Western Academy for Advanced Research
Department of Mathematics
Western University

Western-Fields School in Networks and Neuroscience

September 2022

Instructors: Lyle Muller, Ján Mináč, and Marieke Mur **Dates:** 19-23 September

Course description: Similar in scope to the 2021 Western-Fields Seminar Series in Networks and Neuroscience, this one-week intensive school brings together advanced students for a week of training in networks, nonlinear dynamics, machine learning, and theoretical neuroscience. Lectures will cover graph theory, nonlinear dynamics, machine learning, and advanced algebraic techniques.

Requirements: The course will have lectures in the morning and focused project sessions in the afternoons. We will ask that students prepare some readings before the course, and others during the course week. We will also ask that students prepare their mini-projects prior to the course week, so that they can utilize the time available to progress on their project. For the mini-project, students can use any tools and techniques with which they are familiar, and the instructors will provide support according to their expertise. Communication will occur via the course Slack workspace.

Course outline:

The course will consist of readings, lectures, and student mini-projects. The instructors will ensure that students have access to readings in the Slack workspace. Supplementary readings and materials are optional. All the resources should help you if you need further input or want to expand your knowledge.

Weeks -3 to -1: Preparation

Before the course week, we would like you to begin the required and optional readings. Because the course will move quickly, it will be **ideal** *for you to have the required readings complete before starting, as this will allow you to utilize the course instructors' and TAs' experience effectively in understanding the material more deeply.*

This course will assume a strong foundation in undergraduate applied mathematics (calculus, linear algebra, and differential equations) and will teach advanced methods as needed. If you have any questions about the preparation, please contact the course instructors via the Slack channel to discuss further.

In addition, we would also like you to develop an idea for a **mini-project** *before the course. Please feel free to discuss with instructors and TAs on Slack as you begin to develop these possibilities. On the afternoon of Day 1, we will discuss mini-projects and steps for getting started.*

Day 1: Introduction to the School and Neural Networks (Muller, Mur)

In the morning, we will provide an introduction to theoretical neuroscience and neural networks. We will introduce the tools and techniques used to study neural systems and artificial neural networks. We will introduce an outline of the course and provide an overview of the key topics everyone will learn during the week. In the afternoon, we will begin working on projects with guided discussions.

Required readings

- ☐ Abbott, Larry F (2008). "Theoretical neuroscience rising". *Neuron* 60(3): 489–495
- ☐ Dayan, Peter and Abbott, Laurence F (2005). *Theoretical neuroscience: computational and mathematical modeling of neural systems.* MIT press (Sections 5.1-5.4)
- ☐ Kriegeskorte, Nikolaus and Douglas, Pamela K (2018). "Cognitive computational neuroscience". *Nature Neuroscience* 21: 1148–1160

Optional readings

- ∗ Turner, Nicholas L et al. (2022). "Reconstruction of neocortex: Organelles, compartments, cells, circuits, and activity". *Cell* 185(6): 1082–1100
- ∗ Goodfellow, Ian, Bengio, Yoshua, and Courville, Aaron (2016). *Deep Learning*. `http://www.deeplearningbook.org`. MIT Press, Chapter 6, 8, 9
- ∗ Kriegeskorte, Nikolaus and Golan, Tal (2019). "Neural network models and deep learning". *Current Biology* 29(7): R231–R236,

Additional input

- ☐ Andrew Ng's Deep Learning Specialization
- ☐ 3Blue1Brown Neural Networks Series

! Discussion of mini-projects

Day 2: Nonlinear Dynamics and Networks (Budzinski):

Recent advances in nonlinear dynamics and graph theory make the modeling and study of complex systems possible. Here, we will review some of the principal findings of nonlinear dynamics, synchronization, and complex networks and their applications on problems spanning from physics to computational neuroscience.

Required readings

- ☐ Strogatz, Steven H (2001). "Exploring complex networks". *Nature* 410(6825): 268–276
- ☐ Arenas, Alex et al. (2008). "Synchronization in complex networks". *Physics reports* 469(3): 93–153

Optional readings

- ∗ Rodrigues, Francisco A et al. (2016). "The Kuramoto model in complex networks". *Physics Reports* 610: 1–98
- ∗ Boccaletti, Stefano et al. (2002). "The synchronization of chaotic systems". *Physics reports* 366(1-2): 1–101
- ∗ Lynn, Christopher W and Bassett, Danielle S (2019). "The physics of brain network structure, function and control". *Nature Reviews Physics* 1(5): 318–332

Day 3: Recurrent Neural Networks (Benigno):

Recurrent neural networks are the most general and complex type of neural network in which the neurons interconnect to give web-like connectivity. As a result, these networks exhibit rich dynamics and are capable of sophisticated computations such as memory storage/retrieval and time series forecasting. Here, we will build the mathematical description *of recurrent neural networks from first principles, we will discuss training methods and current challenges, and we will highlight some applications in neuroscience and machine learning.*

Required readings

- ☐ Dayan, Peter and Abbott, Laurence F (2005). *Theoretical neuroscience: computational and mathematical modeling of neural systems.* MIT press (Sections 7.2, 7.4, 8.1, 8.2)
- ☐ Jaeger, Herbert and Haas, Harald (2004). "Harnessing nonlinearity: Predicting chaotic systems and saving energy in wireless communication". *Science* 304(5667): 78–80

Supplementary materials

- ☐ COSYNE 2021 - Tutorial on RNN (Part 1) by Kanaka Rajan
- ☐ COSYNE 2021 - Tutorial on RNN (Part 2) by Kanaka Rajan
- ☐ Linear Systems [Control Bootcamp]

Day 4: Graph Theory and Advanced Algebra (Mináč, Pasini, Nguyen)

We shall review Galois theory, finite fields, linear groups over finite groups, introduction to modern number theory, introduction to graph theory and especially graph spectra and Ramanujan graphs and recent work on joint of circular matrices, spectrum of joins of normal matrices and applications and joins of group rings.

Required readings

- ☐ Artin, Emil and Milgram, Arthur Norton (1998). *Galois theory*. Vol. 2. Dover
- ☐ Shapiro, Helene (2015). *Linear algebra and matrices.* AMS, Providence, Rhode Island (Chapters 3, 4, 11, 15, and 17)
- ☐ Cioabă, Sebastian M (2009). *A first course in graph theory and combinatorics.* Vol. 55. Springer (Chapters 1, 2, and 12)

Optional readings

- ∗ Đoàn, Jacqueline et al. (2022). "Joins of circulant matrices". *Linear Algebra and its Applications*
- ∗ Artin, Emil (2016). *Geometric algebra*. Courier Dover Publications (especially Chapter 4)
- ∗ Stewart, Ian (1990). *Galois theory*. Chapman and Hall/CRC (Chapters 1, 5, 8, 9, 19, 21, and 22; also the expositions in the Introduction and Chapter 25)

∗ Ireland, Kenneth, Rosen, Michael Ira, and Rosen, Michael (1990). *A classical introduction to modern number theory*. Vol. 84. Springer Science & Business Media (Chapters 1, 5, 12 and 13; Chapter 20 contains a nice survey from more recent progress in number theory)

Day 5: Fields Institute Session

On the last day, we will have a session at the Fields Institute (Toronto). The morning will consist of selected presentations of student mini-projects, and the afternoon will consist of keynote lectures (TBA).

! Presentation of selected mini-projects