Module Handbook

Master of Science
"Mathematics of Machine Learning and Data Science"

Universität Heidelberg
Fakultät für Mathematik und Informatik

Version as of 15 July 2026

Form of study: full time

Type of study: consecutive

Regular period of study: 4 semesters

Number of credit points to gain in this study: 120

Date of begin: 1 October 2025

Location of study: Heidelberg

Number of places: 40 p.a.

Fee: According to general regulations of Heidelberg University

Contents

1 Qualification objectives, profile, and particularities of the degree program **3**
- 1.1 Preamble - Qualification objectives of Heidelberg University . . . 3
- 1.2 Profile of the degree program . . . 3
- 1.3 Subject-specific qualification objectives of the degree program . . . 3
- 1.4 Generic qualification objectives of the degree program . . . 4
- 1.5 Particularities of the degree program and module descriptions . . . 5
  - 1.5.1 Description of the teaching and learning forms . . . 5
  - 1.5.2 Modalities for examinations . . . 5

2 Structure of the course, admission **7**
- 2.1 Module types, credit points . . . 7
- 2.2 Model study plan . . . 8
- 2.3 Mobility window . . . 8

3 Compulsory modules **9**
- Ringvorlesung . . . 10
- Data Science Lab . . . 11
- Interdisciplinary Skills . . . 12
- Seminar Machine Learning and Data Science . . . 15
- Specialization Area . . . 16
- Master's Thesis . . . 19
- Master's Thesis Presentation . . . 20

4 Core modules **21**
- Geometric Foundations for Machine Learning . . . 22
- High-dimensional Numerics . . . 23
- Partial Differential Equations in Data Science . . . 25
- Statistical Learning . . . 26
- Variational Methods and Optimization in Machine Learning . . . 27

1 Qualification objectives, profile, and particularities of the degree program

1.1 Preamble - Qualification objectives of Heidelberg University

In its guiding principles for teaching and learning, Heidelberg University defines the following overarching quality objectives, which describe the qualification profile of its graduates:

- the development of subject-specific competencies with a strong research orientation,
- the promotion of transdisciplinary dialogue skills,
- the cultivation of practice-oriented problem-solving competencies,
- the strengthening of personal and social skills, and
- the capacity to assume social responsibility.

1.2 Profile of the degree program

The graduate program *Mathematics of Machine Learning and Data Science* is operated by the Faculty of Mathematics and Computer Science. The graduate program is research-oriented. It deepens and broadens the expertise, enables independent scientific work, lays the foundations for further development of the subject and prepares students for a demanding professional career or a doctorate. Graduates are qualified for roles requiring responsibility and leadership.

The graduate program focuses on the mathematical foundations of machine learning and data science. This includes concepts of teaching from both pure mathematics (topology, differential geometry, dynamical systems) and applied mathematics (statistics, optimization, numerics, functional analysis) and the interplay of concepts required for an in-depth understanding of research topics and for advancing the field. The course program also enables students to develop an understanding of how basic research problems of machine learning and data science stimulate research in mathematics.

Students become familiar with common software used in research and industry by solving concrete practical problems of machine learning and data science in the Data Science Lab. They acquire skills for prototyping algorithms on their own.

Overall, graduates are supposed to become members of the growing community of mathematicians which are qualified to address fundamental problems of machine learning and data science in basic research and in a wide range of application areas.

1.3 Subject-specific qualification objectives of the degree program

Graduates of the graduate program *Mathematics of Machine Learning and Data Science* are expected to possess the following skills:

- They acquired extensive knowledge in mathematical areas relevant to machine learning and data science, enabling them to identify and classify corresponding problems and to contextualise mathematical methods.
- They acquired in-depth knowledge in at least one direction of specialization of machine learning and data science, enabling them to interpret, analyse and evaluate current research.
- They are able to transfer mathematical methods into algorithms for solving concrete problems of machine learning and data science. They know how to operate machine learning software commonly used in research. They acquired programming skills and experience and are able to implement own algorithms.
- They gained experience with team work (problem analysis, discussion of the state of the art and approaches, software development), with reporting and presenting results.

