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# Les Houches 2022 Special Issue: Editorial

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EDITORIAL

ÉCOLE DE PHYSIQUE DES HOUCHES

# Les Houches 2022 Special Issue: Editorial

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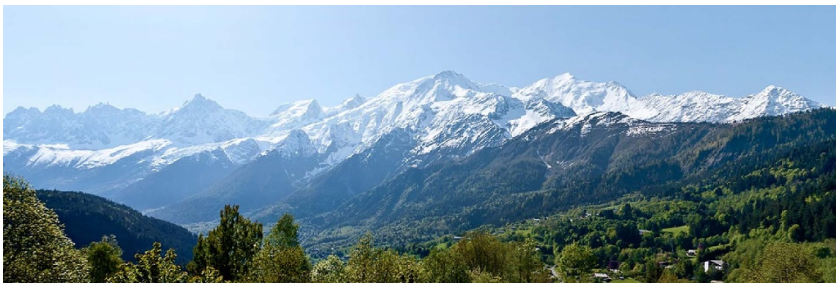
This special issue brings together a collection of chapters based on notes from lectures given at the 'Summer School on Statistical Physics of Machine Learning' held at the Les Houches School of Physics in July 2022. The school was organized by Florent Krzakala and Lenka Zdeborová from Ecole Polytechnique Fédérale de Lausanne, and was aimed at the growing audience of theoretical physicists, applied mathematicians and computer scientists interested in machine learning, neural networks, and high-dimensional statistics.



## 1. A word from the organizers

Organizing a summer school in Les Houches is a special moment, given the history and legacy of this very special place. The connection between statistical physics and computer science has been explored many times in Les Houches, notably in a summer school in 2006 —organized by Jean-Philippe Bouchaud and Marc Mézard—and in a shorter autumn school—organized by us, together with Federico Ricci-Tersenghi—in 2013. As both of us were present on these two occasions, it has been a blessing to witness the impact of these schools in the landscape of research over the last decade. After the deep learning revolution in the mid-2010 s, it was time to organize another school at the intersection of statistical physics and machine learning.

Initially, this school was planned for 2020, but the COVID-19 pandemic decided otherwise. As the world went into confinement, the school was first cancelled, but we were finally lucky enough to organize a shorter, reduced event in the summer of 2020. As per rules related to the pandemic at that precise moment, only participants with permanent residence in the European area were allowed, and rather strict distanciation measures were in place. E.g. only every other seat was occupied, and masks were strictly enforced inside the buildings. This was a very intense moment to organize a conference as the pandemic-related restrictions changed every week. For most of those who came in the summer of 2020, this was the first time after many months of physical isolation from colleagues and in-person discussions. Many things, including the list of lecturers, were improvised, and the event ended up a great success, free of COVID-19-related incidents.

We were given the opportunity to organize the originally planned school in July 2022 with essentially the same list of invited lecturers as planned for 2020. This time, we were able to proceed with the school and gather the current and future leaders in the field for four full weeks in the charming isolation of the Les Houches School of Physics.

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Even in summer 2022, the COVID-19 pandemic was not fully gone, and all lecturers and participants needed to self-test for COVID-19 every week. After a couple of positive cases during the first and the second week of the school, eight members tested positive in the 3rd week, and the library was set up for their isolation and streaming of the lectures from the lecture hall. Despite these minor perturbances, the scientific program ran as planned, and the frontier of the intersection of statistical physics and machine learning was presented.

