| Mod                       | lule na   | me                  |                            |                                     |        |                        |                          |                                 |                                  |     |
|---------------------------|---|---------------------|----------------------------|-------------------------------------|--------|------------------------|--------------------------|---------------------------------|----------------------------------|-----|
|                           | Data Assimilation for Fluid Dynamics  |                     |                            |                                     |        |                        |                          |                                 |                                  |     |
| Mod<br>no.<br>04-1<br>062 | Module<br>no. Credit Poi<br>04-10- 5  |                     | <b>Points</b><br>5 CP      | Workload<br>150 h                   | Self   | <b>-study</b><br>105 h | <b>Duratio</b><br>1 Seme | <b>on</b><br>ster               | F <b>requency</b><br>Irregularly |     |
| Language of Instruction   |   |                     |                            |                                     | Pers   | son respons            | ible for                 | the M                           | odule                            |     |
| Engl                      | English   |                     |                            |                                     |        | Dr. rer. nat           | t. Moritz                | Egert                           | ouure                            |     |
| 1                         | Course  | es of the           | e Modu                     | le                                  |        |                        |                          |                                 |                                  |     |
|                           | Course no. Course name  |                     |                            | Workload (CP) F<br>T                |        | Form<br>Teac           | ı of<br>hing             | Contact<br>Hours<br>per<br>Week |                                  |     |
|                           | 04-10-0   | 622-vu              | Data As<br>Dynami          | similation for Fluid<br>cs          |        | 0                      |                          | Lectur<br>Exerci                | e and<br>se                      | 3   |
| 3                         | <ul> <li>Study Content         Dynamical systems and control theory, feedback control (nudging approach),             observational measurements, asymptotic stability, reference solutions, reconstruction of             solutions without initial data.         Classical data assimilation algorithms (Kalman filter, AOT), resolution of spatial mesh,             nodal interpolation.         Fundamental equations in fluid dynamics, Boussinesq approximation.         Elearning Outcomes         Students understand and are able to apply the notions, methods and results treated in the             course. They develop an advanced level of understanding of partial differential equations             through the methodology of data assimilation and are able to extend their knowledge in     </li> </ul> |                     |                            |                                     |        |                        |                          |                                 |                                  |     |
|                           |   |                     | <u> </u>                   |                                     |        |                        |                          |                                 |                                  |     |
| 4                         | Requir<br>Recom   | mended              | <b>tor Pa</b><br>l: Functi | rticipation<br>ional Analysis, Par  | tial D | Differential E         | quations                 | s I                             |                                  |     |
| 5                         | Form of Final M   | of Exam<br>Iodule H | <b>ination</b><br>Examina  | i<br>ition:                         |        |                        |                          |                                 |                                  |     |
|                           |   | Modul<br>Duratio    | e Exami<br>on 60 m         | ination (Technical<br>in, Standard) | Exar   | nination, ora          | al / writt               | ten Exa                         | aminatio                         | on, |
|                           | Usually the exam is taken in form of a written test, except when there are only a small<br>number of potential participants. In this case, the exam can be taken in the form of an<br>oral exam. The decision about the form of the exam is taken and communicated  |                     |                            |                                     |        |                        |                          | here a<br>ken in<br>commu       | re only<br>the forr<br>inicated  |     |

|    | during the first two weeks of the lecture, based on the prospective number of students taking the exam. |
|----|---|
| 6  | Requirements on the Award of Credit Points  |
|    | Passing Technical Examination ("Fachprüfung")   |
| 7  | Grading   |
|    | Final Module Examination:   |
|    | □• Module Examination (Technical Examination, oral / written Examination,                               |
|    | Weight: 100%, Standard)   |
| 8  | Usability of the Module   |
|    | M. Sc. Mathematics, Mathematics in Data Science   |
| 9  | Literature  |
|    | M. Tucsnak, G. Weiss: Observation and Control for Operator Semigroups (Springer)                        |
|    | S. Reich, C. Cotter: Probabilistic Forecasting and Bayesian Data Assimilation (Cambridge                |
|    | University Press)   |
|    |   |
| 10 | Comment   |
|    |   |
|    |   |

| Mod                       | lule na   | me  |   |   |                            |  |                               |                     |  |                          |
|---------------------------|---|---|---|---|----------------------------|--|-------------------------------|---------------------|--|--------------------------|
|                           | Part  | tial I  | Differ                                    | ential Equat  | ion                        | s I                                      | -                             |                     | •  |                          |
| Mod<br>no.<br>04-1<br>062 | Module         Credit Point           no.         Credit Point           04-10-         9 (           0626/en         9 (   |   | Points<br>9 CP                            | Workload<br>270 h   | <b>Self-study</b><br>180 h |  | <b>Duration</b><br>1 Semester |                     | <b>Frequency</b><br>Every 2.<br>semester |                          |
| Lan                       | guage (   | of Instru   | uction                                    |   | Pers                       | son respons                              | ible for                      | the M               | odule                                    |                          |
| Eng                       | English   |   |   |   | Prof                       | . Dr. rer. nat                           | t. Matthi                     | as Hie              | ber                                      |                          |
| 1                         | Course  | es of the   | e Modu                                    | le  |                            |  |                               |                     |  |                          |
|                           | Course no.Course nameWorkload (CP)Form of<br>Teachi   |   | ı of<br>hing                              | Contact<br>Hours<br>per<br>Week                               |                            |  |                               |                     |  |                          |
|                           | 04-10-0   | )626-vu   | Partial I                                 | Differential Equatior   | ns I                       | 0  |                               | Lectur<br>Exerci    | re and<br>se                             | 6                        |
| 2                         | <b>Study Content</b><br>Classical treatment of important types of equations (e.g. elliptic, parabolic, hyperbolic, dispersive), variational formulation of elliptic problems, regularity of solutions, theory of Sobolev spaces, Galerkin methods, fixed-point methods for non-linear elliptic and parabolic equations, theory of weak solutions for equations in fluid mechanics |   |   |   |                            |  |                               |                     |  |                          |
| 3                         | Learni<br>Studen<br>course.<br>and are  | <b>ng Outo</b><br>its unde<br>. They d<br>e able to | comes<br>rstand a<br>evelop a<br>o extend | and are able to app<br>an advanced level<br>their knowledge i | oly th<br>of ur<br>in thi  | e notions, m<br>nderstanding<br>s field. | ethods a<br>g of parti        | and res<br>al diffe | sults trea<br>erential o                 | ated in the<br>equations |
| 4                         | <b>Requir</b><br>Recom  | ements<br>mendec                                    | <b>for Pa</b><br>l: Functi                | r <b>ticipation</b><br>ional Analysis                         |                            |  |                               |                     |  |                          |
| 5                         | Form of Examination         Final Module Examination:         □• Module Examination (Technical Examination, oral / written Examination, Duration 90 min, Standard)  |   |   |   |                            |  |                               |                     |  |                          |
|                           | Usually the exam is taken in form of a written test, except when there are only a small<br>number of potential participants. In this case, the exam can be taken in the form of an<br>oral exam. The decision about the form of the exam is taken and communicated<br>during the first two weeks of the lecture, based on the prospective number of students<br>taking the exam.  |   |   |   |                            |  |                               |                     |  |                          |
| 6                         | <b>Requir</b><br>Passing  | <b>ements</b><br>g the Te                           | <b>on the</b><br>chnical                  | Award of Credit<br>Examination ("Fac                          | <b>Poin</b><br>chprü       | <b>ts</b><br>ifung")                     |                               |                     |  |                          |

