

TIME TABLE

TIME	Monday	Tuesday	Wednesday	Thursday	Friday
	April 20	April 21	April 22	April 23	April 24
9.00 - 9.45	Registration	Schönlieb	Keip	Doblaré	Doblaré
9.45 - 10.30	Ortiz	Schönlieb	Keip	Doblaré	Doblaré
11.00 - 11.45	Ortiz	Ortiz	Schönlieb	Stainier	Doblaré
11.45 - 12.30	Ortiz	Ortiz	Schönlieb	Stainier	Ortiz
14.00 - 14.45	Réthoré	Schönlieb	Stainier	Stainier	
14.45 - 15.30	Réthoré	Schönlieb	Stainier	Keip (ML)	
16.00 - 16.45	Réthoré	Réthoré	Stainier (DDCM)	Keip (ML)	
16.45 - 17.30	Réthoré (DIC)	Réthoré (DDI)	Poster Session	Keip	
18.00	Welcome Apéritif				

ADMISSION AND ACCOMMODATION

The registration fee is 600.00 Euro + VAT*, where applicable (bank charges are not included). The registration fee includes a complimentary bag, four fixed menu buffet lunches (on Friday upon request), hot beverages, downloadable lecture notes and wi-fi internet access.

Applicants must apply at least one month before the beginning of the course. Application forms should be sent on-line through the following web site: <http://www.cism.it>. A message of confirmation will be sent to accepted participants. Applicants requiring assistance with the registration should contact the secretariat at the following email address: cism@cism.it.

Applicants may cancel their course registration and receive a full refund by notifying CISM Secretariat in writing (by email to cism@cism.it) no later than two weeks prior to the start of the course.

Cancellation requests received during the two weeks prior to the start of the course will be charged a 50.00 Euro handling fee. Incorrect payments are also subject to a 50.00 Euro handling fee.

A limited number of participants from universities and research centres who are not supported by their own institutions can be offered lodging and/or board, if available, in a reasonably priced hotel or student guest house.

Requests should be sent to CISM Secretariat by **February 20, 2020** along with the applicant's curriculum and a letter of recommendation by the head of the department or a supervisor confirming that the institute cannot provide funding. Preference will be given to applicants from countries that sponsor CISM.

Information about travel and accommodation is available on the web site www.cism.it, or can be mailed upon request.

* Italian VAT is 22%.

For further information please contact:

CISM
 Palazzo del Torso
 Piazza Garibaldi 18
 33100 Udine (Italy)
 tel. +39 0432 248511 (6 lines)
 fax +39 0432 248550

Centre International des Sciences Mécaniques
International Centre for Mechanical Sciences



ACADEMIC YEAR 2020
The Erwin Stein Session

DATA-DRIVEN MECHANICS: CONSTITUTIVE MODEL-FREE APPROACH

Advanced School
coordinated by

Michael Ortiz
California Institute of Technology
Pasadena, USA

Laurent Stainier
Centrale Nantes
France

Udine April 20 - 24 2020

DATA-DRIVEN MECHANICS: CONSTITUTIVE MODEL-FREE APPROACH

The classical approaches to modeling and simulation in solid mechanics rely heavily on constitutive models. These provide constitutive equations, which complement the balance equations of field, or boundary-value, problems. Extensive ongoing research efforts are devoted in the scientific community to tune and ever improve constitutive models and equations for various classes of materials and various regimes of solicitation (loading amplitudes and rates, temperature, chemistry, ...), as well as to identify associated parameters. Constitutive models thus present a very large diversity encompassing a wide range of applications, yet this variety also hints at the inherent epistemic uncertainty carried by these models. If the uncertainty associated to constitutive

parameters can be quantified, the uncertainty associated to the models themselves is much more difficult to measure. From a more historical point of view, constitutive models were initially conceived to generalize experimental observations made on specific (typically homogeneous) loading regimes to more general loadings. With the recent progress in imaging techniques, experimental observations are nowadays much richer in information and existing constitutive models are sometimes incompatible with this abundance of data. Data-driven approaches have recently been developed to better exploit the large volumes of modern experimental measures, while attempting to avoid the bias induced by constitutive models. The present course will focus on a global data-driven approach,

completely avoiding the use of models (statistical models or constitutive models), which could thus be labelled as model-free.

The proposed course will constitute a consistent and comprehensive introduction to the model-free data-driven paradigm for computational solid mechanics. After a general introduction to the data-driven paradigm, and how it fundamentally differs from the classical paradigm, the course will take students all the way from acquiring rich mechanical data sets, notably from imaging, to data-driven numerical simulation in nonlinear mechanics of structures. On the way, important aspects such as mathematical foundations of data-driven and machine learning methods, and the necessity and ways to account for the stochastic and imperfect nature of real-life data will be covered. Abundant

data are also generated in multi-scale approaches, and the course will discuss how the data-driven paradigm may be relevant in that context as well. Finally, the current challenges in dealing with non-linearities and history-dependent behaviors will be discussed.

