Introduction to simulation and modeling of complex dynamical systems

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Detailed course description: Many complex systems developed by engineers (e.g. labs on chips, iPads, magnetic resonance imaging scanners, nationwide electrical/gas/oil transportation network, or buildings/automotive/aircraft frames) or found in nature (e.g. the human cardiovascular system, the brain neural network, biological systems, or the geophysical network of oil/water/gas reservoirs) can be viewed as large collections of interconnected dynamical system components. The performance and characteristics of each individual component critically depend on what engineers or scientists refer to as “second order effects”, and can be captured only by resorting to expensive partial differential equation solvers. In addition, components are often affected by random uncertainties in parameters and in geometries.

In this course we will survey several techniques for modeling and simulation and uncertainty quantification of a large variety (e.g. aerospace, mechanical, electrical, energy and biomedical) of engineering and physical complex systems. In particular, upon completion of this course students should be able to:

- Recognize and formulate mathematical structures (e.g. conservation laws and constitutive equations) common to a lot of complex systems.
- Select (and modify) or implement an appropriate steady state solver (e.g. sparse LU vs. iterative methods) for a given linear or linearized complex system description.
- Select, implement and modify an appropriate strategy to facilitate initialization and convergence of a Newton solver for a given nonlinear complex system.
- Select and implement an appropriate technique (e.g. implicit vs. explicit, lower order vs. high order, stable vs. A-stable) for the time domain simulation of a given complex system.
- Select and implement an appropriate strategy (e.g. Shooting Newton or Harmonic Balance) for period state analysis of complex systems (e.g. vibrations in mechanical/structural frames, radio frequency circuits, heart beat cycles).
- Select and implement an appropriate strategy to "reduce" automatically models of system components generated by PDE solvers, while preserving input/output accuracy for a range of parameter values, as well as important physical properties.
- Select and implement an appropriate strategy to “generate” automatically stable parameterized reduced models of system components from input/output measurements.
- Use parameterized reduced order models of system components in order to accelerate optimization, inverse problems in complex systems
- Select and implement uncertainty quantification techniques for stochastic simulation of complex systems affected by random variations in geometries and material properties.

Detailed examples will be presented, drawn from a variety of engineering disciplines e.g. Electrical Engineering (interconnect networks including parasitics; fullwave electromagnetic structures; analog and digital circuits including nonlinear semiconductor devices and Micro-Electro-Mechanical Devices), Mechanical Engineering (frame modeling, heat diffusion, fluid-dynamics and oil transport), Civil Engineering (structural problems, vibrations), Material Sciences (inverse problems for identification of material properties), Biomedical Engineering (biochemical reactions and the human cardio-vascular system).

Prerequisites: Solid background in differential equations and linear algebra. Some very basic programming experience in Matlab, or other programming languages for scientific computing.

Target goal: Provide students access to the state of the art in numerical tools in order to help them with their research projects involving analysis, design and optimization problems in a variety of different engineering and science disciplines dealing with complex systems. The focus of the course will not be on mathematical formalism and rigorous theorem proving, but rather on developing general intuition and practical implementation skills.

Class project and evaluation: students will be working on a project involving modeling and simulation of a complex system either assigned, or chosen from their own field of research. Final evaluations will be based on interaction with the staff during the course and a final presentation or report.

Sort CV: **Luca Daniel** received the Ph.D. degree in Electrical Engineering from the University of California, Berkeley, in 2003. He is currently a Full Professor in the Electrical Engineering and Computer Science Department of the Massachusetts Institute of Technology (MIT). Industry experiences include HP Research Labs, Palo Alto (1998) and Cadence Berkeley Labs (2001). His current research interests include integral equation solvers, uncertainty quantification and parameterized model order reduction, applied to RF circuits, silicon photonics, MEMs, Magnetic Resonance Imaging scanners, and the human cardiovascular system. Prof. Daniel was the recipient of the 1999 IEEE Trans. on Power Electronics best paper award; the 2003 best PhD thesis awards from the Electrical Engineering and the Applied Math departments at UC Berkeley; the 2003 ACM Outstanding Ph.D. Dissertation Award in Electronic Design Automation; the 2009 IBM Corporation Faculty Award; the 2010 IEEE Early Career Award in Electronic Design Automation; the 2014 IEEE Trans. On Computer Aided Design best paper award; and seven best paper awards in conferences.