The scientific field at the intersection between machine learning and statistical physics is not new. In fact, these communities were always very interconnected and indeed, many concepts and algorithms of machine learning have roots in physics. The very words 'Boltzmann machine', 'Free energy', and 'Gibbs sampling' speak for themselves. Perhaps starting with the pioneering work of John Hopfield in 1982 on memory retrieval, many scientific papers were published at the intersections of the two fields, as testified by the pioneers of modern machine learning. Turing prize winner Yann LeCun says in his book 'Quand la Machine Apprend': '*Ma vie professionnelle bascule réellement en 1985 lors d'un symposium aux Houches*'. In his lecture on neural nets, his colleague Geoffrey Hinton recalls how active and influential physicists were in the early days of neural networks and mentions in particular the amazing contribution of '*one really smart physicist, Elizabeth Gardner*', a name very familiar to those versed in spin glass theory. Isabelle Guyon recalls in 'the story of the invention of support vector machines' how two physicists working on the same topics inspired her creation: '*Marc Mezard and Werner Krauth published a paper on an optimal margin algorithm called 'minover', which attracted my attention [...] it was not until I joined Bell Labs that I put things together*'. In the wake of the deep learning revolution, just after the pioneer of statistical physics of complex systems Giorgio Parisi was awarded the Nobel Prize for the development of the replica method (and its use in machine learning, as mentioned by the Nobel committee), it was time to revive this connection once again in Les Houches. At the time of writing this introduction in spring 2024, the Abel Prize was awarded to Michel Talagrand, in part for his mathematical contribution to establishing results stemming from the replica method. It is thus an ideal moment to publish these lecture notes that, we hope, will foster new developments and the ideas of tomorrow.

## 2. The lectures

This special issue collects notes from the lectures given at the summer school. Most of them were written by volunteer participants and revised by the lecturer. Video recordings of the lectures are available on YouTube on the channel LesHouches2022 (individual links are below). We hope that students and researchers from physics, computer science, information theory, machine learning, and mathematics will find these notes instructive and thought-provoking. The collection does not reflect the ordering of the lectures during the 4 weeks of the school that was largely selected to build the methodology with minimal background required and evolve into more advanced topics. We thus list here the lectures in the order in which they were delivered at the school.

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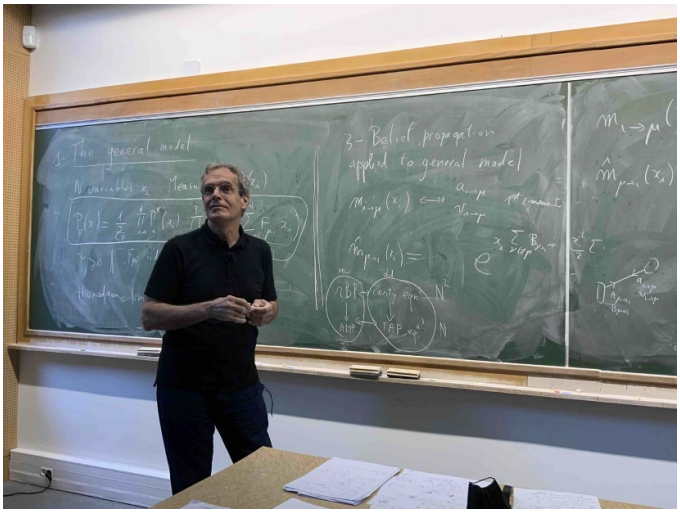
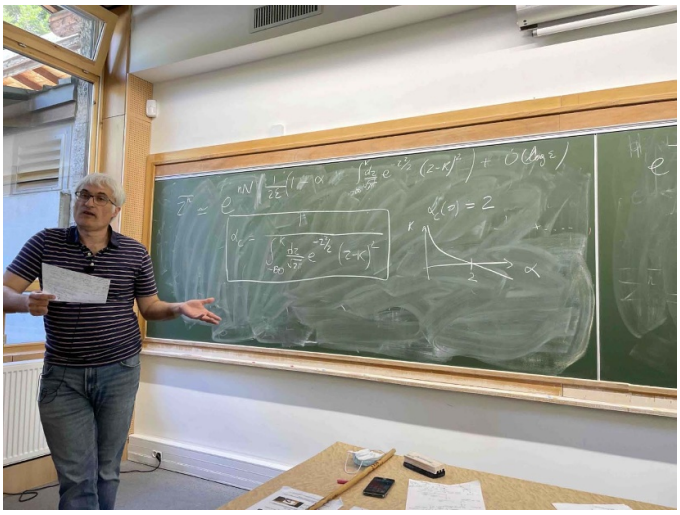
- Marc Mézard's (Bocconi Italy) lecture started the summer school with an introduction to a variety of techniques from statistical physics of disordered systems in a lecture titled '*Belief propagation, Message-Passing and Sparse models*'.



