Computational Neuroscience Exam
COMS30016

Summer 2022

Instructions to students

The exam has seven sections, corresponding to the seven weeks of teaching material. All questions are compulsory. You should consider it open-book in the sense that you can refer to the lecture notes.

Section 1: Brain basics [14 marks]

Q1. Roughly how many synapses are there in the human brain [4 marks]?
a) 10^9
b) 10^{11}
c) 10^{14}
d) 10^{16}
Ans: c (10^{14})

Q2. Roughly how large are human synapses? How does their size compare to the smallest components in a microprocessor? How might the brain still operate effectively given these differences [10 marks]?
Ans: Synapses are around 1 μm [4 marks]. The smallest components in a microprocessor are *much* smaller, about 10 nm [1 marks]. The brain can cope with using much larger components due to huge parallelism / 3D structure [5 marks]

Section 2: Differential equations, leaky integrate-and-fire neurons (14 marks)

Q1. Give the analytical solution to the following differential equation: $dy/dt = -2y - 2$ with $y(t = 0) = 3$. What value will y converge to after a long time, $t \to \infty$? [4 marks]
Ans: Solution: $y = -1 + 4e^{-2t}$ [3 marks] Converges to: -1 [1 mark]

Q2. What are the steady-states of the differential equation $dy/dt = y^2 - 1$? [4 marks]
Ans: $y = -1$, $y = 1$ [4 marks]

Q3. If you must use a large timestep for numerical integration, what numerical integration method should you use and why? [6 marks] Ans: Runge-Kutta (or similar) [3 marks], because it offers greater accuracy for a fixed step size [3 marks].

Section 3: Hodgkin Huxley, modelling neurons, analysing spiking data (14 marks)

Q1. In this model describing ion channel opening and closing $ds_1(t)/dt = \alpha s_0(t) - \beta s_1(t)$, what do $s_0(t)$, $s_1(t)$, α and β represent? [6 marks]
Ans: $s_0(t)$ fraction of channels closed, $s_1(t)$ fraction of channels open [3 marks], α channel opening rate, β channel closing rate [3 marks].

Q2. Describe how to produce a peri-stimulus time histogram. [4 marks]
Ans: histogram of spike-counts [2 marks]; aligned to stimulus onset [2 marks].

Q3. If a signal has $d' = 1$, what does that mean? [4 marks]
Ans: $d' = 1$ implies that the mean value of the signal is one standard deviation unit away from the baseline/noise mean [4 marks].

Section 4: Synapses, synaptic plasticity (16 marks)

Q1. Describe the mechanism of short-term depression. [3 marks]
Ans: Depletion of readily releasable vesicles. [3 marks]

Q2. Describe the key features of spike-timing dependent plasticity [4 marks]
Ans: pre then post gives potentiation [2 marks]; post then pre gives depression [2 marks]

Q3. Is spike-timing dependent plasticity unstable? Explain your reasoning [4 marks]
Ans: It is unstable [2 marks]. Pre then post leads to potentiation, thus an even bigger chance of pre causing a post spike [2 marks]

Q4. Describe how NMDA receptors might implement Hebbian style update rules. [5 marks]
Ans: Magnesium block [1 mark] is released when the post-synaptic synapse is depolarised [2 marks]. When there is also a pre-synaptic vesicle released, the NMDA receptor opens up, calcium flows in, and triggers downstream changes [2 marks].

Section 5: Hippocampus, Hopfield networks (14 marks)

Q1. Why is pattern completion important? [3 marks]
Ans: To notice similarities between current situtation and previous experience. [3 marks]

Q2. What is path integration? What is the main advantage and disadvantage of path integration? [6 marks]
Navigational strategy which estimates position by combining information about from an initial location with velocity and direction [2 marks]. Disadvantage: estimate of position gets worse over time due to noise in direction/velocity estimate [2 marks]. Advantage: works even if no absolute position information is available [2 marks]

Q3. How does hippocampal damage affect pre-existing and new memories. Does this tell us anything about how memories are encoded? [5 marks]
Ans: Hippocampal damage does not disrupt pre-existing memories (i.e. about events that happened days, weeks or years before the hippocampal damage occurred). [2 marks] Hippocampal damage prevents the formation of new memories. [2 marks]. Implies memories are initally encoded in hippocampus then moved to another structure (likely cortex). [1 mark]

Section 6: Visual system, rate coding [14 marks]

Q1. What are the receptive field and tuning curve? How do they differ? [6 marks]
Ans: Receptive field is the region of stimulus space that the cell responds to [3 marks]. Tuning curve is the specific relationship/function mapping stimulus to firing rate [3 marks].

Q2. What does NOT happen to receptive fields as we move up the visual processing hierarchy? [4 marks]
a) Receptive fields become larger.
b) Cells become sensitive to complicated aspects of the visual stimulus.
c) Cells become more multimodal (i.e. also depend on non-visual sensory signals).
d) Firing becomes more sparse.
Ans: d

Q3. What is a topographic map? Give an example. [4 marks]
Ans: Nearby neurons code for similar stimuli [2 marks]. An example (retinotopic/somatotopic etc.) [2 marks].

Section 7: Supervised learning, Cerebellum, temporal difference learning [14 marks]

Q1. Consider the delta rule, where we initially have $w = (0, 1)$. We then do TWO delta-rule updates, with $x = (1, 1)$ and a target of $y^* = 2$ and a learning rate of $\nu = 0.2$. What are the final weights? [4 marks]
a) $w = (0.2, 1.2)$
b) $w = (0.3, 1.3)$

c) $w = (0.32, 1.32)$
d) $w = (0.4, 1.4)$
Ans: c (First update: $\hat{y} = 1$, $\delta = 1$, $\delta \times \nu = 0.2$, $w = (0.2, 1.2)$. Second update: $\hat{y} = 1.4$, $\delta = 0.6$, $\delta \times \nu = 0.12$, $w = (0.32, 1.32)$)

Q2. For which type of conditioning does Rescorla-Wagner break down? [4 marks]
a) Partial
b) Blocking
c) Inhibitory
d) Overshadowing
e) Secondary
Ans: e (secondary)

Q3. Describe each term in the TD error signal $\delta = (V(t+1) + r(t)) - V(t)$. How does this form a useful, informative error signal? [6 marks].
Ans: $V(t+1)$ estimated value at the next time step [1 mark]. $r(t)$ current reward [1 mark]. $V(t)$ estimated value at the current time step [1 mark]. $V(t+1) + r(t)$ is a slightly better estimate of the current value, $V(t)$, as it includes real information from the reward [3 marks].