Unhurried Hardware: Slashing Energy at the Edge with Time-Rich Devices.

Isao H. Inoue

National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, JAPAN.

isaocaius@gmail.com, https://sites.google.com/view/isao/home/slow-ele/

In an era of unprecedented connectivity, countless electronic devices form an intricate network linked to powerful cloud-based supercomputers via the internet. These advanced systems process immense volumes of data using sophisticated machine learning algorithms, delivering valuable insights and actionable feedback. However, despite these remarkable capabilities, there are still critical areas where these benefits are difficult to fully realise—particularly in edge devices that operate in close proximity to individuals and directly interact with their daily lives. Consider devices monitoring biological signals such as brainwaves, blood pressure, glucose levels, or heart rate. While such devices could issue vital alerts based on their observations, constantly uploading sensitive biometric data to the cloud raises significant privacy concerns. At the same time, edge devices face strict power limitations, making energy-intensive techniques like deep learning impractical. Moreover, many phenomena in human-centric environments, including biometric signals, exhibit characteristically long time scales. Processing such slow-evolving data using today's fast digital systems leads to considerable energy inefficiencies.

To address these challenges, we propose the concept of "Slow Electronics." This approach aims to enable ultra-low-power efficient information processing of slow temporal data directly at the edge. Our research focuses on developing neuromorphic devices tailored to long time scales (10 ms to 100 s), designing neural network architectures (e.g., spiking reservoir circuits) to harness these devices, and exploring algorithms that autonomously extract determinism and periodicity from time-series data [1, 2, 3]. In this talk, I will share insights into our findings, and discuss future directions in the realm of Slow Electronics.

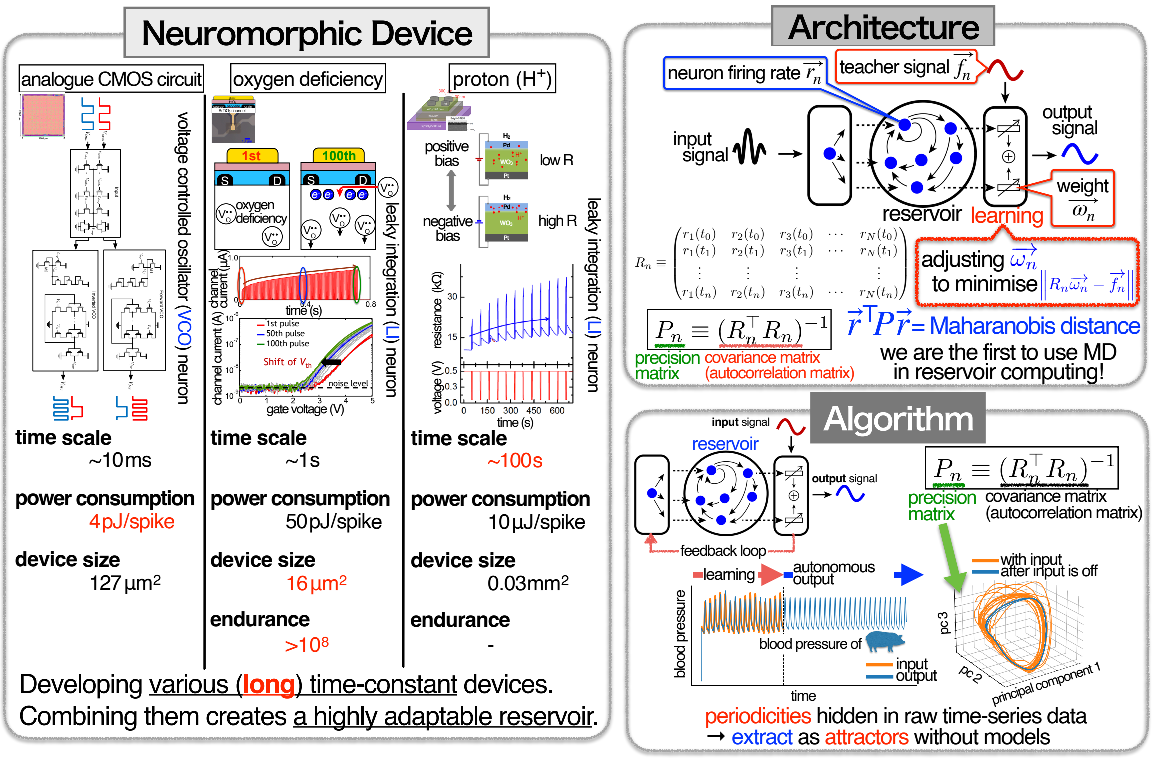

Figure 1: The three key pillars of slow electronics. Selected examples of our present research are shown. Left: Examples of neuromorphic devices with long time constants, including artificial neurons utilising analogue CMOS circuits [2], oxygen vacancies [1], and protons [3], each exhibiting time constants differing by a factor of approximately 100. Top right: Architecture for reservoir computing that interacts with the environment [4]. Bottom right: Algorithms using attractors for time-series data analysis, incorporating reservoirs with feedback loops [5]. By combining these three key pillars of slow electronics, it is possible to create ultra-low-power **devices that stay close to people**.

[1] Inoue, H. *et al.* Taming prolonged ionic drift-diffusion dynamics for brain-inspired computation. *Adv. Mater.* **37**, e2407326 (2025).

[2] Chen, X. *et al.* CMOS-based area-and-power-efficient neuron and synapse circuits for time-domain analog spiking neural networks. *Appl. Phys. Lett.* **122**, 074102 (2023).

[3] Pati, S. P. *et al.* Real-time information processing via volatile resistance change in scalable protonic devices. *Commun. Mater.* **5**, 1–9 (2024).

[4] Tanaka, G. *et al.* Recent advances in physical reservoir computing: A review. *Neural Netw.* **115**, 100–123 (2019).

[5] Tamura, H. & Tanaka, G. Transfer-RLS method and transfer-FORCE learning for simple and fast training of reservoir computing models. *Neural Netw.* **143**, 550–563 (2021).