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Neuromorphic engineering

Superconducting optoelectronic circuits that mimic the brain

Standfirst: A hybrid superconducting optoelectronic circuit could be used to develop spiking neuromorphic networks that operate at the single quantum level.

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Artificial intelligence (AI) systems could simplify and accelerate a range of challenging computational tasks, from the recognition of images and sounds to the behavioural control of autonomous vehicles and robotics systems. However, implementation of state-of-the-art computational algorithms on conventional electronic hardware requires a huge computational and power budget. This limits the complexity of the AI systems that can be created and hinders their wider application. One potential solution is neuromorphic computing[1,2], which aims to emulate the properties of the human brain in terms of adaptive learning, parallel operation, robustness against component failure, and power efficiency. This goal could be achieved through the realisation of a neuromorphic spiking neural network[3].

In simple terms, an artificial spiking neural network is constructed using neurons that communicate to each other using spike signals via synapses connecting the neurons with adjustable weight values. This architecture exploits the bunching of spikes in the temporal or spatial domain to encode analogue data at the input and to perform computation. Proof-of-principle platforms have been developed based on complementary metal–oxide–semiconductor (CMOS) circuits[4], memristors[5], superconducting devices[6] and photonics[7,8]. Common limitations include the number of direct connections between neurons, the fan in/out architecture, and the tunability of temporal dynamics of signals. These prevent the development of more scalable, adaptive, and complex networks, which could be suitable for different emerging application scenarios.

Writing in *Nature Electronics*, Jeffrey Shainline and colleagues at the US National Institute of Standards and Technology and the University of Colorado now report a superconducting optoelectronic architecture that provides a platform for creating synapses operating down to the level of single-photons and single magnetic flux quanta[9]. The approach offers three major advantages: exceptional computational efficiency and low power dissipation for the active elements; an elegant and scalable solution to fan in/out connectivity; and a very large tuning envelope for the synaptic time constant.

The architecture combines several superconducting electronics and sensor components in a full integrated circuit on a single substrate. Setting aside the requirement for cooling, these superconducting components are exceptionally efficient in terms of power consumption. Single-photon detectors are required to convert light pulses at the single-photon level into an ultrafast electrical signal. Superconducting nanowire single-photon detectors based on amorphous molybdenum silicide are used, offering high efficiency, high photon count rate, ease of fabrication with possibility of easy integration on optical waveguides, and relatively simple operation at 1 K temperature[10]. The possibility of single-photon encoding for pre-synaptic events creates the option to directly connect neurons with very low noise, high transmission speed and ultralow power consumption.

Usually, it is not straightforward to perform computation purely with light because to mimic the summation of neuron outputs, high-Q optical cavities with long storage times are required. Creating such cavities, and connecting to many optical waveguides, is almost impossible to achieve in an integrated process. The team have adopted an alternative solution where the output voltage from each superconducting nanowire single-photon detector is converted to a train of ultrafast pulses (around 2 ps duration) representing generation and transmission of single magnetic flux quanta ($\Phi_0 \approx 2.068\times10^{-15}$ Wb) through a network of niobium-based Josephson junctions.

A Josephson junction is a tunnel junction between two superconducting regions that allows for tunnelling of Cooper pairs and can be used to control trapping of magnetic flux in superconducting loops. This is the basis of single-flux quantum logic, a paradigm for ultra-high speed and very low power consumption electronics[11]. After generation of current in the leaky integrator via single-flux quantum pulses, the current signal is converted into a voltage signal through a superconducting quantum interference device, a magnetic sensor that offers excellent sensitivity, as well as low noise and power dissipation[12]. This is used as the dendritic receiving loop circuit. The resulting output from the dendritic receiving loop is a voltage with characteristic amplitude, duration, and time decay, depending on the input, the circuit design, and the operating parameters.

A powerful advantage of this synaptic scheme is its versatility — it can be designed and operated within an exceptionally wide range of parameters. For example, the temporal output can vary from sub-microsecond to milliseconds making it suitable for interfacing with a variety of systems, from computation and artificial intelligence systems (at fast timescales) to biological systems (at slower timescales). Its scalability is promising (Fig. 1) due to the inductive coupling of the dendritic receiver with direct connection to neurons, removing the issue of latency encountered in standard architectures using multiplexing.

The next steps in the development of this technology are clear. Standard Josephson junctions could be replaced with an alternative design to further reduce the footprint of the superconducting circuit elements and allow for operation above liquid helium temperature ($T \approx 4.2$ K) (ref. 13). This will be beneficial for the scalability of the architecture and also to mitigate the real energy consumption (including the cryogenic overhead) in this and other applications of superconducting devices and electronics. The on-chip integrated synapse developed by Shainline and colleagues — which can be implemented in a spiking neural network — is an important milestone in the advance of optoelectronic neuromorphic computing.

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Competing interests
The authors declare no competing interests.

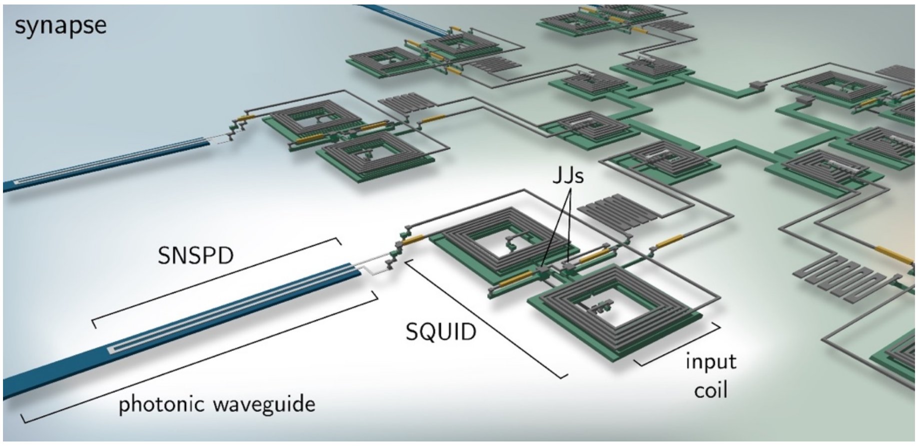

Figure 1 Integration of a superconducting optoelectronic synapse within a spiking neural network. Large scale implementation of a neuromorphic spiking network using the proposed superconducting optoelectronic design. Pre-synaptic signal encoded in light pulses routed through the photonic waveguide is converted into electrical signal by the superconducting nanowire single-photon detector (SNSPD). This electric signal generates a single flux quantum pulse train via a Josephson junction (JJ) based generator and is converted into current pulses through a JJ-based leaky integrator. Finally, a superconducting quantum interference device (SQUID) converts the current pulse into a voltage pulse. Image courtesy of J. Shainline NIST, USA**.**