- Remi Monasson (ENS Paris) continued [videos] and had the monumental task of discussing and explaining the replica method. His lecture '*Replica method for computational problems with randomness: principles and illustrations*'.



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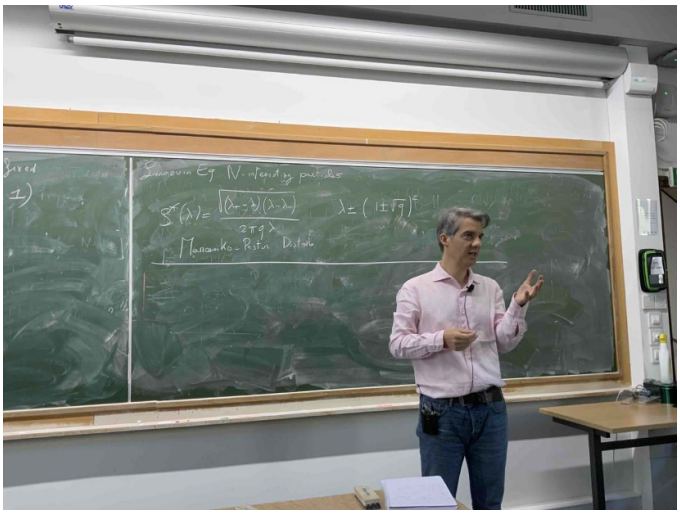
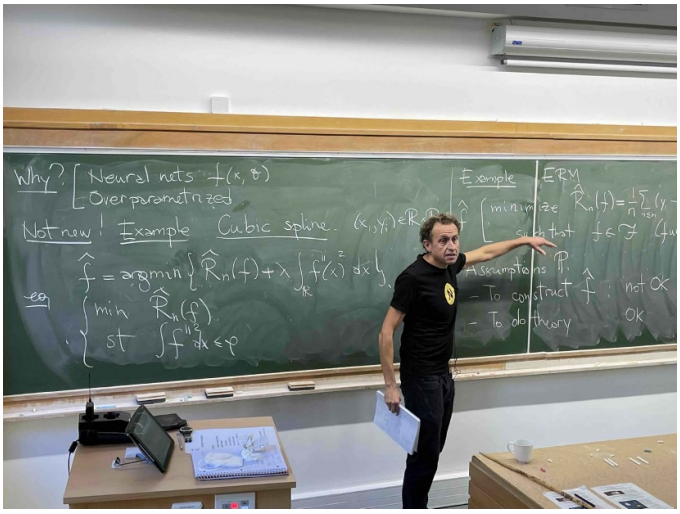
- Nathan Srebro (TTI Chicago) [videos] introduced the fundamental concepts of the theory of deep learning from the computer science side '*Applying statistical learning theory to deep learning*'.

- Giulio Biroli (ENS Paris) [videos] reviewed many concepts from spin glasses about their landscape and the behaviour of dynamics in the landscape in his lecture '*High-Dimensional Non-Convex Landscapes and Gradient Descent Dynamics*'.



- Sara Solla (Northwestern Univ.) [videos], while she could not attend the workshop in presence, gave a lecture on Zoom introducing '*Statistical Physics, Bayesian Inference and Neural Information Processing*'.

- Andrea Montanari (Stanford) [videos] gave a series of lectures summarizing a large part of the progress obtained in the last few years in '*Neural networks from a nonparametric viewpoint*' including results about generalization properties of kernel methods, random features and neural tangent kernel.

