Principles of Modeling for Cyber-Physical Systems

Instructor – Madhur Behl (madhur.behl@virginia.edu)

CS 6501 - 013 / SYS 6581 – 005 | TuTh 2:00PM - 3:15PM | Rice Hall 340

"Essentially, all models are wrong, but some are useful" [George Box, 1976] ...

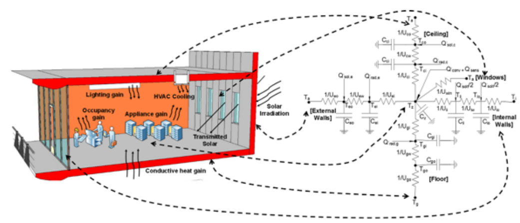
This course is about building useful models.!

Design of complex and reliable cyber-physical systems (CPS) requires the creation of mathematical models, both of the environment and of the system itself. Such models allow us to analyze, control, verify, and optimize a system's performance. The modeling choice is largely dictated by the intended use of the model plus the intricacies of the underlying physical domain. This course will provide a solid foundation for understanding different modeling paradigms, and explore them through a deep dive and hands on implementation for three CPS domains: **Energy, Medical, and Automotive cyber-physical systems.** Students will come out of this course with advanced and transferrable knowledge of model-based design methods and tools, and will be ready for tackling multi-disciplinary systems projects. In addition, you will become domain experts in energy, medical, and automotive cyber-physical systems.

Topics to be covered:

- Modeling for predictive control
- Black-box, gray-box, and white-box modeling
- Dynamical system & time series modeling
- Model construction (state-space, timed automata, & data-driven)
- Linear and non-linear parameter estimation
- Model tuning and over fitting
- Model validation
- Model abstraction/order reduction
- Model checking
- Sensitivity analysis
- Data-driven, end-to-end modeling
- Modeling and testing of control loops

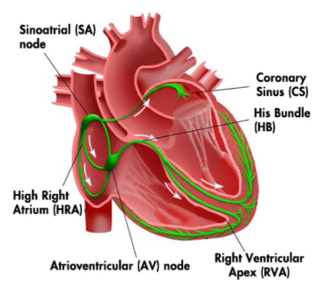
Energy CPS modeling + predicitve control – Buildings consume nearly half of all energy produced in the United States. 75% of all electricity produced in the U.S. is used to just operate buildings.



You will learn how first-principles of physics can be used to create a 'thermal' RC-network model of the energy-use dynamics of any building. We will train and evaluate these models using real data from buildings. We will then use these models to optimize the operation of the building's heating, ventilation, and air-conditioning (HVAC), and lighting systems to make them more energy and cost-efficient. We will also explore alternative data-driven methods for building modeling.

You will learn to use the following tools: **EnergyPlus, MLE+,Matlab (SysID,StateSpace)**

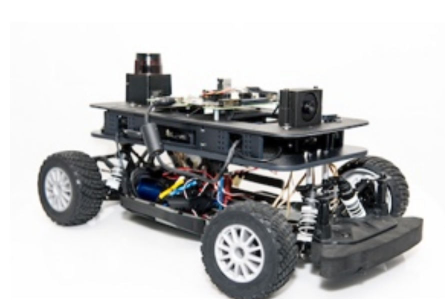
Medical CPS modeling + model checking - Life-saving medical devices, like pacemakers and defibrillators, require a rigorous approach to verifying their safety. How do we ensure that the software on implantable medical devices will perform safely under all conditions?



We will first tackle the question: *How do you mathematically model the human heart?* We will use timed automata to create a virtual heart electrophysiology model which will allow us to formally verify implantable cardiac devices. You will learn about the principles model checking, and verification.

You will learn to use the following tools: **Simulink, StateFlow, UPPAAL**

Automotive CPS modeling + end-to-end learning – End-to-end learning where direct camera inputs can be converted into control actions for an autonomous vehicle is redefining the way we think about modeling automotive systems.



In this fast paced module, you will learn about how to model and test automotive control systems. You will learn how to generate code directly from the model implementation. We will then learn about deep convolution networks and use them for designing an end-to-end learning module for a self driving car.

You will learn to use the following tools: **TORCS, TensorFlow,**

Prerequisites

Ordinary differential equations
Prior experience working with MATLAB and Simulink
Some familiarity with Python
Mathematical maturity (e.g., you were comfortable in a Calculus, or Stat class or you didn't panic in an Advanced Probability class)

Grading Criteria

This course does not have a midterm or a final exam.
The final grade is determined on the basis of completing weekly assignments, and readings in all the modules.
Each module is equally weighted.

The breakdown of weekly worksheets is given below:

Module 1 – Energy CPS: Overall grade (1/3)
The grade breakdown within this module is as follows:

Worksheet 1: 10%
Worksheet 2: 30%
Worksheet 3: 30%
Worksheet 4: 30%

Module 2 – Medical CPS: Overall grade (1/3)
The grade breakdown within this module is as follows:

Worksheet 1: 35%
Worksheet 2: 35%
Worksheet 3: 30%

Module 3 – Automotive CPS: Overall grade (1/3)
The grade breakdown within this module is as follows:

Worksheet 1: 00%
Worksheet 2: 35%
Worksheet 3: 35%

Office Hours

When: Every Monday from 2-3pm unless otherwise specified.
Where: Rice Hall 423

Schedule

Ordering of lectures and due dates of assignment are subject to minor changes.

	Module	Topic	Assignment
Week 1		Course introduction	
		First-principles and state-space modeling	Worksheet 1 out
Week 2	Energy CPS	Energy CPS and HVAC basics	
	Energy CPS	'RC' network building modeling	Worksheet 2 out

			Worksheet 1 due.
Week 3	**Energy CPS**	Introduction to EnergyPlus + Tutorial	
	Energy CPS	Parameter estimation algorithms	Worksheet 3 out Worksheet 2 due
Week 4	**Energy CPS**	Model sensitivity analysis	
	Energy CPS	Predictive control for buildings	Worksheet 4 out
			Worksheet 3 due
Week 5	**Energy CPS**	Energy CPS wrap up lecture	
	Energy CPS	Worksheet 4 class presentation.	Worksheet 5 out Worksheet 4 due
Week 6	**Medical CPS**	Med CPS overview + implantable Cardiac devices	
	Medical CPS	Virtual heart modeling with timed automata	Worksheet 5 due Worksheet 6 out
Week 7	**Medical CPS**	Model checking	
	Medical CPS	UPPAAL tutorial	Worksheet 7 out Worksheet 6 due
Week 8	**Medical CPS**	Simulink model walkthrough	
	Medical CPS	UPPAAL worksheet discussion	Worksheet 7 due. Reading assignment
Week 9	**Medical CPS**	Parameter synthesis for timed automata	
	Medical CPS	Other heart models	
Week 10	**Automotive CPS**	Automotive CPS overview	
	Automotive CPS	Perception, planning, and control for autonomous cars.	
Week 11	**Automotive CPS**	NN and multilayer perceptron	Worksheet 8 out
	Automotive CPS	Convolution NN	
Week 12	**Automotive CPS**	End-to-end learning overview	Worksheet 9 out Worksheet 8 due
	Automotive CPS	Auto CPS implementation discussion + walkthrough	
Week 13		Data-driven modeling other examples Tree based models, ensemble learning	Worksheet 9 due
		Course wrap up.	