Quantum Ephaptic Coupling

Towards Bio-Inspired Quantum Machine Learning

Outline

- Ion Channels
- Ion Pumps
- GHK Equation and Electrochemical Balance
- Hodgkin Huxley Equation
- Time Dependent Schrodinger Equation
- Scattering
- Tunneling
- Ephaptic Coupling Equation

Outline (contd.)

- Quantum Ephaptic Tunneling
- The Equations
- Crank Nicolson Discretization
- MATLAB Implementation of Algorithm
- Simulation Results
- Interpretation
- Theoretical Expectations
- Next Steps

Ion Channels

- Key channels carry potassium ions
- Another set of channels carry sodium ions
- Focus on voltage gated sodium channels
- There is a sensor on a gate that opens the gate when the potential on the sensor-side is at a certain value and closes it otherwise.
- When the gate is open, the channel conducts sodium ions.
- The channel is embedded in the cell membrane

Ion Pumps

- They pump ions from one side to the other, AGAINST the gradient established electrochemically
- This restores the ion channel concentration balance on the two sides, after the action potential and within the refractory period

GHK Equation and Electrochemical Balance

- GHK Equation tells us the effective potential, given the concentrations of the various ions inside and outside the cell

Hodgkin Huxley Equation

- Tells us the time variation of the transmembrane potential
- Based on the membrane capacitance and conductance
- Partial differential equation

Schrodinger Equation

- Tells us the time evolution of the wavefunction of a particle
- The wavefunction encodes the probability of finding the particle at various spatial locations

Scattering

- Say a free particle approaches a potential barrier
- We can compute the incident wave function and the ‘reflected’ or scattered wave function
- They will need to satisfy boundary conditions at the barrier

Tunneling

- If the barrier height is low enough
- Some fraction of the wave function tunnels through
- This transmitted fraction can also be computed, along with the reflected and incident components

Ephaptic Coupling Equation

- Extends the HH equation
- Consider two or more HH equations
- The equations get coupled due to “return” current in the extracellular medium
- This coupled set is the ephaptic coupling equation

Quantum Ephaptic Tunneling

- Consider two ion channels separated by a portion of membrane
- These two will bear Schrodinger particles in one direction
- The intervening membrane will offer a potential barrier in the orthogonal direction
- Due to statistical mechanics effects, some Schrodinger particles will also go sideways
- Due to quantum tunneling effects, some of these particles will be exchanged between the channels

The Equations

- One can write down the equations as a set of coupled SE’s with the coupling coming from the tunneling current
- This is a first pass that doesn’t include the stat. mech. details

Crank Nicolson Discretization

- The written down PDEs can be discretized in space and time using the Crank Nicolson method

Simulation

- The discretized equations are simulated in MATLAB

Theoretical Analysis

- One should be able to do an exact analysis for the tunneling fraction
- One should be able to compute the exact mean value of expected positions of the two streams

Next Steps

- After the analysis and validation of simulation
- Consider the CMBN (2024) result which proposes the axon tract as a learning machine
- In similar vein propose the quantum ephaptic effect as a learning algorithm
- The algorithm’s learning performance should be compared with current state-of-the-art QML techniques