Overall, graduates are qualified to actively contribute to current research on mathematical aspects of machine learning and data science and to tackle challenging problems in any related field of application.

1.4 Generic qualification objectives of the degree program

Graduates of the graduate program *Mathematics of Machine Learning and Data Science* should possess the following basic competencies of an interdisciplinary nature in the context of related research in mathematics.

- They are able to recognize the structure of applied problems of machine learning and data science and to classify them from the viewpoint of mathematics.
- They are used to scrutinise and to contextualise the pertinent research literature and to judge the potential both for research in mathematics and for applications to problems of machine learning and data science.
- The education through the graduate program enables them to recognize their knowledge gaps and to fill them.
- They possess theoretical and practical skills for solving problems of machine learning and data science. They flexibly use these skills in novel and unfamiliar situations.
- They have the competence to work in a team and to take on more prominent responsibility in a team (team leadership).
- They communicate effectively in professional matters in English, orally and in writing. In particular, they are proficient in communicating their own conclusions to practitioners based on the current state of the art and to exchange ideas with experts on an international scientific level.

Overall, graduates are qualified for a PhD project and to fill research positions in academia and industry devoted to machine learning and data science or a related field of application.

1.5 Particularities of the degree program and module descriptions

1.5.1 Description of the teaching and learning forms

- **Lecture:** Presentation of the course content by the lecturer using appropriate media; interaction and questions are possible.
- **Exercise:** Exercises and smaller parts of the syllabus are explained; questions, interaction and discussion by and with the students to understand the syllabus and the example exercises.
- **Seminar:** Independent development of a scientific topic, preparation and delivery of a presentation with subsequent questions and discussion of the participants about the presentation.
- **Practicum:** Project work on the basis of a programming task, independent development of software including documentation, coordination of subtasks and solutions within a team, preparation of a project report and a presentation of the project.

1.5.2 Modalities for examinations

At the beginning of each course, the details and, in particular, any deviations from the modalities for examinations listed below, will be announced by the lecturer.

Many modules have a uniform regulation for the awarding of CPs (Credit Points), so this regulation is described in detail here and then only referred to in the module descriptions.

Rules for awarding CPs. CPs are awarded if the final examination is passed. The details of the final examination are described in the individual module descriptions. Many modules include exercise sessions using various models. The requirements for admission to the final examination are determined by the lecturer at the beginning of the course and announced in writing.

Examination scheme. This part of the module description specifies the number of attempts which are allowed to pass the module, according to the examination regulations. Once an examination is passed, it cannot be repeated in order to improve the grade.
1+1: after the first attempt, there is only one repetition possible.

Examination period. Two exam periods have been designated for the written exams at the end of each semester. The first exam period lasts three weeks and consists of the last week of the lecture period and the first two weeks of the lecture-free period. The second exam period lasts three weeks and consists of the last two weeks of the lecture-free period and the first week of the lecture period. In exceptional cases, exams may take place outside of these exam periods; lecturers must announce such exceptions at the beginning of the course.
For oral exams, the dates are set by the lecturers.

Examination dates. For modules offered once a year or less frequently, and for which the module exam is a written exam, two exam dates are always offered following the module. These exams are scheduled during the first and second exam periods, respectively. Students choose which of the offered exam dates they wish to take.
For smaller (irregularly offered) modules, exceptions to this rule may be made. The lecturers must announce any such exceptions at the beginning of the course.
For modules that are offered every semester and have a written exam as the module exam, there

is only one exam date following the module, within the first exam period. Students who fail or withdraw for a valid reason may retake the exam in the following semester.

2 Structure of the course, admission

2.1 Module types, credit points

The assignment of an individual course to a module can be recognized by the *module code*. For almost all modules of the graduate program *Mathematics of Machine Learning and Data Science*, the module code begins with ML, followed by several letters or numbers: MLXYZ.

Compulsory modules
These modules are mandatory for every enrolled student. Students learn basics about the mathematical foundations of machine learning and data science from the viewpoints of each mathematical core area. This provides also the basis for specializing in one or two core areas by choosing elective and specialization courses accordingly. The following list gives an overview of the compulsory modules, their codes, credit points and offered.