| -  |  |
|----|--|
| 7  | Grading  |
|    | Final Module Examination:  |
|    | <ul> <li>Module Examination (Technical Examination, oral / written Examination,<br/>Weight: 100%, Standard)</li> </ul> |
| 8  | Usability of the Module  |
|    | M. Sc. Mathematics, Mathematics in Data Science  |
| 9  | Literature   |
|    | L.C. Evans: Partial Differential Equations (AMS)   |
|    | D. Gilbarg, N.S. Trudinger: Elliptic Partial Differential Equations of Second Order                                    |
|    | (Springer)   |
|    | M. Renardy, R.C. Rogers: An Introduction to Partial Differential Equations (Springer)                                  |
|    |  |
| 10 | Comment  |
|    |  |
|    |  |

| Мос        | lule na   | me                     |                            |  | _               |                               |                       |                   |                       |                    |
|------------|---|------------------------|----------------------------|--|-----------------|-------------------------------|-----------------------|-------------------|-----------------------|--------------------|
|            | Macl  | nine I                 | learni                     | ng for Fluid                               | l Dy            | namics                        |                       |                   |                       |                    |
| Moo<br>no. | lule  | Credit                 | Points                     | Workload                                   | Self            | -study                        | Duratio               | on                | Freque                | encv               |
| 04-1       | 0-  | 5 CP                   |                            | 150 h                                      |                 | 150 h                         | 1 Seme                | ster              | Irregularly           |                    |
| 062        | 7/en  |                        |                            |  |                 |                               |                       |                   |                       |                    |
| Lan        | guage o   | of Instru              | iction                     |  | Pers            | son respons                   | ible for              | the M             | odule                 |                    |
| Eng.       | lisn<br>Course  | a of the               | Madu                       | 1  | Proi            | . Dr. rer. na                 | t. Dieter             | Botne             |                       |                    |
| L          | Course  |                        | Cours                      |  |                 | Workload                      | ( <b>C</b> D)         | Form              | of                    | Contact            |
|            | Course  | : 110.                 | Cours                      | ename                                      |                 | WORKIOau                      | (CP)                  | Teac              | hing                  | Hours              |
|            |   |                        |                            |  |                 |                               |                       | 0                 |                       | per                |
|            | 04 10 0   | ( )7                   | <b>Ъ / с. – 1. ÷</b>       | - Ii ( Fl: I                               |                 |                               |                       | <br>  T           | 1                     | week               |
|            | 04-10-0   | 1627-vu                | Dynami                     | cs   |                 | 0                             |                       | Exerci            | e and<br>se           | 0                  |
| 2          | Study   | Conten                 | t                          |  |                 |                               |                       |                   |                       |                    |
| 3          | <ul> <li>Navier-Stokes Equations (NSE) for two-phase incompressible flows with mass transfer. The unstructured Finite Volume method. The ALE and VOF methods for simulating incompressible two-phase flows. Deep Learning (DL) for general function approximation. Deep Learning for segregated solution algorithms for NSE. Physics-informed Machine Learning (Pi-ML) - a collocation method with Artificial Neural Networks. Designing Pi-ML models for segregated solution algorithms for NSE, and curvature approximation for two-phase flows.</li> <li>3 Learning Outcomes The students can derive Navier-Stokes equations for two-phase incompressible flows with mass transfer from first principles, they can discretize PDEs using the unstructured finite volume method, and describe the relevant algorithms of the ALE and VOF two-phase flow simulation methods. The students can describe the training process of a Deep Neural Network, and the construction and training of a Physics-Informed Neural Network for (coupled) Partial Differential Equations. In exercsies, students gather hands-on experiences in simulating incompressible two-phase flows using OpenFOAM, and</li></ul> |                        |                            |  |                 |                               |                       |                   |                       |                    |
| 4          | <b>Requir</b><br>Recom  | ements<br>mended       | <b>for Pa</b><br>l: Partia | <b>rticipation</b><br>l Differential Equa  | tions           |                               |                       |                   |                       |                    |
| 5          | Form o<br>Final M   | of Exam<br>Iodule H    | <b>ination</b><br>Examina  | ition:                                     |                 |                               |                       |                   |                       |                    |
|            |   | • Modul<br>Duratio     | e Exam<br>on 60 m          | ination (Technical<br>in, Standard)        | Exar            | nination, ora                 | al / writt            | ten Exa           | aminatic              | on,                |
|            | Usually<br>numbe  | r the exa<br>r of pote | am is ta<br>ential pa      | ken in form of a w<br>articipants. In this | rittei<br>case, | n test, excep<br>, the exam c | t when t<br>an be tal | here an<br>ken in | re only a<br>the form | a small<br>1 of an |

