + Ex.cl. 1 SWS								
Content	Enumerative geometry	of alge	ebraio	cur	ves,	in parti	cular in the	plane.		
	Tropical enumerative p	roblem	s and	d mul	tiplic	ities.				
	Combinatorial methods	s, floor	diagr	ams	and	lattice	paths.			
	Correspondence theor	ems for	curv	es ir	n the	plane	through give	en points.		
	Real counts, Welsching	ger inva	arian	s an	d pol	ynomia	al invariants			
Objectives	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 discourse.									
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Introduction to Tropical Enu-	L	f	2	3	yes	wr. o.	90-180	g	100
	In this module an exercise ce examination the coursework roral is decided by the instruct	nust ha	ıve b	een a	acqu	red as ired. W	hether the	examination	pation is writ	in the
Literature	Possible References :				-					
	Grigory Mikhalkin, Joh	annes I	Rau:	Trop	ical (geome	try. Manusc	ript 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, E=essay, P=portfolio Teaching Format: 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 Cho									hoice
ECTS-Points	5									
Workload - Time in Class - Self-Study	1101111001011	Time in Class: Self-Study: 105 h						dy:		
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 + Ex.cl. 1 SW	S								
Content	Plane curves of higher	genus								
	Multiplicities.									
	Welschinger invariants.									
	 Lattice paths. 	Lattice paths.								
	Floor diagrams.	Floor diagrams.								
	 Hurwitz numbers. 									
	Tropical moduli spaces.									
Objectives	The students deepen their knowledge on the combinatorics of plane tropical curves. They get acquainted with various methods to enumerate tropical curves, as well as with various enumerative problems which can be solved with the aid of tropical 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 discourse.									
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Tropical Enumerative Geome	- L	f	2	3	yes	wr. o.	90-180	g	100
	try - Part 2	Е	f	1	2	you	or.	o. 20-30	9	100
	In this module an exercise cer examination the coursework noral is decided by the instructor	nust ha	ave b	een a	acqu	ired. W	hether the	examination	is writ	
Literature	Possible References :									
	Diane Maclagan, Berno Grigory Mikhalkin, Joha							-	2015.	

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 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, E=essay, P=portfolio Teaching Format: 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							Module: ory Module	with C	hoice
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 + Ex.cl. 2 SWS									
Content	 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 deeper they have exemplarily experi students are capable of nam assessing and explaining the In the exercise classes they I the terms, statements and more to new problems, to analyse	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 Credits / Grading (Weighting 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	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the head of the examination board.								

Other

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
Abbreviations: Grading System	g=graded, ng=not graded
Examination Type	: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
Teaching Format	: 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
1	and the control of th

Module Number: MAT-50-12	Module Title: Information Geometry						Type of I	Module: ory Module	with C	hoice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time ii 30 h	n Cla	ss:			Self-Study: 60 h				
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	3									
Language of Instruction	German	erman									
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS									
Content	ships for parametric sta	 Foundations of Information Geometry (e.g. Fisher information metrics and dual relationships for parametric statistical models, Kullback-Leibler divergence, natural gradient). Application to neural data processing (in particular supervised learning in artificial neural networks). 									
Objectives	to problems in information th	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 Credits / Grading (Weighting 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 wr of the examination board.	itten or	oral	is de	cideo	d by the	e instructor v	vith approva	l by the	head	
Literature	Possible References :										
	Shun-Ichi Amari, Hiros	hi Naga	aoka	: Me	thods	s of Info	ormation Ge	ometry. AM	IS 200	1.	
	Anthony C. C. Coolen Processing Systems. (, Reim DUP 20	er K 05.	uehr	ı, Pe	ter So	llich: Theor	y of Neura	Inforn	nation	
	• Shun-Ichi Amari: Natu 1998.	ral Gra	dien	t wor	ks E	fficient	ly in Learniı	ng. Neural (Compu	ıtation	
	Yann Ollivier: Riemar Information and Inferer				r Ne	ural N	etworks I -	Feedforwa	rd Net	works.	
Transfer	The module belongs to the Stutial Geometry and Stochastics can be included in the Section Specialisation, in accordance	. Taking s <i>Stud</i> j	g into	acce sus, A	ount [:] A <i>dvai</i>	the cho	osen persona Inowledge in	al Study Spe Mathematic	ecialisa es or E	tion, it <i>lective</i>	
Prerequisites	Basic knowledge from differer geodesics) and from stochast				Riema	annian	metrics, cor	nnections a	nd curv	/ature,	

Responsible Persons	Christoph Bohle
, , ,	=graded, ng=not graded
Examination Type : N	IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, leproject, 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-50-13	Module Title: Information Geometry and Net	ıral Da	ata P	roces	ssing	ı 2	Type of I	Module: ory Module	with C	hoice	
ECTS-Points	3										
Workload - Time in Class - Self-Study		Γime iι 30 h	n Cla	ss:			Self-Study: 60 h				
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German										
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS									
Content	 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 of to problems in information theorems in the results of the lecture and they	ry and	d stat	istics	s. Th	e stude	ents can nar				
Requirements for obtaining Credits / Grading (Weighting 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 writed the examination board.	ten or	oral	is de	cideo	d by the	instructor v	vith approva	l by the	e head	
Literature	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 1998. Yann Ollivier: Riemannian Metrics for Neural Networks I - Feedforward Networks. Information and Inference, IMA 2015.										
Transfer	The module belongs to the Si Differential Geometry. Taking be included in the Sections S Specialisation, in accordance of	into a tudy F	ccou ocus	nt th , <i>Ad</i>	e cho vanc	osen p ed Kno	ersonal Stu owledge in I	dy Specialis Mathematic	sation, s or E	it can <i>lective</i>	
Prerequisites	The module Information Geom	etry a	nd N	eura	l Dat	a Proc	essing 1 is a	a prerequisi	te.		

Responsible Persons	Christoph Bohle
Abbreviations: Grading System : g	=graded, ng=not graded
Examination Type : M	IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
	electure, 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-50-14	Module Title: Mathematical Aspects of Dee	o Learı	ning	1			Type of I	Module: ory Module	with C	Choice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time i	n Cla	ISS:			Self-Study: 60 h				
Duration	1 Semester										
Frequency	not regularly	ot regularly									
Term	1-3	3									
Language of Instruction	German	erman									
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS									
Content	descent. Probabilistic science. • Classical architectures)supervised learning m • Transformer models, a applications in natural	 Artificial neural networks and their training using backpropagation/stochastic gradient descent. Probabilistic interpretation. Mathematical problems arising in neural network science. Classical architectures for computer vision (CNNs) and sequential data (RNNs). (Self-)supervised learning methods. Transformer models, a modern architecture based on the attention mechanism, and its applications in natural language processing (GPT) and computer vision. Simple neuroscience models for neural networks. Biological plausibility of backpropaga- 									
Objectives	The students have learned th networks and biologically mo architectures and mathematic	re plau al que	ısible stior	e alte is ari	rnati sing	ves. T	hey are fan framework.	niliar with co The studen	ontem ts can	porary name	
Requirements for obtaining Credits / Grading (Weighting if applicable)	and prove the central results of	Type of Course	Status	e and	ECTS STORY	Coursework Coursework	Type of Exam Exam Line of Example 2 and Example	Dur. of Exam (min)	Grading	Weight for Grade	
	Mathematical Aspects of Deel Learning 1) L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is wr of the examination board.	itten or	oral	is de	cided	by the	instructor v	vith approva	by the	e head	
Literature	Possible References: Ian Goodfellow, Yoshua Bengio, Aaron Courville: Deep Learning. MIT 2016. Simon J. D. Price: Understanding Deep Learning. MIT Press 2023. Christopher M. Bishop, Hugh Bishop: Deep Learning - Foundations and Concepts. Springer 2024.										
Transfer	The module belongs to the Stutial Geometry und Stochastik. can be included in the Section Specialisation, in accordance	Taking s <i>Stud</i>	into <i>y Fo</i> d	acco cus, A	unt t A <i>dvai</i>	he cho nced K	sen persona nowledge in	al Study Spe Mathematic	cialisa s or E	ition, it <i>lective</i>	

Prerequisites	Basic Concepts of Mathematics (Analysis 1+2, Linear Algebra, Stochastics) are assumed.							
Responsible Persons	Christoph Bohle							
Abbreviations: Grading System : g=graded, ng=not graded								
Examination Type : I	MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio							
Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class P=project, S=seminar, IC=inverted classroom								
Status : c	p=obligatory, f=facultative							
Other : I	n=hours, o.=or, s.M.=see module description, SWS=contact hours per week							

Module Number:	Module Title:						Type of I	Module:					
MAT-50-15	Introduction to Riemann Sur	faces					Compuls	ory Module	with C	hoice			
ECTS-Points	5	T											
Workload - Time in Class - Self-Study	Workload: 150 h	Time 45 h	ie in C า	lass:			Self-Stud 105 h	dy:					
Duration	1 Semester	Semester											
Frequency	not regularly	ot regularly											
Term	1-3	-3											
Language of Instruction	German or English	German or English											
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 1 SV	ecture 2 SWS + Ex.cl. 1 SWS											
Content	Coverings and fundar	Coverings and fundamental groups.											
	Topological classifica	tion of	f the s	surfac	es.								
	Theorem of Riemann	-Hurw	vitz.										
	Differential forms and	l integ	ration	١.									
	Sheaves and cohomo	ology.											
	Theorem of Riemann	-Roch	٦.										
	Serre duality.												
	Kobayashi metric.												
	Theorem of Picard.												
Objectives	Students develop an approabased on local-to-global rea of rigidity resulting from an fundamental questions natu these can ultimately be used interrelated and in many cas proving the essential results connections. Students will be in the subject area.	asonin alytica urally d to an ses mu s of the	ng. In al prop lead in nswer utually e lectu	the copertient to income the depth of the de	oncers. Us reasi ions. ender well	ot of ho sing the ngly ab They le t. The s as asse	lomorphy, the sheaf constract concearn how gestudents are essing and e	hey grasp the cept, stude ceptualisation cometry and ce capable of explaining the cepture.	ne prin nts se ons and analys namir ne pres	ciples e how d how sis are ig and ented			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	1	Type of Course	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Introduction to Riemann Surfaces		L 1	f 2 f 1	3 2	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 instru module may exceptionally be points will be awarded for th	must octor we offere	t have with ap ed by t	been pprovi the le	acqual by cturer	ired. W the hea withou	hether the and of the ex	examination amination b	is writ	ten or – The			

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, E=essay, P=portfolio Teaching Format: 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						Type of Compuls	Module: ory Module	with C	hoice	
ECTS-Points	6										
Workload - Time in Class - Self-Study		Time ii 60 h	n Cla	ss:			Self-Stud	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	-3										
Language of Instruction	English	nglish									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SW	ecture 2 SWS + Ex.cl. 2 SWS									
Content	Riemannian manifolds.										
	Geodesics.										
	Curvature.										
	Geometry of submanife	lds.									
Objectives	The students have learned a manifolds from a classical poir. The students were exposed sufficient to study their role in notions of curvature was de differential geometry was ac prove the essential statements developed in the lecture and critically challenge the current Through homework assignment and independent acquaintance lectures. They learn how to to develop solution strategies solutions and to stand for ther	t of vieto import of the impor	w. In ortar rent and by in the concept into the concept the concep	addi at geo areas the e ex pts fi a lan earce rcise notio se m n an	tion, omet so of control stud erciserom frequency the class ons, so ethood wit	topics of the to	related to go ults involving itial geome and familiaritions. They ure as well vork. They a edific area. udents deve ents, and m ew problem roup. They	eodesics weing geodesic try. Intuition ty with comey are able to as to explain are able to come elop a confice tethods explains, to analystare able to	re discress which for various name in the collescribulent, practical and the collections are the collections.	ussed. th are arious ons in e and ontext e and recise, in the m and	
Requirements for obtaining Credits / Grading (Weighting 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	g	100	
		E	f	2	3		or.	o. 20-30			
	In this module an exercise cer examination the coursework r oral is decided by the instructor	nust ha	ive b	een a	acqu	ired. W	hether the	examination	is writ		
Literature	Possible References :										
	John M. Lee: Riemann Barret O'Neill: Semi-R Press 1983.										

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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						
Language of Instruction	English						
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	WS					
Content	group. The course will focus discrete counterparts. Origin during a famous horse ride a and the underlying theory in A fundamental idea for under as spectrum preserving defocase symmetric matrices. We study an important class geometric) solutions. This class urface theory and classical surface theory, and spectral upon an integrable systems. The KdV equation is related interpreted as a dynamical syrelated to the geometry of Li lecture are related to the geolin a sequel to the lecture, it	on equations related to the Korally a mathematical model for along a canal, equations of Kd' volves various mathematical derstanding and solving KdV ty ormations of underlying auxilia of explicit solutions that include ass of solutions can be describ mechanics. The relevant part theory will be explained in the interpretation of the QR-algorid to geometry in several different on the space of parametric e algebras and Lie groups; the ometry of Riemann surfaces is planed to explain how infinitions.	pe equations is their interpretation ry linear operators - in the simplest as solitons and finite gap (or algebroded using a combination of Riemann is of classical mechanics, Riemann is electure. We will also briefly touch thm of numerical linear algebra. Frent ways: for example, it can be rized curves in the plane; it is deeply a special solutions discussed in the				
Objectives							

Other

Requirements for obtaining Credits / Grading (Weighting 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 3	yes	wr. o. or.	90-180 o. 20-30	g	100	
Literature	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 head of the examination board.										
Literature	Possible References :										
	 Olivier Babelon, Denis Betems. CUP 2004. 	Olivier Babelon, Denis Bernard, Michel Talon: Introduction to classical integrable systems. CUP 2004.									
	Leonid A. Dickey: Soliton	Leonid A. Dickey: Soliton equations and Hamiltonian systems. World Scientific 2003.									
	Alan C. Newell: Solitons i	in ma	then	natics	s and	d physic	cs. SIAM 19	85.			
	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 Stuferential Geometry and Mathe Study Specialisation, it can be in Mathematics or Elective Special respective section.	<i>matic</i> nclude	<i>al P</i> ed in	<i>hysio</i> the	s. Secti	Taking ions <i>St</i>	into accou	nt the chos Advanced k	en per <i>(nowle</i>)	rsonal dge in	
Prerequisites	The module Introduction to Com Basic knowledge of differential necessary.										
Responsible Persons	Christoph Bohle, Frank Loose										
Examination Type : M	=graded, ng=not graded T=master's thesis, or.=oral exam, =lecture, LE=lecture with integrated								•		

Module Number: MAT-50-18	Module Title: Integrable Systems (and Infin	ite Dime	ensior	nal Li	e Alg	jebras)	Type of Compuls	Module: ory Module	with C	hoice		
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	in Cla	iss:			Self-Stud	dy:				
Duration	1 Semester	1 Semester										
Frequency	not regularly	not regularly										
Term	1-3											
Language of Instruction	English											
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	VS										
Content	group. The course will focus discrete counterparts. Origin during a famous horse ride a and the underlying theory in A fundamental idea for under as spectrum preserving defocase symmetric matrices. 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 can nnection have ad ethods e them	name ns. cquire of the and	e and ed a d e lect to wo	provention proving pro	ve the dent, p They hon solu	central resul recise and ave learned tion strateg	ts of the lect independen I to transfer ies on their	ture an t hand the me own c	d they ling of ethods or in a		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Integrable Systems (and Infinite Dimensional Lie Algebras)	п Type of Course	t Status	SMS 4 2	8 9 ECTS	Sex	Type of Exam or. o.	Onr. of Exam (min) 90-180 0. 20-30	ص Grading	Weight for Grade		
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the head of the examination board.											

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
Abbreviations:	

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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-50-19	Module Title: Mathematical Aspects of Deep	Learr	ning :	2			Type of I	Module: ory Module	with C	hoice
ECTS-Points	3									
Workload - Time in Class - Self-Study		Time ii 30 h	n Cla	ss:			Self-Stud	ly:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS								
Content	Search and reinforceme Towards multimodal lar and draw and allow cor Uses of neural networks simulation, inverse prol	 Mechanisms behind (mathematical) reasoning in large language models (like GPT o1). Search and reinforcement learning. Towards multimodal large language models: how to make large language models see and draw and allow comprehension and creation of images. Uses of neural networks in applied mathematics (engineering) e.g. modeling with PDEs, simulation, inverse problems. For example physics informed neural networks, neural operators, 3d reconstruction from 2d images. 								
Objectives	Students are familiar with some current problems in Deep Learning and with applications within or with relevance to Mathematics. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.							ng the		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Mathematical Aspects of Deep Learing 2	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100
	Whether the examination is wri of the examination board.	tten or	oral	is de	cideo	d by the	instructor v	vith approva	l by the	head
Literature	Possible References :									
	Ian Goodfellow, Yoshua	Beng	io, Aa	aron	Cou	ville: [eep Learnii	ng. MIT 201	6.	
	Simon J. D. Price: Unde	erstand	ding	Deep	Lea	rning.	MIT Press 2	2023.		
	Christopher M. Bishop Springer 2024.	, Hugh	n Bis	hop:	Dee	ep Lea	rning - Fou	ndations ar	nd Con	cepts.
Transfer	The module belongs to the Stutial Geometry und Stochastik. can be included in the Sections Specialisation, in accordance	Taking Study	into <i>Foc</i>	acco sus, A	unt t A <i>dvai</i>	he cho nced K	sen persona nowledge in	al Study Spe Mathematic	ecialisa es or <i>E</i>	tion, it <i>lective</i>
Prerequisites	In terms of content, the mod prerequisite.	lule M	athe	matio	cal A	Aspects	of Deep L	earning 1	modul	e is a

Responsible Persons	Christoph Bohle								
Abbreviations: Grading System : g	Grading System : g=graded, ng=not graded								
Examination Type : M	IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio								
	electure, 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-50-22	Module Title: Algebraic Topology 2						Type of	Module:	with Cl	hoice		
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time i	in Cla	ss:			Self-Stud	dy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	VS										
Content	Further development	of singu	ılar ho	omolo	ogy t	heory.						
	Simplicial complexes	and the	ir sim	plicia	ıl hor	nology						
	CW spaces and their	CW spaces and their cellular homology.										
	Axiomatic homology.											
	Homological algebra.											
	Cohomology.											
	 Homology and Cohon 	nology v	with c	oeffic	cients	S.						
	Product structures in	homolo	gy an	d coł	nomo	ology.						
	The Poincaré duality t	heorem	for to	polo	gical	l manifo	olds.					
Objectives	The students extend their a constructions. They deepen the even technically very challer essential results of the lecture. In the exercise classes they have terms, statements and method new problems, to analyse the They are able to present their	heir knouging tast e as we ave accords of the	owledgesks. The last as a	ge in The s asses a co ture. ork o	abst tude ssing nfide They n so	ract mants are and example of the and example of the area of the a	athematical capable of capable of capable of capable the cise and ind earned to treategies o	disciplines to naming and presented ependent har ansfer the non their own	accord provir connecting andling nethods or in a	nplishing the ctions. of the sonto team.		
Requirements for obtaining Credits / Grading (Weighting 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	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this madula an arrain	E	f f	2	3	rod			not!:-	in +l= -		
	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 head of the examination board.										

