Mathematics Today, IMA 50(5), 262-264.

Brain Inspired Computing

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In April 2010, my colleague, Jon Borresen, and I visited Professor John Bancroft (Head of Business Development) and a few of his colleagues at Daresbury Science Park to pitch our idea on oscillator-based computing. Within half an hour of that meeting Professor Bancroft was insisting that MMU needed to patent the idea straight away.

So what was the idea? Essentially, the invention is inspired by brain dynamics – using threshold oscillators to perform binary computation and memory. The average human brain consists of some 100 billion neurons with up to 100 trillion synaptic connections between them. The human body contains mainly oscillatory cells such as neurons, heart cells, muscle cells and retinal cells, for example. The human heart beats (oscillates) at a rate of 60-80 beats per minute and neurons are natural threshold oscillators that beat (fire) 1000 times faster. The power of the brain comes from the high connectivity and that is what we are attempting to exploit here. Neurons communicate with one another via synaptic connections and neurotransmitters, converting electrical signals to chemical signals and back to electrical signals again.

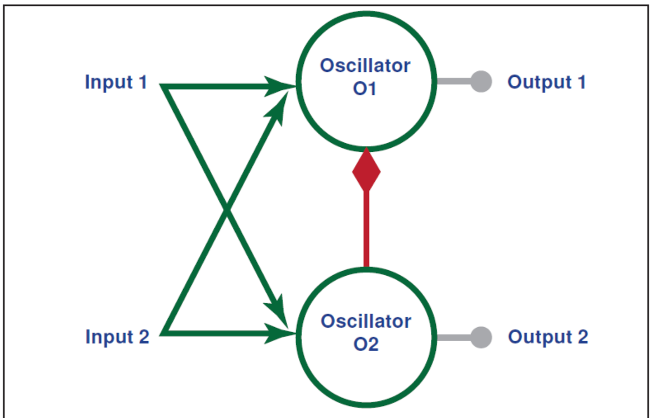

Figure 1: *Schematic of a binary oscillator half-adder (a half-adder is the basic component of all computers). The oscillators O1 and O2 are threshold oscillators. The green and red arrows depict excitatory and inhibitory connections, respectively.*

These neurotransmitters can be excitatory, where a firing neuron can turn a connecting neuron on (cause it to oscillate), or inhibitory, where a firing neuron can inhibit or prevent a connecting neuron from oscillating.

In terms of the invention, an oscillation is equivalent to a one in binary and no oscillation is a zero. The idea is to do standard computing using circuits with neuronal type dynamics. The simplest computing system is the binary half adder which just adds two bits together: 0+0=0, 0+1=1,1+0=1 and 1+1=10. Figure 1 shows a schematic of the patented binary oscillator half-adder [1] consisting of two threshold oscillators, four excitatory connections and one inhibitory connection. Recall that a threshold oscillator will only oscillate once a certain threshold has been achieved.

We were able to simulate the binary half-adder using the MATLAB® package and certain differential equations that modelled the threshold oscillators. The results are shown in Figure 2, which demonstrates that the half-adder is functioning correctly.

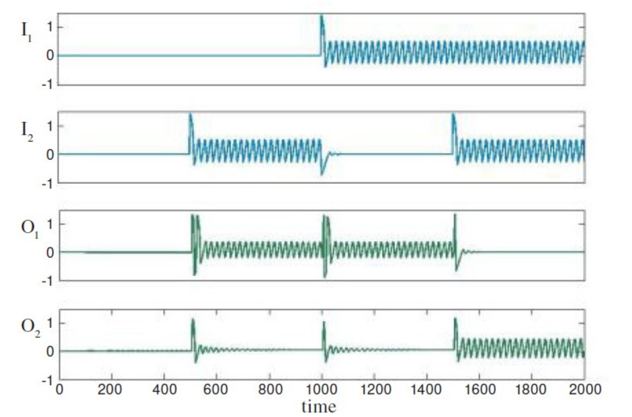

Figure 2: *Time series output for the binary oscillator half-adder depicted in Figure 1. An oscillation is equivalent to a binary one and no oscillation is zero. The O_1 trace represents the units row and the O_2 trace the tens row. Looking down the columns from left to right, $0+0=0$, $0+1=1$, $1+0=1$ and $1+1=10$, as required.*

Referring to Figures 1 and 2, if there is no input, there is no output. If either Input 1 (I_1) or Input 2 (I_2) is oscillating, then the threshold of oscillator O1 is reached but the threshold of oscillator O2 is not. If both Input 1 (I_1) and Input 2 (I_2) are oscillating, then the threshold of oscillator O1 is reached and the threshold of oscillator O2 is reached, but oscillator O2 inhibits oscillator O1 and prevents it from oscillating.