|          | oral exam. The decision about the form of the exam is taken and communicated during<br>the first two weeks of the lecture, based on the prospective number of students taking the<br>exam. |
|----------|--|
| 6        | Requirements on the Award of Credit Points   |
| 0        | Passing the Technical Examination ("Fachprüfung")  |
| 7        | Grading  |
| <i>'</i> | Final Module Examination:  |
|          |  |
|          | □• Module Examination (Technical Examination, oral / written Examination,  |
|          | Weight: 100%, Standard)  |
|          |  |
| 8        | Usability of the Module  |
|          | M. Sc. Mathematics, Mathematics in Data Science  |
|          | in ber mattematics, mattematics in Data Science  |
| 9        | Literature   |
|          | Moukalled, F., Mangani, L., Darwish, M. (2016). The finite volume method. In The finite volume method in computational fluid dynamics (pp. 103-135). Springer, Cham.                       |
|          | Maric, Tomislav, Jens Hopken, and Kyle Mooney. "The OpenFOAM technology primer." (2014).   |
|          | Karniadakis, G. E., Kevrekidis, I. G., Lu, L., Perdikaris, P., Wang, S., Yang, L. (2021).<br>Physics-informed machine learning. Nature Reviews Physics, 3(6), 422-440.                     |
|          | Physics-Based ML in OpenFOAM - OpenFOAM Workshop Training:<br>https://youtu.be/uKo3RD3yYrU?list=PLwSEyKg12dVYbpC2wy_RT2_azGUwZPCQ9   |
|          | OpenFOAM Data-Driven Technical Committee source code repositories:<br>https://github.com/OFDataCommittee   |
| 10       | Comment  |
|          |  |

| Mod   | lule na  | me           |                                 |                             |                              |             |                    |                                |             |   |
|---|--|--------------|---------------------------------|-----------------------------|------------------------------|-------------|--------------------|--------------------------------|-------------|---|
|   | Effi   | icient       | t Meth                          | ods for Data                | a As                         | similati    | on                 |                                | 1           |   |
| Moc<br>no.<br>04-1<br>0619                            | Module<br>no.Credit PointsWorkload04-10-5 CP150619/en  |              | Workload<br>150 h               | Self                        | Self-study<br>105 h 1 Semest |             | o <b>n</b><br>ster | n Frequency<br>ter Irregularly |             |   |
| Lan   | guage o  | of Instru    | iction                          |                             | Pers                         | son respons | ible for           | the M                          | odule       |   |
| Eng   | lish   |              |                                 |                             | Prof                         | Dr. rer. na | t. Jan Gi          | esselm                         | ann         |   |
| 1   | Course   | es of the    | e Modu                          | le                          |                              |             |                    |                                |             |   |
| Course no.Course nameWorkload (CP)Form of<br>Teaching |  | ı of<br>hing | Contact<br>Hours<br>per<br>Week |                             |                              |             |                    |                                |             |   |
|   | 04-10-0  | 619-vu       | Efficien<br>Assimila            | t Methods for Data<br>ation |                              | 0           |                    | Lectur<br>Exerci               | e and<br>se | 3 |
| 2   | Study Content<br>Bayesian Formulation of Data Assimilation problems, Kalman smoothing, Markov-Chain<br>Monte-Carlo method, Variational approaches (4DVar), Sequential approaches and 3DVar,<br>Kalman filter and Ensemble Kalman filter; nudging methods (e.g. Luenberger observer),<br>model reduction methods;<br>implementation of the above methods  |              |                                 |                             |                              |             |                    |                                |             |   |
| 3   | Learning Outcomes         The students know the most important methods of variational and sequential data assimilation. They understand their properties and numerical challenges arising when these methods are used in practise.         They can choose appropriate data assimilation methods for specific applications and they can implement and analyse these methods.   |              |                                 |                             |                              |             |                    |                                |             |   |
| 4   | Requirements for Participation         Recommended: Einführung in die Stochastik (Introduction to Stochastics), Gewöhnliche         Differentialgleichungen (Ordinary Differential Equations), Einführung in die         Numerische Mathematik (Introduction to Numerical Analysis)  |              |                                 |                             |                              |             |                    |                                |             |   |
| 5   | Form of Examination         Final Module Examination:         □• Module Examination (Technical Examination, oral / written Examination, Duration 60 min, Standard)         Usually the exam is taken in form of a written test, except when there are only a small number of potential participants. In this case, the exam can be taken in the form of an oral exam. The decision about the form of the exam is taken and communicated during the first two weeks of the lecture, based on the prospective number of students |              |                                 |                             |                              |             |                    |                                |             |   |
|   | taking   | the exa      | m.                              |                             |                              |             |                    |                                |             |   |

| 6  | Requirements on the Award of Credit Points<br>Passing Technical Examination ("Fachprüfung")   |
|----|---|
| 7  | Grading<br>Final Module Examination:<br>│□• Module Examination (Technical Examination, oral / written Examination,<br>Weight: 100%, Standard)   |
| 8  | <b>Usability of the Module</b><br>M. Sc. Mathematics, Mathemaics in Data Science  |
| 9  | <b>Literature</b><br>Kody Law, Andrew Stuart, Konstantinos Zygalakis; Data Assimilation: A mathematical<br>introduction, Springer, 2015<br>Mark Asch, Marc Bocquet, Maelle Nodet; Data Assimilation: Methods, Algorithms and<br>Applications, SIAM 2016 |
| 10 | Comment   |