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, E=essay, P=portfolio Teaching Format: 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						Type of Compuls	Module: ory Module	with C	hoice
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h	Time ii 30 h	n Cla	ss:			Self-Stud	dy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	A selection of the following to	pics wil	l be	cover	ed:					
	Basic concepts of hor	notopy t	heor	y;						
	 Homotopy group of sp 	heres;								
	Spectral sequences;									
	K-theory;									
	Characteristic classes.									
Objectives	With the in-depth knowledge introduced to current areas of which can lead to a Master possible doctorate in algebra essential results of the lecture	of resea s thesis ic topolo	rch a s, for ogy.	nd the examing The s	ney ta mple stude	ackle a . They ents are	small resear will also late capable of	arch projectay the foun naming an	t thems dations d provi	selves, s for a ng the
Requirements for obtaining Credits / Grading (Weighting 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	be expl	aine	d by t	he e	xamine	er at the beg	jinning of th	e cour	se.
Literature	Possible References :									
	Allen Hatcher: Algebra	aic topo	logy.	Cam	nbrid	ge Univ	ersity Pres	s 2009.		
	Allen Hatcher: Vector	bundles	and	K-th	eory.	Manu	skript 2009.			
	 John W. Milnor, Jame 1974. 	s D. Sta	shef	: Ch	aract	eristic	classes. Pr	inceton Uni	versity	Press
		res on th	ne h-	coboi	rdism	theore	em. Princeto	on Universit	y Press	1965.
Transfer	Differential Geometry. Takin be included in the Sections	John W. Milnor: Lectures on the h-cobordism theorem. Princeton University Press 1965. 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.								it can <i>lective</i>

Prerequisites In terms of content, the modules Algebraic Topology 1 and 2 are prerequisite for participati in this module.							
Responsible Persons Frank Loose							
"	graded, ng=not graded IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio						
Teaching Format : 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-50-25	Module Title: Applied topology 1						Type of I	Module: ory Module	with C	hoice
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h	Time ii 30 h	n Cla	ss:			Self-Stud	ly:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3	1-3								
Language of Instruction	German	German								
Forms of Teaching and Learning	Lecture 2 SWS									
Content	Simplicial complexes a	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 Credits / Grading (Weighting 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 wi of the examination board.	itten or	oral	is de	cideo	d by the	instructor w	vith approva	by the	head
Literature	Possible References: Herbert Edelsbrunner, John L. Harer: Computational Topology. AMS 2010. Robert Ghrist: Elementary Applied Topology. Create Space 2014. Sergey V. Matveev: Lectures on Algebraic Topology. EMS 2006.									
Transfer	The module belongs to the s Geometry and Stochastics. sections into account, the mod Knowledge Mathematics or E	Taking dule car	the be a	pers assig	onal ned	specia to the S	alisation and	d the restric	ctions	of the
Prerequisites	There are no further prerequi	sites.								
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, E=essay, P=portfolio Teaching Format: 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						Type of Compuls	Module: ory Module	with C	hoice
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h	Time ii 30 h	n Cla	ss:			Self-Stud	dy:		
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	 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 Credits / Grading (Weighting 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 w of the examination board.	ritten or	oral	is de	cideo	d by the	e instructor v	vith approva	l by the	e head
Literature	Possible References:									
Transfer	the chosen personal Study S vanced Knowledge in Mathem	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	The contents of the module from differential geometry is			olog	y 1' a	are ass	sumed. Mor	reover, basi	c know	/ledge
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, E=essay, P=portfolio Teaching Format: 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 Dist	ributio	ns			Type of I	Module: ory Module	with C	hoice		
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in Cla	ıss:			Self-Stud	ly:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SV	VS										
Content	A selection of the following to	A selection of the following topics will be covered:										
	Locally convex topological vector spaces, Frechet spaces, LF spaces and LB spaces.											
	Duality: Hahn-Banacl	Duality: Hahn-Banach theorem, dual space, topologies on the dual space.										
	Generalised functions	Generalised functions, Radon measures and distributions.										
	 Properties of distribut 	ions an	d ope	ratio	ns or	n the sp	cace of distr	ibutions.				
	Applications and exar	nples.										
Objectives	Students master the basic prand understand how to apply Students are also able to na questions of mathematical pand proving the essential resented connections. In the exercise classes they be terms, statements and methor new problems, to analyse the They are able to present the	this to to the me the hysics of the sults have accords of the means and the substitution and the substitution are the substitution and the substitution and the substitution are the substitution are the substitution are the substitution and the substitution are	he the main can be of the quired to w	eory c appl e trea e lect a co ture.	of ger ication ited value ture nfide They on so	neralise ons of t with it. as wel ont, pre- ont, pre- lution s	ed functions the theory a The student as assess cise and ind learned to treat trategies o	according to nd show wh s are capab sing and ex ependent ha ansfer the n n their own	L. Sch nich cla ole of na plainin andling nethods or in a	wartz. ssical aming ig the of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Topological Vector Spaces and Distributions	п Type of Course	- Status	SMS 2	s ECTS	Coursework	Type of Exam or. o.	Onr. of Exam (min) 0. 20-30	Grading	Weight for Grade		
	In this module an exercise of examination the coursework oral is decided by the instruc	ertificat must h	e is to ave b	be a	acqui acqu	ired. W	hether the	examination	i is writ			

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, E=essay, P=portfolio Teaching Format: 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 Surfaces							Type of Module: Compulsory Module with Choice				
ECTS-Points	5	5										
Workload - Time in Class - Self-Study								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 + Ex.cl. 1 SW	Lecture 2 SWS + Ex.cl. 1 SWS										
Content	Uniformisation of Riem	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 Credits / Grading (Weighting 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 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 head of the examination board. – The module may exceptionally be offered by the lecturer without exercise classes; in this case, only 3 credit points will be awarded for the module instead of 5.							ten or – The				
Literature	Possible References :											
	Hershel M. Farkas, Irwi	n Kra:	Rien	nann	Surf	aces. S	Springer 199	92.				
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	The module Introduction to F Bachelor of Science Mathema								dules	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, E=essay, P=portfolio Teaching Format: 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									
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									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS									
Content	Compact Riemann su	ırfaces.								
	Normalisation of plan	e curves.								
	Topological genus.									
	Coverings.									
	Forms and integration	1.								
	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.									
	Topology of non-comp	nact Riemann surfaces								
	1 Topology of Hori-comp	Jact Hiemann 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Algebraic Curves and Riemann Surfaces	L ü	f	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise certificate is to be acquired as couexamination the coursework must have been acquired. Whet oral is decided by the instructor with approval by the head of module may exceptionally be offered by the lecturer without execution of the module instead of 9.						thether the ead of the ex at exercise c	examination amination b	is writ	ten or – The
Literature	Possible References :	Possible References :								
	Frederice Mangolte: Rea	l Alge	ebrai	c Var	ietie	s. Spri	nger 2020.			
	Robert Silhol: Real Algeb	oraic	Surfa	aces.	Spr	inger 1	989.			
	Riccardo Benedetti, Jean-Jacques Risler: Real Algebraic and Semi-algebraic Sets							Sets.		
	 Editions Herrmann 1990. Alex Degtyarev, Viatcheslav Kharlamov: Topological properties of real du côté de chez Rokhlin. arXiv:math/0004134. 						of real algeb	raic var	rieties:	
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 to function theory of ordinary dif							s well as the	introd	uction
Responsible Persons	Ivo Radloff									
Abbreviations: Grading System : g=graded, ng=not graded										
1	T=master's thesis, or.=oral exam,							-	•	
	=lecture, LE=lecture with integrated =project, S=seminar, IC=inverted				=ser	ninar o	r lecture, E=	exercise cla	ss, T=t	utorial,
	obligatory, f=facultative									

Module Number: MAT-50-30	Module Title: Geometric Group Theory Type of Module: Compulsory Module with Choice									hoice	
ECTS-Points	9										
Workload - Time in Class - Self-Study		Time ii 90 h	n Cla	ss:			Self-Stud	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SW	Lecture 4 SWS + Ex.cl. 2 SWS									
Content	 Group actions on graph 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 onto 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 necessary to argue for it in a critical discourse.										
Requirements for obtaining Credits / Grading (Weighting 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	f	4	6	VAS	wr. o.	90-180	g	100	
		Е	f	2	3	yes or. o. 20-30				100	
	In this module an exercise cer examination the coursework noral is decided by the instructor	nust ha	ive b	een a	acqui	ired. W	hether the	examination	is writ		
Literature	Possible References :										
	 Clara Löh: Geometric Group Theory - an Introduction. Springer 2017. Thorsten Camps, Volkmar Große Rebel, Gerhard Rosenberger: Einführung in die kombinatorische und die geometrische Gruppentheorie. Heldermann Verlag 2008. 										

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching 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-50-40	Module Title: Gromov-Witten Theory							Module: ory Module	with C	hoice		
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: 180 h	Time in	n Cla	ss:			Self-Stud	ly:				
Duration	1 Semester	1 Semester										
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English	German or English										
Forms of Teaching and Learning	Lecture 3 SWS + Ex.cl. 1 SV	Lecture 3 SWS + Ex.cl. 1 SWS										
Content	 Moduli spaces of stab Moduli spaces of stab Universal families, Forgetful maps, Gluing maps, Gromov-Witten invaria Computation of Grom Divisor equations, 	 Forgetful maps, Gluing maps, Gromov-Witten invariants, Computation of Gromov-Witten invariants, 										
Objectives	Students are based on their knowledge in Algebraic geometry introduced into the current research field of Gromov-Witten theory and enumerative geometry. The students know and understand important example classes of enumerative invariants and know how to present them as cut products on moduli spaces. Students master the basic algorithms for calculating Gromov-Witten invariants. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods onto 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 Credits / Grading (Weighting 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 E	f	3	4,5 1,5	yes	wr. o. or.	90-180 o. 20-30	g	100		
		In this module an exercise certificate is to be acquired as coursework. Whether the examination is written or oral is decided by the instructor with approval by the head of the examination board.										

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, E=essay, P=portfolio Teaching Format: 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:						Type of				
MAT-55-02	Non-Linear Functional Analysis Compulsory Module with C									hoice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in Cla	ass:			Self-Stud	dy:			
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 n	nappir	ngs a	nd gr	adient	mappings.				
	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 Credits / Grading (Weighting if applicable)	Title	- Type of Course	Status	SWS	n ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Non-Linear Functional Analysis	ü		2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	examination the coursework	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the head of the examination board.									

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

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

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

Status : o=obligatory, f=facultative

Module Number:	Module Title: Operator Theory						Type of	Module: ory Module	with C	hoice		
ECTS-Points	9						Compuis	ory wodule	WILIT	lioice		
Workload - Time in Class - Self-Study	Workload: 270 h	Time i	n Cla	ss:			Self-Stud	ly:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS											
Content	Operator semigroups	and abs	stract	Cau	chy p	oroblen	ıs.					
	Theorem of Hille-Yosida.											
	Applications of concrete evolution equations.											
	Spectral theory of semigroups and their generators.											
	Asymptotic of semigroup	oups.										
	 Applications: Semigroups of 	ordinary	and	narti	al dif	foronti	al equations					
	Semigroups of the semigroups of the semigroup of the se	•		•		icicilli	ai equations	',				
	 Semigroups of of 	control t	heory	/.								
Objectives	Students have understood are able to deal with concreprove well-posedness using solutions. The students are as well as assessing and explored in the exercise classes they be terms, statements and method new problems, to analyse the They are able to present their	ete evol the Hille capable plaining ave acq ods of th em and	ution -Yosi of na the p uired e lect to w	equalida the ming reservation a continue.	ation leore and nted nfide They on so	is in them and proving connection, prection, but in the lation sets in the lation set in the lation sets in the lation set in the lation sets in the lation set in the lation sets in th	is abstract discuss the g the essenctions. cise and independent of the strategies of	form. They e qualitative tial results of ependent has ansfer the non their own	vare a behavior the leading andling nethods or in a	ble to our of ecture of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
		L	f	4	6	V65	wr. o.	90-180		100		
	Operator Theory	ü	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 ha	ave b	een a	acqui	ired. W	hether the	examination	is writ			

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, E=essay, P=portfolio Teaching Format: 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: Operator Algebras		Type of Module: Compulsory Module with Choice								
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h								
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English	erman or English									
Forms of Teaching and Learning	Lecture 4 SWS										
Content	 Spectral theory in Ba Commutative Banach Naimark. The spectral theorem Operator topologies a Kaplansky's density t Von Neumann algeb construction of exam The axiomatics of C*- 	spaces and their spectral proposace and their spectral proposace and the representate algebras and the representate for normal operators of a Hilk and von Neumann's bicommunity heorem. First and their classification and W^* -algebras, the theorem he representation theorem of	ion theorem of Gelfand and Gelfand- pert space. tant theorem. according to Murray-von Neumann, on of Gelfand-Naimark-Segal theorem								
Objectives	theory of operator algebras. the example of von Neumar how taking a higher point o questions to be dealt with an proving the essential results connections. In the exercise classes they terms, statements and methonew problems, to analyse the	They have learnt the interplay on algebras and their classific f view, i.e. the axiomatic nation of the lecture as well as asserted acquired a confident, precods of the lecture. They have learn and to work on solution is	concepts, results and methods of the between algebra and topology using sation. The students also recognise ture of the problem, allows different students are capable of naming and essing and explaining the presented cise and independent handling of the earned to transfer the methods onto strategies on their own or in a team. defend them in critical discourse.								

Status

Other

: o=obligatory, f=facultative

Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Operator Algebras	L	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100	
		ü	f	2	3				_		
	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 head of the examination board.										
Literature	Possible References :	ossible References :									
	Bruce Blackadar: Operator algebras. Springer 2006.										
	Ola Bratelli, Derek Robinson: Operator Algebras and Quantum Physics. Springer 1997.										
	 Richard Kadison, John Ringrose: Fundamentals of the Theory of Operator Algebras I - IV. AMS 1997. 										
	Gert Pedersen: Analysis	now.	Spri	nger	199	5.					
	• Shoichiro Sakai: C^* - and	W^*	Alge	bras	. Spr	inger 1	998.				
	Masamichi Takesaki: The	eory o	of Op	erate	or Alç	gebras	I - II. Spring	jer 2002.			
Transfer	The module belongs to the <i>St Mathematical Physics</i> . Taking in be included in the Sections <i>Stu Specialisation</i> , in accordance wi	nto a Idy F	ocus	nt th , <i>Ad</i>	e cho vanc	osen p ed Kno	ersonal Stud Swledge in I	dy Specialis Mathematics	sation, s or <i>El</i>	it can ective	
Prerequisites	The content of the Functional Ar	nalys	is mo	odule	is p	rerequi	site for part	icipation in t	his mo	dule.	
Responsible Persons	Ulrich Groh, Rainer Nagel										
Examination Type: M Teaching Format: La	=graded, ng=not graded IT=master's thesis, or.=oral exam, =lecture, LE=lecture with integrated =project, S=seminar, IC=inverted	d exe	cise	s, SL		•		-	•		

Module Number:	Module Title: Ergodic Theory						Type of I	Module: ory Module	with Cl	hoice		
ECTS-Points	9						Compuis	ory woodle	WILLI OI	110106		
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in Cla	ss:			Self-Stud	ly:				
Duration	1 Semester						-					
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	Lecture 4 SWS + Ex.cl. 2 SWS										
Content	Topological and measure-theoretical dynamical systems.											
	Recurrence and mixing properties.											
	Ergodic theorems of v	on Neu	ımanı	and	Birk	hoff.						
	Spectral theory of the	Koopm	an op	erat	or.							
	Operators with discre	te spec	trum (Haln	nos-v	on Ne	umann)					
	Applications in stocha	stics ar	nd nui	mber	theo	ry.						
Objectives	The students have familiaris of ergodic theory. They have and topology using the exart analytical perspective makes. The students are capable of assessing and explaining the lin the exercise classes they be terms, statements and method new problems, to analyse the They are able to present the	re expended in possion in possion naming expreser accords of the possion and the possion in possion	rience dynai ble to and nted c quired ne lec d to w	ed the mic some deal coroving a content of the corotal	e proyster with ng the ection fide Theyon so	ofound ms and and so e esse ns. nt, pre- have lution s	interplay be d their class live various partial results cise and independent to treat earned to treatrategies of	etween mea ification. The problems sind of the lectu ependent has ansfer the nown their own	asure to be functon multane re as wandling nethods or in a	heory tional- eously. vell as of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Ergodic Theory	□ Type of Course	f	SMS 4	o ECTS	Sex	Type of Exam o. o.	Dur. of Exam (min) 0.20-30	Grading	UVeight for Grade		
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	ave b	een a	acqui	ired. W	coursework /hether the o	. For partici examination	is writ			

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 <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	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, E=essay, P=portfolio Teaching Format: 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: Control Theory						Type of Compuls	Module: ory Module	with C	hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ıss:			Self-Stud	dy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SW	ecture 4 SWS + Ex.cl. 2 SWS								
Content	- Controllability, ob Kalman criterion - Stabilisability thr - 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 important of are able to use the theory in a of naming and proving the estimate presented connections. In the exercise classes they have terms, statements and method new problems, to analyse the They are able to present their	reas of sential we acq ds of the em and	appl resul resul luired le lec I to w	icatio ts of a co ture. ork c	n sucthe Infide They	ch as n ecture ent, pre- have lution s	nechanics. Tas well as a cise and ind learned to tractions.	The students issessing ar ependent har ansfer the non their own	are cand explandling nethodor in a	apable aining of the s onto team.
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Control Theory	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 r oral is decided by the instruct	nust ha	ave b	een a	acqu	ired. W	hether the	examination	is writ	

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 <i>Study Specialisation Analysis and Differential Geometry</i> . Taking into account the chosen personal Study Specialisation, it can be included in the Sections <i>Study Focus</i> , <i>Advanced Knowledge in Mathematics</i> or <i>Elective Specialisation</i> , in accordance with the restrictive requirements of the respective section.
Prerequisites	There are no further prerequisites.
Responsible Persons	Rainer Nagel
Abbrariations	

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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	'S				Type of Compuls	Module:	with C	hoice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: 180 h	Time i 60 h	n Cla	ss:			Self-Stud	dy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SW	Lecture 2 SWS + Ex.cl. 2 SWS								
Content	Starting from the classical theorems of Perron and Frobenius on the spectrum of positive matrices, positive linear mappings to C^* - and W^* -algebras and their spectral and algebraic properties are analysed. The ergodic properties of these operators, i.e. the convergence of powers and means, can then be derived from these. We then discuss the generalisation to operator semigroups. Applications of the theory can be found in mathematical physics, among others.									
Objectives	Students learn the basic spectral properties of positive operators on C^* - and W^* -algebras and the connections with non-commutative ergodic theory. In the seminar following the lecture, students can work on topics that lead to a Master's thesis. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. Students will be able to reflect and critically analyse the current state of research in the subject area.									
Requirements for obtaining Credits / Grading (Weighting 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 o	2	3	no	wr. o. or.	90-180 o. 20-30	g	100
	Whether the examination is word the examination board. — exercise classes; in this case	The mo	dule	may	exce	ptional	ly be offere	d by the lec	turer w	rithout
Literature	Possible References :									
	 Tanja Eisner, Markus Theory. Springer 2015 Ulrich Groh: Spectral Preprint. 				J	·		·		
Transfer	The module belongs to the Mathematical Physics. Takin be included in the Sections Specialisation, in accordance	g into a Study F	ccou ccus	nt th , <i>Ad</i>	e ch vanc	osen p ed Kno	ersonal Stu <i>wledge in l</i>	dy Specialis Mathematic	sation, s or <i>El</i>	it can <i>ective</i>
Prerequisites	Knowledge from functional ar	nalysis	and c	pera	itor a	lgebra	s is assume	ed.		
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, E=essay, P=portfolio Teaching Format: 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: Non-Commutative Ergodic Th	eory					Type of I	Module: ory Module	with C	hoice	
ECTS-Points	9						-				
Workload - Time in Class - Self-Study	Workload: 270 h	Time ii 90 h	n Cla	ss:			Self-Stud	ly:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	1-3									
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 4 SWS										
Content	and discussed. Then, based are defined. With the help o commutative dynamical syster	Firstly, the essential basic concepts and properties of C* and W* algebras are introduced and discussed. Then, based on commutative theory, non-commutative dynamical systems are defined. With the help of the so-called cross products it is then shown how such non-commutative dynamical systems can be characterised with the help of the group representation. The significance in mathematical physics is always emphasised.									
Objectives	ergodic theory, i.e. of dynam fascinating interplay between spectral-theoretical) behaviou axiomatic and structural poin simultaneously. The students lecture as well as assessing a In the exercise classes they haterms, statements and method	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 onto new problems, to analyse them and to work on solution strategies on their own or in a team.									
Requirements for obtaining Credits / Grading (Weighting 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	ü	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	nust ha	ive b	een a	acqu	ired. W	hether the	examination	is writ		
Literature	Possible References :										
	of Ergodic Theory. Spr Bruce Blackadar: Ope Alai Guichardet: Systè Dirk Werner: Funktion	 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, E=essay, P=portfolio Teaching Format : 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:						Type of		6				
MAT-55-10	Pseudo Differential Operator	8					Compuls	ory Module	with C	hoice			
ECTS-Points	3												
Workload - Time in Class - Self-Study	Workload: 90 h	Time i 30 h	n Cla	ss:			Self-Stud 120 h	ly:					
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	ecture 2 SWS											
Content	Fourier transform and	Fourier transform and Sobolev spaces.											
	Pseudodifferential operation	Pseudodifferential operators on manifolds.											
	Finite propagation velo	Finite propagation velocity.											
	Fredholm operators as	nd ellipt	ic co	mple	xes .								
	The heat conduction k	ernel a	nd th	e loc	al inc	dex the	orem.						
	The Atiyah-Bott-Patod	i theore	m.										
	Von Neumann algebra	s and r	epres	senta	tions	S .							
	The L2 index theorem												
Objectives	Students learn basic technic geometry. They will understa how both merge into the more transition from one to the oth will be able to use theoretica will learn to use modern app. The students are capable of as assessing and explaining critically analyse the current.	nd the of e gene er resu approaches naming the pre	conneral calles in aches of Lagrand	ection solu s to s 2 the I proved co	betwood betwoo	ween d pseud technic specifi o prove the ess ctions.	ifferential ar o-differentia ques for diffe c problems e deep grou sential resu Students w	nd integral o I operators erential equ in concrete p theoretica Its of the led	perator and ho ations. cases. I stater cture a	rs and they They They ments. s well			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Pseudo Differential Operator	s L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100			
	Whether the examination is w of the examination board.	ritten or	oral	is de	cided	by the	instructor v	vith approva	l by the	head			

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:						Type of I	Module:					
MAT-55-11	Introduction to Harmonic Ana	alysis					Compuls	ory Module	with C	hoice			
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud 180 h	ly:					
Duration	1 Semester	1 Semester											
Frequency	not regularly												
Term	1-3												
Language of Instruction	German												
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	VS											
Content	Fourier series and Fo	urier tra	nsfor	matio	on.								
	Plancherel theorem a	nd inver	se th	eore	ms.								
	Poisson summation for	rmula.											
	tempered distributions	S.											
	Additionaly a selection	n of the	follov	ving t	topic	s will b	e covered:						
	LCA groups;												
	- general Fourier												
	non-abelian groSobolev-spaces	•	ı repr	esen	itatio	ns;							
	Singular integra												
	Poisson integra												
Objectives	Students can combine algel They recognise the interplay and can apply the knowledg theory. They understand the into various function spaces results of the lecture as well In the exercise classes they h terms, statements and metho new problems, to analyse th They are able to present thei	betwee e gaine interac . The st as asse ave acq ods of th em and	en the d from tion of tudent ssing puired le lect	proper this proper this are and a co-ture.	perties to coup to complete cape of the ca	es of fu questioneory a pable of aining ent, pred have lutions	nctions and ns in physic and analysis of naming a the present cise and inde learned to treat strategies o	their Fouries, analysis and gain of and proving the deconnection of the deconnection of the deconnection of their own an in critical	er trans and nu leep ins the ess ons. andling nethods or in a	forms umber sights ential of the s onto team.			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Introduction to Harmonic	г Type of Course	J Status	SMS 4	9 ECTS	Sework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Analysis	E	f	2	3		or.	o. 20-30					
	In this module an exercise context examination the coursework oral is decided by the instruction	must ha	ave b	een a	acqu	ired. W	hether the ϵ	examination	is writ				

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, E=essay, P=portfolio Teaching Format: 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							Module: sory Module	with C	hoice
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	German								
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SWS									
Content	Fourier transformation.									
	Covering-, decompos	ition- an	d inte	erpol	ation	theore	ems.			
	Singular integrals, Po	isson int	tegra	s.						
	Hardy- and BMO-spa	ces, mu	ltiplie	r the	orem	ıs, Little	ewood-Pale	y theory.		
Objectives	The students got to know t euclidean space. The studer lecture as well as assessing In the exercise classes they have terms, statements and method new problems, to analyse the They are able to present the	nts are of and exp nave acq ods of the nem and	apab olainir uired e lec to w	le of ng the a co ture. ork c	name pre nfide They on so	ing and esented ent, pred have l lution s	d proving that connection cise and ind learned to the strategies of the contractions.	e essential ras. ependent haransfer the naster own	results andling nethods or in a	of the of the s onto team.
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Harmonic Analysis in Eu-	L	f	4	6	yes	wr. o.	90-180	g	100
	clidean Space	E	f	2	3		or.	o. 20-30		
	In this module an exercise context examination the coursework oral is decided by the instruction	must ha	ave b	een a	acqu	ired. W	hether the	examination	is writ	

Literature	Possible References :
	• Charles L. Feffermann, Elias M. Stein: ${\cal H}^p$ spaces of several variables. Acta Mathematica 129, pp. 137-193, 1972.
	 Christopher D. Sogge: Fourier integrals in classical analysis. Cambridge University Press 2017.
	 Elias M. Stein: Singular integrals and differentiability properties of functions. Princeton University Press 1970.
	Elias M. Stein: Harmonic analysis. Princeton University Press 1993.
	Elias M. Stein, Guido Weiss: Introduction to Fourier analysis on Euclidean spaces. Princeton University Press 1971.
Transfer	The module belongs to the 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 modules functional analysis and Introduction to Harmonic Analysis are a prerequisite for participation in this module.
Responsible Persons	Reiner Schätzle
Abbreviations: Grading System : g	=graded, ng=not graded

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:						Type of				
MAT-55-13	Harmonic Analysis on Abelia	ın Group	os				Compuls	ory Module	with C	hoice	
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										
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	VS									
Content	Locally compact group	Locally compact groups, existence and uniqueness of Haar measures.									
	 Convolution algebras, 	Banach	n alge	ebras	s, the	Gelfar	nd-Neumark	theorem.			
	LCA groups, Pontryaç	LCA groups, Pontryagin duality, Plancherel theorem, structure theory of LCA groups.									
Objectives	monic analysis and know ho topological/analytical/geomet structures such as C^* -algeby. The students are capable of assessing and explaining the ln the exercise classes they have terms, statements and method new problems, to analyse the	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 onto 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Harmonic Analysis on	L	f	4	6	yes	wr. o.	90-180	g	100	
	Abelian Groups In this module an exercise ce examination the coursework oral is decided by the instruc	must ha	ave b	een a	acqu	ired. W	hether the	examination	pation is writ		
Literature	Possible References :										
	Anton Deitmar: A first	course	in Ha	armo	nic A	nalysis	s. Springer	2005.			
	Anton Deitmar, Siegfr	ied Echt	erho	ff: Pr	rincip	les of l	Harmonic A	nalysis. Spr	inger 2	2008.	
	Edwin Hewitt, Kennet	n Ross:	Abst	ract	harm	nonic a	nalysis. Vol.	I. Springer	1979.		
	Walter Rudin: Fourier	analysis	s on	group	os. J	ohn W	iley 1990.				