One major advantage in using this threshold oscillator logic is that processing power can be doubled with a linear increase in components. As well as performing superfast computing using threshold oscillators, it is also possible to store memory [2]. There are added advantages in using oscillators as memory devices as switches can be caused by ballistic propagation in which case a single pulse (which does not use much power) can cause a switch. Using transistors, as in modern computers, requires line charging which consumes a lot of power.

The oscillators depicted in Figure 1 could be composed of biological neurons, super-cooled Josephson junctions (JJs), memristors, transistors or optical components. We are currently pursuing two avenues of research: firstly, the manufacture of super-cooled, superfast, low energy computers using JJs and secondly the development of neuronal assays to test drugs for neuronal disfunction.

JJs are natural threshold oscillators that oscillate up to 100 million times faster than neurons. They are super-cooled, operating at 4 Kelvin (-269.15 °C), and require very little power to operate. In 2010, scientists at Colgate University, Hamilton, NY, USA, published a paper [3], where JJs were used to simulate neurons. In collaboration with HYPRES Inc. NY, USA (a digital superconductor company), they are hoping to simulate parts of the brain using physical JJ circuits – they claim that they will be able to simulate human brain development over decades in a matter of minutes using their circuitry.

In October 2011, we visited HYPRES Inc. (one of the few manufacturers of JJ circuitry in the world) to pitch our idea. The visit went extremely well, and the very next day HYPRES Inc. disclosed that they had built the world's fastest Arithmetic Logic Unit (ALU) based on JJ technology, however, they did not use our circuitry. As a result of the meeting, we were invited to the 14th International Superconductive Electronics Conference at Cambridge, MA, USA, and a paper was later published in the Proceedings [4]. We are currently seeking funding to develop our ideas with Colgate University and HYPRES Inc.

One of the major problems to overcome with building superfast computers using this technology is concerned with the high connectivity between the oscillators. However, we believe that this is no longer a hurdle with the advent of the memristor.

It has long been believed that there are only three fundamental passive circuit elements, the capacitor, the inductor and the resistor. In 1971, Chua [5] used mathematics to prove the existence of a fourth fundamental nonlinear element which acts like a resistor with memory, he called the new device the memristor. In 2008, Hewlett Packard Laboratories announced that they had built a titanium dioxide memristor [6] and they are currently building devices for computer logic, nanoelectronic memories and neuromorphic computer architectures. Interested readers can find more information by watching a number of You Tube videos filmed by HP Labs. It has been estimated that the memristor industry could be worth up to 250 billion dollars and devices could be commercially available as early as 2020. We believe that future computers could be built using highly connected JJs using memristors acting like axons.

More recently, in August 2014, IBM researchers demonstrated the TrueNorth 5.4-billion-transistor chip consisting of 4096 neurosynaptic cores interconnected via an intrachip network that integrated one million programmable spiking transistor-based-neurons and 256 million configurable synapses [7]. Each neuron is connected to 256 other neurons showing very high connectivity - which is exactly what is required if binary oscillator computing is ever to be successful.

The second avenue of research currently being developed is concerned with biological neurons. In the brain, the power used in gathering thousands of sensory inputs and interpreting and storing data is estimated to run to 25W. A comparable transistor-based computer would require 100MW of power. The basic component of the biological brain is the electrically excitable cell, the neuron, which processes and transmits information by electro-chemical signalling. As described above, the threshold oscillators depicted in Figure 1 could be composed of biological neurons. A schematic of a typical neuron is shown in Figure 3.