Code	Compulsory module	CP	offered
MLR	Ringvorlesung	8 CP	every winter semester
MLDSL	Data Science Lab	8 CP	every semester
MLIS	Interdisciplinary Skills	8 CP	every semester
MLSMLDA	Seminar Machine Learning and Data Science	12 CP	every semester
MLSA	Specialization Area	24 CP	every semester
MLMT	Master's Thesis	30 CP	continuous
MLMTP	Master's Thesis Presentation	6 CP	continuous

The masters thesis is presented to the supervisors of the thesis.

Core modules
Students have a restricted choice for choosing core modules, in order to ensure a sufficiently broad education in at least three core areas, yet at a deeper technical level. The examination regulations requires three core modules, each 8 CP, to be completed, overall 24 CP. Core modules are provided for each core area. They are encoded and offered as follows.

Code	Compulsory elective core module	offered
MLC1	Geometric Foundations for Machine Learning	every winter semester
MLC2	High-dimensional Numerics	every summer semester
MLC3	Partial Differential Equations in Data Science	every summer semester
MLC4	Statistical Learning	every winter semester
MLC5	Variational Methods and Optimization in Machine Learning	every winter semester

2.2 Model study plan

module	CP	semester
Ringvorlesung	8	1
Data Science Lab	8	2
three Core modules	24	1 and 2
Interdisciplinary Skills	8	1 and 2
Seminar Machine Learning and Data Science	12	2 and 3
Specialization Area	24	2 and 3
Master's Thesis	30	3 and 4
Master's Thesis Presentation	6	4
Total		**120 CP**

Thus in the first year the Ringvorlesung 8 CP, the Data Science Lab 8 CP, three Core modules 24 CP, the Interdisciplinary Skills 8 CP, first half of the Seminar Machine Learning and Data Science 6 CP and one course of 6 CP in the Specialization area have to be completed. In the second year the second half of the Seminar Machine Learning and Data Science 6 CP, the bigger part of the specialization area 18 CP, the Master's Thesis 30 CP and the Master's Thesis Presentation 4 CP have to be completed.

2.3 Mobility window

The mobility window for the graduate program *Mathematics of Machine Learning and Data Science* usually comprises the second and third semesters. For this reason the CPs for the compulsory Data Science Lab, scheduled for the first year, can also be acquired in the third semester. The courses for the modules Seminar Machine Learning and Data Science, Specialization Area and Cross-disciplinary Competencies are suitable for a stay abroad.

The planning of a study visit should be started early. Especially for a stay abroad, the organization phase can take up to one year. Information about studying abroad within the Erasmus program can be found here.

3 Compulsory modules

This chapter specifies the compulsory modules. According to the examination regulations, the following seven modules have to be completed.

Code	**Compulsory module**	**CP**
MLR	Ringvorlesung	8 CP
MLDSL	Data Science Lab	8 CP
MLIS	Interdisciplinary Skills	8 CP
MLSMLDA	Seminar Machine Learning and Data Science	12 CP
MLSA	Specialization Area	24 CP
MLMT	Master's Thesis	30 CP
MLMTP	Master's Thesis Presentation	6 CP

The supervisor of the Master's thesis can require up to 16 CP for specific courses as a precondition for supervision. In compulsory module Seminar Machine Learning and Data Science, students must complete exactly two seminars. There are various seminars offered each semester to choose from. In compulsory module Interdisciplinary Skills and Specialization Area, students can choose between different courses, depending on the course offerings. The format, CP and workload depends on the individual courses. For the Specialization Area the following information applies to the format, credits and workload of the individual courses:

format and CP	Lecture 2 SWS (4 CP)
workload	120 h: 30 h lecture, 75 h homework and independent follow-up work, 15 h exam preparation.
format and CP	Lecture 2 SWS + Exercise 2 SWS (6 CP)
workload	180 h: 30 h lecture, 30 h exercises, 105 h homework and independent follow-up work, 15 h exam preparation.
format and CP	Lecture 4 SWS (6 CP)
workload	180 h: 60 h lecture, 90 h homework and independent follow-up work, 30 h exam preparation.
format and CP	Lecture 4 SWS + Exercise 2 SWS (8 CP)
workload	240 h: 60 h lecture, 30 h exercises, 120 h homework and independent follow-up work, 30 h exam preparation.