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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 Genera	al Grou	ıps				Type of I	Module: ory Module	with C	hoice	
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										
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SW	IS .									
Content	Representation theory	• Representation theory of compact groups, Peter-Weyl theorem. • Representation theory of general groups. • trace formula and applications to the Heisenberg group and $SL_2(\mathbb{R})$.									
Objectives	The students have 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 onto 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 Credits / Grading (Weighting if applicable)	Title Harmonic Analysis on General Groups In this module an exercise ce	Type of Course	f Status	SMS 4 2	6 3 ECTS	Coursework	wr. o. or.	90-180 o. 20-30	G Grading	Weight for Grade	
	examination the coursework in oral is decided by the instruct	must h	ave b	een a	acqu	ired. W	hether the	examination	is wri		
Literature	Possible References : • Anton Deitmar, Siegfrie	nd Eab	torbo	ff∙ Dr	inoin	loc of l	Jarmonio A	nalveis Spr	ingor (2008	
	Gerald B. Folland: A Mathematics. Boca Ra Michael E. Taylor: Nor	cours aton 19	e in 95.	abstr	act l	narmor	nic analysis	. Studies i	_		
Transfer	The module belongs to the S into account the chosen personal focus, Advanced Knowledge restrictive requirements of the	nal Stu <i>in Mati</i>	idy S hema	pecia tics o	ılisati or <i>Ele</i>	on, it c	an be includ	led in the Se	ections	Study	

Prerequisites	In terms of content, the module Harmonic Analysis on abelian groups is a prerequisite for participation in this module.
Responsible Persons	Anton Deitmar
Examination Type : M	=graded, ng=not graded IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio =lecture F=lecture with integrated exercises SI = seminar or lecture F=exercise class T=tutorial

Status : o=obligatory, f=facultative

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

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

Module Number: MAT-55-15	Module Title: Selected Chapters from Opera	ator Th	eory				Type of I	Module: ory Module	with C	hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study		Time in Class: 90 h Self-Study: 180 h								
Duration	1 Semester	1 Semester								
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SW	5								
Content	Spectral theory of restri- lus.	cted a	nd ur	nresti	ricted	d linear	operators,	especially sp	oectral	calcu-
	Spectral theory of posit	ive op	erato	rs – l	Perro	n-Frob	enius theor	y.		
	Spectral theory for ope	Spectral theory for operators of ergodic theory.								
Objectives	They can then apply this to complete behaviour. They are also ablusted as stochastics, ergodic the proving the essential results of connections. In the exercise classes they hat terms, statements and method new problems, to analyse the	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 onto 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 the s onto		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Selected Chapters from Oper	- L	f	4	6	yes	wr. o.	90-180	g	100
	ator Theory	E	f	2	3		or.	o. 20-30		
	In this module an exercise cer examination the coursework n oral is decided by the instructo	nust ha	ave b	een a	acqu	ired. W	hether the	examination	is wri	
Literature	Possible References :									
	Klaus Jochen Engel, Fequations. Springer 20		Nag	el: C	ne-p	oarame	eter semigro	oups for line	ear evo	olution
	Markus Haase: The Fu		al Ca	lculu	s for	Sector	rial Operator	rs. Birkhäus	er 200	6.
Transfer	The module belongs to the S Mathematical Physics. Taking be included in the Sections S Specialisation, in accordance	into a	ccou ocus	int th s, <i>Ad</i>	e ch vanc	osen p ed Kno	ersonal Stu owledge in I	dy Specialis Mathematic	sation, s or E	it can lective

Prerequisites	Solid knowledge of operator theory, in particular Hille-Yosida theory for operator semigroups is a prerequisite.
Responsible Persons	Rainer Nagel
	graded, ng=not graded IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, eproject, S=seminar, IC=inverted classroom

Status : o=obligatory, f=facultative

Module Number: MAT-55-22	Module Title: Partial Differential Equations						Type of I	Module: ory Module	with C	hoice	
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 or English										
Forms of Teaching and Learning	Lecture 4 SWS	_ecture 4 SWS									
Content	Schauder estimates.	Schauder estimates.									
	Calderon-Zygmund es	stimate	S.								
	Harnack's inequality.										
	Hölder regularity.										
	Viscosity solutions.										
	Existence of solutions	accord	ding to	Per	ron.						
	Evans-Krylov theorem	١.									
Objectives	After the students have lea Differential Equations, this kn to current research questions results of the lecture as well In the exercise classes they h terms, statements and metho new problems, to analyse the They are able to present thei	owledges. The sas assetted as assetted as assetted as of the ancient and ancient ancient ancient as	ge is on stude essing quired to work the state of the sta	leepents and a co ture.	ened re ca expl nfide They on so	Stude pable aining nt, pred have lution s	ents are preport naming a the present cise and independent to treatment to treatment of the contractions are presented to the contractions are	pared for an nd proving t ed connection ependent hat ansfer the n n their own	d introdictions in the essential constant in	duced ential of the s onto team.	
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	- Type of Course		SWS	n ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Partial Differential Equations	ü	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	ertificate must h	e is to ave b	be a	acqui acqui	ired. W	hether the	examination	is writ		

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:	

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format : 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							Module: ory Module	with C	hoice		
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 + Ex.cl. 2 SW	'S										
Content	The course will consider PDE aspects of minimal surfaces, beginning with the existence theory for minimal graphs with prescribed boundary data. Emphasis will be placed on the De Giorgi-Nash estimate, which is one of the key achievements of 20th Century mathematics, and is foundational in the study of quasilinear elliptic and parabolic equations. We will also explore connections between minimal surfaces and the Allen-Cahn equation, which is a semilinear equation arising in the theory of phase transitions. Here the focus will be on rigidity results for entire solutions (namely the Bernstein problem and closely related De Giorgi conjecture) and their use in proving regularity via rescaling.											
Objectives	The students obtain an advar understanding of connections will acquire an array of new on objects governed by nonli applications of Sobolev theory. Moser iteration, and the use when these techniques are appeared as the statements and continuous in the lecture and to put it in challenge the current state of In the exercise classes they be the terms, statements and me onto new problems, to analyteam. They are capable of prediscourse.	s between technical techni	een the questifferer aling a totonice to a rom the rection in equire of the mane.	for ential entia	eory stab equa comp ormu n pro cture ework speci confid ure.	and prilishing tions. actnessulae. Sublem. as well as The fic areadent, properties and solutions and properties areadent, properties and properties areadent, properties areadent, properties and properties area and properties are an area and properties are an area and properties are area and properties are area and properties are area and properties are area and properties area and properties are area and properties area.	ofound prob quantitative These techn s argument tudents will They are ab I as to expla y are able to a. recise and in ave learned ution strates	plems in geo e and qualit iques includes, Stampace be able to a le to name a in the conte o describe a independen I to transfer gies on theil	ometry. ative c de adva chia itel assess and pro- ext deve and cri t handl the me	They ontrol anced ration, if and we the eloped tically ing of thods or in a		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Nonlinear Elliptic Partial Differential Equations in Minima	al 🖵	t Status	SMS 4	e ECTS	Coursework	Type of Exam wr. o. or.	Dur. of Exam (min) 0.20-30	ص Grading	Weight for Grade		
	Surface Theory E f 2 3 or. o. 20-30 g Too 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 head of the examination board.											

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, E=essay, P=portfolio Teaching Format: 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 Yamabe Problem	Type of I	Module: ory Module	with C	noice					
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	conformally equivalent to one with constant sectional curvature. The appropriate higher-dimensional distance of the provincial sectional curvature. The appropriate higher-dimensional distance of the provincial section of the so-called Yamabe problem, introduced by Yamabe in 1960. The flaws in his proof were fixed only in 1984, by combining the works of Trudinger, Aubin, Schoen, and others. This course provides an overview of the complete proof of the Yamabe problem, which is extremely rich in techniques of calculus of variation, geometric analysis, and elliptic partial differential equations. It also employs crucial results of mathematical relativity, such as the Positive Mass Theorem, which is motivated by physics but possesses powerful analytical consequences. Moreover, basic results for non-compact manifolds or manifolds with boundary and the parabolic analogue, the Yamabe flow, will be discussed.									
Objectives	students are familiar with bas (sub-critical) Yamabe energy study the conformal Green's students are also familiar wit Positive Mass Theorem, still the main ideas of the proof of the minimal surface theory concepts from the lecture as into a larger framework. The research in the specific area Through homework assignment and independent acquaintal lectures. They learn how to	The students can state the Yamabe problem and explain the structure of the proof. The students are familiar with basic methods of the calculus of variation, particularly concerning the (sub-critical) Yamabe energy functionals and the associated elliptic semi-linear PDEs. They can study the conformal Green's function and relate it to the solvability of the Yamabe problem. The students are also familiar with the notion of mass in mathematical relativity and the renowned Positive Mass Theorem, still linking it to the solution of the Yamabe problem; they can provide the main ideas of the proof of the Positive Mass Theorem and, in particular, master elements of the minimal surface theory. 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 Credits / Grading (Weighting if applicable)	Title Partial Differential Equation in Conformal Geometry: the Yamabe Problem		J. Status	SWS 2	ω ECTS	Se Coursework	wr. o. or.	Dur. of Exam (min) 0. 20-30	Grading	Weight for Grade
	Whether the examination is w of the examination board.	ritten o	r oral	is de	cided	by the	instructor v	vith approva	by the	head

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, E=essay, P=portfolio Teaching Format: 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-55-27	Module Title: Fully Non-Linear Elliptic Equations						Type of Module: Compulsory Module with Choice			
ECTS-Points	5									
Workload - Time in Class - Self-Study		Γime ir I5 h	n Cla	ss:			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 + Ex.cl. 1 SWS	3								
Content	Solution of general fully Solution of the Monge-A			•		s with e	elliptic equa	tions.		
Objectives	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.					idents ng the e of a ations able of				
Requirements for obtaining Credits / Grading (Weighting 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	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise certificate is to be acquired as coursework. For participation in the examination the coursework must have been acquired. Whether the examination is written or oral is decided by the instructor with approval by the head of the examination board. — The module may exceptionally be offered by the lecturer without exercise classes; in this case, only 3 credit points will be awarded for the module instead of 5.						ten or – The			
Literature	Possible References :									
	order elliptic equations. Applied Mathematics 37 • Luis A. Caffarelli, Josep nonlinear second-order elliptic, equations. In: 209-252.	 Luis A. Caffarelli, Joseph Kohn, Joel Spruck: The Dirichlet problem for nonlinear second-order elliptic equations. I. Monge-Ampere equation. In: Communications on Pure and Applied Mathematics 37,3 pp. 369-402. Luis A. Caffarelli, Joseph Kohn, Luis Nirenberg, Joel Spruck: The Dirichlet problem for nonlinear second-order elliptic equations. II. Complex Monge-Ampere, and uniformly elliptic, equations. In: Communications on Pure and Applied Mathematics 38,2 pp. 209-252. David Gilbarg, Neil S. Trudinger: Elliptic Partial Differential Equations of Second Order. 					em for formly 3,2 pp.			

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 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, E=essay, P=portfolio Teaching Format: 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						Type of I	Module:	with C	hoice
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: 90 h	Vorkload: Time in Class: Self-Study:								
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS									
Content	 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 analysis, in learn how the level surfaces used to obtain statements a to algebraic topology, which The students are capable of assessing and explaining the	n partice of non- bout the analyse naming	ular t dege e hor es th and	he the neration notor e top orovi	neory te fui oy ty oolog ng th	of dyrnctions pe of r y (of n e esse	namical sys , so-called l nanifolds. T nanifolds) u	tems. In pa Morse funct They also bi sing algebra	rticula ions, c uild a l aic me	r, they an be oridge thods.
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Morse Theory Whether the examination is w	L ritten or	f oral	2 is de	3 cided	no by the	wr. o. or.	90-180 o. 20-30 vith approva	g I by the	100 e head
Literature	of the examination board. Possible References: John Milnor: Morse Theorems 1961. Morris W. Hirsch: Diffe 1988.									

Transfer	The module belongs to the <i>Study Specialisation Studienschwerpunkt Analysis and Differential Geometry</i> and <i>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 differentiable manifolds and of dynamic systems is helpful.
Responsible Persons	Frank Loose
Abbreviations:	=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, E=essay, P=portfolio Teaching Format: 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-55-32	Module Title: Selected Chapters from Dynamical Systems Theory							Module: ory Module	with C	hoice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time ii 30 h	n Cla	ss:			Self-Study: 60 h				
Duration	1 Semester						•				
Frequency	not regularly										
Term	1-3										
Language of Instruction	German or English										
Forms of Teaching and Learning	Lecture 2 SWS										
Content	A selection of the following to	pics wil	l be	cover	ed:						
	dynamical systems as	solutio	n flov	vs of	ordii	nary ar	nd partial dif	ferential eq	uations	s;	
	isomorphic invariants of	• isomorphic invariants of dynamical systems, especially the discrete spectrum;									
	linear skew-product flows;										
	applications in number theory, combinatorics and stochastics.										
Objectives	Students are familiar with qualitative questions in the theory of ordinary and partial differential equations and the methods used to analyse them. On the basis of solid knowledge of functional analysis, operator theory and ergodic theory, they have experienced the diverse applicability of abstract mathematical concepts. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.							ctional pility of			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Selected Chapters from Dynamical Systems Theory	/- L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is word the examination board.	itten or	oral	is de	cideo	d by the	e instructor w	vith approva	l by the	head	
Literature	Possible References :										
	 Tanja Eisner, Balint Farkas, Markus Haase, Rainer Nagel: Operator theoretic aspects of ergodic theory. Springer 2015. Manfred Einsiedler, Thomas Ward: Ergodic theory: with a view towards Number Theory. Springer 2011. David Kerr, Hanfeng Li: Ergodic theory: independence and dichotomies. Springer 2016. 							heory.			
Transfer	The module belongs to the S be included in the Sections S Specialisation. Taking into accin the Sections Study Focus, in accordance with the restrict	Study Fount the Advance	ocus e cho ced k	, <i>Ad</i> sen <i>nowl</i>	<i>vanc</i> perso ledge	ed Kno onal St e in Ma	owledge in I udy Speciali thematics o	<i>Mathematic</i> sation, it car r <i>Elective S</i>	s or E	<i>lective</i> cluded	

Prerequisites In terms of content, the module Dynamic Systems Prerequisite for participation in this module.							
Responsible Persons	Rainer Nagel						
	g=graded, ng=not graded						
Examination Type : I	MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio						
Teaching Format : L=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom							
Status : c	p=obligatory, f=facultative						
Other : I	n=hours, o.=or, s.M.=see module description, SWS=contact hours per week						

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-leLeeuw-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.					
The students have learnt how abstract theories (here dynamic systems, Koopman systems) can be developed and further abstracted from concrete questions (in number theory). They can apply the techniques developed in these areas, to deal with concrete (e.g. number-theoretical or ergodic-theoretical) problems. The students have thus learnt important examples of the usefulness of abstract mathematical theories. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods onto 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.					
Weight for Grade					
100					
in the tten or					
nics of					
alance solutions of a line of the solution of					

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, E=essay, P=portfolio Teaching Format: 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						Type of Compuls	Module: sory Module	with C	hoice	
ECTS-Points	9	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time i	n Cla	ss:			Self-Stud	dy:			
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 + Ex.cl. 2 SV	Lecture 4 SWS + Ex.cl. 2 SWS									
Content	First and second varia	tion for	varif	olds.							
	Monotonicity formula.										
	Allard's integral comp.	actness	theo	rem.							
	Lipschitz approximation	n.									
	tilt-excess descent.										
	Allard's regularity thec	rem.									
	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 monto new problems, to analy team. They are capable of p discourse.	The stand expended and expended expended and expended and expended and expended and expended and	stude apab plainir equire of the n and	nts vole of a control of the control	vill be nami e pre confic ure. vork	e prepaing and escented dent, part they had not been to be the prepared to be the prepare	ared for and proving the connection recise and lave learned ution strate.	d guided to e essential r ns. independen d to transfer gies on thei	proble results t hand the me	ems of of the ling of ethods or in a	
Requirements for obtaining Credits / Grading (Weighting 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. or.	90-180 o. 20-30	g	100	
		E ertificate	f	2	3		J.,	0. 20 00			

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

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

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

Status : o=obligatory, f=facultative

Module Number: MAT-55-43	Module Title: Area Minimising Flows							Module: ory Module	with C	hoice	
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 + Ex.cl. 1 SW	/S									
Content		Compactness theorem for integral flows. Regularity of area minimising flows.									
Objectives	After having learned the essential notions and methods of geometric measure theory, this knowledge is deepened. The students will be prepared for and guided to problems of recent research. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods onto 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 Credits / Grading (Weighting 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 cer is written or oral is decided by	tificate i	s to b	e ac	quire						
Literature	Possible References:										
Transfer	The module belongs to the 3 into account the chosen person Focus, Advanced Knowledge restrictive requirements of the	onal Stud in Math	dy S _l emai	ecia ics o	lisati r <i>Ele</i>	on, it c	an be includ	ded in the Se	ections	Study	
Prerequisites	Knowledge from the module Measure Theory is expected		ducti	on to	Ge	ometri	c Measure	Theory and	d Geo	metric	

Responsible Persons	Reiner Schätzle							
, , ,	Grading System : g=graded, ng=not graded							
Teaching Format : L	AT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio = lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom							
Status : o	=obligatory, f=facultative =hours, o.=or, s.M.=see module description, SWS=contact hours per week							

Module Number: MAT-55-46	Module Title: Elastic Curves							Module: ory Module	with C	hoice
ECTS-Points	3									
Workload - Time in Class - Self-Study	Workload: Time in Class: 30 h						Self-Stud	ly:		
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	 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.						ory of			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Elastic Curves Whether the examination is wi	ritten or	f oral	2 is de	3 cideo	no by the	wr. o. or.	90-180 o. 20-30 vith approva	g I by the	100 e head
Litavatura	of the examination board.									
Literature	Possible References: Filippo Gazzola, Hans-Problems, Springer 20		oh G	runaı	u, Gu	ıido Sw	reers: Polyh	armonic Bou	undary	Value
	David Gilbarg, Neil S. Springer 1998.	Truding	ger: I	Ellipti	с ра	rtial dif	ferential eq	uations of s	econd	order.
	Joel Langer, David A. S Geom. Band 20, Num						ature of clos	sed curves,	J. Diffe	rential
	John M. Lee: Introduction	tion to s	moo	th ma	anifo	lds. Sp	ringer 2013			
	Michael Struwe: Varia	tional M	etho	ds. S	Sprin	ger 200	08.			

