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Modern classical conditioning: replacing a learning circuit in the brain

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A programmable chip can replace the ability of the cerebellum to learn a timed eye-blink response to a sound.

Interfacing with the brain is possible in certain circumstances. There are input devices that replace damaged senses, for example cochlear prostheses for the deaf. Then there are output devices to replace muscles and the nerves that control them, such as robotic arms. But what about internal damage in the brain? Would it be possible to replace a brain area that has been destroyed by, for example, a stroke, or that has degraded with age?

Pursuing the aims of the ReNaChip project, our work investigates the possibility of aiding recovery from brain damage. Here, we targeted a small neural circuit in the brain that can learn a timed reaction to a stimulus and aimed to develop a programmable chip that could replace this circuit. The real-time behavioral recovery made possible by the chip provides a proof-of-concept demonstration for the functional rehabilitation of more complex neuronal systems.

Learning in this neural circuit occurs via "classical conditioning." Therefore, we modeled the neural interactions that may underlie this learning.[1] In this model, inputs consist of a neutral stimulus (e.g., a sound) followed by an aversive stimulus (e.g., a puff of air to the eye). These inputs converge from different pathways on the Purkinje cells of the cerebellum. Then, over repeated trials, synaptic plasticity acts to stabilize the timing of what is called a conditioned response (e.g., an eye blink that anticipates the puff of air). We aimed to build a neuromorphic model of this learning behavior and connect it to the inputs and outputs of the cerebellum in real time.

A chip that replaces a part of the brain needs to be able to record the inputs to that area and also stimulate its outputs. To do so, in our first experiments, we used an external amplifier and stimulator hardware (which could later be integrated to create one small, implantable chip). Once the subtle electrical signals that come from electrodes in the brain are large enough to

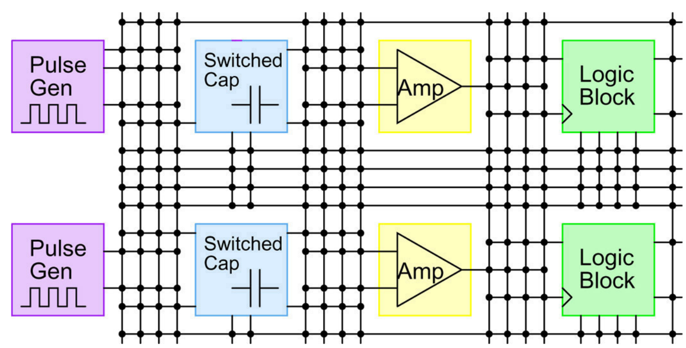

Figure 1. *A field-reprogrammable array. Basic building blocks are laid out in an island topology, where they can be connected together using the surrounding switches. The blocks are of four types: logic blocks to provide digital glue logic; switched capacitors (Switched Cap), which can behave as capacitors, resistors, or analog switches; amplifiers (Amp), which can be used to impose thresholds, or together with resistors and capacitors to make filters; and pulse generators (Pulse Gen), which can drive clocked logic and switched capacitor resistors.*

work with, they must be filtered to detect the neural activity that the stimuli cause. This filtering has to happen in real time because reactions can take place after only tens of milliseconds. We filtered the electrical signals using several channels in parallel to get better quality information. The rest of the neural model operates on these detected stimuli, also in real time, so that its outputs can be used to stimulate the correct response.

Many neuromorphic engineers begin with arrays of neuron circuits and use them to perform computations. We took a different approach. We realized that the basic electronic building blocks we needed for filtering neural signals and for constructing neural models were the same. While we began to design a chip for this task, our partners kept improving the neural model and the filtering strategy. Therefore, we created a field-programmable array by putting many basic building blocks on

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the chip in an island topology. Here, each of these building blocks is an 'island' surrounded by a 'sea' of switches (see Figure 1). By turning on certain switches, we can connect the blocks together to create the circuits we need to create the neuromorphic model of the cerebellum and the filters for the neural signals.[2] Devices such as this are very common in the digital world, as well as having specific niches in the analog world. Our device mixes together digital and analog signals (they are not kept in separate domains). It is specialized for neural prosthetic applications by choosing a good mix of the most useful components (see Figure 1) and carefully controlling the current that components use (and the speed at which they operate). Low-power operation is very important in devices that will be implanted in the brain. Our method for reducing the speed of the digital circuitry has led to some interesting additional uses.[3]