Ringvorlesung

LV-Nr. L 1100151000 E 1100151001	**Name** Ringvorlesung	**Abbreviation** MLR
CP 8	**Duration** one semester	**Offered** every winter semester
Format lecture 4 SWS, exercises 2 SWS	**Workload** 240h; lecture 60h, exercises 30h, self-dependent subsequent work 120h, preparation for the exam 30h.	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** several lecturers	**Examination scheme** 1+1
Learning objectives	At the end of the course, students will be able to classify problems and to recognize subfields of machine learning and data science and to relate them to relevant mathematical topics. In addition, they will be able to associate major tasks of data science and machine learning with mathematical problem formulations and mathematical methods for solving them.	
Learning content	- Overview of machine learning and data science, - Brief introduction into relevant mathematical methods from each area of specialization.	
Requirements for participation	none	
Requirements for the assignment of credits and final grade	Successful completion of the exercises is a prerequisite for sitting the graded written examination that concludes the module.	
Useful literature	to be announced in the lecture	

Data Science Lab

LV-Nr. 1100151002	**Name** Data Science Lab	**Abbreviation** MLDSL
CP 8	**Duration** one semester	**Offered** every semester
Format Practicum 6 SWS	**Workload** 240h; 160h work on the project (optionally in small groups), 50h self-dependent study, 30h documentation and presentation of results.	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** several lecturers	**Examination scheme** 1+1
Learning objectives	Students are able to solve practical problems of machine learning and data science and can prototype algorithms on their own by using common software used research and industry. This will enable them to transfer mathematical methods of data analysis and machine learning into software-based solutions tailored to application problems.	
Learning content	- Implementing solutions to practical machine learning and data science problems in Python, - Using common data science and deep learning frameworks, e.g. scikit-learn, pandas, PyTorch, JAX, etc.	
Requirements for participation	Ringvorlesung (MLR); programming skills in Python	
Requirements for the assignment of credits and final grade	Students give a presentation to report on the results, discuss them and defend their findings. During the presentation, they must clearly demonstrate their individual contribution to the final result. The presentation is assessed in conjunction with a written summary, which must be submitted in advance.	
Useful literature	to be announced when the course starts	

Interdisciplinary Skills

LV-Nr.	**Name** Interdisciplinary Skills	**Abbreviation** MLIS
CP 8	**Duration** two semesters	**Offered** depends on the individual courses
Format depends on the individual courses	**Workload** depends on the individual courses	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English or German	**Lecturer(s)** depends on the individual courses	**Examination scheme**
Learning objectives	Interdisciplinary skills (in German: Übergreifende Kompetenzen ÜK) refer to study contents, key competencies and additional qualifications that go beyond subject-specific knowledge and convey personality and job-related competencies that are essential in today's professional life (in and outside of research). The learning objectives depend on the courses chosen and can be found in heiCO.	

Learning content	There are various choices available. Prior consultation with the chairperson of the examination board is recommended. Introduction to LaTeX: 3 CP, lecture 2 SWS + Exercises 2 SWS, successful participation IT Project Management: 3 CP, lecture 2 SWS, pass the final examination Software Economics: 3 CP, lecture 2 SWS, pass the final examination Study Abroad: 3 CP for 3 month stay abroad, submit and pass a written report about the experiences Education through Summer School, Holiday Course, or Conference: 1 CP for 30 hours event, submit and pass a written report about the event From the Master of Computer Engineering the modules Entrepreneurship, Tools and C++ Practice can be chosen. For the module description please refer to the module handbook of the Master Computer Engineering course of studies. Within the framework of the ÜK, courses from the university's range of courses that do not belong to this study program can be accepted. In this case the credit points of the courses are transferred. Courses from the heiSKILLS Competence and Language Centre at Heidelberg University can also be accepted. heiSKILLS enables the acquisition of individual and interdisciplinary competencies and the development of qualification profiles beyond traditional university studies. The web page is https://www.heiskills.uni-heidelberg.de/en where students will find language courses and courses from the Career Service and Study Skill Courses. For language courses the credit points of the courses are transferred. For courses offered by the Career Service and Study Skill Courses i.e. on Scientific Writing, Critical thinking etc. it is essential to consult with the Examination Office beforehand. Courses of the Heidelberg University Computer Center (URZ) can not be credited. Furthermore, irregular offers of the faculty marked as ÜK can be taken.

