Contents

1 Introduction and Recap

1.1 Random Projection and Cap (RP&C)

Review of fly olfaction and what RP&C is. He views RP&C as an important operation. In flies it maps binary vectors to other binary vectors, but in humans it repeats, resulting in a sequence of vectors. A natural question is whether this converges.

A theorem he proves in his recent ITCS paper (with Vempala and others) is that this process *does* converge quickly, and converges faster with stronger plasticity. Intuitively, plasticity improves stability.

1.2 About the class

Comment raised by a student that there's too much of a difference between the homeworks and the lecture material. Response: Papadimitriou thinks we *need* to experience frustration and learning beyond our level. They're also trying to present material from lots of orthogonal directions, and think that it's also important to know *something* about the topics that we learn about in homework.

Question raised about fields with substantial intersection between theory and practice.

Response: Physics is the most successful example of this. Neuroscience has had lots of physicists work on this but without complete success, which is part of the reason Christos is working on this now; he has a different perspective as a computer scientist.

Books mentioned include "Rhythms in the Brain" by Busaki, and "Why Only Us" by Chomsky.

Next three weeks: reinforcement learning, language, and evolution/development.

2 Assemblies

We want a logic to understand the brain, not even necessarily an algorithmic description. The assembly hypothesis is part of this model.

2.1 Operations

Recall that assemblies can be thought of as a *data structure* for the brain, so like any data structure it should have methods or operators. Specifically, in coming up with operators, we should make sure that they are both *useful*, in the sense that they can explain at least one experiment, and they should be *plausible*, meaning that they can be compiled down to synapses.

These include:

- Project(x,A,y)
- Affinity/Association
  This is well-preserved under Project(x,A,y), and similar stimuli should project to similar assemblies.

  [Insert graph of projected overlap as a function of stimulus overlap from slides]

  We can then consider *association graphs*, in which each node corresponds to a different assembly and there is an edge between each overlapping assembly with weight equal to how much overlap there is between those assemblies.
- Reciprocal Project(x,A,y) [Insert diagram from slides]
- Merge(x,y,A,z) [Insert diagram from slides]
  Note that for mathematical simplicity, we assume that only one assembly is activate at once in any given area of the brain.
- Associate(x,y,A,z) [Insert diagram from slides]
- Activate
- Area-read
- Assembly-read

2.2 Modes of computation

2.2.1 Turing Machine Computation

It turns out that this is (unsurprisingly) Turing-Complete.

Theorem: these operations allow us to, with high probability, simulate an arbitrary Turing machine with $\sqrt{n}$ space. Essentially we can use Project(x,A,y) to simulate the tape, and use the other operations as control commands.

2.2.2 Associative Computation

The activation of overlapping assemblies may trigger pattern completion. The association graph can be thought of as a powerful probabilistic programming system. For example, "Russian" and "Stanford" complete to "Vlad".

2.2.3 Learning (half spaces)

We can think of neurons as sparse binary vectors. Then two assemblies correspond to linearly separable clusters of such neuron vectors. These clusters are also preserved by projections.

2.2.4 m-ary relations

Creating m-ary relations between assemblies, such as subject-verb-object.

3 Language

Some neuroscientists warned him that he should study language last, after understanding the rest of the brain. Papadmitriou thinks otherwise, and that it's important to consider the environment of the brain, of which language is a significant part.

Hypothesis: Language evolved to exploit the brain's strengths. The brain was very similar genetically to what it was like before we had languages.

Recommends the book "Why Only Us" by Chomsky. He conjectures that we had an *internal* language for a long time before language between people developed.

3.1 Experiments

3.1.1 Poepell Experiment

It turns out that every spoken language "ticks" at 4Hz, which he suggests reflects a feature of the brain. In this "beautiful" experiment, they took a sequence of one-syllable words at this frequency. Applying Fourier analysis showed that (as expected) there were peaks at 4Hz. Then they did something similar, but where each section of four words collectively made up a sentence. Again applying Fourier Analysis, there were peaks at 1Hz and 2Hz in addition to at 4Hz, implying that there are oscillations in the brain at these frequencies as well that are involved in language.