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, 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, E=essay, P=portfolio Teaching Format: 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-55-47	Module Title: Type of Module: Geometric Measure Theory – Varifolds Compulsory Module with Choice							hoice		
ECTS-Points	5	5								
Workload - Time in Class - Self-Study		Time ii 45 h	n Cla	ss:			Self-Stud	dy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 1 SWS	3								
Content	 Monotonicity formula. Allard's integral compact Lipschitz approximation 	 First and second variation for varifolds. Monotonicity formula. Allard's integral compactness theorem. Lipschitz approximation. 								
	tilt-excess descent. Allard's regularity theorem.	em.								
Objectives	After the students have learnt Measure Theory, this knowled prepared for and introduced naming and proving the essent presented connections. In the exercise classes they have terms, statements and method new problems, to analyse their They are able to present their	dge is to currial res re acques of the mand	deeprent ults of uired e lected to w	oene rese of the a co ture. ork c	d with arch lectural	th a vie questi ure as v ent, pred have l lution s	ew to varial ons. The s well as asse cise and ind earned to tr strategies o	collities. Students are essing and e ependent has ransfer the mention their own	dents ve capa explaining andling nethods or in a	vill be ble of ng the of the s onto team.
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Geometric Measure Theory - Varifolds	- L E	f	1	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise cer examination the coursework moral is decided by the instructor	iust ha	ıve b	een a	acqui	ired. W	hether the	examination	is writ	
Literature	Enrico Giusti: Minimal s	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								

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, E=essay, P=portfolio Teaching Format: 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								Type of Module: Compulsory Module with Choice			
ECTS-Points	5										
Workload - Time in Class - Self-Study		Time i 45 h	n Cla	ISS:			Self-Stud	dy:			
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 + Ex.cl. 1 SWS	ecture 2 SWS + Ex.cl. 1 SWS									
Content	General and rectifiable	flows.									
	Deformation theorem.										
	Surface minimizing flow	S.									
Objectives	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 onto 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 Credits / Grading (Weighting 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	- <u>L</u>	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100	
	examination the coursework m	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 head of the examination board.									
Literature	Possible References :										
	Herbert Federer: Geom	etric r	neas	ure t	heor	y. Sprir	nger 1969.				
	Enrico Giusti: Minimal s	urface	es an	d fur	nction	ns of bo	ounded varia	ation. Birkhä	auser 1	1984.	
	Leon Simon: Lectures 1984.	on ge	ome	tric r	neas	ure the	eory. Austra	alian Nation	al Uni	versity	

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, E=essay, P=portfolio Teaching Format: 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)						Type of I	Module: ory Module	with C	hoice		
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 90 h	Time ii 30 h	n Cla	.ss:			Self-Stud	ly:				
Duration	1 Semester											
Frequency	not regularly	not regularly										
Term	1-3											
Language of Instruction	Deutsch und Englisch											
Forms of Teaching and Learning	Lecture 2 SWS											
Content	Structure theory of the	• Structure theory of the Lie group $SL_2(\mathbb{R}).$										
	Introduction to the rep	• Introduction to the representation theory of $SL_2(\mathbb{R}).$										
	Computation of the unitary dual.											
	Proof of the explicit Plancherel formula.											
Objectives	With the $SL_2(\mathbb{R})$ the 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	$SL_2(\mathbb{R})$	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100		
Literature	Possible References :											
	Anthony Knapp: Repr Serge Lang: SL2(R).				of s	emisim	ple groups.	PUP 2001.				
Transfer	The module belongs to the Differential Geometry. Takin be included in the Sections Specialisation, in accordance	g into a <i>Study F</i>	ccou ccou	nt th s, <i>Ad</i>	e cho <i>vanc</i>	osen p ed Kn	ersonal Stu owledge in I	dy Specialis Mathematic	sation, s or <i>E</i>	it can <i>lective</i>		
Prerequisites	There are no further prerequ	isites.										
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, E=essay, P=portfolio Teaching Format: 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						Type of I	Module: ory Module	with C	hoice		
ECTS-Points	5						'					
Workload - Time in Class - Self-Study	Workload: 150 h	Time ii 45 h	n Cla	SS:			Self-Stud	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 + Ex.cl. 1 SWS											
Content	 Modular forms for the module group and its congruence subgroups. Examples: Eisenstein series, Ramanujan delta function, theta series. Modular curves. Arithmetic applications and conjectures. Hecke operators. The L-function of a modular form and its connections with elliptic curves. 											
Objectives	Students have familiarised the automorphic forms in example between modular, real represe of naming and proving the est the presented connections. In the exercise classes they hat terms, statements and method new problems, to analyse the They are able to present their	s and a entation sential ve acq Is of the m and	re ab theoresul uired e lect to w	le to ory a ts of a co cure. ork o	use t nd ac the l nfide They on so	them. T delic L- ecture ent, pred have	They have ur functions. The as well as a cise and independent to the strategies of t	nderstood the he students ssessing an ependent ha ansfer the m n their own	e conn are cand and expl andling nethod or in a	ection apable aining of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting 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 o. H	90-180 o. 20-30	g	100		
	In this module an exercise cer examination the coursework r oral is decided by the instruct	tificate	ive b	een a	acqui acqu	ired. W	hether the ϵ	examination	is writ			
Literature	Possible References: Deitmar, Anton: Autom Goldfeld, Dorian: Autor University Press 2015. Serre, Jean-Pierre: A control	norphic	forn	ns an	nd L-f	function	ns for the gro	oup GL(n,R)	. Caml	oridge		

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 : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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: Type of Module: Cohomology and Sheaves Compulsory Modu									hoice			
ECTS-Points	9												
Workload - Time in Class - Self-Study		Time i 60 h	n Cla	ss:			Self-Stud	dy:					
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 + Ex.cl. 2 SWS												
Content	It 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 understa They understand mechanisms have learned to abstract arbitr cohomology theory as a general isations of function spaces for proving the essential results of connections. Students will be a in the subject area.	that c ary ma al obst topolo f the le	ombi ather acle gical ecture	ne a natic theor ques e as	lgebral the ry in stions well a	raic, ge eories applica s. The as asse	ometric and using categoretions and to students are essing and e	I analytic me ory theory, to use sheave to capable of explaining the	ethods. o appr s as ge namir ie pres	They eciate eneraling and sented			
Requirements for obtaining Credits / Grading (Weighting 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 2	6	yes	wr. o. or.	90-180 o. 20-30	g	100			
	Whether the examination is wri of the examination board. – TI exercises; in this case, only 6	tten or	dule	may	exce	ptiona	lly be offere	d by the lec	turer w				
Literature	Possible References :												
	Saunders Mac Lane: C	ategor	ies fo	or the	e wor	king m	athematicia	n. Springer-	Verlag	1971.			
	Allen Hatcher: Algebrai	c topo	logy.	Can	nbrid	ge Univ	ersity Pres	s 2002.					
	Glen Bredon: Sheaf the	ory. S	pring	ger-V	erlag	1997.							
	Joseph Rotman: An inti	oduct	ion to	hon	nolog	gical al	gebra. Sprir	nger-Verlag	2008.				

Transfer	The module belongs to the Study Specialisations Algebra and Geometry and Analysis and Differential Geometry. Taking into account the chosen personal Study Specialisation, it can be included in the Sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	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, E=essay, P=portfolio Teaching Format : 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 I	Module: ory Module	with C	hoice			
ECTS-Points	6												
Workload - Time in Class - Self-Study	Workload: 180 h	Time i 60 h	n Cla	ss:			Self-Stud	dy:					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German												
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SWS												
Content	Historical examples of the question of consistency (limits; parallel axiom; set-theoretic paradoxes).												
	Philosophical foundational programs (logicism; formalism; intuitionism).												
	The Hilbert program and Gödel's theorems.												
	Gentzen's transfinite (consiste	ncy p	roof	for n	umber	theory.						
	Alternative approache	s to cor	nsiste	ncy (inclu	ıding G	ödel's T).						
	Current situation of co	onsisten	cy pr	oofs.									
Objectives	Students learn about the hist formal mathematical theories this question mathematically in mathematical tools to be about and, to a certain extent, to ca proving the essential results connections. In the exercise classes they have the problems, to analyse the They are able to present their	arose, a y. They cally ar le to cor rry them of the le ave acq ods of th	as we are a and phomprel out to we were a week as well	ell as able to iloso nend them as verse as verse according to the control of the	the reconstruction the selve well and the selve miles and the selve miles and the selve and the selv	elevant tegoris ally. Ir corresp es. The as asse ent, prec have I	modern tede the problem addition, conding prostudents are essing and educate and independent to the trategies of the problem.	chniques for em of non-cathey have a cofs of non-cathe capable of explaining the ependent has ansfer the non their own	investige contract acquire contract namin ne presundling or in a	gating liction and the liction g and ented of the s onto team.			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Consistency Proofs	L	f	2	3	yes	wr. o.	90-180	g	100			
		E	f	2	3		or.	o. 20-30					
	In this module an exercise or examination the coursework oral is decided by the instruc	must ha	ave b	een a	acqui	ired. W	hether the	examination	is writ				

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, E=essay, P=portfolio Teaching Format: 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: Theory of Mathematical Proof	S					Type of Compuls	Module:	with C	hoice		
ECTS-Points	6							<u> </u>				
Workload - Time in Class - Self-Study	Workload:	Time ii 60 h	n Cla	ss:			Self-Stud	dy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SWS											
Content	 Gentzen's proof of cons Ordinal number analysi Provable recursive fund 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	calculations for mathematical are capable of naming and pro explaining the presented conn current state of research in the In the exercise classes they ha terms, statements and method	Students are familiar with the methods and results of modern proof theory, in particular with calculations for mathematical theories and their metamathematical properties. 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. 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 onto new problems, to analyse them and to work on solution strategies on their own or in a team.										
Requirements for obtaining Credits / Grading (Weighting 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 E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise cer examination the coursework n oral is decided by the instructo	nust ha	ive b	een a	acqu	ired. W	hether the	examination	is wri			
Literature	Possible References : • Wolfram Pohlers. Proof	Theor	y. Sp	oring	er 20	009.						
Transfer	The module belongs to the S Differential Geometry. Taking be included in the Sections S Specialisation, in accordance	into a Study F	ccou ocus	nt th s, <i>Ad</i>	e cho vanc	osen p ed Kno	ersonal Stu <i>owledge in l</i>	dy Specialis Mathematic	sation, s or E	it can <i>lective</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
Examination Type : M	=graded, ng=not graded IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio =lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial,

Status : o=obligatory, f=facultative

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

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

Module Number:	Module Title: Type of Module:											
MAT-55-65	Explicit Mathematics						Compuls	ory Module	with C	hoice		
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in Cla	ıss:			Self-Stud	ly:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SWS											
Content	 Applicative theories. Explicit mathematics. Universes in explicit mathematics. Applications in proof theory. 											
Objectives	Students are familiar with ar systems of analysis and are students are capable of nar assessing and explaining the critically analyse the current. In the exercise classes they be terms, statements and method new problems, to analyse the They are able to present the	familiar ming ar ne presented the presented the state of ave accords of the mandards.	with production with the content of	their oving I con arch I a co ture. ork c	functine the nection the in the interior of th	tion in essent ions. Se subject, predictions, land in the land in	proof-theore ial results of tudents will be tarea. Coise and ind learned to trattegies o	etical investion the lectural be able to ependent has ansfer the nontheir own	gations e as w reflect andling nethods or in a	s. The vell as of and of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Explicit Mathematics	L	f	2	3	yes	or.	90-180	g	100		
		E	f	2	3			o. 20-30				
	In this module an exercise or examination the coursework offered by the lecturer witho the module instead of 6.	must h	ave l	oeen	acqı	uired	- The modu	le may exce	eptiona	ally 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
Abbreviations: Grading System : g	=graded, ng=not graded
Examination Type : M	T=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial,

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

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

: o=obligatory, f=facultative

Status

Other

Module Number:	Module Title:						Type of I		0				
MAT-55-70	Selected Chapters from Fund	tional	Analy	SIS			Compuls	ory Module	with C	noice			
ECTS-Points	6												
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in Cla	ss:			Self-Stud	ly:					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German or English												
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SW	Lecture 2 SWS + Ex.cl. 2 SWS											
Content	A selection of the following to	pics wi	ill be d	cover	ed:								
	Topological vector spaces and duality theory.												
	(LB) and (LF) spaces and distributions.												
	Compactness concepts (Eberlein's theorem, Banach-Alaoglu, Krein-Milman, Smulian).												
	Theorems from topolo tional analysis.	gy (Tie	etze, l	Jrysc	hn, S	Stone-	Cech) and t	heir applica	tions in	func-			
	Uniform spaces.												
Objectives	Students are familiar with the to apply their methods and re such as the theory of distribution connections to other parts of are capable of naming and prexplaining the presented concurrent state of research in the new problems, to analyse the They are able to present their	esults tutions. mather oving the nection ie subjected ave accurates ds of the	o con They matics he ess s. Stu ect ar quired he lect to w	crete haves, sucception sential identing ea. a conture. ork o	e exa e rec ch as al res s will nfide They on so	mples cognises measi sults of be ab ent, pre- have lutions	from the fieled and under the lecture and the lecture and the lecture and independent and the lecture and the trategies of	Id of function erstood the restood the restood the restood to restood the restood to res	mal and many of The stu ssessing analyst andling nethods or in a	alysis, cross- dents g and se the of the s onto team.			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Selected Chapters from Funtional Analysis	Р Туре of Course	t Status	SMS 2	ε ECTS	Oursework	Type of Exam o. or.	Dur. of Exam (min) 0. 20-30	Grading	Weight for Grade			
	In this module an exercise ce examination the coursework oral is decided by the instruct	rtificate	e is to ave b	be a	icqui acqui	ired. W	hether the	examination	is writ				

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, E=essay, P=portfolio Teaching Format: 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 their A	Type of Compuls	Module: cory Module	with C	hoice					
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 3 SWS + Ex.cl. 1 SV	VS								
Content	Basics on operator alg	gebras	(C*-a	ılgebi	as, a	ılgebra	ic states, inc	ductive limits	s);	
	 Introduction to algebra examples); 	raic de	form	ation	quar	ntizatio	n (general	set-up, coh	erent :	states,
	 Applications to the classical limit of quantum mechanics and statistical mechanics including asymptotic emergence (phase transitions, large deviations (entropy), spontaneous symmetry breaking). 									
Objectives	The students have obtained 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Operator Algebras and their Applications to Statistical	<u> </u>	f	3	4,5	yes	wr. o.	90-180 o. 20-30	g	100
	Mechanics E f 1 1,5 Or. 0. 20-30 G. 20-30									
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, E=essay, P=portfolio Teaching Format: 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 Equation	ns						Type of Module: Compulsory Module with Choice			
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time	ime in Class: 0 h			Self-Stud	Self-Study: 60 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	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. 						ci 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.						. They s them a view				
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Geometric Evolution Equ	r Type of Course	- Status	SWS 2	ω ECTS	Goursework	Type of Exam o. o. c.	Dur. of Exam (min)	Grading	Weight for Grade	
	tions Whether the examination is word the examination board.	ritten o	r oral	is de	cided	d by the	instructor v	o. 20-30 vith approva	l by the	e head	
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			to Pa	rtial	Differe	ntial Equatio	ns and basi	ic knov	vledge	
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, E=essay, P=portfolio Teaching Format: 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 I	Module: ory Module	with C	hoice	
ECTS-Points	3	3									
Workload - Time in Class - Self-Study		Time in Class: 30 h					Self-Study: 60 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	Lecture 2 SWS									
Content	 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 Credits / Grading (Weighting 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 writ of the examination board.	ten or	oral	is de	cideo	d by the	e instructor v	vith approva	by the	e head	
Transfer	The module belongs to the <i>St</i> into account the chosen persor <i>Focus</i> , <i>Advanced Knowledge ii</i> restrictive requirements of the	nal Stu n <i>Math</i>	dy S nema	pecia tics d	alisati or <i>Ele</i>	ion, it c	an be includ	led in the Se	ections	Study	
Prerequisites	Knowledge from the module In of differential geometry are rec			to Pa	rtial	Differe	ntial Equatio	ns and basi	c knov	vledge	
Responsible Persons	Carla Cederbaum, Gerhard Hu	uisken									

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:					Type of I				
MAT-60-03	Topics in Mathematical Relativ	ty					Compuls	ory Module	with C	hoice
ECTS-Points	3									
Workload	Workload:	Γime i	n Cla	ss:			Self-Stud	ly:		
- Time in Class - Self-Study	90 h 30 h 60 h									
Duration	1 Semester									
Frequency	regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 2 SWS	_ecture 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 Credits / Grading (Weighting 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 writ of the examination board.	ten or	oral	is de	cideo	d by the	instructor w	vith approva	l by the	head
Transfer	Mathematical Physics. Taking be included in the Sections S	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	In terms of content, the module Equations are assumed.	s Mat	hema	atical	Rela	ativity a	and Introduct	tion to Partia	al Diffe	rential
Responsible Persons	Carla Cederbaum, Gerhard Hu	iisken								

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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							Module: ory Module	with C	hoice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SV	Lecture 2 SWS + Ex.cl. 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Space-Like Hypersurfaces i	n L	f	2	3	yes	wr. o.	90-180 o. 20-30	g	100
	Lorentzian Manifolds	Е	f	2	3	yes	or.			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 head of the examination board.									

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
Abbreviations:	

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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							Module: sory Module	with C	hoice		
ECTS-Points	6											
Workload - Time in Class - Self-Study		Time ii 60 h	n Cla	ss:			Self-Stud	dy:				
Duration	1 Semester	I Semester										
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English	rman or English										
Forms of Teaching and Learning	Lecture 3 SWS + Ex.cl. 1 SWS	cture 3 SWS + Ex.cl. 1 SWS										
Content	measure. Generalized curvature of Gromov-Hausdorff and	 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	problems in metric geometry. I properties are stable in the limit and concrete curvature notions geometry and general relativity results of the lecture as well as In the exercise classes they have the terms, statements and metonto new problems, to analysis	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 onto 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 necessary to argue for it in a critical										
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Limits of Spaces	ш г Type of Course	J Status	SMS 3	9 4,5 1,5	Coursework	Type of Exam or.	Dur. of Exam (min) 0. 20-30	ص Grading	Weight for Grade		
	In this module an exercise certi is written or oral is decided by t											
Literature	Possible References: • Jeff Cheeger, David Ebi • Dimitri Burago, Yuri Bur • Mikhail Gromov: Metr Springer 2007.	ago, S	erge	i Ivar	no: A	Cours	e in Metric	Geometry. A	AMS 2	001.		

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, E=essay, P=portfolio Teaching Format : 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: Type of Module: The Ricci Flow of Riemannian Metrics Compulsory Module with Choice										
ECTS-Points	6										
Workload - Time in Class - Self-Study		Γime i 80 h	n Cla	ss:			Self-Stud	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	3									
Language of Instruction	German or English	erman or English									
Forms of Teaching and Learning	Lecture 2 SWS	cture 2 SWS									
Content	techniques, e.g. tensor maximu of solutions and resulting class the monotonicity of functionals of possible singularities, with a	e lecture introduces the basic properties of the Ricci flow and develops the necessary chniques, e.g. tensor maximum principles and regularity estimation. The long-term existence solutions and resulting classifications for metrics of positive curvature are presented. Finally, a monotonicity of functionals according to Perelman is derived and used for the classification possible singularities, with an outlook on the surgery methods of Hamilton and Perelman, ich have led to the proof of the Poincaré and geometrisation conjectures.									
Objectives	Riemannian geometry. At the sassumptions on the curvature parabolic equations and have consequences for the geomet capable of naming and proving	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 Credits / Grading (Weighting 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 Riemannian Metrics	L ü	f O	2	3	no	wr. o. or.	90-180 o. 20-30	g	100	
	Whether the examination is writ of the examination board. – Th exercise classess; in this case,	ne mo	dule	may	exce	ptiona	lly be offere	d by the lec	turer w	vithout	
Literature	Possible References :										
	Simon Brendle: Ricci-flo	w and	d the	sphe	ere th	neorem	. AMS 2010	Э.			
	Peter Topping: Lectures	on th	e Ric	ci-Fl	ow. I	_ecture	Notes 200	6.			
	Richard Hamilton: Riem 17, 1982.	annia	n 3-r	nanif	olds	with po	sitive Ricci	curvature. J	. Diff.	Geom.	
Transfer	The module belongs to the S Mathematical Physics. Taking be included in the Sections S Specialisation, in accordance of	into a tudy F	ccou ocus	nt th	e ch vanc	osen p ed Kno	ersonal Stu owledge in l	idy Specialis Mathematic	sation, s or E	it can <i>lective</i>	
Prerequisites	Knowledge from the module Int knowledge in differential geom					ifferen	tial Equation	ns as well as	fundar	mental	

Responsible Persons	Carla Cederbaum, Gerhard Huisken
, ,	=graded, ng=not graded
Teaching Format : L	IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio = lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, project S. cominar IC inverted eleganors.
Status : o:	=project, S=seminar, IC=inverted classroom =obligatory, f=facultative =hours, o.=or, s.M.=see module description, SWS=contact hours per week

Module Number: MAT-60-07	Module Title: Special Relativity						Type of I	Module: ory Module	with C	hoice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time ii 30 h	n Cla	ss:			Self-Stud	ly:			
Duration	1 Semester										
Frequency	not regularly	oot 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. 							some		
Objectives	Students have learnt and understood the derivation of the special theory of relativity and important concepts such as length contraction and time dilation. They are familiar with important paradoxes that arise. Students have developed an intuition for various aspects of the theory of relativity. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections.							ortant eory of			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Special Relativity Whether the examination is word the examination board.	ritten or	oral	2 is de	3 cided	no d by the	wr. o. or.	o. 20-30	g I by the	100 e head	
Literature	Possible References :										
	Albert Einstein: Relati Thomas A. Moore: Six Robert Resnick: Introd Bernard Schutz: A First	ideas t	hat s to Sp	hape ecia	ed ph	nysics: ativity.	unit R. McG Wiley 2007.	iraw-Hill 200	03.	s 2009.	
Transfer	The module belongs to the <i>Mathematical Physics</i> . Takin be included in the Sections <i>Specialisation</i> , in accordance	g into a Study F	ccou	nt th , <i>Ad</i>	e ch	osen p ed Kn	ersonal Stu owledge in I	dy Speciali: <i>Mathematic</i>	sation, s or E	it can <i>lective</i>	
Prerequisites	Knowledge from the module of differential geometry are re			o Pa	rtial	Differe	ntial Equatio	ns and basi	ic knov	vledge	
Responsible Persons	Carla Cederbaum, Gerhard H	Huisken									

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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-60-08	Module Title: Null Geometry in General Rel	Module Title: Type of Module: Null Geometry in General Relativity Compulsory Module with Choice										
ECTS-Points	5							<u> </u>				
Workload - Time in Class - Self-Study		Time i 45 h	n Cla	ss:			Self-Stud	dy:				
Duration	1 Semester	1 Semester										
Frequency	not regularly	ot regularly										
Term	1-3	-3										
Language of Instruction	English	inglish										
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS										
Content	like vector fields and curves, a degenerate induced metric surfaces in higher codimension	This module provides an introduction to null geometry. Topics include the properties of light-ke 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	analyse known and new questi in cosmology and astrophysic methods and are able to ques the mathematical results deri the MAT-65-11 module and co able to name and prove the m relationships presented. The s of the lecture as well as asses In the exercise classes they ha terms, statements and method	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 onto new problems, to analyse them and to work on solution strategies on their own or in a team.										
Requirements for obtaining Credits / Grading (Weighting 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 ü	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100		
	examination the coursework r oral is decided by the instruc- module may exceptionally be	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 head of the examination board. – The module may exceptionally be offered by the lecturer without exercise classes; in this case, only 3 credit points will be awarded for the module instead of 5.										
Literature	Possible References :											
	Barrett O'Neill: Semi-R	ieman	nian	Geor	netry	. Acad	emic Press	1983.				
	Johannes Sauter: Folia tion (ETH Zürich), url: 11850/150826.											