Requirements for participation	depends on the individual courses
Requirements for the assignment of credits and final grade	depends on the individual courses
Useful literature	depends on the individual courses

Seminar Machine Learning and Data Science

LV-Nr. 1100143XXX 1100144XXX	**Name** Seminar Machine Learning and Data Science	**Abbreviation** MLSMLDS
CP 12 (6 for each seminar)	**Duration** 2 Seminars each one semester	**Offered** every semester
Format 2 Seminars each 2 SWS + Tutorial 2 SWS	**Workload** 2 seminars each of 180h; thereof 60h seminar and tutorial 120h preparation of presentation and supervision	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** depending on teaching offer	**Examination scheme** 1+1 for each seminar
Learning objectives	- Ability to skim and scrutinise the research literature, to classify and understand the scientific content, and to explain and present it to peers in a condensed and comprehensible way, - Ability to discuss lectures given by other students, and to recognize and comment on the essential points in a concise and respectful way, - Getting to know and recognising good and bad styles of writing of scientific research papers.	
Learning content	Research topics and scientific content of a collection of research papers compiled by the lecturer beforehand.	
Requirements for participation	Core module of the corresponding area is recommended. Further recommended prior knowledge will be announced by the lecturer.	
Requirements for the assignment of credits and final grade	The module consists of two seminars, each of which concludes with a graded exam. This exam consists of a presentation lasting approximately 40 to 90 minutes, active and passive participation in other presentations, and a written report on the presentation (approximately 10 pages). The length, format, and content of the report are evaluated and graded. Students must pass the exam to receive the CP. The final grade for the module is calculated based on the grades from the exams for the two seminars, each of which is weighted at 6 CP.	
Useful literature	to be announced by the lecturers	

Specialization Area

LV-Nr.	**Name** Specialization Area	**Abbreviation** MLSA
CP 24	**Duration** two semesters	**Offered** every semester
Format depends on the course	**Workload** previously described, depends on the format and CP of the course	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** alternating	**Examination scheme** 1+1 for each course
Learning objectives	In this module, students acquire an advanced understanding of the fundamental structures, theorems, proofs, and methods in the chosen fields of mathematics. They develop the ability to independently formulate and prove mathematical statements, critically engage with various proof techniques, and analyze and classify problems in order to select appropriate solution strategies. Furthermore, students are enabled to independently explore and study selected topics within mathematics, thereby strengthening their analytical and abstract reasoning skills. Upon successful completion of this module, students will be able to: - Demonstrate a deep understanding of key concepts, structures, and results in the chosen fields of mathematics. - Independently develop and present rigorous mathematical proofs in those fields. - Identify and apply appropriate proof techniques to a wide range of problems. - Analyze and classify mathematical problems based on structural characteristics to determine suitable solution strategies. - Engage critically with advanced mathematical literature related to the chosen fields of mathematics. - Work independently to acquire new knowledge and solve problems in unfamiliar contexts within the chosen fields of mathematics.	

