Memristors: Memory, Biology and Computation

(Advertised as Memristors: Biology, Computation and Materials)

Introduction

I'm going to start in a slightly strange place by asking the question, what are you? What is the important part of what you are? Is it your species, that you're human? Your body? Your brain? Your thoughts? Emotions? Deeds and misdeeds? Past history? Future plans? Skills and abilities? What?

A lot of these things I've listed relate to the same thing, so I can ask the question:

1: What Are You Without Your Memories?

Your beliefs, your loves, your skills, your knowledge, your identity, your opinions, your vices, your dreams, your neuroses, everything is a result of your ability to remember.

So,

2: What is Memory?

I’m not going to go too deep into it as there is are entire fields that do, but I just wanted to draw your attention to a few facets of what is covered by the seemingly simple word ‘memory’. This slide just covers long term memory and we have two types, the explicit, which is the stuff you realise that you remember, and the implicit, which is the stuff you don’t necessarily realise you remember.

So, episodic memory is everything that’s happened to you in your life, it’s the narrative you tell yourself and everyone else about What happened to you and Why you’re who you are today. Semantic memory is your knowledge, everything you know and the reason why you’re paid to work here!

Then we have the Implicit memory. Procedural memory covers skills you had to practice, driving a car, typing on a keyboard, working in a lab and the rest of these are simpler, emotion based memories.

So you see, memory can cover a lot.

Then there is the related field of learning

<u>3: Learning and Memory</u>

On the left is a non-exhaustive list of types of learning, and on the right is a list of words associated with memory. The two ideas are intertwined. You obviously could not learn anything without being able to remember.

Now there are a few types of learning and memory that I will come back to. There's associative learning, like Pavlov's dog experiment, where a response gets associated with new stimulus.

Another type is enculturization where an individual learns what's expected of them in their culture. This is closely related to the (somewhat trendy) management term institutional memory, which is the sum total of all information, both knowledge, behavioural paradigms and skills possessed by an organisation. UWE's institutional memory includes all those emails filling up our inbox, the rebranding, our skills, the fact we all go for lunch at 12:30.

4: Is Learning and Memory Only a Property of Higher Animals?

Since evolution was accepted, people have started to ask questions about when in the evolutionary history various intelligent behaviours arose.

So are all these ways of learning and types of memory only a property of higher animals?

No. Meet the slimes, Polycephalum Physarum, is a type of slime mould, found in the HP woods at this time of year.

It is only a single celled organism and it;s an odd one. It’s eukaryotic, but has many nuclei in one huge interlinked cell which forms a network and explores it’s space to find food.

Now, experiments have been done where the slime mould was exposed to a periodic blasts on cold air and the mould hardened. After training, it would harden before the blast when it expected it, even if there was no blast of air.

Think for a moment, this is a single-celled simple and dumb organism which is able to anticipate repeated events, but it has no brain to speak of (despite its name), how is it doing it?

5: Ants as Institutional Memory

Here is a more complex example. I imagine that everyone here is familiar with ants setting out pheromone trails, gathering food and bringing it back to the nest. This is a textbook example of emergent behaviour where the whole is many times more complex than the sum of the parts. Or rather, the complicated behaviour and intelligence of an ant colony is more than would be predicted by study of a single ant.

This is interesting and we now that insect colonies exhibit a social intelligence. But can we ask where this memory is stored? I mentioned institutional intelligence earlier, for hte ant colonies it’s made up of the behavioural paradigms for the castes of ants, the pheromones trails and behavioural responses.

So we can see there is learning and memory involved in the actions of simpler creatures.

Lets jump up in complexity for a moment and consider animals which have a brain.

6: How Does the Brain Work?

Now, no one knows the answer to this, so I’m not going to speculate too much. I think we can all agree that most thinking is done somewhere within the head, so I'm just going to review some of things we know about what's in there.

The

8: Hodgkin-Huxley Model

Is well known. We have a lipid membrane as represented by this capacitor and ion transfer across these channels.

9: Hebbian Learning and STDP

The ion transfer gives rise to an action potential which propagates through the network of neurons. Essentially, neurons of the brain are joined together into networks and the strength of the connections can be modulated. This is at the root of learning and memory.

Hebbian learning is named after Donald Hebb who put it succinctly as 'neurons that fire together wire together'. If two neurons fire at the same time it is more likely that they are related and over time the strength of the connection and ease of firing increase.

