AM 254/ES 254: Information Processing and Statistical Physics

Fall 2016

HARVARD
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School of Engineering
and Applied Sciences

Instructor:	Prof. Yue M. Lu Maxwell Dworkin 231, Phone: 617-496-8615 e-mail: yuelu@seas.harvard.edu, web: http://lu.seas.harvard.edu
Meeting time:	Monday and Wednesday 10:00 am – 11:30 pm, Room: MD 223
Office hours:	Tuesdays 4:00 pm – 6:45 pm, Room: Maxwell Dworkin 231. Additional office hours may be scheduled by emails.
Teaching fellow:	Hong Hu Maxwell Dworkin 113 e-mail: honghu@g.harvard.edu Office hours: TBA
Exercise sections:	TBA
Grading:	Homework: 35% 48-hour take-home midterm: 25% Final project (presentation + report): 40%

1. Motivations and Course Overview:

Modern information processing systems deal with massive amounts of data in the presence of large statistical uncertainty. The performance and behaviors of such systems often exhibit phase transitions (e.g., threshold SNR, cutoff rates, etc.), due to the interactions of a large number of random variables with complex correlation structures. Methods developed in statistical physics have been tremendously successful in understanding the macroscopic properties of many-body interactive systems. They have also been gradually recognized as an indispensable tool in the study of information processing systems and algorithms.

The goal of this course is to introduce students to several fundamental notions and methods in statistical physics that have been successfully applied to the analysis of information processing systems. Discussions will be focused on studying such systems in the infinite-size limit, on analyzing the emergence of phase transitions, and on understanding the behaviors of efficient algorithms. This course seeks to start from basics, assuming just undergraduate probability and analysis, and in particular assuming no knowledge of statistical physics. It is essentially self-contained, developing the necessary concepts, tools, algorithms, and rigorous theory step-by-step, in as much detail as possible. Students will take an active role by exploring and applying what they learn from the course to their preferred applications, including but not limited to signal processing, communications, machine learning, imaging, control, power networks, and biological data analysis.

2. Prerequisites:

Probability theory, analysis, linear algebra, and mathematical maturity. No prior knowledge of statistical physics or information theory is assumed. Knowledge of MATLAB will be useful.

3. Textbooks:

We will not follow a particular book, but there are a number of useful references:

- Hidetoshi Nishimori, *Statistical Physics of Spin Glasses and Information Processing*, Oxford University Press, 2001.
- Marc Mezard and Andrea Montanari, *Information, Physics, and Computation*, Oxford University Press, 2009.
- Neri Merhav, *Statistical Physics and Information Theory*, Foundations and Trends in Communications and Information Theory, 2010.
- Manfred Opper and David Saad, *Advanced Mean Field Methods: Theory and Practice,* MIT Press, 2001.

We will also draw on recent research articles that are relevant to specific parts of the course. Lecture notes will be provided after every lecture.

4. Homework:

There are six problem sets, assigned every other week. Covering different aspects of the course material, the problem sets contain both paper-and-pencil problems and computer simulations.

5. Midterm exam:

There will be one 48-hour take-home midterm exam. It is open-book, but no collaboration is allowed in completing the exam.

6. Final project:

Students will complete a project that illustrates the concepts and methods developed in the course. The applications can be drawn from the students' own areas of research, including but not limited to signal processing, communications, machine learning, imaging, control, power networks, and biological data analysis. The project will be graded on the quality of your written report (8 pages) and your in-class presentation.

7. Collaboration policy:

Students are encouraged to collaborate and discuss homework assignments among themselves and with the TF and the instructor. However, after discussions with peers/teaching staffs, make sure that you can work through the problem yourself and ensure that any answers you submit for evaluation are the result of your own efforts. In addition, you must cite any books, articles, websites, lectures, etc. that have helped you with your work using appropriate citation practices. Similarly, you must list the names of students with whom you have collaborated on problem sets.

8. Accommodations:

Students who need academic adjustments or accommodations because of a documented disability should speak with the instructor by the end of the second week of the term (Friday, September 9).

8. List of Topics:

The following are some of the topics to be covered in this course:

1. Background and motivating applications
2. Probabilistic concepts:
    a. Entropy and typical sequences
    b. The Boltzmann distribution
    c. Gibbs free energy and the variational principle
    d. Large deviations techniques
    e. Graphical models
    f. Monte Carlo methods (MCMC algorithms)
3. Notions of statistical physics and exactly solvable models
    a. Free energy
    b. 1D Ising model, the transfer matrix method (hidden Markov chains)
    c. Curie-Weiss model, phase transitions (mean field approximation)
    d. The random energy model (Shannon's random code ensemble)
    e. The Sherrington-Kirkpatrick model (Random combinatorial optimization)
4. Analysis tools
    a. The replica trick
    b. Recent rigorous results (Hamiltonian interpolation)
    c. The cavity method
5. Algorithms
    a. Factor graphs and belief propagation
    b. Approximate message passing
    c. State evolution
    d. Stochastic approximations
    e. Propagation of chaos

The discussions of the theory/tools will be interleaved with their applications in analyzing information processing systems. Example applications include compressed sensing, biological sequence analysis, anomaly detection, network analysis, and online learning algorithms using neural networks.

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OUTLINE AND PLAN FOR FALL SEMESTER 2016

Date	Topic	Note	Homework	
			Assigned	**Due**
Wednesday, Aug. 31	Introduction and probability review			
Monday, Sep. 5	No lecture	Labor Day		
Wednesday, Sep. 7	Basic notations of statistical physics		HW 1	
Monday, Sep. 12	No lecture	Yue's out of town. We will schedule two make-up lectures.		
Wednesday, Sep. 14				
Monday, Sep. 19	Curie-Weiss Model			
Wednesday, Sep. 21	The Random Energy Model, I		HW 2	HW 1
Monday, Sep. 26	No lecture	Yue's out of town. We will schedule a make-up lecture.		
Wednesday, Sep. 28	The Random Energy Model, II			
Monday, Oct. 3	Replica Method, I			
Wednesday, Oct. 5	Replica Method II		HW 3	HW 2
Monday, Oct. 10	No lecture	Columbus Day		
Wednesday, Oct. 12	Phase transitions in compressed sensing			
Monday, Oct. 17	Phase transitions in neural networks			
Wednesday, Oct. 19	Belief propagation, I	**Midterm Exam**	HW 4	HW 3
Monday, Oct. 24	Belief propagation, II			
Wednesday, Oct. 26	BP, TAP, SK model, I			
Monday, Oct. 31	BP, TAP, SK model, II	**Deadline to turn in a one-page project proposal**		
Wednesday, Nov. 2	Compressed Sensing, AMP		HW 5	HW 4
Monday, Nov. 7	No lecture	Yue's out of town. We will schedule a make-up lecture.		
Wednesday, Nov. 9	Compressed Sensing, AMP			
Monday, Nov. 14	Online learning			
Wednesday, Nov. 16	Propagation of chaos, I		HW 6	HW 5
Monday, Nov. 21	Propagation of chaos, II			
Wednesday, Nov. 23	No lecture	Thanksgiving recess		
Monday, Nov. 28	Project Presentation			
Wednesday, Nov. 30	Project presentation			HW 6