Special Session 3B – New Topic:

Why Nanoscale Physics Favors Quantum Information & Why Computing is Possible in Spite of Quantum Uncertainty

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As transistor dimensions approach atomic scale, quantum-mechanical effects such as tunneling and spin become important ingredients in accurate performance models of integrated circuits. Theoretical work suggests that power-density required to separate signal from noise motivates a departure from common practice of representing logic 0s and 1s by charges, voltages or currents. Conventional information processing relies on discretized analog signals to convey digital information. This is problematic at the nanoscale due to the inherent uncertainty and noise that manifest themselves in many different ways, already plaguing leading-edge CMOS technologies. At the nanoscale signals are drowned by noise, much of it quantum-mechanical in origin. Therefore we depart from the simple discretization of analog signals, and instead rely on ”a two-valued quantum degree of freedom” suggested in 1924 by Paul Dirac, now commonly known as the *spin* of nuclei, electrons and other particles. Spin is an example of a logical quantum bit or *qubit*, which replaces the conventional bit in quantum computing. Qubits can also be implemented by the polarization (horizontal and vertical) of photons. A well-publicized demonstration by IBM in 2000 subjected nuclear-spin qubits to quantum gates implemented by RF pulse trains. More recent work shows that such stationary qubits can be converted into “flying” photonic qubits, and back, while single-photon quantum communication has been demonstrated at distance of 100 kilometers in the open air.

While quantum information processing seems inevitable at the nanoscale in one form or another, the behavior of quantum circuits can differ drastically from that of modern digital electronics. A key difference lies in the fact that quantum behavior is inherently uncertain. For example, state measurement is probabilistic and the measurement process itself affects the state being measured. Nevertheless, practical computation is possible in the quantum domain, and, in a few important cases, quantum algorithms can achieve far higher computation speeds than any comparable classical algorithms. Moreover, advantage can be taken of quantum uncertainty to achieve highly secure digital communications. Quantum behavior also has both digital and analog aspects, and quantum devices are highly error-prone. For example, quantum gate operations are defined by analog parameters that allow small errors to arise and propagate to other gates. Unlike classical analog signals, however, qubits are amenable to error correction. Qubits have many more failure modes than are found in non-quantum circuits. For example, quantum signal states are inherently unstable and tend to decay rapidly due to interaction with the environment (decoherence). In spite of this, highly effective error-correction methods are known for quantum computation. This talk will discuss computation with quantum circuits, and show how their behavioral uncertainty can be overcome. In particular, the challenges of modeling, testing and tolerating errors in quantum circuits will addressed.