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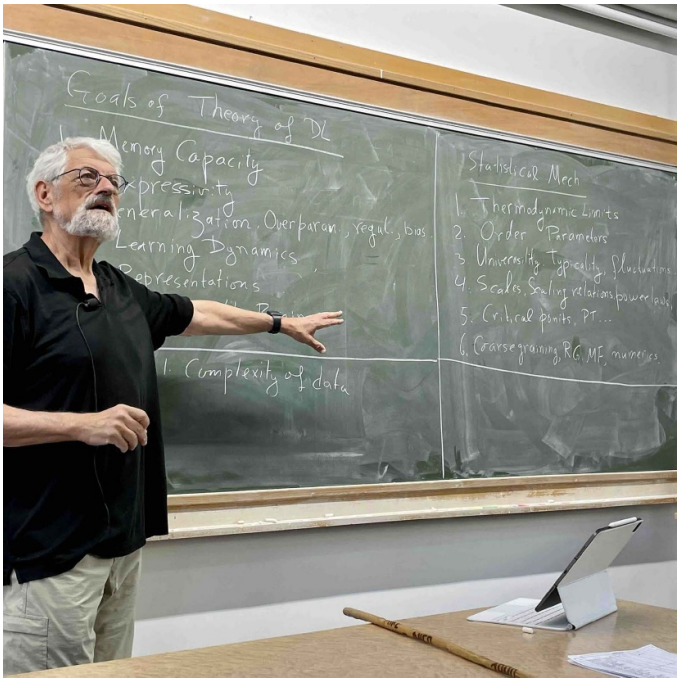
- Haim Sompolinsky (Harvard and Hebrew Univ) [videos] gave a lecture on '*Statistical Mechanics of Machine Learning*' focusing partly on Bayesian learning in deep networks and constructing a hierarchy of kernels to describe it.




- Boaz Barak (Harvard) [videos] discussed key concepts from computation complexity for problems arising in tensor estimation up to deep learning in a lecture called '*Computational Complexity of Deep learning: Fundamental limitations and Empirical phenomena*'.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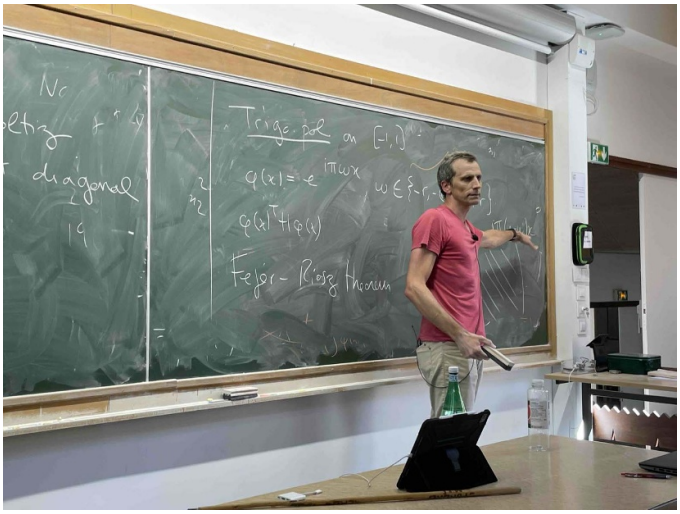
- Michael I. Jordan (Berkeley) [videos] gave a set of forward-looking lectures '*On decisions, dynamics, incentives, and mechanism design*' connecting machine learning and optimization to decision making.


- Francis Bach (Inria, ENS) [videos] gave a lecture about sum-of-squares in a set of courses titled '*Sums-of-squares: from polynomials to kernels*'.