| Mod                                | lule na   | me        |                   |                            |                     |                               |                               |                  |                                 |   |
|------------------------------------|---|-----------|-------------------|----------------------------|---------------------|-------------------------------|-------------------------------|------------------|---------------------------------|---|
|                                    | Numerics of PDEs with Uncertain Data  |           |                   |                            |                     |                               |                               |                  |                                 |   |
| Moc<br>no.<br>04-1<br>062          | Module<br>no.Credit Points04-10-9 CP0620/en   |           | Points<br>9 CP    | Workload<br>270 h          | Self-study<br>180 h |                               | <b>Duration</b><br>1 Semester |                  | <b>Frequency</b><br>Irregularly |   |
| Language of Instruction<br>English |   |           |                   | Pers<br>Prof               | son respons         | <b>ible for</b><br>t. Jens La | <b>the M</b><br>ang           | odule            |                                 |   |
| 1                                  | Course  | es of the | e Modul           | le                         | <b>I</b>            |                               |                               |                  |                                 |   |
|                                    | Course no. Course na  |           | e name            |                            | Workload            | (CP)                          | Form of<br>Teaching           |                  | Contact<br>Hours<br>per<br>Week |   |
|                                    | 04-10-0   | 620-vu    | Numeri<br>Uncerta | cs of PDEs with<br>in Data |                     | 0                             |                               | Lectur<br>Exerci | e and<br>se                     | 6 |
| 2                                  | <ul> <li>Study Content</li> <li>Examples of PDEs, weak solutions of elliptic PDEs,<br/>finite element method, error estimates,<br/>strong formulations of elliptic PDEs with uncertain data,<br/>Monte Carlo finite elements, multi-level</li> <li>Monte Carlo finite elements,<br/>weak formulations of elliptic PDEs with uncertain data, stochastic Galerkin method,<br/>Karhunen-Loeve</li> <li>expansion,<br/>weak solutions of<br/>parabolic PDEs, Method of Lines or Rothe Method with finite</li> <li>elements,</li> <li>implementation of the above methods</li> </ul> |           |                   |                            |                     |                               |                               |                  |                                 |   |
| 3                                  | Learning Outcomes<br>Students will be able to describe, explain and apply the main<br>design principles of numerical solution methods for linear elliptic and parabolic partial<br>differential equations with deterministic as well as uncertain data. They will be able to<br>analyze, evaluate, implement and compare the methods.   |           |                   |                            |                     |                               |                               |                  |                                 |   |
| 4                                  | Requirements for Participation<br>Recommended: Introduction to Numerical Analysis, Numerical Methods for Ordinary<br>Differential Equations   |           |                   |                            |                     |                               |                               |                  |                                 |   |
| 5                                  | Form of Examination         Final Module Examination:         □• Module Examination (Technical Examination, oral / written Examination, Duration 90 min, Standard)  |           |                   |                            |                     |                               |                               |                  |                                 |   |

|    | Usually the exam is taken in form of a written test, except when there are only a small number of potential participants. In this case, the exam can be taken in the form of an |
|----|---|
|    | oral exam. The decision about the form of the exam is taken and communicated  |
|    | during the first two weeks of the lecture, based on the prospective number of students  |
|    | taking the exam.  |
| 6  | Requirements on the Award of Credit Points  |
|    | Passing Technical Examination ("Fachprüfung")   |
| 7  | Grading   |
|    | Final Module Examination:   |
|    | □• Module Examination (Technical Examination, oral / written Examination,   |
|    | Weight: 100%, Standard)   |
| 8  | Usability of the Module   |
|    | M. Sc. Mathematics, Mathemaics in Data Science  |
| 9  | Literature  |
|    | S. Brenner, R. Scott: Mathematical Theory of Finite Element Methods, Texts in Applied Mathematics, Vol. 15, Springer, 2008  |
|    | S. Larsson, V. Thomée: Partial Differential Equations with Numerical Methods.   |
|    | Texts in Applied Mathematics, Vol. 45, Springer 2003.   |
|    | G. J. Lord, C. E. Powell, and T. Shardlow. An Introduction to Computational Stochas-  |
|    | tic PDEs. Cambridge University Press, 2014.   |
| 10 | Comment   |
|    |   |
|    |   |

| Мос                                  | lule na   | me   |  |   |                         |                                   |                  |                               |             |                                 |  |
|--------------------------------------|---|--|--|---|-------------------------|-----------------------------------|------------------|-------------------------------|-------------|---------------------------------|--|
|                                      | Scal  | Lable  | Linea                                      | ar Solvers fo   | or D                    | ata Scie                          | nce              |                               |             |                                 |  |
| Moc<br>no.<br>04-1<br>062            | Module<br>no. Cr<br>04-10-<br>0621/en   |  | PointsWorkloadS5 CP150 h                   |   | Self                    | Self-study I<br>105 h             |                  | <b>Duration</b><br>1 Semester |             | <b>Frequency</b><br>Irregularly |  |
|                                      |   |  |  | Dore  | son respons             | ible for                          | tho M            | odulo                         |             |                                 |  |
| Fnolish                              |   |  |  | Prof  | Dr. rer. nat            | L.Jens L                          | ang              | ouuie                         |             |                                 |  |
| 1                                    | Course  | es of the  | Modu                                       | 1e  |                         |                                   |                  |                               |             |                                 |  |
| Course no. Course name Workload (CP) |   | Form of<br>Teaching                                  |  | Contact<br>Hours<br>per<br>Week                                 |                         |                                   |                  |                               |             |                                 |  |
|                                      | 04-10-0   | 621-vu   | Scalable<br>Science                        | e Linear Solvers for I  | Data                    | 0                                 |                  | Lectur<br>Exercia             | e and<br>se | 3                               |  |
| 2                                    | 2 Study Content<br>Preconditioning of linear systems of equations,<br>conjugate gradient method, linear iterative<br>methods, preconditioning with<br>incomplete decompositions, subspace correction methods,<br>hierarchical bases and multigrid methods,<br>bandwidth minimisation  |  |  |   |                         |                                   |                  |                               |             |                                 |  |
| 3                                    | <b>Learni</b><br>Studen<br>design<br>evaluat  | <b>ng Outo</b><br>ts will b<br>principl<br>te, imple | comes<br>be able t<br>les of sc<br>ement a | to describe, explain<br>alable linear solve<br>nd compare the m | n and<br>rs for<br>etho | apply the m<br>Data Scienc<br>ds. | nain<br>ce. They | will be                       | e able to   | analyze,                        |  |
| 4                                    | <b>Requir</b><br>Recom  | rements<br>mended                                    | <b>for Pa</b><br>l: Introd                 | <b>rticipation</b><br>luction to Numeric                        | cal Ar                  | nalysis                           |                  |                               |             |                                 |  |
| 5                                    | <ul> <li>Form of Examination</li> <li>Final Module Examination:         <ul> <li>Module Examination (Technical Examination, oral / written Examination, Duration 60 min, Standard)</li> </ul> </li> <li>Usually the exam is taken in form of a written test, except when there are only a small number of potential participants. In this case, the exam can be taken in the form of an oral exam. The decision about the form of the exam is taken and communicated during the first two weeks of the lecture, based on the prospective number of students taking the exam.</li> </ul> |  |  |   |                         |                                   |                  |                               |             |                                 |  |
| 6                                    | Requirements on the Award of Credit Points<br>Passing Technical Examination ("Fachprüfung")   |  |  |   |                         |                                   |                  |                               |             |                                 |  |