Learning content	In this module a variety of lectures are offered. These lectures build on the content covered in the five core modules and therefore constitute a specialisation in these five areas. This includes also current research topics from the researchers in this field in the faculty. Area Geometric and Topological Methods is based on the core module Geometric Foundations for Machine Learning (MLC1): Lectures explore various advanced topics in geometry and topology in greater depth. These include, for example: Differential Geometry, Geometric Group Theory, Symplectic Geometry, Contact Geometry, Metric Geometry, Topological Data Analysis Area High Dimensional Approximation and Integration is based on the core module High-dimensional Numerics (MLC2): Lectures explore various advanced topics in numerical mathematics in greater depth. These include, for example: Numerical Methods for Bayesian Inverse Problems, Theory of Deep Learning Area Advanced Topics in Partial Differential Equations is based on the core module Partial Differential Equations in Data Science (MLC3): Lectures explore various advanced topics in analysis and mathematical modelling in greater depth. These include, for example: Partial differential equations in both discrete and continuous settings, Calculus of variations, Functional analytical methods Area Probabilistic and Statistical Methods is based on the core module Statistical Learning (MLC4): Lectures explore various advanced topics in mathematical statistics and probalitity theory in greater depth. These include, for example: Advanced Time Series Analysis, Statistics of continuous-time processes, Local Asymptotic Normality and Semiparametrics, Nonparametric Minimax Theory, Statistics of Inverse Problems, Bayesian Statistics, High-Dimensional Statistics Area Variational Methods and Optimization is based on the core module Variational Methods and Optimization (MLC5): Lectures explore various advanced topics in variational methods and optimization in greater depth. These include, for example: Basic Probability Distributions and Functionals, Measure Transport, Bregman divergences, Variational Approaches, Unsupervised learning, Network architectures, Minimizing Functionals of Probability Measures, Generative Models, Geometric Deep Learning
Requirements for participation	Core module of the corresponding area is recommended. Further recommended prior knowledge will be announced by the lecturer.

Requirements for the assignment of credits and final grade	Each lecture is concluded with a written or oral examination. If a lecture is accompanied by exercises, successful completion of the exercises is a prerequisite for sitting the examination. The final module grade is calculated by weighting the grads for the individual lectures according to their respective credit points.
Useful literature	to be announced in the lecture

Master's Thesis

LV-Nr.	**Name** Master's Thesis	**Abbreviation** MLMT
CP 30	**Duration** six months	**Offered** continuous
Format Supervised self-study	**Workload** 900 h work elaborating an individual research topic, documented in a thesis.	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** varying	**Examination scheme** 1+1
Learning objectives	- Use of the acquired technical knowledge and methods to independently solve a complex problem from data science, machine learning and its applications, - Ability to independently produce a written thesis, with scientific content and organized according to the international standard: Introduction (briefly: overview, motivation, scientific topic, state of the art, own contribution), background material, sections detailing the own contribution, optionally: experimental results and discussion, conclusion.	
Learning content	Independent scientific work on a demanding problem from the fields of data science, machine learning and its applications.	
Requirements for participation	Examination Regulations (PO): a minimum of 45 credits. Work on the Master?s thesis should begin by the end of the third semester at the latest. The Master?s thesis supervisor may require up to 16 credits in specific courses as a prerequisite for supervision.	
Requirements for the assignment of credits and final grade	Passing the graded master's thesis is a prerequisite for receiving the credit points. The Master's thesis involves regular meetings with the supervisor as well as the written thesis itself.	
Useful literature	to be announced by the supervisor	

Master's Thesis Presentation

LV-Nr.	**Name** Master's Thesis Presentation	**Abbreviation** MLMTP
CP 6	**Duration**	**Offered** continuous
Format Seminar	**Workload** 180h; Preparation of the presentation, delivery and subsequent discussion	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** Thesis supervisor	**Examination scheme** 1+1
Learning objectives	The students - acquire, practice and demonstrate the ability to present their own research in a scientific presentation, - are able to put their own work in the context of the current state of the research field and to communicate assumptions, methods and results, - gain skills and experience in discussing questions regarding their own research work.	
Learning content	- Presentation and defense of the content of the Master's thesis, especially the advantages and limitations as well as a comparison to the current state of the art, - Discussion of questions by peers and academics.	
Requirements for participation	Completed Master's thesis (recommended).	
Requirements for the assignment of credits and final grade	The module is completed with a graded evaluation of the presentation (approximately 30-60 minutes) and the student's ability to defend the results of his/her work in the face of questions and comments (approximately 15-45 minutes). Total time should not exceed 90 minutes. The grade must be at least a pass for the CP to be awarded. The final grade of the module is determined by the grade of the evaluation.	
Useful literature		

4 Core modules

The modules listed in this chapter serve as an introduction to a mathematical core area of the graduate program *Mathematics of Machine Learning and Data Science*. They typically build on a bachelor's degree.

