# Dynamical Neuromorphic computing with nanoscale magnetic oscillators

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In this work, we prove that nanoscale magnetic oscillators called spin-torque nano-oscillators[1-3] can be used to emulate the oscillatory behavior of collections of neurons. We first highlight their two main assets for neuromorphic computing: their exceptional ability to synchronize and their well-controlled magnetization dynamics. We then demonstrate experimentally that a single spin-torque oscillator can realize neuromorphic tasks such as spoken digit recognition reaching state of the art performances. For many tasks such as facial recognition, speech recognition or prediction, the brain processes information much faster and with much less power than any computer. Some models interpret the way brain process information treating the neurons as interconnected non-linear oscillators. In particular, reservoir computing is a recently introduced braininspired computing paradigm [4]. Its efficiency at dealing with complex cognitive tasks such as speech recognition or chaotic series prediction has already been demonstrated [5].

Reservoir computing can be implemented with a recurrent network (the reservoir) composed of an assembly of interconnected oscillators with fixed connections. A fast input signal, encoding the data to process, is applied to the network. The input signal modifies the frequency and amplitude of each oscillator. Different input waveforms will create different transient dynamics in the network, allowing for separation and classification. The responses of all the oscillators are recorded and recombined. This recombination corresponds to the output of the computation. When the input signal is applied to the reservoir of coupled oscillators, the initial problem (classifying the inputs) is projected non-linearly in a higher dimensional state where separation is easier. If the number of non-linear oscillators is sufficient, the projection of the initial problem in the reservoir state is linearly solvable. It is then sufficient to recombine linearly the response of the different oscillators of the reservoir in order to generate different outputs for different inputs. The optimum coefficients are determined using a training procedure, which consists in a simple linear regression. In other words the working principle of reservoir computing is to leverage non-linearity to transform the problem in another one that is easier to solve. Reservoir computing is one of the few neural network approaches demonstrated in hardware. However, existing implementations are restricted to FPGAs or optical systems, where the power consumption is high and oscillators are not nanometric [4,5].

In this context, spin-torque nano-oscillators are particularly promising building blocks for reservoir computing. They have a nanometric size and low energy consumption, they are compatible with CMOS and can be built in large quantities. In addition, these oscillators are highly non-linear and can synchronize to each other. They are therefore ideal candidates to mimic neurons [6]. Here we give the first experimental demonstration of neuromorphic computing with spin-torque nano-oscillators. We show that a single oscillator can emulate the behavior of a whole neural network. By time multiplexing the input waveform we create a temporal complexity which is the analog of the spatial complexity of a network. By exciting the oscillator with this preprocessed signal, we generate complex transient dynamics that we record and recombine. In order to have good performances in term of noise, we use vortex based spin-torque nano-oscillators with FeB free layer. The dynamics of our oscillator is controlled through the applied dc current and magnetic field. By changing these two parameters we have tuned the oscillator operating point to optimize the neural network-like behavior.

By leveraging the transient dynamics of our spin-torque vortex oscillator, we have performed several cognitive tasks. First we have tested our system with a simple pattern recognition task, which consists in discriminating sequences of sine and squares randomly disposed in the input waveform. This task is not trivial since the recognition is piecewise, which means that at each moment the system should recognize if the input value belongs to a square or a sine. We achieved a perfect recognition of sines and squares. Then we moved to speech recognition task, which is more complex. Our input signals are recorded digits said by 5 different speakers. After recombining the transients of the oscillator response, we were able to recognize which digit was said and which speaker said it with a success rate of 99,8% [7]. Our results are comparable to the best results observed in hardware reservoir computing [4,5] and open the path to building large spintronics neural networks that exploit magnetization dynamics for computing.

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