Written Examination EITP25

June 2nd 2022

Useful constants:

$$\hbar = 1.055 \times 10^{-34}\ Js$$

$$k_B = 1.381 \times 10^{-23}\ J/K$$

$$m_0 = 9.109 \times 10^{-31}\ kg$$

$$\varepsilon_0 = 8.85 \times 10^{-12}\ Fm^{-1}$$

$$e = q = 1.602 \times 10^{-19}\ C$$

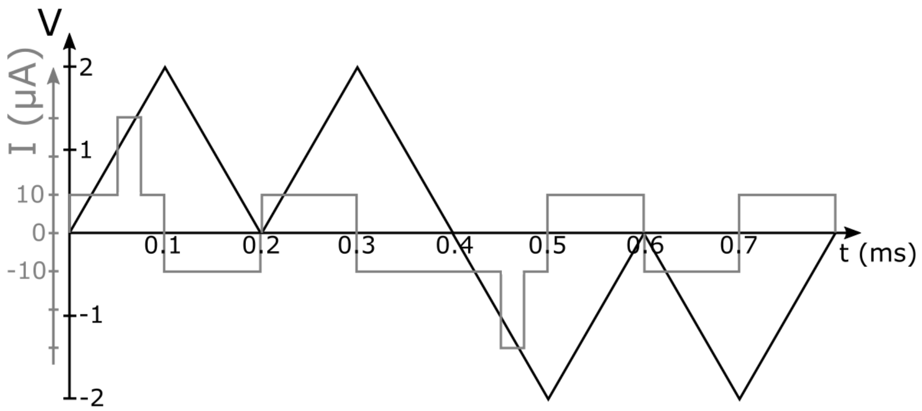
$$c = 2.998 \times 10^{8}\ m/s$$

You may use a calculator and one A4 page of notes.

Solve the Six tasks below. Maximum score is 60p.

1. **Input encoding to crossbar array**
   a) Describe amplitude encoding and what is the benefit and drawback of it.
   b) Describe analog temporal encoding and what is the benefit and drawback of it.
   c) Using digital temporal encoding show how the binary number 101101 is represented as input to the crossbar array.

2. **Ferroelectric memories**
   a) Calculate and draw the P-E curve from the measurement data below, given a device area of $2 \times 10^{-9}\ m^2$ and ferroelectric thickness of 10 nm:



   b) Which of the following FTJs will have the highest tunneling electroresistance? Please explain carefully.

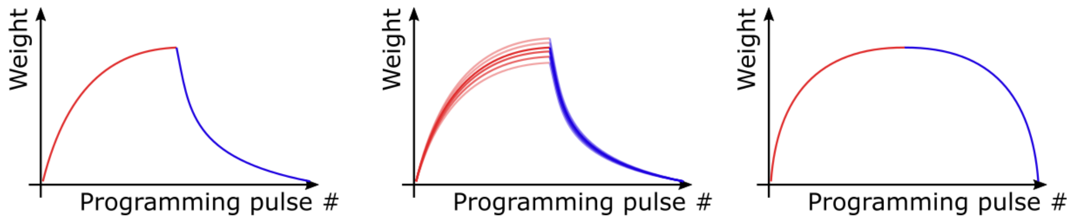
	Structure	Ferroelectric thickness
A	Metal-ferro-Metal	1 nm
B	Metal-ferro-Metal	4 nm
C	Metal-ferro-Semiconductor	6 nm

3. Machine learning hardware

a) Explain why Graphics Processor Units (GPUs) are so successful for inferencing and training of artificial neural networks in machine learning.

b) Describe the problem that in-memory computing is solving and how it does it.

c) Which of the following non-ideal memristor programming responses is the most and which is the least harmful for in-memory computing? Please motivate your answer.

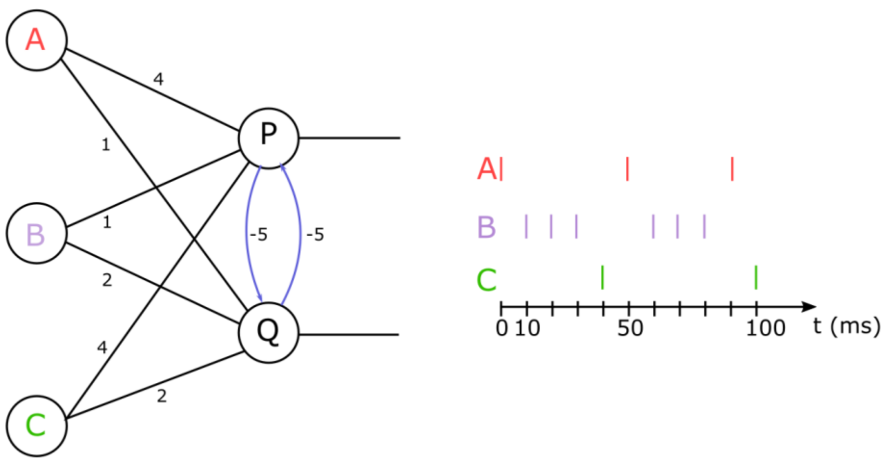


Case A: No device variation, asymmetric   Case B: Device-to-device variation, asymmetric   Case C: No device variation, symmetric

d) Explain how one can represent negative weights in a crossbar in-memory computing system.

4. Spiking Neural Networks

a) A network of Integrate-and-Fire neurons is connected as in the picture below, where the numbers indicate the magnitude of the synapse weight G_{ij}. Neuron thresholds are 10 mV, and each spike from A, B or C contributes (for simplicity!) $\Delta V\ [mV] = G_{ij}$ to the membrane potential of P and/or Q. Given the spike pattern for A, B and C below, plot the resulting membrane potentials and output spike patterns of P and Q in the time interval 0 < t < 100 ms.



b) Explain in detail how one can train an SNN in an unsupervised fashion via STDP.

5. Emerging memory technologies

a) MRAM, PCM as well as RRAM need a specific current density to switch between the high and low resistive state. Describe how this can be a limitation to their scalability.

b) Explain what gives rise to the resistance contrast in a magnetic tunnel junction.

c) Explain what is the reason for having limited retention of the memory state in FeFET devices? How can one avoid this problem?

6. Sneak currents

a. Consider a 100x100 crossbar of memristors with $G_{on}(1\ V) = 10\ \mu S$ and $G_{on}/G_{off} = 100$, and non-linearity factor $\eta = \frac{I(1\ V)}{I(0.5\ V)} = 1000.$ and. If one selects a single device, calculate the current I_{sel} through this device and the total sneak currents (I_{sneak}), in the worst case when the selected device is in the off state = G_{off} and all others are in on-state = G_{on} using the V/2 biasing approach.

b. Access devices can be used to further reduce sneak currents. Excluding three-terminal access devices (transistors), choose suitable access devices for PCM and RRAM memristors, respectively. Don't forget to clearly motivate your answer.