The core modules are compulsory elective moduls. Altogether 3 modules (24 CP) have to be completed. Each core module has 8 CP.

It is recommended that students complete two modules in the first semester and the third in the second semester. In this case, 4 CPs of the Interdisciplinary Skills will be completed in the first semester and the remaining 4 CPs in the second semester. If all three modules are completed in the first semester, the 8 CPs of the Interdisciplinary Skills should be completed in full in the second semester. If only one module is completed in the first semester and the other two modules in the second semester, the 8 CPs for Interdisciplinary Skills should be completed in the first semester.

Code	**Core module**	**offered**
MLC1	Geometric Foundations for Machine Learning	every winter semester
MLC2	High-dimensional Numerics	every summer semester
MLC3	Partial Differential Equations in Data Science	every summer semester
MLC4	Statistical Learning	every winter semester
MLC5	Variational Methods and Optimization in Machine Learning	every winter semester

The individual descriptions of the core modules are listed below.

Geometric Foundations for Machine Learning

LV-Nr. L 1100152000 E 1100152001	**Name** Geometric Foundations for Machine Learning	**Abbreviation** MLC1
CP 8	**Duration** one semester	**Offered** every winter semester
Format lecture 4 SWS, exercises 2 SWS	**Workload** 240 h; thereof 60 h lectures, 30 h exercises, 120 h self-dependent subsequent work and homework, 30 h exam preparations	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** alternating	**Examination scheme** 1+1
Learning objectives	At the end of the course, students will be able to associate major tasks of data science and machine learning with geometrical problem formulations and with geometrical methods for solving them. In addition, they are introduced to the research area concerned with enhancing methods in geometry, in particular Riemannian geometry, by machine learning.	
Learning content	- Basic differential geometry, including Riemannian manifolds and curvature, principal and vector bundles - Hyperbolic, Euclidean, spherical geometry; comparison theorems - Information geometry e.g., Wasserstein and Fisher-Rao metrics - Lie groups and homogeneous spaces, examples relevant to machine learning - Optional: graphs and synthetic notions of curvature, Simplicial approximations	
Requirements for participation	Recommended: foundational course on geometry and topology (Grundlagen der Geometrie und Topologie)	
Requirements for the assignment of credits and final grade	Successful completion of the exercises is a prerequisite for sitting the graded written examination that concludes the module.	
Useful literature	to be announced in the lecture	

High-dimensional Numerics

LV-Nr. L 1100152002 E 1100152003	**Name** High-dimensional Numerics	**Abbreviation** MLC2
CP 8	**Duration** one semester	**Offered** every summer semester
Format lecture 4 SWS, exercises 2 SWS	**Workload** 240 h; thereof 60 h lectures, 30 h exercises, 120 h self-dependent subsequent work and homework, 30 h exam preparations	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** alternating	**Examination scheme** 1+1
Learning objectives	At the end of the course the students will have developed a solid understanding of stochastic modeling and parametrisations of differential equations in science and engineering. They will be able to compute approximations and estimators used to quantify uncertainties in high-dimensional parameter-dependent problems, and analyze errors and computational complexities of the corresponding numerical methods.	
Learning content	Uncertainty Quantification: - Parametric Models - Model problems - Parameter regularity High-dimensional integration: - Monte Carlo methods - Sampling from random fields - Quasi-Monte Carlo - Sparse-grids - Multilevel methods High-dimensional approximation: - Regularity for infinite-parametric functions - Stochastic collocation - Low-rank tensor approximation - Random features	
Requirements for participation	Recommended: foundational course in Numerics	
Requirements for the assignment of credits and final grade	Successful completion of the exercises is a prerequisite for sitting the graded written examination that concludes the module.	