The is a subtlety to this in that you only want connections to be increased where the firing of one neuron cuased the firing of the second.

This is what spike-time-dependent plasticity deals with.

10: Are Brains Like Computers?

The metaphor that our brains are like computers is something of a cliché, we’ve all heard it, but I posit that it isn’t a very satisfying comparison. No one really takes it seriously, because a computer is a dumb, very fast, adding machine, whereas once a baby starts to interact with the world (beyond sleeping) it seems to be doing something fundamentally different.

11: Are Brains Like Computers? List

This isn’t a complete list, but here I’ve tried to identify some of the differences. The main thing is that even if the signals propagating through the brain can be digital, ie the synapses fires or not, the connection weights are more analogue and the output is more vague. We can split the world into binary classifiers, but it’s usually a mark of intelligence and maturity to deal with shades of grey. There is the field of fuzzy logic which tries to encompass this srot of thing, but I think you’ll agree with me that computers are currently naturally black and white thinkers.

And, it might seem irrelevant, but I find that squishy and not-squishy, although binary descriptors, encompass a lot about the differences between brains are computers.

One final thing, I’m comparing the brain with a computer. This picture shows a motherboard, some RAM slots and some processors. In a computer, the memory storage is located in the harddisc and RAM, in separate componants to the part that does the thinking, namely the processor.

So what would happen if we could combine the memory with the processor?

12: Memristor: The Memory Resistor

13: What are Memristors?

Memory resistors or resistors with memory are a step in that direction. They are electrical resistors, but within them they can store a state, ie remember something and this makes them capable of learning.

14: Chemistry of Memristors

Memristors can be made from many things but in general they are made of binary oxides or more complex oxides. This is the archetypical memristor as announced by Stan Williams at HP in 2007. The device works because there are two forms of titanium dioxide, the normal stoichiometric phase and this magneli phase which has lost some oxygen ions. The Magneli phase has a metal like conductance and stoichiometric TiO_2 is a semi-conductor, thus these two types of materials have vastly different resistances. As a voltage is put across the memristor, the vacancies move, increasing the amount of magneli compared to normal and changing the reistance. When the power is removed the vacancies stay there and thus a state is encoded and the memristor can remember. This is why people are interested in using them in computers, there would be no need to wait for the state to be loaded into the RAM if your RAM was made of memristors and thus computers would start up quicker.

15: Behaviour of Memristors

This a theoretical I-V curve for a memristor. The main thing to note is that at a give voltage there are 2 possible currents you could measure and each of these correspond to a different state. As the memristor goes round this loop it carries with it the memory of what had happened to it before.

16: Mathematics of Memristors

The memristor is the formally-missing 4^{th} fundamental circuit element. The others are the resistor, the capacitor and the inductor. It was postulated to exist by Leon Chua based on the fact that when you write out the things you can measure in an electronic circuit, all of them are linked by an equation that defines a device or a fundamental relationship, except this one. There was no device to link magnetic flux to charge and, because it made the diagram look pretty and the laws of physics do seem to like symmetry, he postulated the memristor would fill this gap.

This is his relationship here, the Chua Memristance fills this gap between the charge and the magnetic flux.

17: Use of Memristor Theory to Model Learning and Memory

So what has this got to do with learning and memory? Well firstly, memristor theory has been successful in modelling learning and memory.

18: Use of Memristors in Neural Nets

Neural nets are a computation technique whereby they attempt to model brain-like computers in software. Here my colleague David put memristors in between neurons to control the connection weights. The neural net was then given the very simple task of learning how to navigate a robot round a maze. Evolution was done on the neural net to try and evolve a brain-circuit that could figure out how to do this task. The most interesting thing was that the connection weights varied during the task, showing that the neural net was learning directly from the environment, in between the evolutionarily directed changes.

- Memristive Model of Slime Learning

Here, the slime learning experiment I described earlier where a single-celled organism was able to learn to expect a puff of air at a known frequency was modelled by a circuit containing only 4 circuit elements of which one was a memristor.

- Plastic Memristor Mimics Pond Snail Learning

Here a single memristor shows it's capable of learning. The pond snail was conditioned by feeding it sugar and stroking it's lips at the same time. Over time, the snail would open its mouth when touched even if there was no sugar on the spatula. This behaviour has been narrowed down to [] neurons which control the mouth opening. Here a single memristor exhibits the same behaviour [RESEARCH THIS!]