The course will also include a series of practical hands-on sessions, where the students will experiment with the data-driven approach, starting from a series of images from which to extract data, process it to construct a material database, and use this database in a data-driven simulation. A hands-on training session on coding data-oriented algorithms in the open source machine learning framework TensorFlow™ will also be proposed. Relevant software will be provided to participants for installation on their own computers.

PRELIMINARY SUGGESTED READINGS

Kirchdoerfer T, Ortiz M (2016) Data-driven computational mechanics. *Computer Methods in Applied Mechanics and Engineering* 304:81-101, doi:10.1016/j.cma.2016.02.001.

Kirchdoerfer T, Ortiz M (2017) Data-driven computing with noisy material data sets. *Computer Methods in Applied Mechanics and Engineering* 326:622-641, doi:10.1016/j.cma.2017.07.039.

Ayensa-Jiménez J, Doweidar MH, Sanz-Herrera JA, Doblare M (2018) A new reliability-based data-driven approach for noisy

experimental data with physical constraints. *Computer Methods in Applied Mechanics and Engineering* 328:752-774, doi:10.1016/j.cma.2017.08.027.

Conti S, Müller S, Ortiz M (2018) Data-driven problems in elasticity. *Archives in Rational Mechanics and Analysis* 229:79-123, doi:10.1007/s00205-017-1214-0.

Nguyen LTK, Keip MA (2018) A data-driven approach to nonlinear elasticity. *Computers & Structures* 194:97-115, doi:10.1016/j.compstruc.2017.07.031.

Ayensa-Jiménez J, Doweidar MH,

Sanz-Herrera JA, Doblare M (2019) An unsupervised data completion method for physically-based data-driven models. *Computer Methods in Applied Mechanics and Engineering* 344:120-143, doi:10.1016/j.cma.2018.09.035.

Arridge S, Maass P, Öktem, O, Schönlieb CB (2019) Solving inverse problems using data-driven models. *Acta Numerica* 28:1-174, doi:10.1017/S0962492919000059.

Eggersmann R, Kirchdoerfer T, Reese S, Stainier L, Ortiz M (2019) Model-free data-driven inelasticity. *Computer Methods in Applied*

Mechanics and Engineering 350:81-99, doi:10.1016/j.cma.2019.02.016.

Leygue A, Seghir R, Réthoré J, Coret M, Verron E, Stainier L (2019) Non-parametric material state field extraction from full field measurements. *Computational Mechanics*, doi:10.1007/s00466-019-01725-z.

Stainier L, Leygue A, Ortiz M (2019) Model-free data-driven methods in mechanics: material data identification and solvers. *Computational Mechanics*, doi:10.1007/s00466-019-01731-1.

INVITED LECTURERS

Manuel Doblare - University of Zaragoza, Spain
5 lectures on: handling data with random properties in data-driven applications; using physical knowledge to improve data handling with example to data filling in missing data problems; introducing the concept of physically-informed machine learning with examples in the prediction of input-output relations in problems defined by PDE systems and in extracting internal state knowledge.

Marc-André Keip - University of Stuttgart, Germany
5 lectures on: variational approaches to distance-minimizing data-driven computational mechanics with applications in elasticity; Artificial-Neural-Network (ANN) assisted computational homogenization of experimental microstructures based on image recognition; hands-on training session on implementing ANN algorithms in an open-source machine-learning code.

Michael Ortiz - California Institute of Technology, Pasadena, USA
6 lectures on: data-driven computational mechanics (DDCM) in linear and non-linear elasticity, general principle, distance minimization algorithms, extension to dynamics, noisy data and maximum-entropy data-driven solver; results from mathematical analysis of DDCM, convergence properties; extension to history-dependent behaviors, representational paradigms for material history, examples.

Julien Réthoré - CNRS, Centrale Nantes, France
6 lectures on: basics of digital image correlation (DIC) and its resolution; numerical algorithms for the optical flow problem; the uncertainty / resolution compromise and regularization techniques; Finite Element Model Updating (FEMU) methods; data-driven identification (DDI) approach, formulation and implementation; hands-on session in DIC and DDI with applications to linear and non-linear elasticity.

Carola-Bibiane Schönlieb - University of Cambridge, UK
6 lectures on: inverse imaging problems; variational regularization models and partial differential equations; sparsity-promoting regularisation and total variation; applications to tomography, image segmentation, motion estimation and image fusion; mathematical analysis and numerical algorithms; machine learning approaches such as learned iterative reconstruction and learned regularisers with deep neural networks.

Laurent Stainier - Centrale Nantes, France
6 lectures on: distance minimizing data-driven algorithms; integrated mechanical design approach combining DDI+DDCM; importance sampling issues; hands-on session (DDI based DDCM for nonlinear elasticity); algorithmic strategies and data representation for history-dependent Data-Driven simulations; examples and illustration of the methodology in elasto-plasticity.

LECTURES

All lectures will be given in English. Lecture notes can be downloaded from the CISM web site. Instructions will be sent to accepted participants.