Embracing uncertainty: a photonic approach to probabilistic computing

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Unlike artificial neural networks (ANNs), which focus on maximizing accuracy, biological systems excel at handling uncertainty. This ability is believed to be essential for adaptability and efficiency, yet traditional ANNs, implemented on deterministic hardware, struggle with capturing the full probabilistic nature of inference. To address this limitation, Bayesian neural networks (BNNs) replace deterministic parameters with probability distributions, allowing us to distinguish between epistemic uncertainty (due to limited data) and aleatoric uncertainty (arising from noise). By incorporating Bayesian inference, BNNs enable uncertainty quantification and allow for out-of-distribution detection in cases of incomplete data. However, processing probabilistic models remains a challenge for conventional digital hardware, which relies on deterministic von Neumann architectures that separate memory from computation. In electronic crossbar arrays, memristors exhibit inherent stochasticity, making them suitable for probabilistic inference. Yet, sequential sampling and variability in memristive materials present obstacles.

To address these challenges, I will outline recent progress in photonic computing architectures that harness hardware noise as a computational resource rather than a constraint. Using nanoscale phase-change materials enables encoding and processing probabilistic information in an in-memory computing fashion. By transitioning to photonic crossbar arrays, we can achieve parallel probabilistic operations using chaotic light as a physical entropy source for random number generation. This approach paves the way for energy-efficient, high-speed probabilistic machine learning beyond the limitations of conventional hardware.