| 7  | Grading<br>Final Module Examination:<br>│□• Module Examination (Technical Examination, oral / written Examination,<br>Weight: 100%, Standard)  |
|----|--|
| 8  | <b>Usability of the Module</b><br>M. Sc. Mathematics, Mathemaics in Data Science   |
| 9  | <b>Literature</b><br>Wolfgang Hackbusch, Iterative Solution of Large Sparse Systems of Equations, 2nd ed.<br>2016,<br>Applied Mathematical Sciences Vol. 95, Springer International Publishing, 2016 |
| 10 | Comment  |

| Мос                                     | lule na   | me                       |                            |                    |                               |                                 |                                 |                  |             |   |
|---|---|--------------------------|----------------------------|--------------------|-------------------------------|---------------------------------|---------------------------------|------------------|-------------|---|
|   | Deer  | Lear                     | ning                       | Lab                |                               |                                 |                                 |                  |             |   |
| Moduleno.Credit Points04-10-5 CP0618/en |   | <b>Workload</b><br>150 h | <b>Self-study</b><br>105 h |                    | <b>Duration</b><br>1 Semester |                                 | <b>Frequency</b><br>Irregularly |                  |             |   |
| Language of Instruction Pers            |   |                          |                            |                    | son respons                   | ible for                        | the M                           | odule            |             |   |
| Eng                                     | lish  |                          |                            |                    | Prof                          | . Dr. Yann D                    | lisser                          |                  |             |   |
| 1                                       | Course  | es of the                | e Modul                    | le                 |                               |                                 | (                               |                  |             |   |
|   | Course no. Course name Workload (C  |                          | (CP)                       | Form<br>Teac       | i of<br>hing                  | Contact<br>Hours<br>per<br>Week |                                 |                  |             |   |
|   | 04-10-0   | 618-vu                   | Deep Le                    | arning Lab         |                               | 0                               |                                 | Lectur<br>Exerci | e and<br>se | 3 |
| 2                                       | <b>Study Content</b><br>introduction to deep learning, mathematical foundations, Keras and TensorFlow,<br>classification, convolutional neural nets, adversarial deep learning, text generation<br>Possible societal implications will be addressed in the lecture  |                          |                            |                    |                               |                                 |                                 |                  |             |   |
| 3                                       | <ul> <li>Learning Outcomes</li> <li>The students know and understand the concepts and methods taught in the course and can apply them. They have a thorough understanding of the formal foundations of deep learning. They are able to independently expand their knowledge of the field and pursue supervised research projects.</li> <li>Students are able to contextualize subject matter within the social context, critically assess the consequences, and act ethically and responsibly accordingly.</li> </ul> |                          |                            |                    |                               |                                 |                                 |                  |             |   |
| 4                                       | Requirements for Participation         Recommended:         Algorithmic Discrete Mathematics         Einführung in die Optimierung (Introduction to optimization)         programming expertise (ideally Python)  |                          |                            |                    |                               |                                 |                                 |                  |             |   |
| 5                                       | Form of Examination         Final Module Examination:         □• Module Examination (Study Examination, Paper, Standard)         Study Examination ("Studienleistung"): Presentation  |                          |                            |                    |                               |                                 |                                 |                  |             |   |
| 6                                       | Requir  | ements                   | on the                     | Award of Credit    | Poin                          | ts<br>"                         |                                 |                  |             |   |
|   | Passing   | s study                  | Examina                    | auon ("Studieniels | sung                          | J                               |                                 |                  |             |   |
| 7                                       | Gradin  | ıg                       |                            |                    |                               |                                 |                                 |                  |             |   |

|         | Final Module Examination:   |
|---------|---|
|         | □• Module Examination (Study Examination, Paper, Weight: 0%, Standard)              |
| 8       | Usability of the Module   |
|         | M. Sc. Mathematics, Mathematics in Data Science                                     |
|         |   |
| 9       | Literature  |
| 9       | Literature<br>Deep Learning with Python (2nd edition) - François Chollet            |
| 9       | Literature<br>Deep Learning with Python (2nd edition) - François Chollet            |
| 9<br>10 | Literature<br>Deep Learning with Python (2nd edition) - François Chollet<br>Comment |
| 9<br>10 | Literature<br>Deep Learning with Python (2nd edition) - François Chollet<br>Comment |

| Мос                                       | lule na  | me                                      |                                     |  |                     |                                      |                              |                         |             |        |
|---|--|---|-------------------------------------|--|---------------------|--------------------------------------|------------------------------|-------------------------|-------------|--------|
|   | Opti   | imizat                                  | ion M                               | Methods for M                              | lasc                | hine Lea                             | rning                        |                         | 1           |        |
| <b>Moc</b><br><b>no.</b><br>04-1<br>062   | odule<br>0.Credit PointsWorkloadSelf-studyDuration<br>105 hFre<br>Evi<br>ser-10-<br>24/en5 CP150 h105 h1 SemesterEvi<br>ser  |   | <b>Freque</b><br>Every 2<br>semeste | F <b>requency</b><br>Every 2.<br>semester  |                     |                                      |                              |                         |             |        |
| <b>Language of Instruction</b><br>English |  |   |                                     |  | <b>Pers</b><br>Prof | <b>son respons</b><br>. Dr. rer. nat | <b>ible for</b><br>t. Marc F | <b>the M</b><br>Pfetsch | odule       |        |
| 1   | Course   | es of the                               | e Modu                              | le   |                     |                                      |                              |                         |             |        |
|   | Course no. Course name Workload (CP)   |   | (CP)                                | Form<br>Teac                               | ı of<br>hing        | Contact<br>Hours<br>per<br>Week      |                              |                         |             |        |
|   | 04-10-0  | 624-vu                                  | Optimiz<br>Maschir                  | ation Methods for<br>ne Learning           |                     | 0                                    |                              | Lectur<br>Exerci        | e and<br>se | 3      |
| 2   | <b>Study</b><br>Founda<br>Comple   | <b>Conten</b><br>ations of<br>etion, Sj | t<br>f Masch<br>parse Re            | ine learning, Class<br>egression, Lasso, N | ificat<br>[eura]    | ion (Suppor<br>l Networks (          | t Vector<br>Deep Le          | Masch<br>arning         | nines), M   | Iatrix |
| 3   | Learning Outcomes         After taking the course, the students have insight into maschine learning. In particular, they know which mathematical optimization methods can be applied in this context and know their properties.  |   |                                     |  |                     |                                      |                              |                         |             |        |
| 4   | <b>Requir</b><br>Recom<br>Optimi   | <b>ements</b><br>mended<br>zation       | f <b>or Pa</b><br>: Introd          | rticipation<br>uction to Optimiza          | ation               | , Discrete O <sub>I</sub>            | otimizati                    | on or l                 | Nonline     | ar     |
| 5   | <b>Form o</b><br>Final M   | o <b>f Exam</b><br>Iodule H             | i <b>nation</b><br>Examina          | ition:                                     |                     |                                      |                              |                         |             |        |
|   |  | • Modul<br>Duratio                      | e Exami<br>on 60 m                  | ination (Technical<br>in, Standard)        | Exar                | nination, ora                        | al / writt                   | en Exa                  | aminatic    | on,    |
|   | Usually the exam is taken in form of a written test, except when there are only a small<br>number of potential participants. In this case, the exam can be taken in the form of an<br>oral exam. The decision about the form of the exam is taken and communicated during<br>the first two weeks of the lecture, based on the prospective number of students taking the<br>exam. |   |                                     |  |                     |                                      |                              |                         |             |        |
| 6   | <b>Requir</b><br>Passing   | ements<br>g Techni                      | on the                              | Award of Credit<br>mination ("Fachpr       | Poin<br>üfung       | <b>ts</b><br>g")                     |                              |                         |             |        |
| 7   | Gradin   | ıg                                      |                                     |  |                     |                                      |                              |                         |             |        |