Useful literature	to be announced in the lecture

Partial Differential Equations in Data Science

LV-Nr. L 1100152004 E 1100152005	**Name** Partial Differential Equations in Data Science	**Abbreviation** MLC3
CP 8	**Duration** one semester	**Offered** every summer semester
Format lecture 4 SWS, exercises 2 SWS	**Workload** 240 h; thereof 60 h lectures, 30 h exercises, 120 h self-dependent subsequent work and homework, 30 h exam preparations	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** alternating	**Examination scheme** 1+1
Learning objectives	At the end of the course the students will have developed a solid understanding of the mathematics of PDEs and Pattern Formation and evolution of measures and their relevance for machine learning and data science. At the end of the course, they will be able to apply major concepts to machine learning. Moreover, the students will learn how to interpret graph-based models as discretizations of partial differential equations, and therefore draw conclusions on machine learning methods on large graph by using methods from PDE theory.	
Learning content	Introduction to Calculus of Variations, Introduction to Optimal Transport, some measure theoretical methods for PDEs, PDEs on measure spaces	
Requirements for participation	Recommended: foundational course: Functional analysis	
Requirements for the assignment of credits and final grade	Successful completion of the exercises is a prerequisite for sitting the graded written examination that concludes the module.	
Useful literature	to be announced in the lecture	

Statistical Learning

LV-Nr. L 1100152006 E 1100152007	**Name** Statistical Learning	**Abbreviation** MLC4
CP 8	**Duration** one semester	**Offered** every winter semester
Format lecture 4 SWS, exercises 2 SWS	**Workload** 240 h; thereof 60 h lectures, 30 h exercises, 120 h self-dependent subsequent work and homework, 30 h exam preparations	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** alternating	**Examination scheme** 1+1
Learning objectives	At the end of the course, students will be able to associate major tasks of data science and machine learning with statistical problem formulations and with statistical and probabilistical methods for solving them. In addition, they are introduced to the research area concerned with enhancing methods in statistics and probalitity theory by machine learning.	
Learning content	I.Statistical learning: Linear models, high-dimensional models, Lasso, kernel methods for nonparametric density and data fitting II. Empirical process theory: Uniform laws of large numbers (Bracketing, finite dimensional approximation), Symmetrisation, Univariate exponential inequalities (Inequalities of Hoeffding, Bennett, Prokhorov, Bernstein), Set indexed empirical processes (Glivenko-Cantelli classes, Vapnik-Cervonenkis classes), Uniform laws of large numbers (Covering numbers), Concentration inequalities (Tsirelson-Ibragimov-Sudakov inequality, Talagrand?s inequality)	
Requirements for participation	Recommended: foundational course: Statistics & stochastic	
Requirements for the assignment of credits and final grade	Successful completion of the exercises is a prerequisite for sitting the graded written examination that concludes the module.	
Useful literature	to be announced in the lecture	

Variational Methods and Optimization in Machine Learning

LV-Nr. L 1100152008 E 1100152009	**Name** Variational Methods and Optimization in Machine Learning	**Abbreviation** MLC5
CP 8	**Duration** one semester	**Offered** every winter semester
Format lecture 4 SWS, exercises 2 SWS	**Workload** 240 h; thereof 60 h lectures, 30 h exercises, 120 h self-dependent subsequent work and homework, 30 h exam preparations	**Availability** M.Sc. Mathematics of Machine Learning and Data Science
Language English	**Lecturer(s)** alternating	**Examination scheme** 1+1
Learning objectives	At the end of the course, students will be able to associate major tasks of data science and machine learning with variational problem formulations and with variational and optimization methods for solving them. In addition, they are introduced to the research area concerned with enhancing methods of numerical optimization by machine learning.	
Learning content	The lecture covers variational and optimization methods in the context of major tasks of data science and machine learning: data embedding and representation; supervised, semi-supervised and unsupervised learning; classification, regression and density estimation using discriminative and generative models; structured prediction. Besides established classical methods, deep learning will be a central theme, including applications to numerical optimization.	
Requirements for participation	Recommended: foundational course on optimization (Grundlagen der Optimierung)	
Requirements for the assignment of credits and final grade	Successful completion of the exercises is a prerequisite for sitting the graded written examination that concludes the module.	
Useful literature	to be announced in the lecture	