Guiding Questions on Brain and Computation

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Chapter 1: Introduction

Q1: What is computational neuroscience? What questions are typically asked in computational neuroscience?

Q2: What kinds of tools are used in neuroscience? What is the focus of computational neuroscience within neuroscience?

Q3: Computational neuroscience attempts to build computational models of the brain and nervous systems. What is a model? What is a descriptive model? What is an explanatory model?

Q4: Emergence and adaptation are distinguishing properties of the brain. What are they? Can we build artificial neural networks that exhibit these properties and solve problems like the brain does?

Chapter 2: Neurons and Conductance-Based Models

Q1: What components does a neuron have? What are their functional roles? How does a neuron transmit signals to a neighboring neuron? What's the action potential of the neuron? How are they generated and propagated?

Q2: What's the synaptic transmission? What's presynaptic cell and what's postsynaptic cell? Describe the detailed procedure for synaptic transmission? What kinds of neurotransmitters are involved? How do excitatory and inhibitory synapses differ? How do chemical synapses differ from electrical synapses.

Q3: Describe the time-course of postsynaptic potentials. What is the excitatory postsynaptic potential (EPSP)? What is the inhibitory postsynaptic potential (IPSP)? Give examples of EPSP and IPSP using an α -function.

Q4: What is the structure and role of ion channels? How does an ion channel involve with generating action potentials? Describe the detailed procedure for generating action potentials. What is the refractory period? What are its role and implications?

Q5: What is the Hodgkin-Huxley model? Describe a circuit representation of the model. Give the mathematical model and explain it. What are the assumptions?

Chapter 3: Spiking Neurons and Response Variability

Q1: What is an integrate-and-fire (IF) neuron? Describe the mathematical model. How is it different from conductance-based models of neurons? How does an IF neuron respond to a constant input current?

Q2: What is the gain function? How does it change with respect to the reset potential and refractory time?

Q3: Give a formal description of the spike-response model. In this model, how does the response in the membrane potential change following a presynaptic spike. How does the response in the membrane potential change following the last postsynaptic spike. Give examples of spike-response functions

Q4: Spike trains are not regular. How do we measure the variability of the spike time? What is the interspike interval (ISI)? What is the coefficient of variation, or C_v? Can we use C_v to check if the spike trains follow the Poisson process?

Q5: Lognormal distribution can be used to model ISI distributions of a leaky IF neuron. Use Fig. 3.7 to explain this. Poisson distribution can be used to model the input spike trains. Use Fig. 3.8 to explain this.

Chapter 4: Neurons in a Network

Q1: How are the human brain organized? What's the Brodmann's number? Name the four lobes of the human brain? Which cortical areas are responsible for which cognitive functions?

Q2: The neocortex consists of six layers. How are the cortical layers structured? Show the connectivity patterns between neurons in a cortical layer. Neocortex has also columnar organization and topographic maps. How is the visual field, for example, represented topographically? Show the structure of somatosensory map.

Q3: Give the following numbers on cortical parameters: neuronal density, synaptic density, number of synapses per neuron, proportion of inhibitory synapses, time duration of spikes, velocity of spike, length of axon, synaptic cleft length, synaptic transmission delay due to diffusion.

Q4: Cortical neurons typically fire with a background activity of 5 Hz with variance of 3 Hz. If a neuron has 10000 excitatory synapses, how many spikes are arriving in the time interval of 1 ms?

Q5: If 100 presynaptic spikes (100 Hz) lead to 2 postsynaptic spikes (2 Hz) during 1 ms, what is the synaptic efficiency?

Q6: How is information transmitted in large random networks? Consider a large random network of 10^{10} neurons. Each of these neurons connects to 10000 other neurons. If we stimulate 1000 sensory neurons, what is the probability of a neuron receiving a single spike? What is the probability of a neuron receiving two spikes? How big (or small) is this number? What does this mean?

Q7: What are the advantages of a population code? How to compute the average population activity of neurons? Describe the average dynamic behavior of a population of neurons. Describe the spike response model of the postsynaptic neurons using the average synaptic efficiency.

Q8: Describe a sigma neuron model. How is the output of the node computed from the inputs and the weighted channels? What kinds of activation functions are adopted? Give their mathematical formula.

Q9: Give the discrete formulation of continuous dynamics of a dynamic sigma node. Give the continuous formation of it by taking $\lim \quad \Delta t \rightarrow \infty$. Describe the leaky integrator dynamic without external input. Give a dynamics formula for the exponential response to short inputs.