|    | Final Module Examination:   |
|----|---|
|    |   |
|    | □• Module Examination (Technical Examination, oral / written Examination,         |
|    | Weight: 100%, Standard)   |
|    |   |
| 8  | Usability of the Module   |
|    | M.Sc. Mathematics, Mathematics in Data Science                                    |
|    |   |
| 9  | Literature  |
|    | Hastie, Tibshirani, Friedman: The Elements of Statistical Learning, Springer 2000 |
|    | Mitchell: Machine Learning. Mcgraw-Hill 1997                                      |
|    | Murphy: Machine Learning: A Probabilistic Perspective, MIT Press 2012             |
|    | Sra, Nowozin, Wright: Optimization for Machine Learning, MIT Press, 2012          |
|    | Miroslav Kubat: An Introduction to Machine Learning. Springer, 2015.              |
|    |   |
| 10 | Comment   |
|    |   |
|    |   |
|    |   |

| Mod                                       | lule na   | me                          |                             |  |                                      |                              |   |                     |             |                                 |
|---|---|-----------------------------|-----------------------------|--|--------------------------------------|------------------------------|---|---------------------|-------------|---------------------------------|
|   | Opti  | imizat                      | ion M                       | lethods in Da                              | ta                                   | Science                      |   |                     | -           |                                 |
| Mod<br>no.<br>04-1<br>062                 | <b>lule</b><br>.0-<br>5/en  | Credit                      | Points<br>5 CP              | Workload Self-study Duration Free Even sem |                                      | Freque<br>Every 2<br>semeste | F <b>requency</b><br>Every 2.<br>semester |                     |             |                                 |
| <b>Language of Instruction</b><br>English |   |                             |                             | Pers<br>Prof                               | <b>Son respons</b><br>. Dr. rer. nat | <b>ible for</b><br>t. Marc P | <b>the M</b><br>fetsch                    | odule               |             |                                 |
| 1   | Courses of the Module   |                             |                             |  |                                      |                              |   |                     |             |                                 |
|   | Course no. Cours  |                             | Course                      | e name                                     |                                      | Workload (CP)                |   | Form of<br>Teaching |             | Contact<br>Hours<br>per<br>Week |
|   | 04-10-0   | 625-vu                      | Optimiz<br>Science          | ation Methods in Da                        | ata                                  | 0                            |   | Lectur<br>Exerci    | e and<br>se | 3                               |
| 2   | <b>Study Content</b><br>data preprocessing, (sparse) principal component analysis; clustering, k-means,<br>semidefinite models; generative and adversarial models; sparse optimization  |                             |                             |  |                                      |                              |   |                     |             |                                 |
| 3   | Learni  | ng Outo                     | comes                       |  |                                      |                              |   |                     |             |                                 |
| 4   | <b>Requir</b><br>Recom<br>Optimi  | ements<br>mended<br>zation  | f <b>or Pa</b><br>l: Introd | r <b>ticipation</b><br>luction to Optimiza | ation                                | ; Discrete Oj                | ptimizati                                 | on or               | Nonline     | ar                              |
| 5   | <b>Form o</b><br>Final M  | o <b>f Exam</b><br>Iodule H | i <b>ination</b><br>Examina | ıtion:                                     |                                      |                              |   |                     |             |                                 |
|   |   | • Modul<br>Duratio          | e Exami<br>on 60 m          | ination (Technical)<br>in, Standard)       | Exar                                 | nination, ora                | al / writt                                | en Exa              | aminatio    | on,                             |
|   | Usually the exam is taken in form of a written test, except when there are only a small<br>number of potential participants. In this case, the exam can be taken in the form of an<br>oral exam. The decision about the form of the exam is taken and communicated during<br>the first two weeks of the lecture, based on the prospective number of students taking the<br>exam |                             |                             |  |                                      |                              |   |                     |             |                                 |
| 6   | <b>Requir</b><br>Passing  | <b>ements</b><br>g the Te   | on the                      | Award of Credit<br>Examination ("Fac       | <b>Poin</b><br>hprü                  | <b>ts</b><br>fung")          |   |                     |             |                                 |
| 7   | <b>Grading</b><br>Final Module Examination:   |                             |                             |  |                                      |                              |   |                     |             |                                 |

|    | <ul> <li>Module Examination (Technical Examination, oral / written Examination,<br/>Weight: 100%, Standard)</li> </ul>   |
|----|--|
| 8  | Usability of the Module  |
|    | M. Sc. Mathematics, Mathematics in Data Science  |
| 9  | Literature<br>Hastie, Tibshirani, Friedman: The Elements of Statistical Learning, Springer 2000<br>Mitchell: Machine Learning. Mcgraw-Hill 1997<br>Murphy: Machine Learning: A Probabilistic Perspective, MIT Press 2012<br>Sra,Nowozin, Wright: Optimization for Machine Learning, MIT Press, 2012<br>Miroslav Kubat: An Introduction to Machine Learning.Springer, 2015. |
| 10 | Comment  |