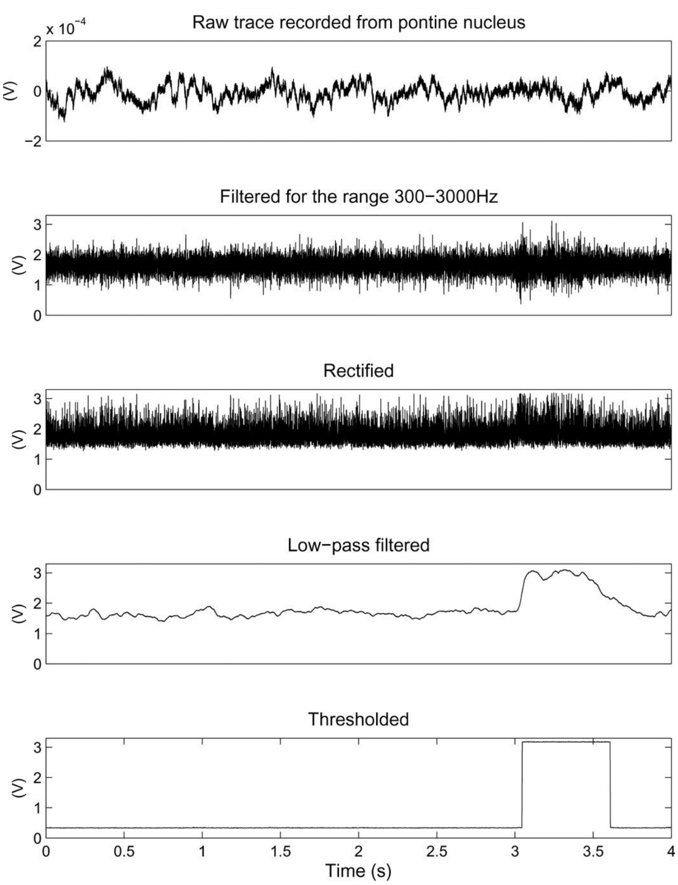

Figure 2. *On-chip, real-time neural signal processing. A signal recorded from the pontine nucleus of the brain of an anaesthetized rat (top) while a sound is played (starting at 3s) is amplified and goes through several filtration stages (middle) to reveal the neural activity related to the sound; this is thresholded (bottom) to detect the sound. These analog filters are constructed from amplifier and switched capacitor components, as well as some digital logic.*

We first conducted our experiments with a software version of the system.[4] Then we used the chip to filter input signals and learn based on recorded bio-signals.[2] Figure 2 shows an example of how our chip detects a stimulus from electrical traces recorded from electrodes. The detected signal becomes one of the digital inputs to a mixed analog-digital implementation of the neural model. This input signal results in an output pulse that triggers a stimulating electrode.

We have successfully demonstrated how to use technology to aid recovery from brain damage by using our chip to replace the learning function in a real-time closed-loop experiment with an anaesthetized animal (publication in progress). Our next step is to modify the programmability of the chip so that it can be applied to different types of neuromorphic modeling.

The authors are members of the Complex Systems Modeling Group at l'Istituto Superiore di Sanità, Rome. This work is part of the EU-funded ReNaChip project (grant agreement no 216809). The project has been carried out in collaboration with several partner organizations, particularly Universitat Pompeu Fabra (Barcelona), Tel Aviv University, and Guger Technologies OG (g.tec), Austria. The raw data in Figure 2 was recorded by Aryeh Taub at Tel Aviv University.

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Simeon A. Bamford received a PhD from the University of Edinburgh in 2009. He now works as part of the Complex Systems Modeling Group at Istituto Superiore di Sanità, where he researches neural and neuromorphic engineering in pursuit of the elegant circuit, the ideal application, and insight into the mind.

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spiking neurons and plastic synapses, the microelectronic implementation of neural models, and the analysis and modeling of data from in vivo electrophysiology. He has co-organized six workshops/schools on neural networks. He recently held several EU, ISS-NIH, and Italian National Institute for Nuclear Research (INFN) grants, and is associated with the INFN. The ISS-NIH is a collaborative program between the Institutes of Health (NIH) of the USA and the Istituto Superiore di Sanità (ISS) of Italy. Since 2008, he has taught neural networks at Rome's Sapienza University (physics department). He has published 30 journal papers and 25 conference papers and book chapters. He is member of the editorial board of Advances in Artificial Neural Systems, a review editor of Frontiers in Computational Neuroscience, and an associate editor of Frontiers in Neuroengineering.

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