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, E=essay, P=portfolio Teaching Format : 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 Equa	Module Title: Type of Module: The Einstein Constraint Equations 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								
Term	1-3								
Language of Instruction	English								
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SV	NS							
Content	- The Einstein ed - The Cauchy pro • The constraint equation - The conformal of the conformation of the	e elliptic theory on closed man f constant mean curvature on	ns. d: ifolds;						
Objectives	partial differential equations tions and analyse properties between the theory and quest and the Yambe problem and geometric analysis and physicapable of naming and provexplaining the presented concurrent state of research in the exercise classes they be terms, statements and method new problems, to analyse the	and thus describe parts of the of the associated solutions. I stions of geometric analysis suare familiar with the interplay clics for answering questions of the essential results of the essential results of the subject area. I have acquired a confident, precipes of the lecture. They have learn and to work on solution s	s constraints into a system of elliptic solution spaces of Einstein's equathey have learnt about connections uch as the scalar curvature problem of methods of Riemannian geometry, general relativity. The students are electure as well as assessing and eto reflect and critically analyse the eise and independent handling of the earned to transfer the methods onto trategies on their own or in a team. defend them in critical discourse.						

Requirements for obtaining Credits / Grading (Weighting 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		or.	o. 20-30	9	
	In this module an exercise certif examination the coursework mu oral is decided by the instructor module may exceptionally be offe points will be awarded for the m	st ha r with ered b	ve be app by the	een a rova e lect	acqui I by t turer	red. W	thether the ear	examination amination b	is writt oard	ten or - The
Transfer	The module belongs to the Stu Mathematical Physics. Taking in be included in the Sections Stu Specialisation, in accordance w	nto a <i>idy F</i>	ccou ocus	nt th , <i>Ad</i>	e cho vanc	osen p ed Kno	ersonal Stud <i>wledge in l</i>	dy Specialis <i>Mathematic</i> s	ation, or <i>Ele</i>	it can ective
Prerequisites	Basic knowledge of differential knowledge of partial differential edge of general relativity is also lecture.	equa	tions	is a	n adv	vantage	e, but not es	sential. Pre	vious k	knowl-
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, E=essay, P=portfolio Teaching Format: 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-60-10								Module: ory Module	with C	hoice		
ECTS-Points	6											
Workload - Time in Class - Self-Study	Workload: 180 h											
Duration	1 Semester											
Frequency	not regularly	not regularly										
Term	1-3	-3										
Language of Instruction	English	nglish										
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SW	ecture 2 SWS + Ex.cl. 2 SWS										
Content	deform curves, hypersurface	Students learn about recent results from the theory of geometric evolution equations that leform curves, hypersurfaces and other submanifolds of an ambient space. Examples are ne flow of hypersurfaces along the mean curvature or flows with other geometrically defined elocities.										
Objectives	equations, which will enable to a Master's thesis or with a proving the essential results connections. In the exercise classes they have terms, statements and methonew problems, to analyse the	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 onto 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam Dur. of Exam (min) Grading					
	Special Topics in Evolution	L	f	2	3	yes	wr. o.	90-180	g	100		
	Equations for Submanifolds	Е	f	2	3	,00	or.	o. 20-30	9	100		
	In this module an exercise ce examination the coursework oral is decided by the instruct	must ha	ve b	een a	acqu	ired. W	hether the	examination	is wri			
Literature	Possible References :											
	Klaus Ecker: Regulari	ty theor	y for	mea	n cui	rvature	flow. Birkha	äuser 2004.				
Transfer	Mathematical Physics. Takin be included in the Sections	The module belongs to the <i>Study Specialisation Analysis and Differential Geometry</i> und <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	Knowledge from the module I of differential geometry is req		tion t	o Pa	rtial	Differe	ntial Equation	ons and basi	c knov	vledge		
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, E=essay, P=portfolio Teaching Format: 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: ory Module	with C	Choice		
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 180 h	Time in	n Cla	ss:			Self-Stud	dy:				
Duration	1 Semester	l Semester										
Frequency	ot regularly											
Term	1-3	3										
Language of Instruction	English	nglish										
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS										
Content	deform curves, hypersurface	students learn about recent results from the theory of geometric evolution equations that eform curves, hypersurfaces and other submanifolds of an ambient space. Examples are ne flow of hypersurfaces along the mean curvature or flows with other geometrically defined elocities.										
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.								as part ng and			
Requirements for obtaining Credits / Grading (Weighting 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	n L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100		
	Whether the examination is w of the examination board.	ritten or	oral	is de	cide	d by the	e instructor v	vith approva	l by the	e head		
Literature	Possible References : • Klaus Ecker: Regulari	ty theor	y for	mea	n cui	rvature	flow. Birkhå	iuser 2004.				
Transfer	The module belongs to the Mathematical Physics. Takin be included in the Sections Specialisation, in accordance	g into a <i>Study F</i>	ccol ocus	int th s, <i>Ad</i>	e ch <i>vanc</i>	osen p ed Kn	ersonal Stu owledge in I	dy Specialis Mathematic	sation, s or E	it can <i>lective</i>		
Prerequisites	Knowledge from the module of differential geometry is rec		tion	o Pa	rtial	Differe	ntial Equatio	ons and basi	c knov	vledge		
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, E=essay, P=portfolio Teaching Format: 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	Type of I	Module: ory Module	with C	hoice							
ECTS-Points	3											
Workload - Time in Class - Self-Study	Workload: 90 h	Time 30 h	in Cl	ass:			Self-Stud	ly:				
Duration	Semester											
Frequency	not regularly											
Term	1-3	-3										
Language of Instruction	English	nglish										
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS										
Content	The course is divided into the general relativity, the causal study singularities and the ce we will study Penrose's cos phenomenon of gravitational some examples of gravitation conjecture. The content is as • Causality theory: — Time orientation • Singularities: — Raychoudhuri's • Black holes: — Cosmic censors	hierarc lebrate mic ce collaps nal colla s follow n, caus equati	hy ard sing nsors e, whapse s: al hie	nd var gularit ship o lich is that a erarch	ious by the conject the rappar y, glo	theore orems cture, s eason ently d obal hyp	ms related to by Penrose some proper for the formation ones not obe overbolicity.	o causality. and Hawking rties of blace ation of sing y the cosmit theorems.	Then v g. And k hole ularities	ve will finally s, the s, and		
Objectives	Students have acquired in-c general relativity. They will lest singularity theorems. They will singularities. They are ablest categorise and explain the r critically scrutinise the current	arn to a Il also (o name elation	apply get ar e and ships	topolo over d prov s pres	ogica view e the ente	I metho of cosi main d. Stu	ods in causa mic censorsh statements dents will be	lity theory a nip conjectur of the lectur able to rep	nd in pr re and r re as w	roving naked vell as		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Gravitational Collapse ar Singularities in General Rel		L/A	SWS 2	s ECTS	Goursework Coursework	Type of Exam o. o. c.	Onr. of Exam (min) 90-180 0. 20-30	Grading	00 Weight for Grade		
	Whether the examination is word the examination board.	ritten c	or ora	l is de	cide	d by the	instructor v	vith approva	l by the	head		

Literature	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.
Transfer	The module belongs to the Study Specialisations Analysis and Differential Geometry and Mathematical Physics. Taking into account the chosen personal Study Specialisation, it can be included in the Sections Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in accordance with the restrictive requirements of the respective section.
Prerequisites	Basic knowledge of relativity is required to follow the course.
Responsible Persons	Carla Cederbaum, Gerhard Huisken

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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 Parab tions	olic Pa	rtial [Oiffere	ential	Equa-	Type of I	Module: ory Module	with C	hoice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in Cla	iss:			Self-Stud	dy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SW	Lecture 2 SWS + Ex.cl. 2 SWS								
Content	 Minimum surface oper Parabolic geometric er Hölder continuity acco 	 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 secon of partial differential equations were learnt to prove the exist are capable of naming and prexplaining the presented con In the exercise classes, studiethods they have learnt and to present their problem soluresearch.	d order s from rence a oving the nection lents he lents he lents he	of the mather nd resonance estimates and the control of the contro	e ellip ematic gular sentia cquir hem	otic and plant of the control of the	nd para nysics a solution sults of onfider pender	abolic type. It and different ons to such the lecture a nce in the to atly to other	Using concretial geometry equations. The same well as as echnical harm problems. The same constant is a same constant and the same c	ete exa y, techr The stu ssessin ndling They are	mples niques dents ag and of the e able
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Non-Linear Elliptic and	- Type of Course	Status	s SWS	b ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Parabolic Partial Differential Equations	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	rtificate	is to ave b	be a	icqui acqui	ired. W	hether the	examination	is writ	

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
Abbreviations: Grading System : g	=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format : 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	Parabo	olic Pa	artial	Diffe	rential	Type of I	Module: ory Module	with C	hoice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time i	in Cla	iss:			Self-Stud	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	1-3									
Language of Instruction	English	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 have terms, statements and method new problems, to analyse the They are able to present their	itions on the second of the se	f the nique the a to or and nted on the lecond to white the conditions are lecond to which the lecond the l	ellipti s we ssoc ther p provi conne a co ture. ork c	c and re le iated or obland the ction of the ction of the ction on so	d parak arnt to d bound ems al e esse ns. ent, pred have lution s	polic type. Uprove the order value pand related ential results cise and independent to trategies o	Ising concre existence a problems. Sequations in of the lectu ependent ha cansfer the n n their own	ete examend regional region dependence as wandling nethods or in a	mples ularity is can dently. Vell as of the is onto team.	
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Fully Non-Linear Elliptic ar Parabolic Partial Differenti Equations		t Status	SMS 2	ε ECTS	Coursework	Type of Exam	On: of Exam (min) 90-180 o. 20-30	a Grading	Weight for Grade	
	Whether the examination is w of the examination board.	ritten o	r oral	is de	cided	by the	instructor v	uith approva	l by the	head	

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
Abbreviations: Grading System : g	=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:		Type of Module:								
MAT-65-05	Groups and Representation	S	Compulsory Module with Choice								
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time in Class: 90 h	Self-Study: 180 h								
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	English	alish									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 S	cture 4 SWS + Ex.cl. 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: symme	tries and degeneracies in qua	ntum mechanics, selection rules.								
	Representations of fit tents.	nite groups: group algebra, re	gular representation, ideals, idempo-								
	Symmetric groups: Y	oung tableaux, Young operato	ors, dimensions and characters.								
	Applications: identications:	l particles in quantum theorie	S.								
	Lie groups: Haar mea	asure, representations, Lie alç	gebras.								
	Tensor representation	ns of classical groups: symme	etry classes, Young tableaux.								
	Applications: SU(2) a	and SU(3) in particle physics (spin, isospin, flavour)								
	Moreover a selection	•									
	·	resentations of the Lorentz an otion of particles in quantum t	- '								
		·	on of semi-simple Lie algebras								
Objectives	to apply these abstract alg thus, developed a deepend physics. The students are for representation theory of grou- essential results of the lectu In the exercise classes they lead terms, statements and meth- new problems, to analyse the	ebraic concepts in the content understanding for the connamiliar with a number of computer in physics. The students are as well as assessing and enave acquired a confident, precods of the lecture. They have been and to work on solution states.	presentation theory. They are able ext of theoretical physics and have, ections between mathematics and plex examples of applications of the re capable of naming and proving the explaining the presented connections. Disse and independent handling of the learned to transfer the methods onto estrategies on their own or in a team. In defend them in critical discourse.								

: o=obligatory, f=facultative

Status

Other

Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Groups and Representations	п г Type of Course	t Status	SMS 4 2	8 B ECTS	Sework	Type of Exam o. o.	Our. of Exam (min) 0. 20-30	Grading	Weight for Grade
	In this module an exercise certif examination the coursework mu oral is decided by the instructor	ıst ha	ve b	een a	acqui	ired. W	hether the	examination	is writ	
Literature	Mechanics. NEO Press	 Possible References: 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 <i>Stu Physics</i> . Taking into account the the Sections <i>Study Focus</i> , <i>Adva</i> accordance with the restrictive rather module cannot be taken tog due to the large overlap in conte	e cho enced equir ether	sen <i>Kno</i> eme	perso wled nts o	onal <i>ge in</i> f the	Study Mathe respec	Specialisation specialisation specialist in the section in the sec	on, it can be lective Spec	e includ cialisati	ded in ion, in
Prerequisites	There are no further prerequisit	es.								
Responsible Persons	Stefan Keppeler									
Examination Type: M Teaching Format: La	=graded, ng=not graded IT=master's thesis, or.=oral exam =lecture, LE=lecture with integrated =project, S=seminar, IC=inverted	d exe	rcise	s, SL				-	•	

Module Number: MAT-65-12	Module Title: Mathematical Quantum Theo	ry					Type of Compuls	Module: sory Module	with C	hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud 180 h	dy:		
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 SV	VS, F	Home	ework A	Assignment	s		
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 a them to analyse known and r physical problems in atom, so spectral and interference the of the mathematical model are examples how the mathematic they enhance their knowledgunderstanding of the listed rown problems from quantum solid state and particle pysic theoretical methods and to quand of the results derived from notions are naturally applied on methods and subjects. Structure of the lecture as winto a larger framework. Through homework assignment and independent acquaintant lectures. They learn how to to develop solution strategies solutions and to stand for the	new propolic state or etical notions theory as and the state of the st	blem te an I mee the re the re and . The their the i the o their are a dexe their the i their the i their their their are the their the re their the re the re the re the re the re the re their the re their the re the re their the re their the re the the re the the re the the re the the the re the the re the re the the the the the the the the the the	es frood parthods frood parthods sults sults are na cods a meth per parthod frood fr	m querticles and deritural sends sends sends en ablaema ance eorien on narrow ethologians, setho de with the control of the co	uantum pysics to quived fro ly appl subject and ca le to initical m and ac less. The me and context sses st stateme ds to m hin a g	theory. The and their restion the restion to the restion the resting the resti	ey are able mathematical relevance are ents experies hysical theorem to analyse ysical proble pectral and the mathem les how the renhance the essential stain the lecture elop a conficient ods expens, to analyse mathematical stain the lecture elop a conficient ods expens, to analyse	to interal mode and adee to the control of the cont	rrelate els via equacy prough nereby, ge and atom, erence model natical vledge ts and populities and put it recise, in the m and
Requirements for obtaining Credits / Grading (Weighting 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
	Theory	Е	0	2	3		or.	o. 20-30		
	In this module students need the exam. The type of examin							n order to be	e admi	tted to
Transfer	Successful completion of me participation in the module A completion of one of the mod is a prerequisite for the partic	dvance ules Ma	ed To athen	pics natica	in M al Qu	athem: uantum	atical Quan Theory and	tum Theory	. Succ	essful

Prerequisites	-					
Responsible Persons	Christian Hainzl, Stefan Teufel					
Abbreviations: Grading System : g=graded, ng=not graded						
Examination Type: N	//T=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio					
	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, P=project, S=seminar, IC=inverted classroom					
Status : c	=obligatory, f=facultative					
Other : h	=hours, o.=or, s.M.=see module description, SWS=contact hours per week					

Module Number: MAT-65-13	Module Title: Mathematical Relativity						Type of Compuls	Module: ory Module	with C	hoice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time ii 90 h	n Cla	ss:			Self-Stud	dy:			
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 Classes 2 SWS, Homework Assignments										
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	use them to analyse known interrelate physical problems through methods from differe mathematical model and the methods and subjects gained Students are able to name a as well as to explain the cont Through homework assignmend independent acquaintar lectures. They learn how to	Students obtain knowledge and understanding of the listed notions and methods and can use them to analyse known and new problems from the theory of relativity. They are able to interrelate physical problems in cosmology and astrophysics and their mathematical models through methods from differential geometry and to question the relevance and adequacy of the mathematical model and the results derived from it. Thereby, they enhance their knowledge on methods and subjects gained throughout the first semester, in particular in module MAT-65-11. 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									
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Mathematical Relativity	п Гуре of Course	o o Status	SMS 4	6 3	Coursework	Type of Exam or. o.	Dur. of Exam (min) 0. 20-30	Grading	Weight for Grade	
	In this module students need the exam. The type of exami							n order to be	e admi	tted to	
Transfer	Successful completion of mo in the module Advanced Top the modules Mathematical Reparticipation in the module S	oics in Melativity	lathe or Ma	mati ather	cal F	Relativi	ty. Success	ful completi	on of o	one of	
Prerequisites	Participation in the module G	eometr	y in F	hysi	cs is	a prere	equisite.				
Responsible Persons	Carla Cederbaum, Gerhard I	Huisken	, Frai	nk Lo	ose		_				

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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-65-14	Module Title: Mathematical Statistical Physi	cs					Type of Compuls	Module: ory Module	with C	hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study		Time ii 90 h	n Cla	ss:			Self-Stud	ly:		
Duration	1 Semester									
Frequency	not regularly, in Summer Sem	ester								
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignments									
Content	are concepts of probability the ensembles, thermal equilibriude processes, Wiener processes, laphase transitions), statistical quality thermal equilibrium, Bose-Einstein	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 a use them to analyse known interrelate fundamental physicand their mathematical mode adequacy of the mathematical their knowledge on methods a probability theory. Students are from the lecture as well as to larger framework. Through homework assignme and independent acquaintance lectures. They learn how to to develop solution strategies solutions and to stand for them	and ne cal co ls via p model nd sub e able texplair nts and e with ransfer on the	ew processor needs and jects to na the dexect the reconstructions.	roble pts, s abilist of the gaine me a cont ercise notio se m en ane	ms fuch tic me resed the nd present constant to the classification of the classification	rom st as equethods ults de rougho rove the levelop sses stratement ds to no hin a g	atistical phy illibrium, irr and to que rived from it out the first se e essential se ed in the le udents deve ents, and m ew problem roup. They	vsics. They eversibility estion the reconstruction the reconstruction the reconstruction that the statements acture and to elop a confident of the statements acture and to elop a confident of the statements, to analysis, to analysis	are a and er levance hey enl particuland core put it lent, prained se ther	ble to ntropy, e and nance lar on ncepts into a recise, in the m and
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Mathematical Statistical	L	0	4	6	yes	wr. o.	90-180	g	100
	Physics In this module students need the exam. The type of examin							o. 20-30		ted to
Transfer	Successful completion of mode Topics in Mathematical Statistics				site fo	or the p	articipation	in the modu	le Adv	anced
Prerequisites	-									
Responsible Persons	Marcello Porta, Roderich Tum	ulka								

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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 Me	chanics					Type of Compuls	Module: ory Module	with C	hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: 270 h	Time ii 90 h	n Cla	ss:			Self-Stud	dy:		
Duration	1 Semester						•			
Frequency	regularly every two years									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignments									
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	and understand several imp mathematical knowledge rele the mathematical treatment the surprising phenomena ar controversial about the orthodebate on fundamental issue results of the lecture as well In the exercise classes they h terms, statements and method	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 onto new problems, to analyse them and to work on solution strategies on their own or in a team.								
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Foundations of Quantum	г Type of Course	4 Status	SMS 4	9 ECTS	Sework	Type of Exam	Dur. of Exam (min)	ص Grading	00 Weight for Grade
	Mechanics	Е	f	2	3	y 63	or.	o. 20-30	9	100
	The type of examination is se	et by the	insti	ructo	r.					
Transfer	The module belongs to the state the chosen personal Study S vanced Knowledge in Mather requirements of the respective	pecialis natics o	ation r <i>Ele</i> e	, it ca	an be	includ	led in the Se	ections <i>Stud</i>	ly Focu	ıs, Ad-
Prerequisites	The basic modules on Analy	sis and	Linea	ar Alç	gebra	are re	quired.			
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, E=essay, P=portfolio Teaching Format: 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:					Type of Module:				
MAT-65-21	Advanced Topics in Mathematical Quantum Theory Compulsory Module with Choice						hoice			
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: 90 h					Self-Study: 180 h				
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lectures 4 SWS + Exercise Classes 2 SWS, Homework Assignments									
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 Credits / Grading (Weighting 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 Theory	L E	0	2	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 the exam. The type of examination is set by the instructor.						ted 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 : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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: Type of Module:									
MAT-65-31	Mathematical Methods for Condensed Matter Physics					Compulsory Module with Choice				
ECTS-Points	6									
Workload - Time in Class - Self-Study		Time ii 60 h	n Cla	ss:			Self-Stud	ly:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 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 b	undle								
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 onto 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		.se					u	Dur. of Exam (min)		rade
for obtaining Credits / Grading		Course				work	Exam	Exan	6	Weight for Grade
(Weighting if applicable)		Type of (Status	SWS	ECTS	Coursework	Type of	ır. of	Grading	eight
,	Title					ŏ			Θ	>
	Mathematical Methods for Condensed Matter Physics	E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise cer examination the coursework moral is decided by the instructor	iust ha	ıve b	een a	acqui	ired. W	hether the	examination	is writ	
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, only know Mathematik are required.	ledge	from	the	basio	cours	es of the fir	st two years	in the	B.Sc.