| Mod                                | lule na  | me   |  |   |   |   |   |   |  |  |
|------------------------------------|--|--|--|---|---|---|---|---|--|--|
|                                    | Firs   | st-ord   | der me   | thods for op  | tim   | ization   | in dat  | ta an   | alyti  | cs   |
| Moc<br>no.<br>04-1<br>062          | IuleCredit PointsWorkloadSelf-studyDu.0-5 CP0 h0 h1 S3/en.00000-1 S  |  | <b>Duratio</b><br>1 Seme                       | <b>Duration</b><br>1 Semester   |   | <b>ncy</b><br>ırl   |   |   |  |  |
| Language of Instruction<br>English |  |  |  | L   | Pers<br>Prof                                | son respons   | <b>ible for</b><br>t. Stefan                                | <b>the M</b><br>Ulbric                          | odule<br>h   |  |
| 1                                  | Course   | es of the  | e Modu   | le  |   |   |   |   |  |  |
|                                    | Course no. Course name   |  |  | Workload (CP)   |   | Form<br>Teac  | n of<br>hing  | Contact<br>Hours<br>per<br>Week                 |  |  |
|                                    | 04-10-0  | 623-vu   | First-or<br>optimiz                            | der methods for<br>ation in data analyti  | CS  | 0   |   | Lectur<br>Exerci                                | re and<br>se   | 0  |
| 2                                  | <b>Study Content</b><br>First-order methods are a highly active research field in optimization, in particular for applications in data analytics. They often combine primal-dual decomposition approaches with relatively simple iteration schemes and provide very efficient structure-exploiting algorithms for challenging large scale problems. This course gives an introduction into the design and theory of first-order proximal point and primal-dual optimization methods. |  |  |   |   |   |   |   |  |  |
| 3                                  | Learni<br>The stu<br>optimiz<br>prepare<br>indepe  | ng Outo<br>Idents a<br>zation n<br>ed for st<br>ndently                                | comes<br>re able<br>nethods<br>cudying         | to apply and inves<br>, in particular prox<br>scientific developr   | tigat<br>timal<br>nents                     | e important<br>point and p<br>s and applica                                       | classes c<br>rimal-du<br>ations in                          | of first-<br>al met<br>this fi                  | order<br>hods. Tł<br>eld                                   | iey are                                      |
| 4                                  | <b>Requir</b><br>Recom   | ements<br>mendec   | <b>for Pa</b><br>l: Introd                     | rticipation<br>luction to Optimiza  | ation                                       | ; Nonlinear   | Optimiza  | ation   |  |  |
| 5                                  | Form of<br>Final M<br>  _ •<br>Usually<br>numbe<br>oral ex<br>the firs<br>exam.  | of Exam<br>Iodule I<br>Modul<br>Duratio<br>7 the exa<br>r of pot<br>am. The<br>t two w | am is ta<br>e ential p<br>e decisio<br>eeks of | ntion:<br>ination (Technical<br>in, Standard)<br>ken in form of a w<br>articipants. In this<br>on about the form of<br>the lecture, based | Exar<br>ritter<br>case,<br>of the<br>on the | nination, ora<br>n test, excep<br>, the exam ca<br>e exam is tal<br>ne prospectiv | al / writt<br>t when t<br>an be tal<br>ken and o<br>ze numb | ten Exa<br>here a<br>ken in<br>comm<br>er of st | aminatio<br>re only a<br>the form<br>unicated<br>tudents t | n,<br>small<br>of an<br>during<br>taking the |
| 0                                  | кеqui  | ements   | s on the                                       | Awaru of Credit   | POIN  | 15  |   |   |  |  |

|          | 1  |
|----------|--|
|          | Passing the Technical Examination ("Fachprüfung")  |
| 7        | Grading  |
| <i>'</i> | Final Module Examination:  |
|          |  |
|          | • Module Examination (Technical Examination, oral / written Examination                    |
|          | Weight: 100% Standard)   |
|          | Weight. 100%, Standard)  |
| 8        | Usability of the Module  |
|          | M. Sc. Mathematics, Mathematics in Data Science  |
|          |  |
| 9        | Literature   |
|          | Stephen Boyd, Neal Parikh, Eric Chu, Borja Peleato, Jonathan Eckstein: Distributed         |
|          | Optimization and Statistical Learning via the Alternating Direction Method of Multipliers, |
|          | Foundations and Trends in Machine Learning Vol. 3, No. 1 (2010), 1–122.                    |
|          | Antonin Chambolle, Thomas Pock: A First-Order Primal-Dual Algorithm for Convex             |
|          | Problems with Applications to Imaging, Journal of Mathematical Imaging and Vision, Vol.    |
|          | 40, No. 1 (2011), 120-145.   |
|          | Christian Clason, Tuomo Valkonen: Intoduction to Nonsmooth Analysis,                       |
|          | arXiv:2001.00216v3, https://doi.org/10.48550/arXiv.2001.00216                              |
|          |  |
|          |  |
| 10       | Comment  |
| 10       | Comment  |
|          |  |
|          |  |