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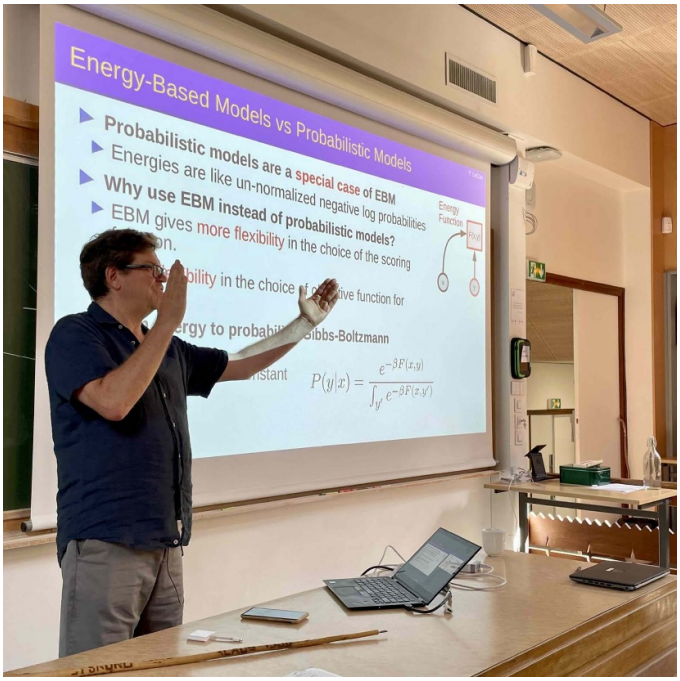
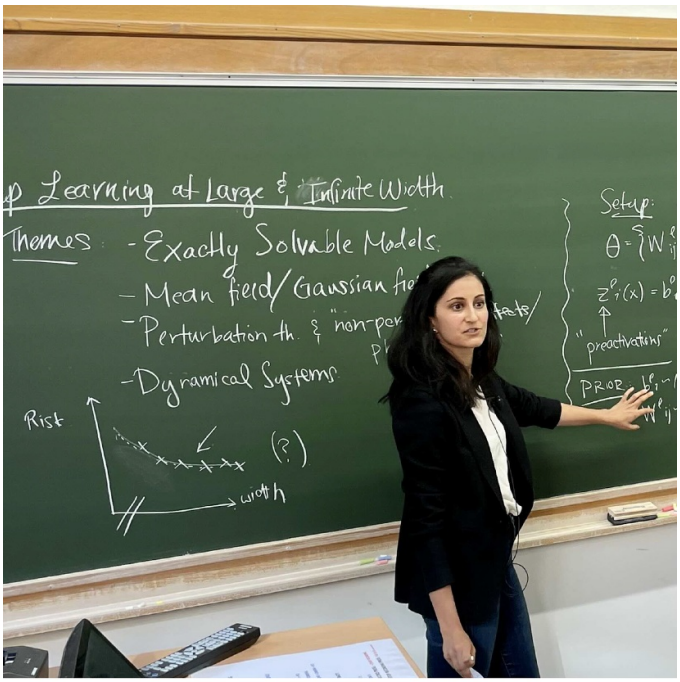
- Yann LeCun (Facebook & NYU) [videos] talked about the future and perspectives of deep learning in his lectures '*From machine learning to autonomous intelligence*'.




- Yasaman Bahri (Google) and Boris Hanin (Princeton) [videos] described the behaviour of infinite-width neural networks, as well as their corrections and extensions, in a lecture called '*Deep Learning at Large and Infinite Width*'.