Other

Responsible Persons	Stefan Teufel					
Abbreviations: Grading System : g=graded, ng=not graded						
Examination Type : N	IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio					
	electure, 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							hoice		
ECTS-Points	6									
Workload - Time in Class - Self-Study		Time i 60 h	in Cla	iss:			Self-Stud	dy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SWS									
Content	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.									
Objectives	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 effect. 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 Credits / Grading (Weighting 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 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 head of the examination board.									
Transfer	The module belongs to the <i>specialisations Analysis and Differential Geometry</i> and <i>Mathematical Physics</i> . Taking the personal specialisation and the restrictions of the sections into account, the module can be assigned to the Section <i>Specialisation</i> , <i>Specialisation Knowledge Mathematics</i> or <i>Elective Specialisation</i> .									

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

Grading System : g=graded, ng=not graded

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

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

Status : o=obligatory, f=facultative

Module Number: MAT-65-33	Module Title: Wave Equations of Relativistic	Module Title: Wave Equations of Relativistic Quantum Mechanics						Module: ory Module	with Cl	hoice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: 180 h									
Duration	1 Semester	1 Semester								
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English	erman or English								
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SW	ecture 2 SWS + Ex.cl. 2 SWS								
Content	Klein-Gordon equation	Klein-Gordon equation.								
	Dirac equation.	Dirac equation.								
	Representation Theory of the Lorentz Group.									
	Relativistic Many-Partic	cle Sys	tems	(Mu	lti-Tir	me For	malism).			
Objectives	mechanics. They learn analysolutions of the Klein-Gordon properties. The students are a They are able to name and properties are able to describe and area. Through homework assignment and independent acquaintant lectures. They learn how to the solutions of the	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 Credits / Grading (Weighting if applicable)	Title	- Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Wave Equations of Relativis- tic Quantum Mechanics	E	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100
	In this module an exercise cert is written or oral is decided by	n this module an exercise certificate is to be acquired as coursework. Whether the examination s written or oral is decided by the instructor with approval by the head of the examination board.								

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, E=essay, P=portfolio Teaching Format: 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-65-36	Module Title: Quantum Information Theory						Type of I	Module: ory Module	with C	hoioo
							Compuis	ory wodule	WILIT C	noice
Workload - Time in Class - Self-Study	9 Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud	ly:		
Duration	1 Semester	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	ecture 4 SWS								
Content	universality and meas Quantum algorithms: Quantum communicate coding. Quantum key Physical realizations: Decoherence and ope Quantum error correct Alternative quantum of	 Basic notions on the universal quantum computer: Quantum gates, quantum circuits, universality and measurements. Quantum algorithms: Deutsch-Jozsa, Shor and Grover. Quantum communication: No-cloning theorem, quantum teleportation and superdense coding. Quantum key distribution. Physical realizations: DiVincenzo criteria, Cirac Zoller quantum computer, Circuit QED. Decoherence and open quantum systems. Quantum error correction. Fault tolerant quantum computing. Alternative quantum computing models: Adiabatic quantum computation. Introduction to the theory of entanglement: Definition, criteria and measurement of entanglement, multipartite entanglement. 								
Objectives	processing. They understand have learnt how to program algorithms work and can deserror correction and entangle of physical realisations of a proving the essential results connections. In the exercise classes they have the terms, statements and method new problems, to analyse the	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 onto 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Quantum Information Theor	y L ü	f	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100
	examination the coursework									

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:						Type of I	Module:		
MAT-65-37	Matrix Analysis and Applicat	ions					Compuls	ory Module	with C	hoice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 3 SWS + Ex.cl. 1 SV	WS								
Content	Foundations of opera	Foundations of operators and matrices: Square matrices and tensor products.								
	Mappings and algebr	as.								
	Positive matrices.	Positive matrices.								
	Functional calculus a	Functional calculus and derivations.								
	Matrix monotone fund	ctions ar	nd co	nvexi	ty.					
	Matrix means and ine	qualitie	S.							
	Applications in quanti	um infor	matio	n the	ory.					
Objectives	analysis. They have become including topics such as more quantum Markov triplets, etc analysis in quantum informatessential results of the lecture. In the exercise classes they be terms, statements and method new problems, to analyse the	Students have acquired in-depth knowledge of matrix analysis from the perspective of functional analysis. They have become familiar with some aspects of analysis in the context of matrices, including topics such as monotone matrix functions, matrix averages, majorisation, entropies, quantum Markov triplets, etc. They are also familiar with several typical applications of matrix analysis in quantum information 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 onto 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 Credits / Grading (Weighting if applicable)	Title Marix Analysis and Applications	ш г Type of Course	J Status	SMS 3	SLO3 4,5	Sex	Type of Exam or. o.	Onr. of Exam (min) 90-180 0. 20-30	Grading	Weight for Grade
	In this module an exercise c examination the coursework oral is decided by the instruc	ertificate must ha	is to	be a	cqui acqui	ired. W	hether the	examination	is writ	

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, E=essay, P=portfolio Teaching Format: 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:Type of Module:Hamiltonian SystemsCompulsory Module with Computer of Module with Comp									hoice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: 90 h						Self-Stud	dy:		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German or English									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	ecture 4 SWS + Ex.cl. 2 SWS								
Content	mechanics. This builds a brid	ne module provides an introduction to the theory of Hamiltonian systems as used in classical echanics. 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	Symplectic manifolds and the canonical 1-form of the cotangent bundle.								
	Darboux-Moser theorem	Darboux-Moser theorem.								
	 Lagrangian and Hami 	Lagrangian and Hamiltonian systems.								
	Integrable systems ar	Integrable systems and Arnold-Liouville theorem.								
	Moment mappings.									
	Symplectic reduction.									
	Symplectic manifolds	and tori	c effe	ects.						
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 onto 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 Credits / Grading (Weighting 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	2	6 3	yes	wr. o. or.	90-180 o. 20-30	g	100
	examination the coursework	or 0 20-30 9 1								

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, E= essay, P= portfolioTeaching Format : 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-65-39	Module Title: Propagation of Chaos	7,						hoice		
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 270 h 180 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS									
Content	Interacting many body	system	ıs (qı	uantu	ım aı	nd clas	sical), impo	rtance of co	rrelatio	ons.
	Mean-field situations (e	e.g., Vla	asov)	and	colli	sions (Boltzmann).			
	Explicit treatment of co	rrelatio	ns.							
	Large deviations from the expected value.									
Objectives	linear equations. They are ab microscopic many-body systemechanical situations. Base understand how the independence is intime (propagation of chaos). But of the respective situation.	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 Credits / Grading (Weighting 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.	90-180	g	100
		?	f	2	3	, , ,	or.	o. 20-30	9	
	In this module an exercise cer examination the coursework n oral is decided by the instructo	nust ha	ıve b	een a	acqu	ired. W	hether the	examination	is wri	
Literature	Possible References :									
	Louis-Pierre Chaintron ods and applications. a					agation	of chaos: a	review of m	odels,	meth-
	Francois Golse: Mean-					ical Dy	namics. arX	(iv:2201.020	05.	
Transfer	The module belongs to the Stu into account the chosen perso Focus, Advanced Knowledge restrictive requirements of the	nal Stu <i>in Math</i>	dy S _l ema	oecia t <i>ics</i> o	ılisati or <i>Ele</i>	on, it c	an be includ	led in the Se	ections	Study

Prerequisites	In addition to the basics of analysis and linear algebra, the content of the Stochastics module is a prerequisite.						
Responsible Persons							
'	g=graded, ng=not graded MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio						
Teaching Format : L	_=lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial,						

Status : o=obligatory, f=facultative

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

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

Module Number: MAT-65-40	Module Title: Interacting Many-Body Quan	Module Title:Type of Module:Interacting Many-Body Quantum SystemsCompulsory Module with Choice								hoice
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	ot regularly								
Term	1-3	3								
Language of Instruction	German	erman								
Forms of Teaching and Learning	Lecture 4 SWS	cture 4 SWS								
Content	 Bose-Einstein conden Mean-field theory. Nonlinear Schrödinger Hartree- and Hartree- 	 Bosons and fermions. Bose-Einstein condensation. Mean-field theory. Nonlinear Schrödinger equation. Hartree- and Hartree-Fock theory. Bogoliubov approximations. 								
Objectives	many body systems. They unnumber in a certain area is someonic nature leads to the formaling regimes, interacting ronnlinear evolution equation calculate the leading order of	Students have learned about the difference between Fermions and Boson and its impact on many body systems. They understand that, at cold temperatures, the fluctuations of the particle number in a certain area is significantly suppressed for Fermions. They understand how the Bosonic nature leads to the famous effect of Bose Einstein condensation and that, in certain scaling regimes, interacting many body systems can in good approximation be described by nonlinear evolution equations. Finally they are able to give higher order corrections and to calculate the leading order correlations between the particles. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the								
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Propagation of Chaos	?	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 ha	ave b	een a	acqu	ired. W	hether the	examination	is writ	
Literature	Possible References: Elliott H. Lieb, Robert of the Bose Gas and it Niels Benedikter, Mare Quantum Dynamics. S	s Cond	lensa rta ,	ition. Benja	Birk	häuser	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	There are no further prerequisites.
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, E=essay, P=portfolio Teaching Format : 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 Differe	Type of Compuls	Module: ory Module	with C	hoice							
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time ii 90 h	n Cla	ss:			Self-Study: 180 h					
Duration	1 Semester	1 Semester										
Frequency	regularly											
Term	1-3											
Language of Instruction	German or English	erman or English										
Forms of Teaching and Learning	Lecture 4 SWS	ecture 4 SWS										
Content		umerical covering of boundary value problems of stationary (i.e. time independent) ordinary nd elliptic partial differential equations, with emphasis to the methods of finite elements.										
Objectives	of boundary value problems of naming and proving the essent presented connections. In the exercise classes they hat terms, statements and method new problems, to analyse the	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 onto 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 the s onto team.		
Requirements for obtaining Credits / Grading (Weighting 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	r- L ü	f	4	6	yes	wr. o. or.	90-180 o. 20-30	g	100		
	In this module an exercise cer examination the coursework r oral is decided by the instructor	nust ha	ave b	een a	acqu	ired. W	hether the	examination	is writ			
Literature	Possible References : • Dietrich Braess: Finite • Wolfgang Hackbusch: 7 1986.				_	-		tialgleichung	gen. Te	eubner		
Transfer	The module belongs to the Staking into account the choser Study Focus, Advanced Know with the restrictive requirement	n perso vledge	nal S in Ma	tudy a <i>thei</i>	Spec matic	cialisati s or <i>El</i>	on, it can be <i>ective Spec</i>	included in	the Se	ctions		
Prerequisites	Knowledge of the numerical a	lgorithi	ms m	odul	e is l	nelpful,	but not ma	ndatory.				
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, E=essay, P=portfolio Teaching Format: 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:Type of Module:Numerics of Instationary 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	regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 4 SWS	ecture 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	of boundary value problems of naming and proving the essent presented connections. In the exercise classes they hat terms, statements and method new problems, to analyse the	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 onto 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 the s onto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam (min) Grading					
	Numerics of Instationary	L	f	4	6	yes	wr. o.	90-180	g	100		
	Differential Equations	ü	f	2	3	, , ,	or.	o. 20-30	9			
	In this module an exercise cer examination the coursework moral is decided by the instructor	nust ha	ve b	een a	acqu	ired. W	hether the	examination	is writ			
Literature	Possible References :											
	Ernst Hairer, Gerhard W Springer 1996.	<i>l</i> anner	: Sol	ving	Ordir	nary Di	fferential Eq	uations II. S	tiff Pro	blems.		
	Vidar Thomee: Galerkir	Finite	Eler	nent	Meth	nods for	Parabolic F	Problems. S	pringer	1997.		
Transfer	The module belongs to the S Taking into account the chosen Study Focus, Advanced Know with the restrictive requiremen	persoi ledge	nal S in Ma	tudy a <i>ther</i>	Spec matic	cialisati s or <i>El</i>	on, it can be <i>ective Spec</i>	included in	the Se	ctions		
Prerequisites	Knowledge from the module helpful, but not absolutely nec			Math	ema	tics of	Stationary	Differential	Equation	ons is		
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, E=essay, P=portfolio Teaching Format: 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	s - Ana	alysis	and	Nun	nerics	Type of Compuls	Module: ory Module	with C	Choice	
ECTS-Points	9										
Workload - Time in Class - Self-Study		Time i	n Cla	iss:			Self-Stud	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	-3									
Language of Instruction	German or English	erman or English									
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SW	ecture 4 SWS + Ex.cl. 2 SWS									
Content	Bendixson, bifurcation	Non-linear ordinary differential equations: Theorems of Hartman-Grobman and Poincare-Bendixson, bifurcation theory.									
	Numerical approximating integration.	 Numerical approximation: linear multi-step processes, adaptive processes, geometric integration. 									
Objectives	solutions of non-linear ordinary for solving them and are in properties of the students are capable of not assessing and explaining the lin the exercise classes they has terms, statements and method new problems, to analyse the	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 onto 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Ordinary Differential Equa-	L	f	4	6	yes	wr. o.	90-180	g	100	
	In this module an exercise cer examination the coursework noral is decided by the instructor	tificate	ave b	een a	acqu	red as	hether the	examination	ipation	in the	
Literature	Possible References :	VI VVILII	αρρι	Ovai	Dy til	e nead	TOT LITE EXAL		aiu.		
	Lawrence Perko: Differ	ential e	equa	tions	and	dynam	ical system	s. Springer	1993.		
	David Griffiths, Desmortions. Springer 2010.					-	-			equa-	
Transfer	The module belongs to the S Numerical Mathematics and Specialisation, it can be incl Mathematics or Elective Special respective section.	<i>Optimi</i> uded i	<i>satic</i> n the	n. Ta e Se	aking ction	g into a	account the <i>ly Focus</i> , A	chosen per Advanced K	rsonal <i>nowle</i>	Study dge in	

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
Abbreviations:	=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, E=essay, P=portfolio Teaching Format : 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 Ordinary Differential Equations Type of Module: Compulsory Module with Choice										hoice
ECTS-Points	5										
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	-	Cla	ss:			Self-Stud	ly:		
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German	erman									
Forms of Teaching and Learning	Lecture 2 SWS	ecture 2 SWS									
Content	Brief overview of exist	tence	and	d uni	quer	ness	theory	for ODEs.			
	Numerical solutions to	ODE	Ēs.								
	Introduction to optima	I cont	rol	prob	lems	with	ODEs	i.			
	 Existence and unique problems). 	eness	the	eory	for	linea	r quad	ratic optima	al control pr	oblem	s (LQ
	Pontryagin's maximun	n prin	cipl	e.							
	Numerical approximat	tion of	f LC) pro	blen	ıs.					
Objectives	Students are familiar with the tions and various approaches statements on unambiguous essential results of the lecture. In the exercise classes they have terms, statements and method new problems, to analyse the They are able to present their	es to s solva e as v ave a ods of em ar	solv abili well cqu the nd t	ing ty. T as a ired lect o w	the passes a coure.	oroble tude ssing nfide They on so	em. The nts are and execute on the nt, pred	ey are also capable of capable of capable of capable of capable and independent of the carned to trategies of capable of the c	familiar wit naming and presented ependent ha ansfer the n n their own	h qualid provire connection of the connection of	itative ng the ctions. of the s onto team.
Requirements for obtaining			Course				ork	Exam	Dur. of Exam (min)		or Grade
Credits / Grading (Weighting if applicable)	Title	7	lype or C	Status	SWS	ECTS	Coursework	Type of E	Dur. of E	Grading	Weight for Grade
	Optimal Control Theory with Ordinary Differential	ı	L	f	2	3	yes	wr. o.	90-180	g	100
	Equations In this module an exercise ce examination the coursework oral is decided by the instruc	ertifica must	hav	e be	en a	acqui	ired. W	hether the	examination	pation is writ	
Literature	Possible References :			•		-					
	Matthias Gerdts: Optil	mal C	ont	rol c	of OE	Es a	and DA	Es. De Gru	yter 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 : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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 Equation	ons of	Sur	faces	,		Type of I	Module: ory Module	with C	hoice		
ECTS-Points	6											
Workload - Time in Class - Self-Study		ime ii 0 h	n Cla	.ss:			Self-Stud	ly:				
Duration	1 Semester	1 Semester										
Frequency	not regularly	not regularly										
Term	1-3	-3										
Language of Instruction	German	German										
Forms of Teaching and Learning	ecture 2 SWS											
Content	Semi- and fully discretization finite elements and efficient	 Numerical treatment of differential equations on moving (or stationary) surfaces. Semi- and fully discretization of elliptic and parabolic equations on surfaces using surface finite elements and efficient time integrators. Implementation of the algorithms. 										
Objectives	Students have learned the basic methods and techniques of numerics for problems on (moving) surfaces. In particular, they are familiar with the discussed energy techniques, which are very strong, general and rich in application, even in surface-independent areas of numerics. The students are capable of naming and proving the essential results of the lecture as well as assessing and explaining the presented connections. In the exercise classes they have acquired a confident, precise and independent handling of the terms, statements and methods of the lecture. They have learned to transfer the methods onto 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.								e very s. The vell as of the s onto			
Requirements for obtaining Credits / Grading (Weighting 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 cert examination the coursework m oral is decided by the instructor	ust ha	ive b	een a	acqu	ired. W	hether the	examination	is wri			
Literature	Possible References :					•		-		988.		
Transfer	The module belongs to the St Taking into account the chosen Study Focus, Advanced Knowl with the restrictive requirement	oerso edge	nal S in M	tudy a <i>ther</i>	Spec natio	cialisati s or <i>El</i>	on, it can be <i>ective Spec</i>	included in	the Se	ections		
Prerequisites	Knowledge of the numerical alg	gorithi	ns m	odul	e is ł	nelpful,	but not mai	ndatory.				

Responsible Persons	Christian Lubich
Abbreviations: Grading System : g	=graded, ng=not graded
Examination Type : M	T=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, leproject, 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-70-11	Module Title: Stochastic Differential Equat	ons					Type of Compuls	Module: ory Module	with C	hoice	
ECTS-Points	9										
Workload - Time in Class - Self-Study	Workload: 270 h	Time ii 90 h	n Cla	.ss:			Self-Stud	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3										
Language of Instruction	German	rman									
Forms of Teaching and Learning	Lecture 4 SWS	cture 4 SWS									
Content	Stochastic processes.	Stochastic processes, filtrations, martingales.									
	Wiener process, rander	om walk	, Doi	nskei	s th	eorem.					
	Diffusion semigroup, I	to's inte	gral.								
	Solution of a stochast	ic differe	ential	equ	ation						
	Markov property, Mall	Markov property, Malliavin calculus, rough path theory.									
Objectives	differential equations. The structure as well as assess In the exercise classes they have terms, statements and methor new problems, to analyse the	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 onto 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 the s onto team.	
Requirements for obtaining Credits / Grading (Weighting 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	yos	or.	o. 20-30	9	100	
	In this module an exercise context examination the coursework oral is decided by the instruction	must ha	ave b	een a	acqu	ired. W	hether the	examination	is wri		
Literature	Possible References :										
	Bernt Oksendal: Stoc	hastic d	ifferti	al ec	uatio	ns. Sp	oringer 2000).			
Transfer	The module belongs to the S Stochastics. Taking into account in the Sections Study Focus, in accordance with the restrict	ount the Advance	chos ced k	en p	ersoi ledge	nal Stu <i>in Ma</i>	dy Specialis thematics o	sation, it can r <i>Elective S</i>	be in	cluded	
Prerequisites	Knowledge of the modules St from the Bachelor of Science						ntegration a	and Measure	ment 7	heory	

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, E=essay, P=portfolio
	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, leproject, 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-70-12	Module Title: Introduction to Stochastic Differential Equations - Part 1 Type of Module: Compulsory Module wit										
ECTS-Points	5										
Workload - Time in Class - Self-Study		Time ii 90 h	n Cla	ss:			Self-Stud	dy:			
Duration	1 Semester										
Frequency	not regularly										
Term	1-3	-3									
Language of Instruction	German	German									
Forms of Teaching and Learning	ecture 2 SWS + Ex.cl. 1 SWS										
Content		Introduction to Brownian motion and stochastic integration. Only it is a support to for a table at its differential association.									
	·	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 onto 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 the s onto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade	
	Introduction to Stochastic	L	f	2	3	VAS	wr. o.	90-180	0	100	
	Differential Equations - Part 1	Е	f	1	2	yes	or.	o. 20-30	g	100	
	In this module an exercise cer examination the coursework moral is decided by the instructor	iust ha	ıve b	een a	acqu	ired. W	hether the	examination	is writ		
Literature	Possible References :										
	Bernt Oksendal: Stocha	astic d	iffere	ntial	equa	ations.	Springer 20	00.			
Transfer	The module belongs to the <i>Stu</i> Stochastics. Taking into account in the Sections Study Focus, A in accordance with the restrict	nt the Idvanc	chos ed K	en p	ersoi ledge	nal Stu <i>in Ma</i>	dy Specialis thematics o	sation, it can r <i>Elective S</i>	be inc	luded	
Prerequisites	Knowledge from the modules from the Bachelor of Science						n to Integrat	ion and Mea	asure T	heory	
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, E=essay, P=portfolio Teaching Format: 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: Numerics of Stochastic Differe	ential F	auat	ions			Type of I	Module: ory Module	with C	hoice		
ECTS-Points	3		quar				- Compare	.,				
Workload - Time in Class - Self-Study	Workload:											
Duration	1 Semester	l Semester										
Frequency	not regularly	ot regularly										
Term	1-3	-3										
Language of Instruction	German	erman										
Forms of Teaching and Learning	Lecture 2 SWS	cture 2 SWS										
Content	Strong and weak appro Euler-Maruyama methor	 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.								ng the			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Numerics of Stochastic Differential Equations	- L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100		
	Whether the examination is wr of the examination board.	tten or	oral	is de	cided	d by the	e instructor w	vith approva	l by the	e head		
Literature	Possible References : • Peter E. Kloeden, Eckh. Springer 1999.	ard Pla	ten: I	Num	erica	l solutio	on of stocha	stic different	ial equ	ations.		
Transfer	The module belongs to the Sta Stochastics. Taking into account in the Sections Study Focus, in accordance with the restrict	int the A <i>dvanc</i>	chos ed K	en p <i>nowl</i>	ersoi ledge	nal Stu <i>in Ma</i>	dy Specialis thematics o	ation, it can r <i>Elective S</i>	be inc	cluded		
Prerequisites	Knowledge from the Stochast	cs mod	dule	n the	e Bac	chelor	of Science is	s required.				
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, E=essay, P=portfolio Teaching Format: 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:	Type of Module: Compulsory Module with Choice										
	Stochastic Optimal Control in	minite	ווווט	ensic)IIS		Compuis	ory wodule	WILLI C	noice		
ECTS-Points	3						T					
Workload - Time in Class - Self-Study								Self-Study: 60 h				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German or English											
Forms of Teaching and Learning	Lecture 2 SWS											
Content	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 Credits / Grading (Weighting 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	ı L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100		
	Whether the examination is wr of the examination board.	itten or	oral	is de	cideo	d by the	e instructor w	vith approva	l by the	e head		
Transfer	Stochastics. Taking into account the Sections Study Focus, A	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 contents of the module N	umeric	al Ma	ather	natic	s are a	ssumed.					
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, E=essay, P=portfolio Teaching Format : 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												

