Course Syllabus

Skoltech

Course Title Neuromorphic Computing

Course Title (in Russian) Нейроморфные Вычисления

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Co-Instructor

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1. Annotation

Course Description

Over the past decades the concept of neuromorphic computing that relies on imitating and exploiting the mechanisms inherent to biological nervous system has evolved into an interdisciplinary research area at the boundary between advanced computing and computational neuroscience. This direction is largely considered as one of the most promising approach to resolve the critical problems that come with continual miniaturization and ever-increasing power consumption of CMOS technology. A vast number of brain-inspired algorithms and architectures, endowing low-power requirements and massive parallel computing principles, have been attempted for applications, including complex pattern recognition, image processing, and data mining. In parallel, intensive research has been conducted for practical implementation of learning-based artificial synapses and neurons that represent two fundamental building blocks of biological neural networks.

The course is designed to provide the students with basic understanding and familiarize them with recent achievements in the field of neuromorphic engineering as implemented in artificial and spiking neural networks. In the course we will address:

(i) Mathematical modeling of neurons with synapses and cognitive processes;

(ii) Artificial neural networks and spiking neural networks;

(iii) Temporal encoding and learning in spiking neural networks;

(iv) Overview of available hardware architectures for neuromorphic computing;

(v) Memristor-based neuromorphic computing.

Course Description (in Russian)

Область нейроморфных вычислений, основанная на имитации и последующем использовании основных принципов функционирования нервной системы, за последние десятилетия превратилась в междисциплинарное направление исследований на границе между современными численными методами и вычислительной нейробиологией. Практическая реализация нейроморфных вычислений рассматривается в качестве одного из наиболее перспективных подходов, позволяющих избежать сопутствующих стандартной КМОП-технологии проблем, обусловленных требованиями дальнейшей миниатюризации и постоянно растущим энергопотреблением. В частности, алгоритмы и вычислительные архитектуры, работающие по принципу человеческого мозга и, как следствие, обеспечивающие низкое энергопотребление, были успешно применены к решению практических задач, включая распознавание сложных образов, обработку изображений и интеллектуальный анализ данных. Одновременно с этим продолжаются интенсивные исследования, нацеленные на практическую реализацию искусственных синапсов и нейронов, которые представляют собой два фундаментальных элемента биологических нейронных сетей.

Данный курс разработан таким образом, чтобы дать студентам базовое понимание и ознакомить их с последними достижениями в области нейроморфной инженерии, реализованными в искусственных и импульсных нейронных сетях. В рамках курса особое внимание планируется уделить:

(i) математическим моделям нейрона, синапса и процессов обучения;

(ii) искусственным и импульсным нейронным сетям;

(iii) обучению в импульсных нейронных сетях с использованием времени поступления импульса;

(iv) обзору существующих аппаратных решений для реализации нейроморфных вычислений;

(v) имплементации нейроморфных вычислений с использованием мемристоров.

2. Basic Information

Course Academic Level

MSc PhD

Number of ECTS credits

3

Course Prerequisites / Recommendations

Programming (Python), numerical methods (basics), machine learning (basics).

Type of Assessment

Graded

Mapping from grades to percentage:

A:	80
B:	70
C:	60
D:	50
E:	40
F:	0

Term

Term 4

Students of Which Programs do You Recommend to Consider this Course as an Elective?

BSc Programs	Masters Programs	PhD Programs
	Advanced Computational Science Data Science Life Sciences	Computational and Data Science and Engineering Engineering Systems Life Sciences

Maximum Number of Students

	Maximum Number of Students
Overall:	30
Per Group (for seminars and labs):	6

Course Stream

Science, Technology and Engineering (STE)

3. Course Content

Lecture, lab and seminar hour distribution among topics

Topic	Summary of Topic	Lectures (# of hours)	Seminars (# of hours)	Labs (# of hours)
Introduction to bio-inspired AI and neural networks	Mathematical models of a neuron with synapses and cognitive learning. Advantageous and limitations of using neuromorphic computing for real-life applications. Neuromorphic computing for edge intelligence devices.	2	4	
Artificial and spiking neural networks	Three generations of neural networks: single- and multilayer perceptron, deep learning, and spiking neural networks. Training and learning algorithms for spiking neural networks. CNN-to-SNN conversion. Temporal encoding in spiking neural networks. Physical implementation.	2	4	

Topic	Summary of Topic	Lectures (# of hours)	Seminars (# of hours)	Labs (# of hours)
A survey on cognitive computing hardware	Overview of available neuromorphic hardware, including those provided by Intel (Loihi, Pohoiki Springs), IBM (TrueNorth), and academic universities. Basic operation principles, comparison. Possible applications and available simulation tools for running spiking neural networks.	2	4	
Memristor-based neuromorphic computing	A brief survey on memristor technologies. Near- and in-memory computing with memristors. Edge AI processors with ReRAM and memristors.	2	4	

4. Learning Outcomes

Please choose framework for learning outcomes Knowledge-Skill-Experience

Knowledge
After completing the course the students are supposed to be familiar with (a) Mathematical models of neurons with synapses, cognitive processes; (b) Temporal encoding and learning algorithms for spiking neural networks; (c) Available hardware for implementing neuromorphic computing; (d) Neuromorphic computing for edge intelligent devices.

