Assignment: Exploring Neuron Models and Neural Networks

Objective: Investigate and simulate classic biological neuron models and brain-inspired neural network architectures.

1. **Theoretical Investigation of Neuron Models:** Study the following neuron models and learning algorithm:
   - The **Hodgkin-Huxley (HH) Model**.
   - The **Leaky Integrate-and-Fire (LIF) Model**.
   - The **Hebbian Learning** algorithm.
2. **Theoretical Investigation of Spiking Networks:** Study neural network architectures that utilize spiking mechanisms, inspired by the brain:
   - **Spiking Neural Networks (SNNs)**.
   - **Reservoir Neural Networks (RNNs)**.
3. **Programming Simulation (Python):** Implement Python simulations for the models based on the following specific requirements:

   (i) **Hodgkin-Huxley Model Simulation for Action Potential:**
   Requirement: Define all necessary **parameters** and the **six rate functions** (α_x, β_x) of the ion channels. Use an **initial membrane potential** $\mathbf{V_0} = \mathbf{-65}$ mV and apply an **external input current** $\mathbf{I_x}$ (Step Input with magnitude 20 μA/cm^2).
   Plot the **membrane potential (V)**, the **Sodium current** $(\mathbf{I_{Na}})$, and the **Potassium current** $(\mathbf{I_K})$ over time. Explain the roles of $\mathbf{I_{Na}}$ and $\mathbf{I_K}$ during depolarization and repolarization.

   (ii) **Leaky Integrate-and-Fire (LIF) Model Simulation:**
   Simulate the change in the **membrane potential** of a neuron when it receives a **square wave input current** using the LIF model.

   (iii) **Reservoir Neural Network for Time Series Prediction:**
   Use the **Reservoir Neural Network** model (e.g., Echo State Network) to simulate a time series prediction experiment (e.g., using the Mackey-Glass series), demonstrating the accurate prediction of both **near-future** $(x(t+10))$ and **far-future** $(x(t+100))$ values.

References

On Hodgkin-Huxley, LIF Models and Hebbian Learning:

[1] Trappenberg, T. P. (2023). *Fundamentals of computational neuroscience* (3rd ed.). Oxford University Press. [1]

[2] Dayan, P., & Abbott, L. F. (2001). *Theoretical neuroscience: Computational and mathematical modeling of neural systems* (1st ed.). MIT Press. [2]

On Spiking Neural Networks and Reservoir Computing:

[3] Tavanaei, A., Ghodrati, M., Kheradpisheh, S. R., Masquelier, T., & Maida, A. S. (2019). Deep learning in spiking neural networks. *Neural Networks*, *111*, 47–52. [3]

[4] Lukoševičius, M., & Jaeger, H. (2009). Reservoir computing approaches to recurrent neural network training. *Computer Science Review*, *3*(3), 5–17. [4]