| Мос                                       | lule na   | me                  |  |                                      |                    |                                     |                             |                         |                                 |     |
|---|---|---------------------|--|--------------------------------------|--------------------|-------------------------------------|-----------------------------|-------------------------|---------------------------------|-----|
|   | Math  | nemati              | ical S   | statistics                           |                    |                                     |                             |                         |                                 |     |
| Mod<br>no.<br>04-1<br>061                 | <b>lule</b><br>.0-<br>6/en  | Credit              | redit PointsWorkloadSelf-studyDuration9 CP270 h180 h1 Semester |                                      | o <b>n</b><br>ster | r Frequency<br>Every 3.<br>semester |                             |                         |                                 |     |
| <b>Language of Instruction</b><br>English |   |                     |  |                                      | Pers<br>Prof       | son respons                         | <b>ible for</b><br>. Michae | <b>the M</b><br>el Kohl | <b>odule</b><br>er              |     |
| 1   | Course  | es of the           | e Modu   | le                                   |                    |                                     |                             |                         |                                 |     |
|   | Course no. Course   |                     | e name   |                                      | Workload           | (CP) Fo<br>Te                       |                             | ı of<br>hing            | Contact<br>Hours<br>per<br>Week |     |
|   | 04-10-0   | 616-vu              | Mathem   | natical Statistics                   |                    | 0                                   |                             | Lectur<br>Exerci        | e and<br>se                     | 6   |
| 2   | Study Content         Estimation of distributations,         VC theory,         density estimation,         point estimates,         statistical tests,         confidence intervals.         Possible societal implications will be addressed in the lecture.  |                     |  |                                      |                    |                                     |                             |                         |                                 |     |
| 3   | Learning OutcomesThe students know and understand the above mentioned concepts, methods and results,<br>and are able to apply them. They have a deep unterstanding of Mathematical Statistics<br>and are able to learn new knowledge in this field by themselves.Students are able to contextualize subject matter within the social context, critically<br>assess the consequences, and act ethically and responsibly accordingly. |                     |  |                                      |                    |                                     |                             |                         |                                 |     |
| 4   | <b>Requir</b><br>recomr   | ements              | <b>for Pa</b><br>Probab  | rticipation<br>bility theory         |                    |                                     |                             |                         |                                 |     |
| 5   | Form of Final M   | of Exam<br>Iodule H | <b>ination</b><br>Examina                                      | tion:                                |                    |                                     |                             |                         |                                 |     |
|   |   | Modul<br>Duratio    | e Exami<br>on 90 m   | ination (Technical)<br>in, Standard) | Exar               | nination, ora                       | al / writt                  | en Exa                  | aminatio                        | on, |
|   | Usually the exam is taken in form of a written test, except when there are only a small<br>number of potential participants. In this case, the exam can be taken in the form of an<br>oral exam. The decision about the form of the exam is taken and communicated  |                     |  |                                      |                    |                                     |                             |                         |                                 |     |

|    | during the first two weeks of the lecture, based on the prospective number of students taking the exam.                |
|----|--|
| 6  | Requirements on the Award of Credit Points   |
|    | Passing the Technical Examination ("Fachprüfung");   |
| 7  | Grading  |
|    | Final Module Examination:  |
|    | <ul> <li>Module Examination (Technical Examination, oral / written Examination,<br/>Weight: 100%, Standard)</li> </ul> |
| 8  | Usability of the Module  |
|    | M. Sc. Mathematics, Mathematics in Data Science  |
| 9  | Literature   |
|    | Lehmann, Romano: Testing Statistical Hypotheses.   |
|    | Devroye, Lugosi: Combinatorial methods in density estimation   |
| 10 | Comment  |
|    |  |

| Moc                                     | lule na   | me   |                               |                              |                             |                              |                         |                     |                                 |     |
|---|---|--|-------------------------------|------------------------------|-----------------------------|------------------------------|-------------------------|---------------------|---------------------------------|-----|
|   | Stat  | tistic   | al th                         | eory for Dee                 | рL                          | earning                      | 1                       |                     | 1                               |     |
| <b>Moc</b><br><b>no.</b><br>04-1<br>061 | <b>lule</b><br>10-<br>7/en  | Credit PointsWorkloadSelf-studyDuration9 CP270 h180 h1 Semestr |                               | <b>)n</b><br>ster            | n Every 3.<br>ster semester |                              |                         |                     |                                 |     |
| Language of Instruction<br>English      |   |  |                               | Pers<br>Prof                 | son respons                 | <b>ible for</b><br>t. Michae | <b>the M</b><br>el Kohl | <b>odule</b><br>ler |                                 |     |
| 1                                       | Course  | es of the  | e Modu                        | le                           |                             |                              |                         |                     |                                 |     |
|   | Course no. Course   |  | e name                        |                              | Workload (CP)               |                              | Form of<br>Teaching     |                     | Contact<br>Hours<br>per<br>Week |     |
|   | 04-10-0   | 617-vu   | Statistic<br>Learnin          | al theory for Deep<br>g      |                             | 0                            |                         | Lectur<br>Exerci    | e and<br>se                     | 6   |
| 2                                       | Study Contenttypes of neural networks,nonparametric regression and image classification,gradient descent,approximation results for feed forward neural networks,rate of convergence for least squares neural network estimates,analysis of neural networks learned by gradient descentPossible societal implications will be addressed in the lecture   |  |                               |                              |                             |                              |                         |                     |                                 |     |
| 3                                       | Learning Outcomes<br>The students know and understand the above mentioned concepts, methods and results,<br>and are able to apply them. They have a deep unterstanding of Deep Learning and are<br>able to learn new knowledge in this field by themselves.<br>Students are able to contextualize subject matter within the social context, critically<br>assess the consequences, and act ethically and responsibly accordingly. |  |                               |                              |                             |                              |                         |                     |                                 |     |
| 4                                       | <b>Requir</b><br>recomr   | ements   | f <b>or Pa</b><br>Probat      | rticipation<br>bility theory |                             |                              |                         |                     |                                 |     |
| 5                                       | Form of Final M   | of Exam<br>Iodule H<br>Modul                                   | ination<br>Examina<br>e Exami | tion:<br>ination (Technical  | Exai                        | nination, ora                | al / writt              | ten Exa             | aminatio                        | on, |
|   | Duration 90 min, Standard)<br>Usually the exam is taken in form of a written test, except when there are only a small<br>number of potential participants. In this case, the exam can be taken in the form of an<br>oral exam. The decision about the form of the exam is taken and communicated  |  |                               |                              |                             |                              |                         |                     |                                 |     |

|    | during the first two weeks of the lecture, based on the prospective number of students taking the exam.   |
|----|---|
| 6  | <b>Requirements on the Award of Credit Points</b><br>Passing the Technical Examination ("Fachprüfung");   |
| 7  | Grading<br>Final Module Examination:<br>│□• Module Examination (Technical Examination, oral / written Examination,<br>Weight: 100%, Standard)                 |
| 8  | <b>Usability of the Module</b><br>M. Sc. Mathematics, Mathematics in Data Science   |
| 9  | <b>Literature</b><br>Goodfellow, Bengio, Courville: Deep Learning.<br>Györfi, Kohler, Krzyzak, Walk: A distribution - free theory of nonparametric regression |
| 10 | Comment   |