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

Other

Module Number:	Module Title:						Type of		0			
MAT-70-22	Optimisation with Differential I	=quatio	ons				Compuls	ory Module	with C	hoice		
ECTS-Points	9						T					
Workload - Time in Class - Self-Study												
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	Brouwer-Minty theorem, non-linear evolution equations.										
	Gateaux and Frechet d	ifferen	tiabili	ty.								
	Proof of existence of operations	otimal (contr	ols, r	neces	ssary o	ptimality co	nditions.				
	Adjoint, convergent opt	imisati	on m	etho	ds in	Banac	h spaces.					
	Variational discretisation	n cond	epts									
Objectives	Students master the basic p prototypical control problems students are capable of nam assessing and explaining the In the exercise classes they ha terms, statements and method new problems, to analyse the They are able to present their	with co ing an oresenve acq is of th m and	onstra d pro ited o uired e lec to w	aints ving conne a co ture. ork c	in the the ection nfide They on so	e form essent essent ns. ent, pree have lution s	of partial di ial results on cise and ind learned to to strategies o	fferential eq of the lectur ependent ha ransfer the n n their own	uations e as w andling nethod or in a	of the sonto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)										Weight for Grade		
	Optimisation with Differential	L	f	4	6	yes	wr. o.	90-180	g	100		
	Equations	ü	f	2	3	,55	or.	o. 20-30	9	.00		
	In this module an exercise cer examination the coursework n oral is decided by the instructor	nust ha	ave b	een a	acqu	ired. W	hether the	examination	is writ	in the ten or		
Literature	Possible References :											
	Michael Hinze, Rene F constraints. Springer 2		, Mic	hael	Ulbr	ich, Ste	efan Ullrich	: Optimizatio	on with	PDE		

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	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, E=essay, P=portfolio Teaching Format: 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: Numerical Optimisation Type of Module: Compulsory Module with Choice												
MAT-70-25	Numerical Optimisation						Compuls	ory Module	with C	hoice			
ECTS-Points	5												
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud	dy:					
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 equ	ations a	ıs cor	nstrai	nts.								
	Optimization with inection	jualities	as c	onstr	aints								
	Applications:												
	- Economy: resor	urce allo	ocatio	n in l	ogis	tics, inv	vestments, e	etc.					
	 Science: mode design. 	estima	tion a	and a	dap	tation t	o measurer	ment data, e	experin	nental			
	 Engineering: de airplanes, digita 				on o	f techn	ical system	s such as b	ridges	cars,			
Objectives	Students are familiar with the are capable of naming and prexplaining the presented confinition in the exercise classes they have terms, statements and method new problems, to analyse the They are able to present their	oving the nection ave acques of the em and	ne ess s. uired e lec to w	a co ture. ork o	al res nfide They on so	ent, pred have lution s	the lecture a cise and ind learned to tr strategies o	as well as as ependent ha ansfer the n n their own	ssessin andling nethods or in a	g and of the sonto team.			
Requirements for obtaining Credits / Grading (Weighting if applicable)	They are able to present their solutions and, if necessary, defend them in critical discourse. Status SWS SWS Coursework Coursework Type of Exam Dur. of Exam Weight for Grade												
	Numerical Optimisation	L	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100			
		ü	f	1	2								
	In this module an exercise ce examination the coursework oral is decided by the instruc	must ha	ave b	een a	acqui	ired. W	hether the	examination	is writ				

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, E=essay, P=portfolio Teaching Format: 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:						Type of I					
MAT-70-30	Theoretical Aspects of Mach	ine Le	arnin				Compuls	ory Module	with C	hoice		
ECTS-Points	6	ı					_					
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in Cl	ass:			Self-Stud	ly:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	English											
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SWS											
Content	The lecture covers some recent aspects of theoretical machine learning such as:											
	The theory of Reprod	The theory of Reproducing Kernel Hilbert Spaces (RKHS).										
	Applications of RKHS mean embeddings.	 Applications of RKHS theory such as SVMs, kernel regression, kernel PCA, and kernel mean embeddings. 										
	Approximation capab	ilities o	of neu	ral ne	twork	KS.						
	Dynamics of neural n	etwork	s and	the r	neura	l tange	nt kernel.					
	Recent advances in h generalisation.	nigh dir	mens	ional	statis	stics, in	particular o	overparame	trisatio	n and		
Objectives	The students learn the mathe support vector machines and in machine learning and with tools as needed for the disciprove the essential statemer developed in the lecture and critically challenge the curre. Through homework assignmand independent acquaintal lectures. They learn how to develop solution strategie solutions and to stand for the	kernel h their ussion and to put to p	I meth theor and jul I conc t it into e of reand ex th the fer the neir ou	ods. etical ustific epts o a la esearc ercise notic ese m vn ar	They basication from reger ch in e classons, sethold with the constant of the	are fan s, math of algo the lect framev the spe sses st statement ds to n hin a g	niliar with fur- nematical ap- prithms. The ture as well work. They a ecific area. udents deve- ents, and m ew problem roup. They	ndamental mopproach and ey are able as to explain are able to color a conficient of the conficient of	nodern d conce to nam n the co describ dent, pr lained se ther	topics eptual e and ontext e and recise, in the m and		
Requirements		Course	3				_	(min)		rade		
for obtaining Credits / Grading (Weighting if applicable)	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade						
	Theoretical Aspects of Machine Learning			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 instru module may, in exceptional or in this case, only 3 credit points.	must h ctor wi ases, b	te is thave lith ap	oeen prova ered v	acqu Il by vitho	ired. W the hea ut exerc	coursework /hether the cad of the excises at the	For particiexamination amination b	is writ oard.	ten or – The		

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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	Type of Module: Compulsory Module with Choice										
ECTS-Points	9											
Workload - Time in Class - Self-Study		Time ii 90 h	n Cla	ss:			Self-Stud	dy:				
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	(Universal) consistency.										
	Rate convergence.											
	Stone's theorem.											
	Kernel estimator, k-NN	estima	ator.									
	Slow rate convergence	, minin	пах с	onve	rgen	ce rate	S.					
Objectives	Students are familiar with bas universal consistency and rat methods of stochastic learning capable of naming and provir explaining the presented confunction in the exercise classes they hat terms, statements and method new problems, to analyse the They are able to present their	e converse converse considerate considerat	rerge quired esse s. uired e lec to w	nce. d for i ntial a co ture. ork c	They mach resul nfide They on so	y are faine lead its of the nt, pred have l	miliar with rning applicate lecture a cise and ind earned to transfer to trategies o	the basic preations. The sations. The same well as as ependent has ansfer the man their own	inciple studen sessin andling nethod: or in a	s and ts are g and of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	· · · · · · · · · · · · · · · · · · ·									Weight for Grade		
	Statistical Learning Theory for Nonparametric Regres-	L	f	4	6	yes	wr. o.	90-180	g	100		
	sion 1	ü	f	2	3	,50	or.	o. 20-30	9	.00		
	In this module an exercise cer examination the coursework noral is decided by the instructor	nust ha	ave b	een a	acqui	ired. W	hether the	examination	is writ			
Literature	Possible References :											
	Laslo Györfi, Michael k nonparametric regressi					k, Harro	o Walk: A d	istribution-fr	ee the	ory of		

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format : 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 for 2	· Nonpa	aramo	etric	Regr	ession	Type of Compuls	Module: ory Module	with C	Choice
ECTS-Points	9									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Stu 270 h 90 h 180 h							Self-Study: 80 h		
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	German									
Forms of Teaching and Learning	Lecture 4 SWS									
Content	Abstract (strong) consistent imating) function class Examples, in particular neural networks estimated.	 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 onto 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 Credits / Grading (Weighting if applicable)	Title Statistical Learning Theory for Nonparametric Regres-	г Type of Course	J Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	sion 2	ü	f	2	3	yes	or.	o. 20-30	g	100
	In this module an exercise ce examination the coursework r oral is decided by the instruct	nust ha	ave b	een a	acqu	ired. W	hether the	examination	is wri	
Literature	Possible References :									
	Laslo Györfi, Michael I nonparametric regress					k, Harr	o Walk: A d	istribution-fi	ee the	eory of
Transfer	The module belongs to the St Stochastics. Taking into according the Sections Study Focus, in accordance with the restrict	unt the Advanc	chos ced k	en p	erso ledge	nal Stu e <i>in Ma</i>	dy Specialis thematics o	sation, it can r <i>Elective S</i>	be in	cluded
Prerequisites	Knowledge from the module S	Statistic	al Le	arnir	ng 1	is assu	med.			

Responsible Persons	Andreas Prohl
Abbreviations: Grading System : g	=graded, ng=not graded
Examination Type : M	IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, leproject, 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-70-33	Module Title: Theory and Numerics for Conlems	straine	d Op	timis	atior	ı Prob-	Type of Compuls	Module: ory Module	with C	hoice
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	English									
Forms of Teaching and Learning	Lecture 4 SWS									
Content	method with step size control a as well as its variants. The sin this is the convex (non-linear) with (necessary) optimality cor Karush-Kuhn-Tucker conditio	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	The participants have become constrained optimisation prob simplex method, interior point be able to analyse the algorit naming and proving the essen presented connections. In the exercise classes they hat terms, statements and method new problems, to analyse the They are able to present their	lems: to method hms are tial research	hese ods, p nd co ults o uired e lec to w	inclusion inclus	ude glisation re the lection of the	radient on met eir con ure as t nt, pred have l	t methods whods and the holexity. he well as assectise and independent to the trategies o	with step size as SQP metal students are essing and e ependent has ansfer the non their own	e control hod. You e capa xplainio andling nethod or in a	ol, the ou will able of ng the of the s onto team.
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Theory and Numerics for	г Type of Course	- Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Constrained Optimisation Problems	ü	f '	2	3	yes	wr. o. 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 head of the examination board. — 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.	Kanzo	w: T	neori	ie un	d Num	erik restrinç	gierter Optir	mierun	gsauf-

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, E=essay, P=portfolio Teaching Format : 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-70-34	Module Title: Mathematical Introduction to	Data S	cienc	e			Type of I	Module: ory Module	with C	hoice
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	English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 1 SW	'S								
Content	The lecture provides a mathe regression and k-nearest neig and modern classifiers (Perc put on both theoretical foundate)	nbours eptron,	to his	gh-dii 1s, K	nens erne	sional p I Metho	henomena, ods, Neural	dimensional Networks).	ity red	uction, asis is
Objectives	are able to implement k-near (Perceptron, SVM (kernel me convex objectives using gradessential statements and concin the lecture and to put it in challenge the current state of Through homework assignment and independent acquaintan lectures. They learn how to	The students can formulate and solve linear, polynomial and logistic regression models. They are able to implement k-nearest neighbours classification and build and evaluate classifiers (Perceptron, SVM (kernel methods), Neural Networks). Moreover, they know how to optimise convex objectives using gradient-descent techniques. 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 Credits / Grading (Weighting if applicable)	Title Mathematical Introduction to Data Science In this module an exercise ce examination the coursework oral is decided by the instruction module may, in exceptional care	rtificate must ha tor with	ave b n app e offe	een a rova red v	acqui I by t vithou	ired. Withe hea at exerc	thether the older the olde	examination amination b	is writ oard.	ten or – The
Literature	Possible References : • Sven A. Wegner: Math							Springer 20	24.	
Transfer	The module belongs to the Sti Stochastics. Taking into acco in the Sections Study Focus, in accordance with the restrict	unt the <i>Advan</i> d	chos ced k	en p	ersoi ledge	nal Stu e <i>in Ma</i>	dy Specialis <i>thematics</i> o	ation, it can r <i>Elective S</i>	be inc	luded

Prerequisites	Basic knowledge in linear algebra, analysis and probability theory is needed as well as basic knowledge in python programming.
Responsible Persons	Andreas Prohl

Grading System : g=graded, ng=not graded

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

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

Status : o=obligatory, f=facultative

							Type of Module:		
Game Theory Compulsory Modu							ory Module	with C	hoice
3									
Workload: 90 h	Time in Class: 30 h			Self-Study: 60 h					
1 Semester									
not regularly									
1-3									
German or English									
Lecture 2 SWS									
The focus is on Nash and ge	neralise	d Na	sh ec	quilib	rium pr	oblems and	their numer	rical so	lution.
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.									
Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	_	Grading	Weight for Grade
Whether the examination is w					no by the	wr. o. or. e instructor v	o. 20-30	g I by the	100 e head
	xandra	Schv	artz/	: Spi	eltheor	rie. Birkhaeı	ıser 2018.		
Taking into account the chose Study Focus, Advanced Kno	en perso <i>wledge</i>	nal S in Ma	tudy a <i>ther</i>	Spec natio	cialisati s or <i>El</i>	ion, it can be <i>lective Spec</i>	included in	the Se	ections
						e module is	also suitable	e for stu	udents
Andreas Prohl									
=graded, ng=not graded									
							-	•	
				.=ser	ııııar 0	i lecture, E=	exercise cia	აა, I=โ	uloria
project, S=seminar, IC=inverted classroom obligatory, f=facultative									
	Game Theory 3 Workload: 90 h 1 Semester not regularly 1-3 German or English Lecture 2 SWS The focus is on Nash and gether analytical and numerical apparent proving the essential represented connections. Title Game Theory Whether the examination is well of the examination board. Possible References: • Christian Kanzow, Aleasting into account the chose Study Focus, Advanced Knowith the restrictive requirement Basic knowledge of analysis a of related fields with basic means and proving the state of the Taking into account the chose Study Focus, Advanced Knowith the restrictive requirement Basic knowledge of analysis a of related fields with basic means and proving the state of the Taking into account the chose Study Focus, Advanced Knowith the restrictive requirement Basic knowledge of analysis and frequency of the Taking into account the chose Study Focus, Advanced Knowith the restrictive requirement Basic knowledge of analysis and frequency of the Taking into account the chose Study Focus, Advanced Knowith the restrictive requirement Basic knowledge of analysis and frequency of the Taking into account the chose Study Focus, Advanced Knowith the restrictive requirement Basic knowledge of analysis and frequency of the Taking into account the chose Study Focus, Advanced Knowith the restrictive requirement Basic knowledge of analysis and frequency of the Taking into account the chose Study Focus, Advanced Knowith the restrictive requirement Basic knowledge of analysis and frequency of the Taking into account the chose Study Focus, Advanced Knowith the restrictive requirement Basic knowledge of analysis and frequency of the Taking into account the chose Study Focus, Advanced Knowith the Cho	Game Theory 3 Workload: Time if 30 h 1 Semester not regularly 1-3 German or English Lecture 2 SWS The focus is on Nash and generalise Students are familiar with the fund analytical and numerical approaches and proving the essential results of presented connections. Title Game Theory L Whether the examination is written or of the examination board. Possible References: • Christian Kanzow, Alexandra The module belongs to the Study Staking into account the chosen person Study Focus, Advanced Knowledge with the restrictive requirements of the Basic knowledge of analysis and num of related fields with basic mathematical Andreas Prohl Tegraded, ng=not graded AT=master's thesis, or.=oral exam, wr.=electure, LE=lecture with integrated exemples.	Game Theory 3 Workload: Time in Cla 30 h 1 Semester not regularly 1-3 German or English Lecture 2 SWS The focus is on Nash and generalised Nast Students are familiar with the fundamer analytical and numerical approaches to a and proving the essential results of the presented connections. Title Game Theory L f Whether the examination is written or oral in of the examination board. Possible References: • Christian Kanzow, Alexandra Schwith the restrictive requirements of the results of related fields with basic mathematical key and the presented connections.	Workload: 90 h 1 Semester not regularly 1-3 German or English Lecture 2 SWS The focus is on Nash and generalised Nash ederal search and proving the essential results of the lect presented connections. Title Game Theory L f 2 Whether the examination is written or oral is de of the examination board. Possible References: • Christian Kanzow, Alexandra Schwartz The module belongs to the Study Specialisa Taking into account the chosen personal Study Study Focus, Advanced Knowledge in Mather with the restrictive requirements of the respect Basic knowledge of analysis and numerics is as of related fields with basic mathematical know Andreas Prohl	Workload: 90 h 1 Semester not regularly 1-3 German or English Lecture 2 SWS The focus is on Nash and generalised Nash equilible Students are familiar with the fundamental issue analytical and numerical approaches to analysing and proving the essential results of the lecture presented connections. Title Game Theory L f 2 3 Whether the examination is written or oral is decided of the examination board. Possible References: • Christian Kanzow, Alexandra Schwartz: Spin The module belongs to the Study Specialisation Taking into account the chosen personal Study Specialis	Workload: 90 h 1 Semester not regularly 1-3 German or English Lecture 2 SWS The focus is on Nash and generalised Nash equilibrium properties of the lecture as we presented connections. Title Game Theory Under the examination is written or oral is decided by the of the examination board. Possible References: • Christian Kanzow, Alexandra Schwartz: Spieltheory The module belongs to the Study Specialisation Numeralising into account the chosen personal Study Specialisation or Ewith the restrictive requirements of the respective section. Basic knowledge of analysis and numerics is assumed. The of related fields with basic mathematical knowledge. Andreas Prohl	Workload: 90 h Time in Class: 30 h Self-Stud 60 h 1 Semester not regularly 1-3 German or English Lecture 2 SWS The focus is on Nash and generalised Nash equilibrium problems and Students are familiar with the fundamental issues of game theory, analytical and numerical approaches to analysing them. The student and proving the essential results of the lecture as well as assess presented connections. Title Game Theory L f 2 3 no wr. o. or. Whether the examination is written or oral is decided by the instructor v of the examination board. Possible References: • Christian Kanzow, Alexandra Schwartz: Spieltheorie. Birkhaeu The module belongs to the Study Specialisation Numerical Mather Taking into account the chosen personal Study Specialisation, it can be Study Focus, Advanced Knowledge in Mathematics or Elective Spec with the restrictive requirements of the respective section. Basic knowledge of analysis and numerics is assumed. The module is of related fields with basic mathematical knowledge. Andreas Prohl	Game Theory Compulsory Module 3	Workload: 90 h 1 Semester not regularly 1-3 German or English Lecture 2 SWS The focus is on Nash and generalised Nash equilibrium problems and their numerical so Students are familiar with the fundamental issues of game theory. They are familiar analytical and numerical approaches to analysing them. The students are capable of n and proving the essential results of the lecture as well as assessing and explaining presented connections. Title Game Theory L f 2 3 no wr. o. or. 90-180 Game Theory Whether the examination is written or oral is decided by the instructor with approval by the of the examination board. Possible References: • Christian Kanzow, Alexandra Schwartz: Spieltheorie. Birkhaeuser 2018. The module belongs to the Study Specialisation Numerical Mathematics and Optimitaking into account the chosen personal Study Specialisation, it can be included in the Set Study Focus, Advanced Knowledge in Mathematics or Elective Specialisation, in according the respective section. Basic knowledge of analysis and numerics is assumed. The module is also suitable for storelated fields with basic mathematical knowledge. Andreas Prohl

Module Number: MAT-70-51	Module Title: Financial Mathematics and N	umeric	S				Type of I	Module: ory Module	with C	hoice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SW									
Content	fillanseursnascenserial will less financial markets, and the num financial equations. Key topics include the mathem framework, and the use of stooptimisation. By integrating the financial mathematics and research.	Ind numerical techniques that are essential for understanding and solving problems in modern hanceurs design of the provided state o								
Objectives	mathematics and can apply not are able to name and prove the to explain the context develope able to describe and critically Through homework assignment and independent acquaintan lectures. They learn how to	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								
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	- Type of Course	Status	SWS	b ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Financial Mathematics and Numerics	E	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 instruction module may, in exceptional cain this case, only 3 credit points.	rtificate nust ha tor with ses, be	e is to ave b a app e offe	be a een a prova red w	icqui acqui acqu I by t vithou	ired. Withe hea at exerc	thether the old of the excises at the	examination amination b	is writ	ten or – The
Literature	Possible References : • Steven Shreve: Stocha	ıstic Ca	alculu	ıs for	Fina	ınce. S	pringer 200	5.		
Transfer	The module belongs to the Sta Stochastics. Taking into according the Sections Study Focus, in accordance with the restrict	unt the Advanc	chos ced k	en p	ersoi ledge	nal Stu <i>in Ma</i>	dy Specialis thematics o	ation, it can r <i>Elective S</i>	be inc	luded

