

## Invited Talk

Department of Computer Science and Engineering

Indian Institute of Technology Kanpur

Date: March 1, 2019, Time 10:30 AM, Room: KD 101

## Computing with Oscillators

Jaijeet Roychowdhury

(joint work with Tianshi Wang and Leon Wu)

EECS Department

University of California, Berkeley

**Abstract:** In the 1950s, Eiichi Goto and John von Neumann showed how Boolean computation could be performed if logic states are encoded in the phase of oscillatory signals. However, the AC-pumped parametric circuit realizations they proposed were not well suited for scaling and miniaturization, hence their scheme could not compete with the level-based logic now ubiquitous in IC implementations. We show how using DC-powered self-sustaining nonlinear oscillators and exploiting the phenomenon of sub-harmonic injection locking (SHIL), makes it easy to realize phase-logic latches using CMOS IC implementations. We indicate how such a scheme has inherent noise immunity advantages over level-based logic and can potentially perform logical operations in a single cycle with low energy consumption.

Over the last few years, there has been considerable interest in Ising machines, ie, analog hardware for solving difficult (NP hard/complete) computational problems effectively. We present a new way to make Ising machines using networks of coupled self-sustaining nonlinear oscillators that are subharmonically injection locked. Our scheme is theoretically rooted in a novel result that connects the phase dynamics of coupled oscillator systems with the Ising Hamiltonian. We show that the dynamics of appropriately-designed oscillator networks evolve naturally towards local minima of the Ising Hamiltonian. Two simple additional steps (ie, adding noise, and turning sub-harmonic locking on and off smoothly) enable the network to find excellent solutions of Ising problems. We demonstrate our method on Ising versions of the MAX-CUT problem, showing that it improves on previously published results on several problems in the G benchmark set. Our scheme, which is amenable to realization using many kinds of oscillators from different physical domains, is again particularly well suited for CMOS, in which it offers significant practical advantages over previous techniques for making Ising machines.

We present working hardware prototypes using CMOS oscillators.

**Bio:** Jaijeet Roychowdhury is a Professor of EECS at the University of California at Berkeley. His research interests include machine learning, novel computational paradigms, and the analysis, simulation, verification and design of cyber-physical, electronic, biological, nanoscale and mixed-domain systems. Contributions his group has made include the concept of self-sustaining oscillators for Ising-based and von Neumann computation, novel machine-learning techniques for dynamical systems, theory and techniques for oscillator phase macromodels,

injection locking and phase noise, multi-time partial differential equations, techniques for model reduction of time-varying and nonlinear systems, and open-source infrastructures for reproducible research.

Roychowdhury received a Bachelor's degree in electrical engineering from the Indian Institute of Technology, Kanpur, India, in 1987, and a Ph.D. degree in electrical engineering and computer science from UC Berkeley in 1993. From 1993 to 1995, he was with the Computer-Aided Design (CAD) Laboratory, AT&T Bell Laboratories, Allentown, PA. From 1995 to 2000, he was with the Communication Sciences Research Division, Bell Laboratories, Murray Hill, NJ. From 2000 to 2001, he was with CeLight Inc. (an optical networking startup), Silver Spring, MD. From 2001-2008, he was with the Electrical and Computer Engineering Department and the Digital Technology Center at the University of Minnesota in Minneapolis.

Roychowdhury was cited for Extraordinary Achievement by Bell Laboratories in 1996. Over the years, he has authored or co-authored seven best or distinguished papers. He has served on technical and administrative committees within several conferences and professional organizations, including ICCAD, DAC, DATE, ASP-DAC and CEDA. Roychowdhury was a co-founder of Berkeley Design Automation, a startup later acquired by Mentor Graphics. He is a Fellow of the IEEE.