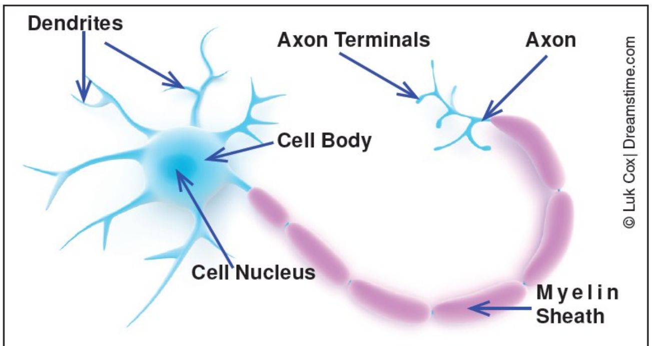

Figure 3: *Schematic of a neuron or nerve cell.*

Two neurons may be coupled together via a synapse, which is a complex membrane junction or gap used to transmit signals between cells. There is a diffusion of neurotransmitters across the synaptic gap that may either depolarize (excite) or hyperpolarize (inhibit) the post synaptic neuron. The typical brain consists of approximately 80% excitatory and 20% inhibitory neurotransmitters. The neuron is a natural threshold oscillator and oscillations can appear either in membrane potential or as rhythmic patterns of action potentials.

There is currently no assay to test drugs on the functionality of neurons. Neurological conditions and disorders affect the brain, spine and the nerves that connect them. A list of some well-known neurological conditions and disorders includes Alzheimer's disease, autism, brain damage, cerebral palsy, Down's syndrome, epilepsy, headache, meningitis, multiple sclerosis, Parkinson's disease, stroke and tetanus, for example. In 2005, the World Health Organisation estimated that neurological disorders affected one billion people worldwide. The most common form of dementia, Alzheimer's disease, currently has no cure and it is estimated that one in 85 people will be affected globally by 2050.

Stem cells are a class of undifferentiated cells which come from embryonic stem cells or adult stem cells. Once extracted, the stem cells are allowed to divide and replicate but not differentiate. The stem cells can then be stimulated to form differentiated cells such as neurons (see Figure 4(a)). Neuronal cultures on a Multi-Electrode Array (MEA) provide a simplified model in which network activity can be manipulated with electrical stimulation sequences through the array's multiple electrodes. Single neurons provide a useful reductionist model, and brain slices from rodents provide more of a realistic model where cortical architecture is maintained (see Figure 4(b)). Thus, the logic and memory circuits can be manufactured using stem-cell derived neurons or existing neurons.

We are currently working with cell biologists at MMU and the University of Reading in order to manufacture the world's first assay for neuronal degradation. The aim of our research is to develop entirely novel neuron-based circuits, which act as a simple biological calculator. Using these circuits, nerve cells affected by neurological disorders can be tested on functioning biological logic and memory circuits that yield consistent and repeatable outputs. The assays may also be constructed from other oscillatory cells of the human/animal body [8].

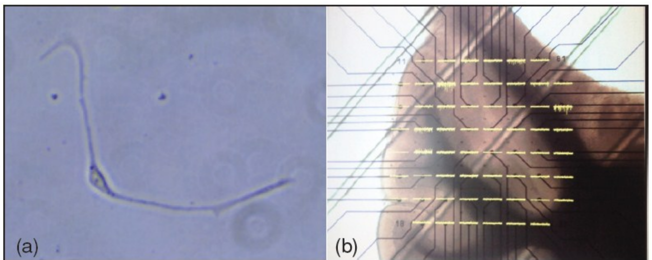

Figure 4: *(a) Mouse stem-cell derived hypothalamic neuron and, (b) Slice of mouse brain sitting atop a Multi-electrode Array. The yellow spike trains show the summative effect of neurons surrounding the relevant electrode.*

This article has demonstrated how a very simple idea in mathematics could have huge applications in the real world. Unfortunately, as demonstrated with the memristor, it could be decades before any of this research bears any fruit. For more information and a gentle introduction to MATLAB, readers are directed to my latest book [9].

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About the Speaker

Dr Stephen Lynch is a world leader in the use of mathematics packages (in particular, MATLAB®, Mathematica® and Maple™) in teaching, learning, assessment and research. He has been using these and other mathematics packages since the mid-1980s. His research area is Dynamical Systems and in particular Binary Oscillator Computing, which he co-invented with Jon Borresen. Stephen is a STEM Ambassador and was instrumental in establishing a Computing and Mathematics Schools Liaison forum in the North West of England, which has now been running for almost 15 years.