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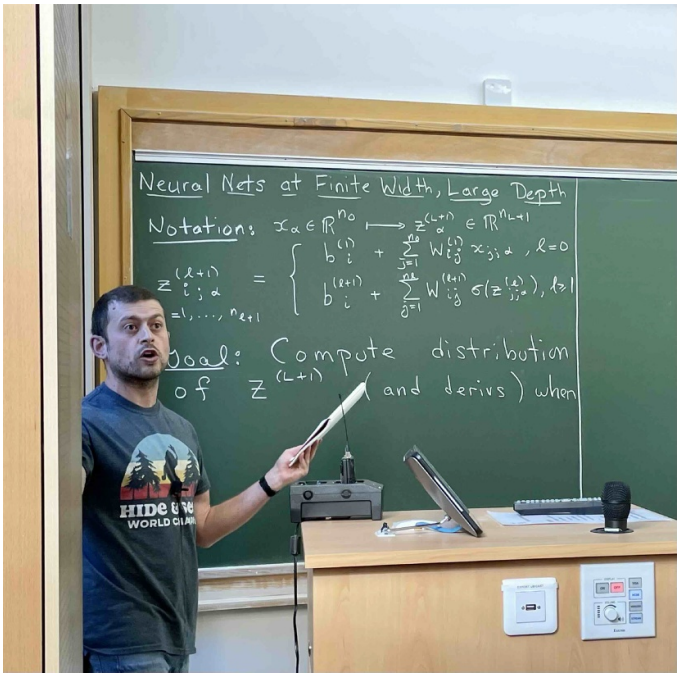
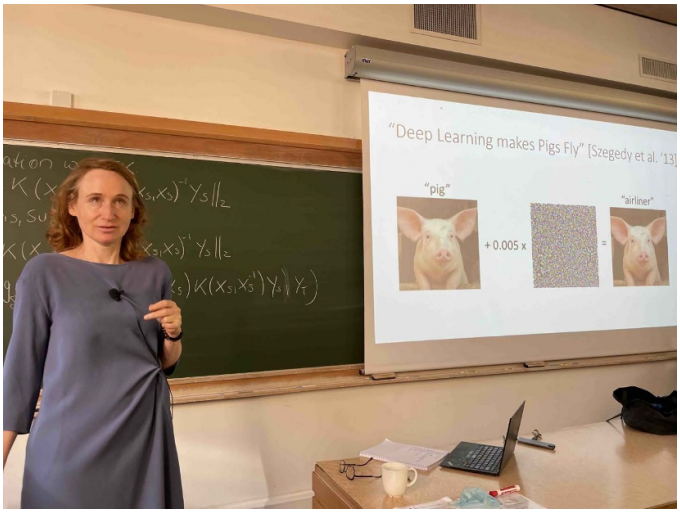



- Julia Kempe (NYU) [videos] gave us a series of lectures on '*Data, Physics and Kernels and how can (statistical) physics tools help the DL practitioner*' spanning several currently active topics such as adversarial training.