[Insert Fourier Analysis plot(s) from slides]

His interpretation/conjecture: we construct *trees*. For example, consider the sentence "bad casts eat fish". Then the brain first combines "bad cats" and "eat fish", then combines these two phrases to form the full four-word sentence.

[Insert syntax tree from slides]

3.1.2 Frankland and Green Experiment

Consider the phrases "ball hit truck" and "truck hit ball". Different areas response to "truck" in these two sentences, suggesting there are locations corresponding to subjects vs objects of a sentence. Moreover, these areas get swapped when you consider the second sentence. However, when you consider the sentence "truck was hit by ball" with the same order of words as the second sentence but with the same meaning as the first, the response areas correspond to that of the first sentence and not the second.

3.1.3 Zaccarella and Friedericci

Completion of sentences light up Broca's Area, but this area isn't lit up by individual words. Moreover, if there is a lesion in this area, the language of that individual becomes incomprehensible. There are connections between it and Wernicke's area, which from around the age of 2 is responsible for vocabulary (among other things). Specifically, myelination of neurons connecting the two areas happens after 2 years.

Wild speculation: believes a fundamental part of language is *generation*. This is in contrast to parsing, which he views as basically just reverse engineering.

He thinks the process of generating language may go something like:

(a) Think of a verb

(b) Project the verb into Wernicke's area

(c) Think of a noun

(d) Project the noun into Wernicke's area

(e) Combine a couple words to create a verb phrase

(f) Then combine word phrases to make a full sentence with an object

[Insert syntax tree diagram from slides here]

Of course, the order depends on the particular language one speaks; he thinks that we have a language-dependent algorithm that articulates this tree.

Remark 3.1. Only humans have asymmetric left/right hemispheres.

4 Motor cortex

Near Broca's area - a fact that is believed to be not coincidental. Compare with *somatosensory cortex*, where sensations *end up*, while the motor cortex is where they start.

The picture of the motor cortex from the 1960's was basically right, but with *lots* of missing details. Moreover, in the motor cortex the map between regions of the brain to the corresponding types of body movement controlled by those areas is plastic; for example, violinists have exaggerated left digit maps.

[insert figure of map from the slides]

4.1 Premotor cortex

Receives lots of information from other parts of the brain and provides input to the motor cortex. Involved in *conditional* movement. It and the motor cortex serve as a control center for many other parts of the brain, including the basal ganglia (which is essential for reinforcement, and is situated deep in the brain), the spinal cord, and the brain stem.

4.2 History of the motor cortex

The classical view is that individual neurons in the motor cortex encode motion, but that cells in encode for *many* different things, and the firing rate of cells in the motor cortex are a function of many parameters, so that we don't yet fully understand this encoding. In other words, the classic view is that we can view the firing rate of neuron i at time t as something like

$$r_i^t = f_i(p_1, ..., p_k)$$

where p_j correspond to parameters like direction, speed, and the state of muscles.

4.3 Paper by Churchland et al.

The paper we were assigned, by Churchland et al., takes an opposing view and considers neurons at the *population* level, which they describe as a huge vector in a large dynamical system of the form

$$\dot{\vec{r}}^t = f(\vec{r^t}, \vec{u^t})$$

They hypothesize that all movement, whether or not it is itself rhythmic, has a rhythmic/oscillatory component.

They don't find anything with PCA so consider jPCA instead. Let A be a data matrix. Then they consider $\dot{A}$ (by looking at the difference of A at a small time scale), and try finding a symmetric matrix M such that $\dot{A} = MA$, which corresponds to the solution $\dot{x} = e^{\mu_i t}$, as well as a skew-symmetric matrix S such that $\dot{A} = SA$, which corresponds to the solution $\dot{x} = e^{\sigma_i t}$. In both cases, the result is sinusoidal, with the eigenvalues of S being imaginary.

(Note: he recommends the last section of the supplemental info part of the paper).

They find that this captures around 30% of the variance. Question: is this whole approach reasonable? He's not sure if it's biased.