Q10. What is a sigma-pi node? Where can we find the interactions between multiple synapses? What is shunting inhibition? Give other examples of nonlinear modulatory effects between synapses that can be modeled as sigma-pi nodes.

Chapter 5: Representations and the neural code

Q1: What is a tuning curve of a neuron? How does it look like? What is the firing rate hypothesis? What is the rate code?

Q2: Explain the differences of rate code, correlation code, and temporal code. Based on a temporal code, a leaky integrator can be used for coincidence detector. How? Can it be done by perfect integrator?

Q3: Show the schematic of a communication channel. Use Fig. 5.6. How is the message x is transmitted to the destination from an information source? What is channel capacity?

Q4: What is a random variable? Define information, information gain, and entropy of a random variable. What is the entropy of a message set with N possible messages that are all equally likely? When is the entropy maximum and when is it minimum?

Q5: What is cross entropy? What is relative entropy? What is Kulback-Leibler (KL) divergence? What is mutual information (MI)? What does it measure? How is the relationship of MI to joint entropy? What is the MI value if two random variables X and Y are independent?

Q6: Using temporal coding, how do you compute the entropy of a spike train of length T given a spike rate r? Using rate coding, how do you compute the entropy of observing N spikes in a time interval T? What is the entropy of a Poisson spike train? What is the entropy of a exponential-distributed spike train?

Q7: Consider population coding, i.e. the encoding of a stimulus pattern in a population of neurons. How can we express the response probability of neurons in the population? How do we decode the stimulus s given a response pattern $\mathbf{r}$ of neurons in the population? i) How to decode it using Bayesian decoding? ii) How to decode it using maximum likelihood estimation? iii) If we do not know the conditional probability distribution, how can we decode the stimulus? iv) How to decode the stimulus using the population vector decoding method?

Q8: Explain three different ways of representing a stimulus in the brain: local representation, fully distributed representation, and sparsely distributed representation.

Q9: What is the sparseness of neural representation? How do you estimate the sparseness given the firing rates of N neurons in response to a set of S stimuli? What is a feature in population coding? Consider the mutual information $I(S; Y)$ between a set of external stimuli s and the response $\mathbf{y}$ of a neural population. Alternatively, consider the mutual information $I(S; \hat{S})$ between a set of external stimuli s and the decoded stimuli $\hat{s}$ from a neural population. What does a large value of mutual information mean? What is the relationship of the mutual information with the sparseness of the neural representation?

Q10: Inferior-temporal (IT) cortex is known to be involved with visual object recognition. We want to know the neural encoding and decoding characteristics in his area. What kinds of experiments can you design to study the neural representations in this area. Hints: think of mutual information and sparseness measures. How sparse is the object representations in the IT area? Use the results in Figures 15 & 16.

Chapter 6: Feed-forward mapping networks

Q1: Consider the problem of mapping from multiple inputs to binary outputs. How can we represent the mapping function? Compare the following methods: look-up table, prototypes, and sigma neuron (perceptron). How is the sigma neuron approach different from the other two methods? Also consider the letter (like the visual image of letter ‘A’) recognition problem. What’s the advantage the sigma neuron approach?

Q2: Design a sigma neuron (perceptron) to implement binary AND gate and OR gate. Can it implement XOR gate? Why or why not? How can we build a single-layer mapping network using multiple sigma neurons? Describe the architecture. How can we build a multilayer mapping network (or multilayer perceptron)? Describe it architecture. The multilayer mapping network is known to be a universal function approximator? What does this mean? What are the assumptions?

Q3: How can we train a sigma neuron? Describe the delta rule (refer to other material, e.g. AI course). How can we train a multilayer mapping network? Describe the idea underlying the backpropogation algorithm. What is the generalization problem in learning? How can we promote good generalization or avoid overfitting?

Q4: The backpropagation algorithm learns only the connection weights of neurons, not the number of hidden neurons and the connectivity of neurons. Does the network size or the connectivity of neurons matter for generalization performance? Can we design the network structure or develop a learning algorithm that can organize the right network structure and size? What is a genetic algorithm? Can we us a GA to network design? How?

Q5: What are recurrent mapping networks? Describe as an example the simple recurrent network (SRN) or Elman network . How is it constructed? Why is it good? For what purpose? Is it a cognitively plausible model of working memory?

Q6: How can we make probabilistic mapping networks? That is, how can we modify the mapping network to generate probability values as output, instead of just the activation values? Compare the three different approaches: winner-take-all, softmax, and cross-entropy methods.