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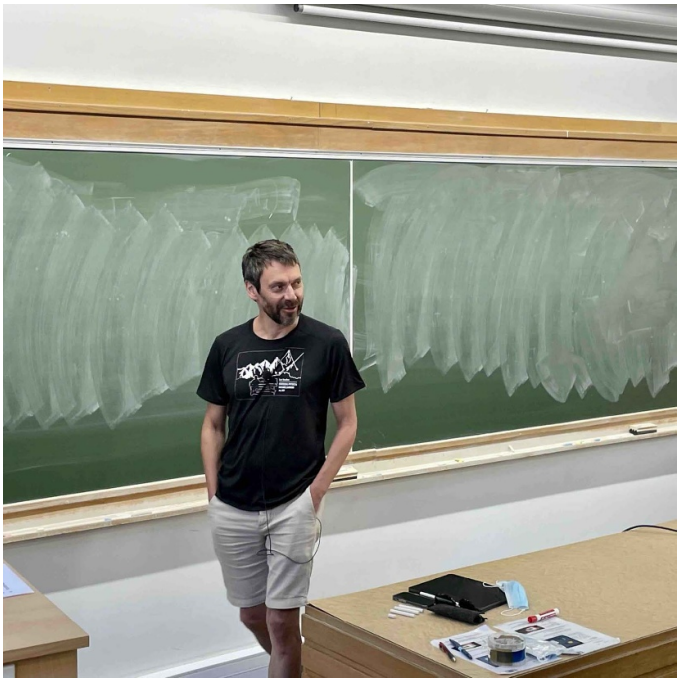
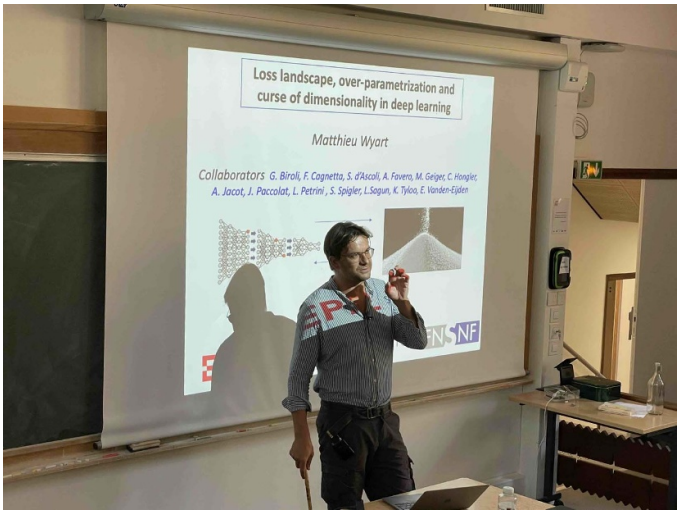
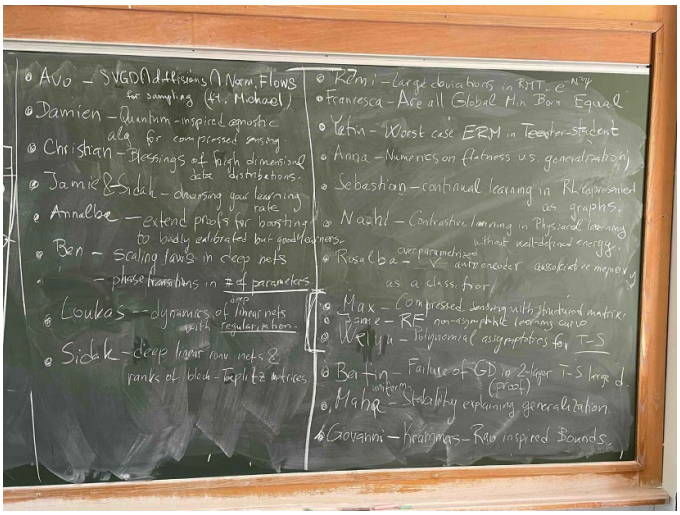
- Eric Vanden-Eijnden (NYU Courant) [videos] taught us about various types of flow-based generative models in a unifying way in a lecture titled '*Benefits of overparametrization in statistical learning, and Enhancing MCMC Sampling with Learning*'.



Matthieu Wyart (EPFL) [videos] presented a seminar titled '*Loss landscape, over-parametrization and curse of dimensionality in deep learning*' that was not collected for the lecture notes.



## 3. Open problems and examples of works the school inspired




Apart from lectures and productive poster sessions, groups of participants worked on open problems presented at the beginning of the school. In the figure above is the blackboard listing the suggested problems. Several of them lead to articles, some of which we list here:

- The open problem on Gaussian equivalence property under spiked data that Bruno Loureiro suggested resulted in the work [1].
- Article [2] originated from an open problem Anna Dawid suggested.
- Article [3] originated from an open problem Francesca Mignacco suggested.

We also give here a list of some of the articles that, in the author's words, started at the school or were directly inspired by the lectures or discussions there.

- Michael Albergo with Eric Vanden-Eijnden started their work on stochastic interpolants [4] at the summer school and already gathered rather considerable attention in the community.
- This paper of Alexander Zlokapa and Boris Hanin originated at the summer school [5].
- The conditional Gaussian equivalence theorem (GET) presented in [6] was motivated by the open problem proposed by Bruno Loureiro about conditions under which the GET breaks.
- Some ideas from [7] by Berfin Simsek originated during discussions at the summer school.