Skill
The students will learn state-of-the-art simulation tools for spiking neural networks.

Experience
Students will get experience on available neuromorphic hardware, its operation principles, advantages and limitations of energy-efficient neuromorphic computing for edge AI.

Learning outcomes of the course are specified in the steering document of the educational program in accordance with the Federal State Educational Standard on the website in Education section / Результаты освоения по учебному элементу в соответствие с ФГОС отражены в описании образовательной программы в разделе Образование

5. Assignments and Grading

Assignment Types

Assignment Type	Assignment Summary	% of Final Course Grade
Midterm Exam	Each group of students out of 2-3 groups will report on a given neuromorphic chip.	30
Team Project	Each group of students out of 2-3 groups will do a small project on memristor-based neuromorphic architecture.	40
Homework Assignments	The personal assignments on numerical simulation of neuromorphic computations. Three in total.	30

6. Assessment Criteria

Assignment 1 Type

Homework Assignments

Sample of Assignment 1

A student is supposed to develop a lerning algorithm for spiking neural network for solving classification task.

Assessment Criteria for Assignment 1

Homework assignment will be operated on a binary grading system pass/fail.

Assignment 2 Type

Team Project

Sample of Assignment 2

In the end of the course, the students will be devided in groups of two-three. Each group will be asked to choose a final project, possible options include but not limited to:

(i) Modeling of a memristor and its performance, as well as testing its analog properties and their response in crossbar arrays.

(ii) Performance of on-chip analog computing, matrix multiplications, and statistical performance of crossbar arrays of memristors using available simulators.

In the end of the course, a group of students will defend its project and provide a short report.

What is evaluated
A. Method

B. Technical quality of work
C. Quality of presentation

A. Method is evaluated by following 3 criteria

a) ability to reach the final goal
b) efficience
c) ease of implementation

B. technical quality evaluated using the following 4 criteria
a) results should be sufficient to actually resolve the problem
b) correctness
c) quality of the results and processing (statistical error evaluation, for example)
d) efficiency and neatness of the code

A - excellent presentation, the problem is well explained; theoretical framework is outlined; paper is well written (it can be very concise but clear); results are logical and generally correct; working and well-written codes; questions well answered; minor inaccuracies permitted
B - good presentation of the project highlighting a problem statement and a solution; some mistakes in the results or in answers to questions; working codes
C - presentation of the problem misses some significant points (either in the written report or oral presentation); presentation unclear; some of the results are illogical, incorrect, or the student cannot explain them; but at least critical questions are answered
D - major gaps in understanding, major inaccuracies in the report and presentation, failure to anwser important questions
E - outline of the project and results partly presented with week answering questions; 0 - no project / irrelevant project presented

Assignment 3 Type Midterm Exam

Sample of Assignment 3

Each group of students will report in class on a given neuromorphic chip.

Assessment Criteria for Assignment 3

The assignment will be graded as "pass" or "fail". Students will be given a passing grade if they demonstrate an understanding and can discuss the potential strengths and weaknesses of the report subject. Otherwise or in case of missed participation, a fail grade will be given.

7. Textbooks and Internet Resources

You can request at most two required textbooks. Additionaly, you can suggest up to nine recommended textbooks.

Required Textbooks	ISBN-13 (or ISBN-10)
Kasabov, N.K. Time-Space, Spiking Neural Networks and Brain-Inspired Artificial Intelligence. Springer, 2019.	9783662577134

Recommended Textbooks	ISBN-13 (or ISBN-10)
Nakajima, K, and Fischer, I. Reservoir Computing - Theory, Physical Implementations, and Applications. Springer, 2020.	9789811316869

Recommended Textbooks	ISBN-13 (or ISBN-10)
Pappachen James, A. (ed.) Deep Learning Classifiers with Memristive Networks. Springer, 2020.	9783030145224
Vourkas, I, and Sirakoulis, GC. Memristor-Based Nanoelectronic Computing Circuits and Architectures. Springer, 2016.	9783319226460

Papers	DOI or URL
Yeon, H., Lin, P., Choi, C., (...), Kim, S., and Kim, J. (2020). "Alloying conducting channels for reliable neuromorphic computing". Nature Nanotechnology	10.1038/s41565-020-0694-5
Qin, Y.-F., Bao, H., Wang, F., Chen, J., Li, Y., and Miao, X.-S. (2020). "Recent Progress on Memristive Convolutional Neural Networks for Edge Intelligence". Advanced Intelligent Systems	10.1002/aisy.202000114
Hung, J.-M., Li, X., Wu, J., and Chang, M.-F. (2020). "Challenges and Trends in Developing Nonvolatile Memory Enabled Computing Chips for Intelligent Edge Devices". IEEE Transactions on Electron Devices	10.1109/TED.2020.2976115

8. Facilities

Software
Python, SPICE

9. Additional Notes