Prerequisites	Knowledge of calculus, linear algebra, basic programming, ordinary differential equations theory and introductory probability is recommended.
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, E=essay, P=portfolio Teaching Format: 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:						Type of I			
MAT-75-02	Combinatorics						Compuls	ory Module	with C	hoice
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 + Ex.cl. 2 SV	vs								
Content	Basic combinatorial o	bjects.								
	Generating functions.									
	 Partial orders, Möbius 	inversi	ion.							
	Method of Polya and	Redfield	d.							
	Symbolic combinatori	cs.								
	Transfer matrix metho	d.								
	Euler-Maclaurin sumr	nation f	ormu	la.						
	Asymptotic methods.									
Objectives	The students have learned to discrete structures and cour mon identities and handling proving the essential results connections. In the exercise classes they have terms, statements and methor new problems, to analyse the They are able to present their	nting pro counting of the I have accords of the	obleming co ectured quired ne lect d to w	efficie e as v a co ture. ork c	urthe ents. well a nfide They on so	rmore The s as asse ant, pree have lutions	they are far tudents are essing and e cise and ind learned to tr strategies o	miliar with a capable of explaining the ependent has ansfer the round their own	pplying namin ne pres andling nethods or in a	g com- g and ented of the s onto team.
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	г Type of Course	- Status	SMS 4	e ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Combinatorics	E		2	3	yes	or.	o. 20-30	g	100
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	ave b	een a	acqui acqu	ired. W	hether the	examinatior	is writ	

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 <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	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
Abbreviations:	

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format : 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						Type of Compuls	Module: ory Module	with C	hoice		
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in Cla	ss:			Self-Stud 180 h	dy:				
Duration	1 Semester											
Frequency	regularly											
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SN	WS										
Content	 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. 											
Objectives	Students can model statistical analyse, compare and apply The students are capable of assessing and explaining the In the exercise classes they be terms, statements and method new problems, to analyse the They are able to present the	statistiche naming presenave accords ods of the nem and	cal es and nted o quirec ne lec d to w	timat provinci conne a co ture. ork c	ion and the ction of the ction	and tes le esse lent, pre- lution s	t methods a ential results cise and ind learned to tr strategies o	and interpret of the lectu ependent ha ansfer the r n their own	their re re as w andling nethods or in a	esults. vell as of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Mathematical Statistics	П Type of Course	f	SMS 4	8 B ECTS	Coursework	Type of Exam or. o.	Dur. of Exam (min) 0. 20-30	۵ Grading	Weight for Grade		
	In this module an exercise c examination the coursework oral is decided by the instruc	ertificat must h	e is to ave b	be a	icqui acqu	ired. W	hether the	examination	i is writ			

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

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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-75-04	Module Title: Stochastic Processes						Type of Compuls	Module: ory Module	with C	hoice			
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in Cl	ass:			Self-Stud	dy:					
Duration	1 Semester												
Frequency	regularly												
Term	1-3												
Language of Instruction	German	German											
Forms of Teaching and Learning	Lecture 4 SWS												
Content	Stochastic processes in cont	Stochastic processes in continuous time, such as											
	Markov processes;	Markov processes;											
	Martingale;												
	Brownian motion, Pois	sson pr	oces	ses a	nd g	eneral	Levy proces	sses;					
	Gaussian processes.												
	Among other things, existenc processes are analysed.	e and c	conve	rgeno	e sta	temen	ts as well as	path prope	rties of	these			
Objectives	The students have learnt the stochastic processes in contare capable of naming and prexplaining the presented cor. In the exercise classes they have terms, statements and method new problems, to analyse the They are able to present their	tinuous roving t inection lave accods of the em and	time the es ns. quire the lea d to v	and ssenti d a co cture. vork o	can I al res onfide They on so	nandle sults of ent, pre- y have slution s	them mather the lecture a cise and ind learned to treat strategies o	ematically. Tas well as as ependent har ansfer the non their own	The stussessing andling nethods or in a	of the s onto team.			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Stochastic Processes	L ü	f	4 2	6	yes	wr. o. or.	90-180 o. 20-30	g	100			
	In this module an exercise context examination the coursework oral is decided by the instruction	must h	ave l	oeen	acqu	ired. W	hether the	examination	is writ				

: o=obligatory, f=facultative

Status Other

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
Abbreviations: Grading System : g	graded, ng=not graded
Examination Type : M	T=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio
,	electure, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial, eproject, S=seminar, IC=inverted classroom
l a	

Module Number: MAT-75-05	Module Title: Percolation Theory						Type of I	Module: ory Module	with C	hoice	
ECTS-Points	3										
Workload - Time in Class - Self-Study	Workload: 90 h	Time ii 30 h	n Cla	iss:			Self-Stud	ly:			
Duration	1 Semester						•				
Frequency	not regularly										
Term	1-3										
Language of Instruction	German	German									
Forms of Teaching and Learning	Lecture 2 SWS	ecture 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 Credits / Grading (Weighting 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: Po						idge Univer	sity Press 2	006.	•	
Transfer	The module belongs to the Si and Stochastics. Taking int included in the Sections Stucialisation, in accordance with	o accou dy Focu	nt th s, Ac	ie ch <i>Ivand</i>	oser ced k	perso <i>(nowle</i>	onal Study S dge in Math	Specialisation of the second s	on, it c E <i>lectiv</i>	an be	
Prerequisites	Knowledge of the module Pr	obability	The	ory i	s hel	pful, bı	ut not essen	tial.			
Responsible Persons	Elmar Teufl, Martin Zerner										

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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						Type of Compuls	Module: ory Module	with C	hoice			
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h	Time 90 h	in Cla	ıss:			Self-Stud	dy:					
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 + Ex.cl. 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 particular for processes with jumps). Stochastic differential equations . 												
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 them lain the have a nethods e them	. The ir intricquire of the and	stud insic ed a d e lect to wo	ents conn confi ure. ork o	can na ections dent, p They h	ime and prose. recise and ave learned tion strateg	ove the cent independen I to transfer ies on their	ral resi t handl the me own o	ults of ling of ethods or in a			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Stochastic Analysis	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 b	een a	acqu	ired. W	hether the	examination	is writ				

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
Abbreviations:	=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, E=essay, P=portfolio

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

Status : o=obligatory, f=facultative

Module Number: MAT-75-07	Module Title: Information Theory						Type of Compuls	Module: ory Module	with C	hoice		
ECTS-Points	9											
Workload - Time in Class - Self-Study	Workload: 270 h	Time i 90 h	n Cla	ss:			Self-Stud	dy:				
Duration	1 Semester											
Frequency	not regularly											
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SV	VS										
Content	 Entropy and entropy rates in the discrete case. Theorem of Shannon-McMillan-Breiman. Entropy rates of Markov chains. Kolmogorov complexity. Data compression. Chanel capacity. Differential entropy. 											
Objectives	Students learn to describe in the basic theory to concrete apply the theoretical concept of naming and proving the extrements are connections. In the exercise classes they be terms, statements and method new problems, to analyse the They are able to present the	random s to spe ssential ave acc ods of the	experior perior	rimer oroble ts of a co ture. ork o	nts arems the lend nfide They	nd stoc in codi ecture nt, pred have l	hastic proceing theory. The same well as a cise and independent of the strategies of	esses. Stude The students assessing ar ependent has ansfer the non their own	ents can are can and explain andling nethods or in a	n also apable aining of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Information Theory	п гуре of Course	t Status	SMS 4	ε g ECTS	Sework	Type of Exam o. o.	Onr. of Exam (min) 90-180 o. 20-30	Grading	Weight for Grade		
	In this module an exercise or examination the coursework oral is decided by the instruc	must ha	ave b	een a	acqui	ired. W	hether the	examination	is writ			

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:	:					Type of I			:			
MAT-75-08	Mathematical Population Ge	netics					Compuls	ory Module	with C	noice			
ECTS-Points	6												
Workload - Time in Class	Workload: 180 h	Time 60 h	in Cla	ss:			Self-Stud	ly:					
- Self-Study													
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German	German											
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 2 SV	VS											
Content	Exchangeable popula	ition mo	dels.										
	Probability of extinction.												
	Descendants and ancestors.												
	Duality of Markoff pro	cesses	-										
	Coalescent processes	s and a	ssocia	ated (conv	ergenc	e rates.						
	Simple mutation mod	els, Ew	ens s	ampli	ng fo	ormula.							
	Statistical applications	s, e.g. e	estima	ting	the n	nutatio	n rate.						
Objectives	In the lecture, students lear an understanding for the int capable of naming and provexplaining the presented con current state of research in the line the exercise classes they be terms, statements and method new problems, to analyse the They are able to present the	eraction ring the nection he subjuave accords of the lem and	n of g esse s. Stu ect ar quired ne lec d to w	eomential udent ea. a co ture. ork c	etric resul s will nfide They on so	and algorithms are algorithms and algorithms and algorithms are algorithms and algorithms and algorithms are algorithms. Algorithms are algorithms. Algorithms are algorith	gebraic met ne lecture as e to reflect a cise and ind learned to tr strategies o	hods. The seas well as as and critically ependent has ansfer the nonthing their own	student sessing analys andling nethods or in a	ts are g and se the of the s onto team.			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title Mathematical Population Genetics	1	f	SWS 2	ω ECTS	Coursework	Type of Exam o.	Dur. of Exam (min) 0.20-30	Grading	Weight for Grade			
	In this module an exercise or examination the coursework oral is decided by the instruc	must h	ave b	een a	acqui	ired. W	coursework hether the	 a. For partici examination	is writ				

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
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Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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:						Type of I		:	L			
MAT-75-09	Point Processes						Compuis	ory Module	with C	noice			
ECTS-Points	6						<u> </u>						
Workload - Time in Class - Self-Study	Workload: 180 h	Time 60 h	in Cla	iss:			Self-Stud	ly:					
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German	German											
Forms of Teaching and Learning	Lecture 2 SWS												
Content	Random measures, p	Random measures, point processes, Poisson processes.											
	Factorial measure, Mecke equation.												
	Transformation, labelling, thinning.												
	Characterisation of po	oint prod	cesse	s.									
	Stationary Poisson pr	ocesse	S.										
	Poisson integrals.												
	Cox processes.												
Objectives	The students have familiaris examples of the theory of po are capable of naming and prexplaining the presented con current state of research in the line the exercise classes they have terms, statements and method new problems, to analyse the They are able to present their	int proc roving the nection he subjuave accords of the eds of the and	esses ne es s. Stu ect ar quirec ne lec d to w	s and sential dentification in the seath of	can al res s will nfide They on so	handle sults of be ab ent, pre- have lution s	them math the lecture a le to reflect a cise and indelearned to treat strategies of	ematically. as well as as and critically ependent ha ansfer the not their own	The stussessing analyse analyse analyse analyse andling nethods or in a	dents g and se the of the s onto team.			
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade			
	Point Processes	L ü	f	2	3	yes	wr. o. or.	90-180 o. 20-30	g	100			
	In this module an exercise contains examination the coursework oral is decided by the instruc	ertificate must h	e is to ave b	be a	icqui acqu	ired. W	hether the	examination	is writ				

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, E=essay, P=portfolio Teaching Format: 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: Graph Theory	Type of I	Module:	with C	hoice							
ECTS-Points	9							,				
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 180 h											
Duration	1 Semester											
Frequency	not regularly	not regularly										
Term	1-3											
Language of Instruction	German											
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SWS											
Content	Basic concepts in gra	Basic concepts in graph theory,										
	Basic graph theory all	gorithms	5,									
	Flows, cuts, connecte	dness, ı	match	nings	,							
	Cycle and cut space ((cohomo	logy	theo	ry),							
	 Spectral graph theory 	, matrix	tree t	heor	em,							
	Planar graphs, theore	m of Ku	ratow	/ski a	and V	Vagner	,					
	Planar embeddings,											
	Graph colorings,											
	Theory of minors.											
Objectives	Students know the basic co use graph theory methods in algebra and be able to benef essential results of the lectur In the exercise classes they he terms, statements and metho new problems, to analyse the They are able to present the	n practic it from the e as we have acq ods of the nem and	e. Them. II as auired e lect to w	ey wasses asses a co aure. ork o	ill als stude ssing nfide They on so	ents are and example of the control	gnise conne e capable of xplaining the cise and ind earned to tr strategies o	ections to got in aming and a presented ependent has ansfer the note their own	eometrd proving connected andling nethods or in a	y and ng the ctions. of the s onto team.		
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade		
	Graph Theory	L	f	4	6	yes	wr. o.	90-180	g	100		
		E	f	2	3	,	or.	o. 20-30				
	In this module an exercise or examination the coursework oral is decided by the instruc	must ha	ave b	een a	acqui	ired. W	hether the	examination	is writ			

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

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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-75-11	Module Title: Markov Chains and Application	ons					Type of Compuls	Module: ory Module	with C	hoice			
ECTS-Points	9												
Workload - Time in Class - Self-Study	Workload: 270 h								Self-Study: 180 h				
Duration	1 Semester												
Frequency	not regularly												
Term	1-3												
Language of Instruction	German or English	German or English											
Forms of Teaching and Learning	Lecture 4 SWS + Ex.cl. 2 SW	Lecture 4 SWS + Ex.cl. 2 SWS											
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 onto 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 Credits / Grading (Weighting 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	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	nust ha	ve b	een a	acqu	ired. W	hether the	examination	is writ				
Literature	Possible References :												
	Pierre Bremaud: Discr	ete Pro	babi	ity M	lodel	s and N	Methods. Sp	oringer 2017	' .				
	Pierre Bremaud: Marke	ov Cha	ins. S	Sprin	ger 1	999.							
	Olle Häggström: Finite sity Press 2002.	Markov	/ Cha	ains a	and A	Algorith	mic Applica	tions. Camb	ridge l	Jniver-			
	Kevin Murphy: Machine	e Learr	ning:	A Pr	obab	ilistic F	Perspective.	MIT Press	2012.				
	James Spall: Introduct	ion to S	Stoch	astic	Sea	rch and	d Optimizati	on. Wiley 20	003.				
Transfer	The module belongs to the Si personal Study Specialisation, edge in Mathematics or Election of the respective section.	it can b	oe ind	clude	d in t	he Sec	tions Study	Focus, Adva	anced I	Knowl-			

Prerequisites	Good knowledge of linear algebra and stochastics is required. Knowledge from the probability theory module is helpful, but is not required.				
Responsible Elmar Teufl Persons					
Examination Type : M	=graded, ng=not graded IT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio =lecture, LE=lecture with integrated exercises, SL=seminar or lecture, E=exercise class, T=tutorial,				

Status : o=obligatory, f=facultative

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

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

Module Number: MAT-75-20	Module Title: Probability Distances for Data Science							Module: ory Module	with C	hoice
ECTS-Points	6									
Workload - Time in Class - Self-Study	Workload: Time in Class: Self-Study: 120 h									
Duration	1 Semester									
Frequency	not regularly									
Term	1-3									
Language of Instruction	English									
Forms of Teaching and Learning	Lecture 2 SWS + Ex.cl. 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 coparticularly optimal transport understand key mathematica aspects, and quantisation, a further obtained an understar of data science. They are ab as categorise and explain the critically scrutinise the curren In the exercises, they have d concepts, statements and meto new problems, to analyse that are able to present their solutions.	distantal results well a ding of le to na relation t state evelope thods from an area.	ces, ts in as the company as the com	diver this a e inte putat and p es pre searc confid ne lec deve	geno area, erplational rove esent h in t dent, cture. lop s	ces, an for insection for inse	d integral patance relateen differer ts and applian statemen dents will becialist area e and indephave learned strategies	probability maded to duality the distances cability in sents of the leader addressed. Dendent apped to transfer alone or in a	letrics. y, geor They lected cture a produc roach the me	They netric have areas s well e and to the thods
Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	- Type of Course	Status	SWS	b ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Probability Distances for Dat Science	ta 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 ha	ave b	een a	acqui	ired. W	hether the	examination	is writ	

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, 2003.
	 Imre Csiszar, Paul C. Shields: Information theory and statistics: a tutorial. Foundations and Trends in Communications and Information Theory 1.4 (2004). 417-528.
	 Ily Tolstikhin et al.: Wasserstein auto-encoders. 6th International Conference on Learning Representations (ICLR 2018)
	 Siegfried Graf, Harald Luschgy: Foundations of quantization for probability distributions. Springer, 2007.
Transfer	The module belongs to the 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	The course is mostly self-contained, but students benefit from basic knowledge in analysis, probability theory, optimisation, and Python.
Responsible Persons	Stephan Eckstein
Abbreviations:	

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format : 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-75-21	Module Title: Bayesian Networks and Causality Type of Module: Compulsory Module with Choice											
ECTS-Points	5											
Workload - Time in Class - Self-Study	Workload: 150 h	Time in Class: 45 h	Self-Study: 115 h									
Duration	1 Semester	1 Semester										
Frequency	not regularly											
Term	1-3	1-3										
Language of Instruction	English											
Forms of Teaching and Learning												
Content	be able to deal with it. The effectively incorporate proba However, human understand as Whenever the sprinkler is are wet, the sprinkler is on, sprinkler, the plants will be sprinkler. In this course, Bayesian ne probability distributions. In padiscussed. Moreover, it will be distributions, but are also able Bayesian networks will be low - Computing probability distributions. Part I: Bayesian Netwown - Computing probability distributions. Part I: Bayesian Netwown - Computing probability distributions. Parameter and - Part II: Bayesian Netwown - Part II:	Uncertainty is a fact of life, and robust artificial intelligence for real life application has to be able to deal with it. Therefore, the development of mathematical representations that effectively incorporate probabilities was a key step in the development of artificial intelligence. However, human understanding goes further than that: We go beyond observing events, such as Whenever the sprinkler is on in my greenhouse, the plants are wet or Whenever the plants are wet, the sprinkler is on, to postulating a relationship of cause and effect: If I turn on the sprinkler, the plants will be wet, but if I water the plants, that will certainly not activate the sprinkler. In this course, Bayesian networks are studied, which are a widely used representation for probability distributions. In particular, commonly used inferenence and learning algorithms are discussed. Moreover, it will be shown that Bayesian networks do not only represent probability distributions, but are also able to express causal relationships. Finally the causal expressivity of Bayesian networks will be looked at, aiming to learn causal structure from observational 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 of 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 Bayesian networks. — Causal structure discovery: Learning causal relationships from data. — Counterfactual identifiability: Answering counterfactual. questions using causal										
Objectives	bility distributions and how the or determine whether two ranked learned to distinguish in ladder: probabilistic, intervestincreasingly detailed knowled assumptions under which can knowledge from lower levels of external interventions using can often be estimated from	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 adder: 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 Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Bayesian Networks and	L	f	2	3	yes	wr. o.	90-180	g	100
	Causality	Е	f	1	2	,,,,	or.	o. 20-30	9	
	Whether the examination is written of the examination board.	en or	oral i	is de	cided	by the	instructor w	vith approval	by the	head
Literature	Possible References : • Judea Pearl: Causality: N 2009.	/lodel	s, Re	easor	ning a	and Inf	erence. Can	nbridge Univ	ersity/	Press
Transfer	The module belongs to the Study Stochastics. Taking into account in the Sections Study Focus, Actin accordance with the restrictive	t the Ivanc	chos ed K	en po <i>nowl</i>	ersoi <i>ledge</i>	nal Stu <i>in Ma</i>	dy Specialis thematics o	ation, it can r <i>Elective S</i>	be inc	luded
Prerequisites	The module Stochastics is assu	med.								
Responsible Persons	Stephan Eckstein									
Abbreviations: Grading System : g	Abbreviations:									

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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-75-22	Module Title: Information Theory, Pattern works	Type of Module: Compulsory Module with Choice									
ECTS-Points	3	3									
Workload - Time in Class - Self-Study	Workload: 90 h	Time in Class: 30 h	Self-Study: 60 h								
Duration	1 Semester										
Frequency	not regularly	not regularly									
Term	1-3										
Language of Instruction	English	English									
Forms of Teaching and Learning	Lecture 2 SWS	Lecture 2 SWS									
Content	- The possibility of code and repet • Entropy and data con - Entropy, condit The idea of typ source coding the source coding the and the Kraft-M Huffman codes • Communication over - Definition of che erasure channel of the codes. • Statistical inference, of the likelihood field in the codes. • Approximation of problem of the codes in the likelihood field in the codes. - The likelihood field in the codes in the likelihood field in the codes in the codes. - Laplace's methoutions.) Monte sampling, Metron ation, exact sar	 Introduction to information theory: The possibility of reliable communication over unreliable channels. The Hamming code and repetition codes. Entropy and data compression: Entropy, conditional entropy, mutual information, Shannon information contented The idea of typicality and the use of typical sets for source coding. Shannon's source coding theorem. Codes for data compression. Uniquely decodeable code and the Kraft-MacMillan inequality. Completeness of a symbol code. Prefix codes Huffman codes. Arithmetic coding. Communication over noisy channels: Definition of channel capacity. Capacity of binary symmetric channel; of binary erasure channel; of Z channel. Joint typicality, random codes, and Shannon'noisy channel coding theorem. Real channels and practical error-correcting codes. 									
Objectives	noisy channel coding – and h They are able to name and p explain the relationships pres	Students are familiar with fundamental concepts of information theory – such as entropy and noisy channel coding – and how these are applied in computing and approximating probabilities. 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.									

Requirements for obtaining Credits / Grading (Weighting if applicable)	Title	Type of Course	Status	SWS	ECTS	Coursework	Type of Exam	Dur. of Exam (min)	Grading	Weight for Grade
	Information Theory, Pattern Recognition, and Neural Net- works	L	f	2	3	no	wr. o. or.	90-180 o. 20-30	g	100
	Whether the examination is written of the examination board.	en or	oral i	s de	cided	by the	e instructor w	vith approva	by the	head
Literature	Possible References : • David J.C. MacKay: Inform	matio	n Th	eory,	Infe	rence, a	and Learnin	g Algorithms	s. CUP	2003.
Transfer	The module belongs to the Study Stochastics. Taking into account in the Sections Study Focus, Actin accordance with the restrictive	t the <i>Ivanc</i>	chos ed K	en p <i>nowl</i>	ersoı <i>ledge</i>	nal Stu <i>in Ma</i>	dy Specialis thematics o	ation, it can r <i>Elective S</i>	be inc	luded
Prerequisites	Only basic knowledge in probab	ility t	heor	y is r	neede	ed.				
Responsible Persons	Stephan Eckstein									

Grading System : g=graded, ng=not graded

Examination Type: MT=master's thesis, or.=oral exam, wr.=written exam, Pr=presentation, E=essay, P=portfolio Teaching Format: 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

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.