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- Article [8] by Gabriele Arpino was greatly enhanced by a discussion the author had with Cédric Gerbelot who pointed to his article on graph-based AMP.
- Two papers by Wu [9, 10] were inspired by the open problem on Gaussian equivalence property under spiked data that Bruno Loureiro suggested.
- The lecture by Haim Sompolinsky inspired the work on article [11].
- The lecture by Eric Vanden-Eijnden inspired work on denoising autoencoders [12, 13].
- Jamie Simon wrote [14] following up on discussions at the school.

## 4. Participants

The following participants were selected from a list of over 300 applicants. The affiliations reflect their institution as of July 2022.

ADOMAITYTE Urte, King's College London UK
ALBERGO Michael, New York University New York USA
ARPINO Gabriel, University of Cambridge UK
BARBIER Damien, EPFL Lausanne Switzerland
BEHRENS Freya, EPFL Lausanne Switzerland
BONNAIRE Tony, ENS Paris France
BRAUN Lukas, University of Oxford UK
BROSSOLLET Antonin, ENS Paris France
CARRELL Annabelle, University of Cambridge UK
CLARTE Lucas, EPFL Lausanne Switzerland
CORNACCHIA Elisabetta, EPFL Lausanne Switzerland
DANDI Yatin, EPFL Lausanne Switzerland
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FAVERO Alessandro, EPFL Lausanne Switzerland
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GHIO Davide, EPFL Lausanne Switzerland
GÖKMEN Doruk Efe, ETH Zurich Switzerland
GRANT Erin, UC Berkeley Berkeley USA
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KARP Stefani, Carnegie Mellon University Pittsburgh USA
KEUP Christian, Wilhelm-Johnen-Jülich Jülich Germany
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LI Yufan, Harvard University Cambridge USA
LOUREIRO Bruno, EPFL Lausanne Switzerland

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MERGNY Pierre, LPTMS Saclay France
MIGNACCO Francesca, IPHT Paris France
MISIAKIEWICZ Theodor, Stanford University, USA
NESTLER Sandra, Jülich Research Centre Jülich Germany
OLIVEIRA SAMPAIO Deborah, IMPA Rio Brazil
PACELLI Rosalba, Bocconi Milano Italy
PESCE Luca, EPFL Lausanne Switzerland
PICCIOLI Giovanni, EPFL Lausanne Switzerland
RAVICHANDRAN Kavya, Toyota Technical Institute Chicago USA
SABANAYAGAM Mahalakshmi, Technical University Munich Germany
SIMON James, UC Berkeley USA
SIMSEK Berfin, EPFL Lausanne Switzerland
SINGH Sidak Pal, MPI for Intelligent systems Tübingen Germany
SORSCHER Ben, Stanford University USA
STEINBERG Julia, CUNY Princeton USA
STEPHAN Ludovic, EPFL Lausanne Switzerland
STERN Menachem, University of Pennsylvania Philadelphia USA
TOMASINI Umberto, EPFL Lausanne Switzerland
TROIANI Emanuele, EPFL Lausanne Switzerland
TSILIVIS Nikolaos, New York University USA
WADIA Neha, University of California Berkeley USA
WAN Yijun, ENS Paris France
WU Denny, University of Toronto Canada
YANAMURA Atsushi, Stanford University USA
ZLOKAPA Alexander, MIT Cambridge USA

## Acknowledgment

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[9] Ba J, Erdogdu M A, Suzuki T, Wang Z and Wu D 2024 Learning in the presence of low-dimensional structure: a spiked random matrix perspective *Advances in Neural Information Processing Systems* vol 36

[10] Wang Z, Denny W and Fan Z 2024 Nonlinear spiked covariance matrices and signal propagation in deep neural networks (arXiv:2402.10127)

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[13] Cui H, Krzakala F, Vanden-Eijnden E and Zdeborová L 2024 Analysis of learning a flow-based generative model from limited sample complexity *ICLR* (https://doi.org/10.48550/arXiv.2310.03575)

[14] Simon J B 2022 On kernel regression with data-dependent kernels (arXiv:2209.01691)


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