Here we’re looking at a problem of how to model ants behaviour. Gathering, the task, can be split into different bits. There’s the searching the environment, locating food and laying trails part, which has been well modelled and understanding this has given rise to useful algorithms in compsci. Here we’re looking at the second part of gathering, how to allocate workers amongst the work.

This is a test problem for Atta, leafcutter ants. There are 5 trees which are leaf food sources and they are of different quality.

Here we’re interested not in modelling the neurons of an animal but hte large scale behaviour of an animal society. This is the institutional memory I talked about earlier: how many ants should go where.

Here, the memristors model the number of ants of a path and that number dynamically changes as the ants move around.

- In a Similar Environment Send Gatherers To the Worst Food Site First

This work has used memristors to give information about how to solve a difficult problem. Memristors in this model automatically encode the effect of diminishing returns whereby adding more gatherers causes a smaller increase in productivity as the number of gatherers rises and the law of low-hanging fruit, ie the easiest stuff will be taken first and so the productivity of an individual resource site decreases with time.

In an environment where the trees are of similar quality, oddly enough, it makes most sense to send most workers to the poorest resource first. This is because the other resources give their best productivity at the start and after make up for the losses at the worst resource. Once that resource is depleted, the now-redundant ants can go to the other sites to try and increase the productivity there.

- In a Poor but Disparate Environment the LeafCutter Method is Best

In a different example, where most the trees are of poor quality, but one is of good quality it makes more sense to follow the leafcutter ants strategy, which is to deplete the best resource and then spread out the gatherers as I described before.

Thus memristors have some use in helping us model larger groups of animals.

- Are Biological Materials Memristive?

But is there more to this? Are biological materials memristive?

- Memristor model of Skin

And the answer is yes. Becasue of the Sweat ducts in the skin, memristive responses are recorded when you apply an alternating voltage to someone’s arm. The lag in the current here is what would give rise to a memristor-like I-V curve.

- Blood Memristors

And you can make memristors out of flowing human blood. They kept the blood warm and flowing and applied alternating voltages and got memrisotr like current responses.

- Leaf Memristors

This is the same group, they’ve making memristors and logic gates out of leaves as well.

- What Are Neurons?

And so we go back to neurons.

- Memristive Systems Model Verusus Hodgkin-Huxley Model

The memristor was predicted to exist in 1971, but an experimental version wasn't made until 2008. In 1976 Chua went looking for things that might be this missing memristor and one of the things he suggested was that a memristive model of synapses would better explain the operation of neurons. The membrane ion channels are memristors.

- Memory Function-Conservation Function Model of Memristors

And perhaps there's more to this as well. This is the memory function conservation function model of memristance. The memory function is the Chua memristance up here. This charge is not electronic charge, and it was because people thought it should be, that no one was able to identify the memristor for so many years. This charge is the ions. Here I'm talking about hte memristor devices I make in the lab. Q relates to the charge associated with the ions. To calculate the effect of that on the measured current, which is mostly to do with the electrons, we need the conservation function.

- Memory Function is Related to the Memory Property

So it was postulated that for each memristor there was a memory property, which is the property of the material that stores a state. In most the memristors I’ve come across this memory property is related to the ions.

- Similarities Between Neurons and Memristors

So what does this tell us about neurons and memristors? Well, they have quite a few similarities. I said on an earlier slide that brains were squishy, I don’t know if that is a necessary property, but titanium dioxide memristors are nanoscale, mesoscopic and soft matter.

They both work based on ion movements. The memory propery for both is related to ions and as such, in terms of memristor theory, they have a misleadingly small magnetic flux associated with their operation.

Finally, networks of memristors are capable of learning.

- Conclusions
- Why are Memristors Exciting the Scientific Community? - 1
- Nanoscale
- Better than transistors?
- Help keep Moore’s Law true

- Smaller, faster, less component computers
- Better than flash memory?
- Building Better Computers...?
- Why are Memristors Exciting the Scientific Community? -2
- Memristors are artificial componants that do the same thing as neurons
- Therefore we can make neural nets from them
- They can learn and remember
- Easier to make A.I. and computers that work like the brain
- Thank you
- Ben de Lacy Costello
- Andrew Adamatzky
- (Gerald) David Howard
- Larry Bull
- You for listening
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